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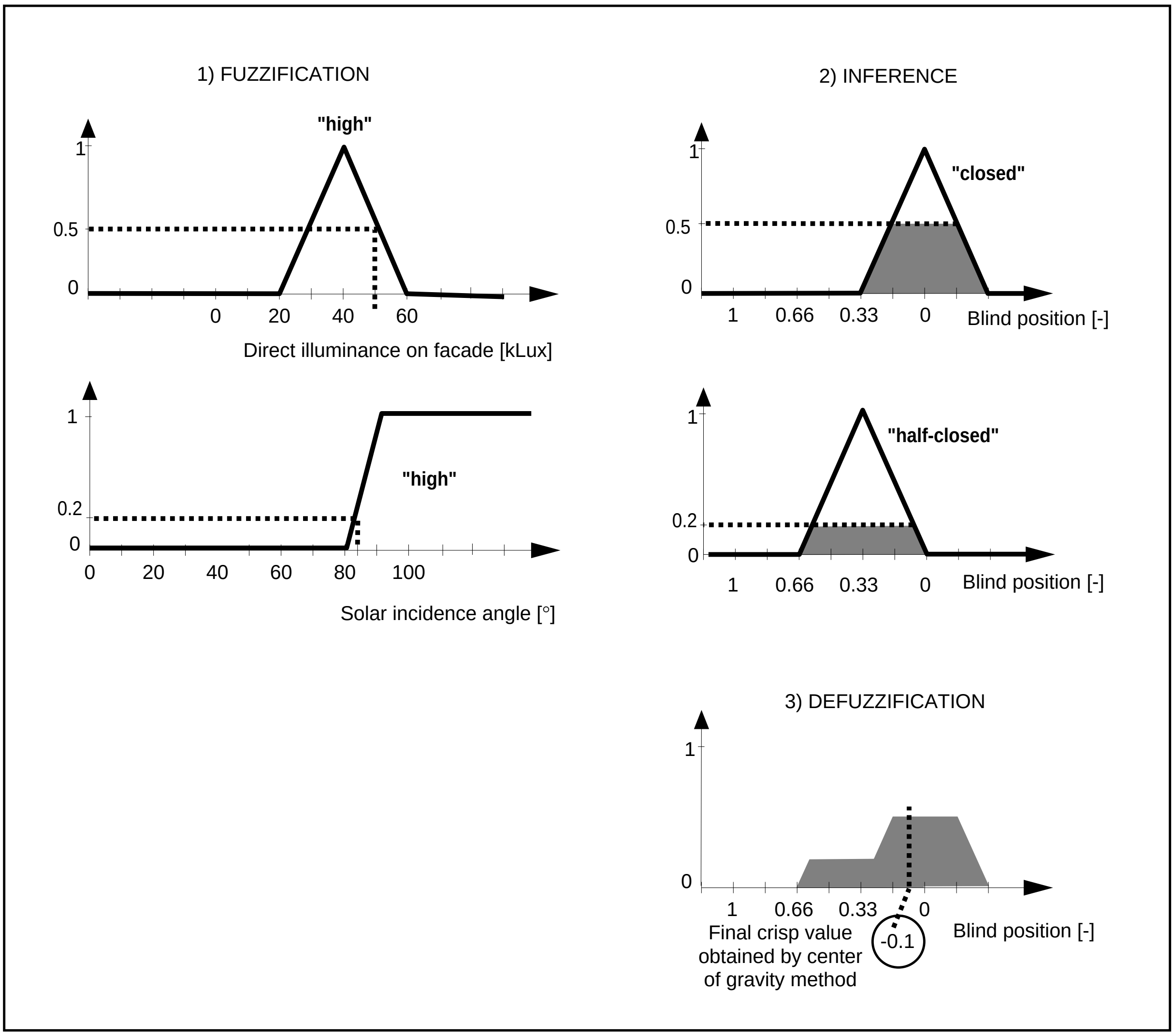
DELTA : A BLIND CONTROLLER USING FUZZY LOGIC



FINAL REPORT - OFEN/BEW Funding No. 50 943

Laboratoire d'énergie solaire et de physique du bâtiment - DA/ITB

November 1996

DELTA : A BLIND CONTROLLER USING FUZZY LOGIC

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1. INTRODUCTION

1.1 A short description of the project

The goal of the project DELTA was to develop an optimal blind controller for a room or a building, taking into account the following factors:

- optimisation of daylighting;
- optimisation of thermal comfort (e.g. to avoid overheating caused by solar gains);
- minimisation of energy consumption (thermal and lighting);
- priority given to the users' wishes.

The project has been undertaken in two steps:

- the elaboration and simulation check of various controller algorithms, including the use of fuzzy logic;
- the experimental check of a controller implemented in an office room of the LESO building, allowing both the validation of the simulation model and the investigation of user response to the various algorithms. The office room is characterised by significant passive solar gains due to the largeness of the window area in proportion to the floor area, and its favourable orientation (South).

The following conditions were given as starting hypotheses:

- the optimisation of blind positioning must take into account both lighting requirements (daylighting and artificial lighting) and passive solar gains in relation with the heating and cooling load of the room;
- the control algorithm must take into account the passive gains (window) and internal gains (office appliances, computers, artificial lighting, persons), using the data from adequate sensors (solar radiation, electricity consumption, IR presence sensor, etc.);
- the control algorithm must be applicable both to buildings equipped with a central control system and to conventional buildings without such equipment; the control algorithm will therefore be available for both types of building, allowing for instance to use it both for new buildings and for renovated buildings. (In the case of the LESO experiment, no central control system will be available.)

1.2 Context of the project

1.2.1 Scientific and technical significance of the project

The control of solar protection blinds is a complex issue so far left without a satisfying answer. Most of the systems used in practice do not take into account all the factors which should be, and they often irritate the users because of too frequent movements which disturb their usual activity. As a consequence, they are often switched off completely, leaving the blind in a permanently inefficient position (for instance always down, even when there is nobody in the room and there would be some possibility of interesting solar gains, or always up, giving some unpleasant glare problems).

The development of an intelligent control algorithm was therefore an interesting task. Such an algorithm had to be based on several criteria (i.e. thermal comfort, daylighting, wind speed, energy consumption and room occupancy) and had to be adjustable by the user.

Fuzzy logic allows the development of a control algorithm that fulfils these requirements. The blind control system can also be integrated into other control systems (temperature and humidity control, artificial lighting control), in order to achieve a permanent optimisation of daylighting and passive solar gains.

1.2.2 Economy and market

Using a good blind control algorithm represents a significant impact on the energy consumption and on the thermal and lighting comfort which can be achieved in buildings. The construction of new buildings or the renovation of existing buildings includes more and more intelligent controller systems, either centralised or by zone. Currently most of these control systems are implemented in office buildings, but the trend will certainly continue in the future, and they will eventually be used in other types of buildings (residential, factories, etc.) as well.

1.2.3 Collaboration and funding

The present project is the continuation of a collaboration between Technical University of Vienna (TUW) and Zumtobel Licht, both in Austria. A first version of the control algorithm, proposed by Zumtobel Licht, was checked (by simulation only) by TUW.

Currently, the project DELTA involves the following participants:
- Landis & Gyr Building Control AG, Zug, Switzerland
- Solar Energy and Building Physics Laboratory (LESO-PB/EPFL), Lausanne, Switzerland
- Technical University of Vienna (TUW), Vienna, Austria (only during the first step)
- Zumtobel Licht AG, Dornbirn, Austria

For the part funded by the Swiss Federal Office of Energy (OFEN/BEW), the LESO-PB has been in charge of leading the collaboration between the project partners. The funding by OFEN/BEW has allowed an experimental check of the first algorithm, and the elaboration of new algorithms and their check, either by simulation or by experimental measurements.

2. BLIND CONTROL: AN OVERVIEW OF THE ISSUE

Basically, blinds play at least three distinct roles:

- daylighting management: protection against glare at places where there are people and achievement of a comfortable visual ambience;
- thermal management: protection against overheating due to too high solar gains (e.g. direct gains through windows), and possible reduction of radiation losses during the night;
- personal comfort management: achievement of a certain degree of privacy and a visual feeling of being "protected" from the outside area.

The project DELTA deals with the first two aspects only. Many studies (at LESO-PB, see for instance [IEA 87]) have been devoted to the optimal use of blinds when considering their thermal role only. However, the conclusions from these studies are not always realistic since they do not take into account the fact that the users do not control the blind position in an optimum way (if they are allowed to at all; if not, they will often get angry against the system because it does not correspond to their wishes, and moreover the thermal optimum is often very far from the daylighting optimum). Usually, they will leave the blind in a position which is likely to be far from the thermal and daylighting optima most of the time.

For the daylighting management aspect, various companies (for example Zumtobel, Somfy, Landis & Gyr) have elaborated systems to control blinds, considering the needed lighting level inside the rooms. From this viewpoint too, the available systems are not always satisfactory: some systems allow a very sophisticated control over the blind position, taking into account several parameters; but many systems are not well accepted by the users, because either they cannot modify the blind position manually and they get irritated by the system, or they do not handle the blind position in an optimum way. Moreover, when users are not present in the room and when there is no presence sensor, they very often forget to switch back to automatic control, which can lead to overheating problems and/or unused solar gains, depending on the season.

In order to elaborate an optimal blind control algorithm, several characteristics of the blinds and related issues have to be considered. The following sections will discuss these points.

2.1 Blind types and efficiency

The blinds can be divided into several categories, considering various aspects of their constitution.

2.1.1 Inside or outside blinds

- Outside blinds: good protection against excessive solar gains (depending on their constitution, they can block up to 100 % of possible solar gains, at the cost of blocking daylighting at the same time), but normally they are very expensive (they must be resistant to outside conditions, e.g. wind and rain).

- Inside blinds: nearly no protection against excessive solar gains (they simply collect the largest part of solar gains and rediffuse them into the room air); on the other hand, they are usually much cheaper; the only exception being opaque insulating elements which can be tightly tied to the window in order to completely block any heat gain through the window.

- Intermediate blinds: some windows are equipped with blinds situated between the glazing panes. The solar protection is a little better than with inside blinds, but not as good as with outside blinds.

All options are equivalent, when considering daylighting.

2.1.2 Blind types and material

- Venetian blinds: they offer the most control flexibility, but two parameters need to be controlled at the same time (the fraction of window obscured by the blind, and the slope of the blades). For most motorised blinds currently available, the slope cannot be easily controlled independently: the blades are horizontal when pulling the blind up, and nearly vertical when pulling it down. Venetian blinds are usually made of metallic blades. Their transmission of radiation may be very low (e.g. less than 1 %, not including the part absorbed and re-emitted as infrared radiation) and so is there transmission of daylighting.

- Textile blinds: usually less efficient (radiation transmission coefficient between 10 and 30 %), less flexible (the only controllable parameter is the fraction of window obscured by blind), but cheaper than venetian blinds (for the same mechanical resistance to outside weather conditions).

- Shutters: much less flexibility of use, but they offer the possibility of using insulating material, which makes them efficient in decreasing the window U-value during the night and efficiently cutting the solar gains even when they are placed inside, at the condition that they are completely closed.

2.1.3 DELTA experiment

The LESO room used for the experiment was already equipped with outside textile blinds. A simple measurement has shown that these blinds cut the solar radiation to about 10 % of the incident radiation (for more details, see section 3.2).

We have decided to keep these blinds, even if they do not represent the best solution. In particular, we know that the users sometimes complain during summer, because even with the blind completely down the solar gains are still too high. On the other hand, the control of such blinds is easier than that of venetian blinds because only one parameter needs to be controlled.

2.2 Thermal aspects

The behaviour of the blind control in the heating season must be very different from that in the hot season. In mid-season, a smooth transition between the two extreme kinds of behaviour should occur progressively.

During the heating season, passive solar gains through the windows should be used the best possible, except if they lead to severe overheating (which can happen, even during winter, especially if the thermal mass is low and/or the window area is large compared to the floor area). The blind can be closed at night, in order to reduce the global U-value of the window (especially for outside blinds), and to increase the mean radiant and comfort temperatures inside the room (for inside blinds).

In contrast, passive gains should be minimized during the hot season, in order to completely avoid overheating. The blinds and windows should be kept open at night, allowing some passive cooling (especially by clear sky, when the night temperature can go much below the day temperature).

The interaction of the heating/cooling system with the blind control should be well investigated. For instance, during late mid-season (just before summer), one should avoid heating in the early morning and try to reduce the solar gains by pulling the blind as low as possible when it is anticipated that the solar gains could lead to overheating.

This issue will be treated in more detail in section 5.4.1.

2.3 Daylighting aspects

In contrast to heating and cooling, daylighting requirements do not depend so heavily on the season. Moreover, the daylighting control can be changed instantly, there is no thermal inertia involved like with thermal behaviour. The blinds should be used to avoid glare when necessary. Several strategies can be elaborated, the most sophisticated ones taking into account the visual comfort of the user, and the most simple ones only the inside illuminance at a reference point (expressed in Lux), either measured by a sensor or calculated by multiplying the outside illuminance by a "daylight factor".

Considering lighting requirements, there is a tight interrelationship between blind control (which control daylighting level) and artificial lighting control. The simpler strategy, used in the DELTA experiment, simply allows an independent control of the artificial lighting, which is adjusted in such a way as to compensate for a lack of daylighting by progressively starting the luminaires.

When there is no user in the room, the blind can be controlled by only taking into account thermal aspects.

For further details, see section 5.4.2.

2.4 Synthetic view of the blind control

There are cases when the thermal and daylighting aspects exhibit contradictory requirements for the blind. For instance during winter, solar gains might be welcome but daylighting will be too strong if the blind is kept up. In such a case, daylighting should be given priority, when there is somebody in the room. When there is no user, only the thermal aspect is considered, allowing for optimized solar gains (i.e. maximized in winter and minimized in summer).

The most important part of the present research work is actually the answer to this issue. We will show how the sometimes contradictory requirements may be given a synthetic answer, and how the priorities have to be considered. The discussion about the controller algorithm and the rule base will be presented in chapter 5.

3. EXPERIMENTAL SETUP : ROOM AND BLIND DESCRIPTION

The present section deals with the description of the room used for the experiment, including the blind and some simple measurements concerning the blind characteristics.

3.1 Room description and characteristics

The LESO building description may be found in either [LESO 81] or [LESO 85]. Basically, the building is made of 9 thermally insulated cells (3 levels with each 3 cells). The Figure 3.2 below shows a picture of the South facade of the LESO building. Most of the cells have space for two office rooms, but some of them have been divided differently, and others not at all, e.g. for a mechanics workshop or a student laboratory.

Figure 3.1 : South facade of the LESO building (the rooms used for the DELTA experiment are highlighted with a thick line)

Figure 3.2 : A closer view of the test rooms' facade

The building was designed to allow an experimental check of various passive solar facades. Most of the 9 cells have a different system each. The two rooms used for the DELTA experiment are included in the middle cell of the lower level. The corresponding facade is the « reference facade » of EPFL Building Step 1 : these rooms have been used to compare the performance of the facade used everywhere in the EPFL Building Step 1, with the performances of other special facades (e.g. a double floor greenhouse, a double skin system, or a high insulation facade manufactured by Geilinger).

The detailed characteristics are given in reference [LESO 85]. Each of the two office rooms used for the DELTA experiment has a floor area of 15.6 m2. The two rooms are similar from the viewpoint of construction, but the users' behaviour is rather different. The simulations have been done on the West room (LESO room # 03). The thermal unit (thermal LESO cell) consists of the two considered office rooms (total 31.2 m2 floor area).

For each office room, the facade (oriented towards the South) consists of the following components :

- a glazed area of 3.77 m2 (triple glazing 4 mm each pane, separated by a 12 mm air gap between each pane) ;
- a 3.55 m2 heavy wall (14 cm concrete) insulated against the outside by 10 cm glasswool, which itself is protected by an aluminium foil (with an air gap between glasswool and aluminium foil in order to allow ventilation) ;
- various frame components which hold the windows (total area 2.85 m2, average U-value 3 W/m2K).

The walls and separations towards the inside spaces of the LESO building have the following characteristics [LESO 81] :

- towards the East (i.e. between the two office rooms used for the DELTA experiment), 14.6 m2 of light wall (two 1.5 cm thick plaster panels separated by a 5 cm air gap) ;
- towards the West, 14.6 m2 of heavy cavity wall (two 10 cm concrete bricks, separated by 8 cm of glasswool) ;
- towards the North, 9.5 m2 of heavy cavity wall (same characteristics as West wall) ;
- ceiling and floor, 15.6 m2 slab sandwich (from bottom to top, 25 cm reinforced concrete, 6 cm insulation, 6 cm screed, 1 cm plastic floor cover).

The relatively small relative importance of the heat transfer between adjacent spaces, when compared to the heat loss towards the outside (less than 5 % of the total heat losses of one cell), implies that a precise modeling of these losses is not essential. Most of the losses occur either directly through the (South) facade, or by air renewal (between the considered cell and the outside, or between the considered cell and the surrounding spaces). The only exception is of course the tight connection between the two office rooms of a same thermal cell, where only a light wall separates the spaces.

Figure 3.3 below shows a plan of the building's ground level. It also shows the good insulation characteristics of the walls between different cells (8 cm glasswool). The floor area of one office room (i.e. half a cell) is 15.6 m2. The South facade, towards the outside, includes 3.77 m2 of triple window glazing (net area), 2.85 m2 of frame components, and 3.55 m2 of heavy wall with 14 cm concrete and 10 cm outside insulation (glasswool).

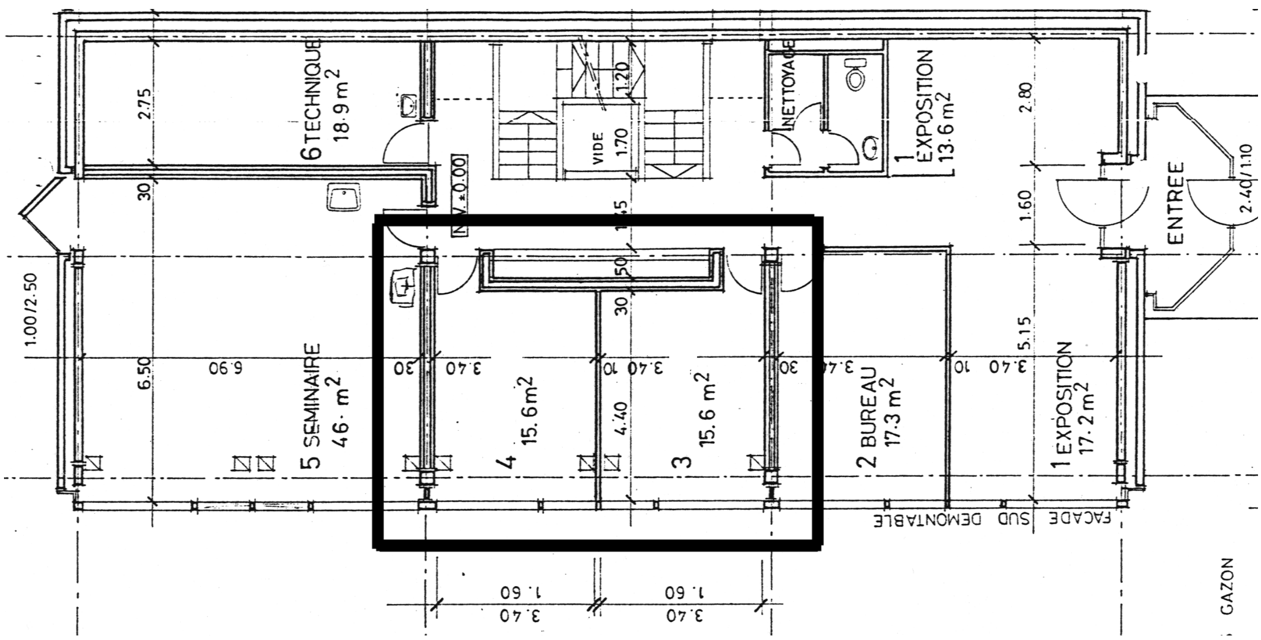

Figure 3.3 : Plan of LESO ground level (the rooms used for the DELTA experiment are highlighted with a thick line)

The ratio of window area to floor area is rather large (24 %). Good solar protection is therefore important in order to avoid summer or mid-season overheating due to high solar gains.

In the original experimental design, we planned to make comparison measurements between the two adjacent rooms belonging to the same thermal cell. One of the rooms would have its blind controlled by the DELTA algorithm and the other directly by the user, or they would be always closed or always open.

We could also have exchanged the roles in order to avoid an experimental bias due to rather different behaviour of the users. Finally, we decided to use the measurements mainly to experiment the users' acceptance of the various blind controller algorithms (using a questionnaire) and to validate the simulation program. For the investigation of the controller algorithm impact, most of the variants were investigated afterwards by simulation only. The advantage of this procedure is the possibility to experiment more algorithms than if we only have the measurements (only one winter season was finally available for the experiment), and to minimize the impact of user behaviour on the energy consumption by using a « standard » user's behaviour for all the simulation runs, which allows a far easier comparison.

3.2 Blind and mechanical control description

The blinds are simple textile outside blinds, of a rather mediocre quality. They roll on a cylinder with can be rotated by an electric engine. The coefficient alpha (the fraction of the glazing not covered by the blind) can be varied between 1 (blind completely up) and 0 (blind down).

The blinds have been connected to the Luxmate system (see section 4.3), which allows the control of the luminaires and blind engine. In order to move a blind, the computer which contains the blind algorithm has to transmit the corresponding command to the Luxmate system. Besides the control, the luxmate system also keeps the current position of the blind.

A simple measurement has been done on the blind, in order to measure its characteristics, both for daylighting and for thermal radiation.

3.2.1 Transmission of daylighting, simple measurement with portable luxmeter

When considering daylighting only, a comparison of the luminance level (in Lux) with the blind completely up and completely down, by overcast sky, has given the following ratio :

E0 (x) / E1 (x) = 0.10 ± 0.02

with E0 (x) = luminance level for alpha = 0 (blind down) at point x
E1 (x) = luminance level for alpha = 1 (blind up), at point x

The value does not significantly depend on the point x chosen (within the limit of the estimated error margin).

3.2.2 Transmission of daylighting, correlation study

In order to check the measurements of the preceding section, another method has been used for deriving daylighting attenuation by the blind. Normal measurements of inside illuminance and outside illuminance have been done during the monitoring periods. These measurements serve to calculate a daylight factor. Since the daylight factor is only defined in a correct way when the sky is overcast (and close to the CIE standard sky), only measurements with such conditions have been selected.

It has also been supposed that the daylight factor varies linearly with the blind fraction alpha. That hypothesis means that the following relation can be used to give the daylight factor :

DF (alpha,x) = DF0 (x) * (1 - alpha) + DF1 (x) * alpha

with DF0 (x) = daylight factor at point x, for alpha = 0 (blind down),
DF1 (x) = daylight factor at point x, for alpha =1 (blind up).

The two figures below show the result for two different points chosen in the room. For the first one, near the window, the values of DF0 and DF1 are 0.019 ± 0.003 and 0.148 ± 0.01 respectively, which leads to a blind transmission factor of 0.13 ± 0.03. For the second point, situated rather deep in the room, the values of DF0 and DF1 are 0.006 ± 0.002 and 0.037 ± 0.005, which gives a blind transmission factor of 0.16 ± 0.06.

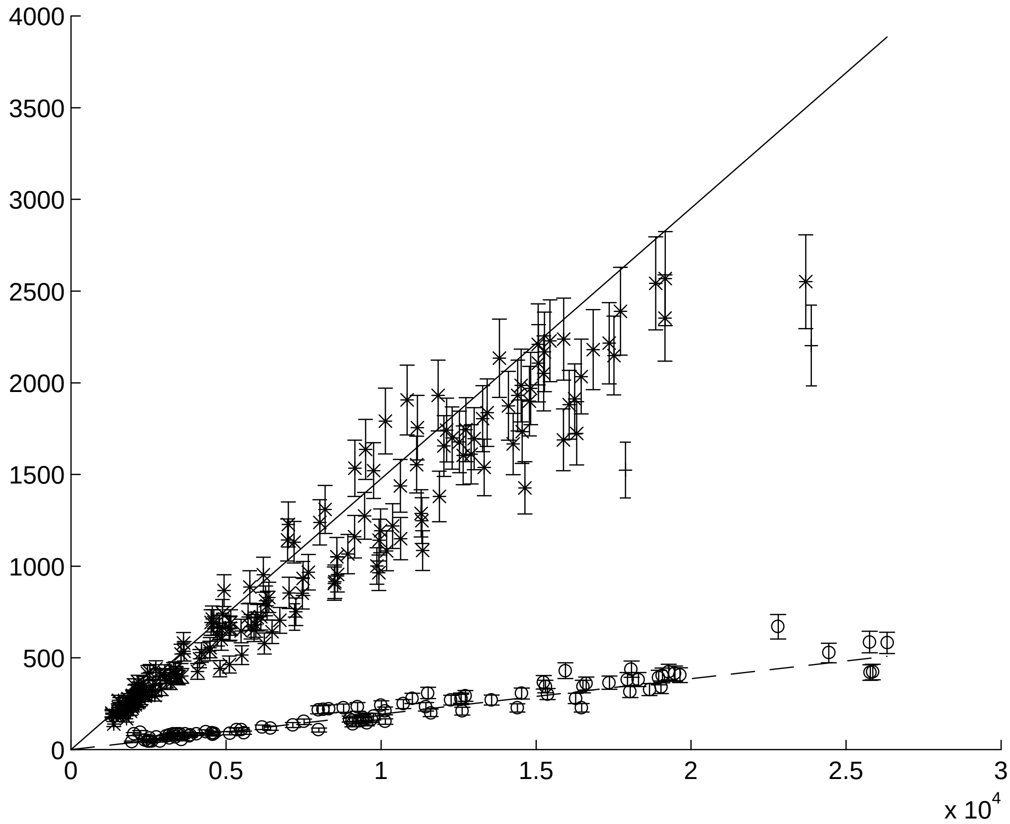

Figure 3.4 : Correlation between outside illuminance on a horizontal plane (lux) and inside illuminance on a horizontal plane at the desk level (lux), for overcast sky and various values of alpha (blind position) ; the two continuous lines represent the fitted values of daylighting factors DF0 (lower line) and DF1 (upper line) ; the inside illuminance is considered on a point rather close to the window

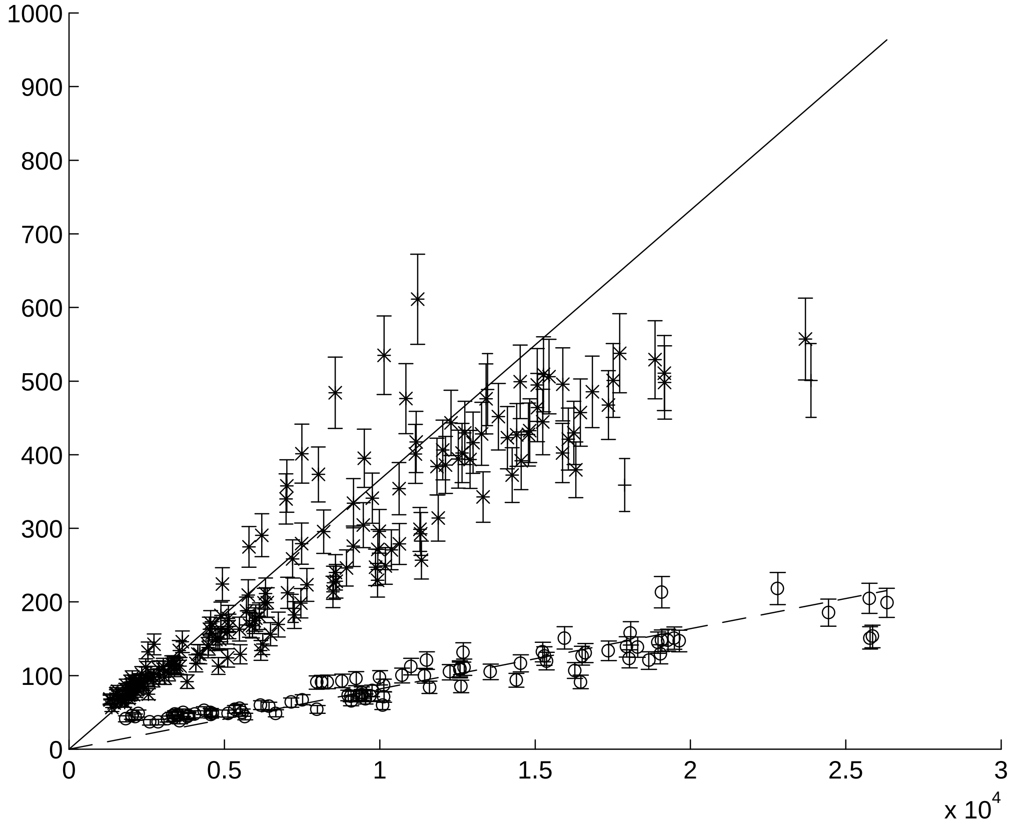

Figure 3.5 : Correlation between outside illuminance on a horizontal plane (lux) and inside illuminance on a horizontal plane at the desk level (lux), for overcast sky and various values of alpha (blind position) ; the two continuous lines represent the fitted values of daylighting factors DF0 (lower line) and DF1 (upper line) ; the inside illuminance is considered on a point far from the window

These values, although not very accurate, are in relatively fair agreement with the value measured by the simple method of the preceding paragraph.

3.2.3 Transmission of thermal radiation, blind up

The transmission of thermal radiation is a little more complex. A simple experimental setup was installed in order to monitor the solar radiation power on a vertical plane (parallel to the window) during several days. The setup is represented in Figure 3.6.

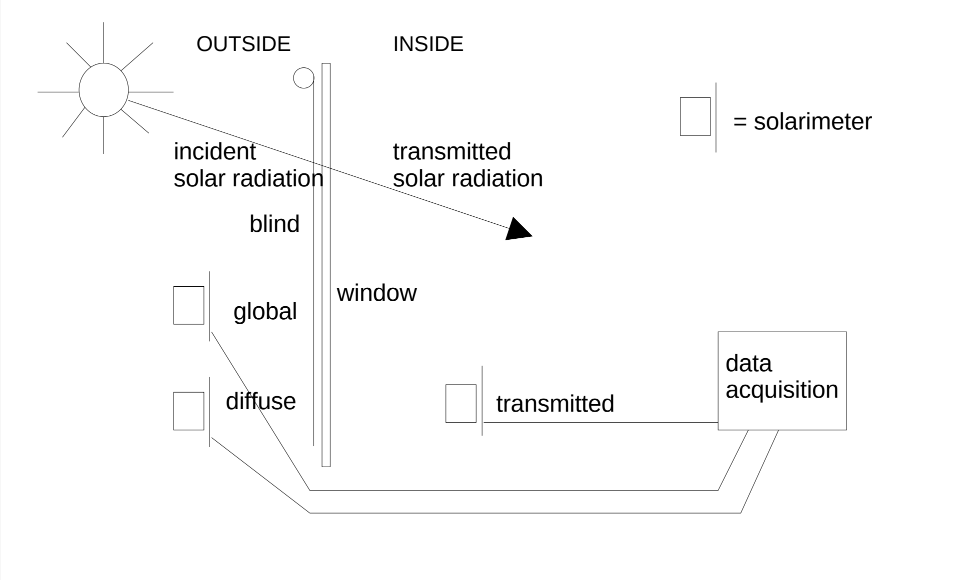

Figure 3.6 : Experimental setup to measure solar thermal radiation transmission as a function of incidence angle of incident radiation

Measurements have been made both for sunny weather and overcast sky, and both with the blind up and down. The first correlation was made with the blind up, using a theoretical expression for the radiation transmission as a function of the incidence angle (see for example [Duffie 74]).

$$\tau = \tau ref \cdot \tau abs$$

where τref is the transmission due to reflection (i.e. if there was no absorption), and τabs is the transmission due to absorption (i.e. if there was no reflection). This expression is an approximation, only valid when τref and τabs are not too far from 1.

The reflection part, taking into account multiple reflection at the interfaces glass-air, is given by the following expression :

$$\tau ref = \frac{1 - \rho}{1 + (2n-1) \cdot \rho}$$

where ρ is the reflection coefficient at one glass-air interface, and n is the number of glazings. The term ρ is given by :

$$\rho = 0.5 \cdot \left(\left(\frac{\sin(\theta 2 - \theta)}{\sin(\theta 2 + \theta)}\right)^2 + \left(\frac{tg(\theta 2 - \theta)}{tg(\theta 2 + \theta)}\right)^2 \right)$$

where θ is the incidence angle, θ2 is the angle of the radiation in the glass (θ2 = arcsin(sin(θ)/ref), and ref if the refraction index (1.526 for normal glass).

On the other hand, τabs is given by the expression :

$$\tau abs = \exp (-kext \cdot l)$$

where kext is the extinction coefficient, and l the total distance of radiation in the glass ($l = e / \cos(\theta 2)$, where e is the total glass thickness).

If we perform measurements with various values of θ, and with different types of weather conditions (sunny or overcast), we can try to adjust the following function :

$$I_{gl,tr} = I_{dir,inc} \cdot \tau_{dir}(\theta) + I_{diff,inc} \cdot \tau_{diff}$$

where Idir,inc is the direct incident radiation [W/m2], Idiff,inc is the diffuse incident radiation [W/m2], and Igl,tr is the global radiation transmitted ; τdir(θ) is the transmission coefficient given over as a function of the incidence angle θ, and τdiff is the transmission coefficient for diffuse radiation. Finally, we can adjust 2 coefficients : the extinction coefficient kext, and the diffuse radiation transmission τdiff. The values adjusted over several days are the following :

$$k_{ext} = 4 \pm 2 \ [m^{-1}]$$

$$\tau_{diff} = 0.51 \pm 0.05$$

3.2.4 Transmission of thermal radiation, blind down

In order to give the value of thermal transmission of the combination blind plus glazing, several blind models can be thought of. The first idea is to consider the blind as a simple attenuator of the thermal radiation, either direct or diffuse, with a constant attenuation whichever the incidence angle is. From the plots, it is evident that this hypothesis is wrong.

The correct hypothesis for our blind (the result would perhaps not be the same for another type of blind), is to consider the blind as a diffuser. It follows therefore that when the blind is down, the thermal radiation transmitted to the inside is independent from the incidence angle, and simply given by the expression :

$$I_{gl,tr} = \tau_0 \cdot I_{gl,inc}$$

where Igl,inc is the global incident radiation [W/m2], Igl,tr is the global transmitted radiation [W/m2], and τ0 is the (constant) transmission coefficient of the blind plus window combination, when the blind is down (alpha = 0). We measured the following value for τ0 :

$$\tau_0 = 0.066 \pm 0.010$$

4. EXPERIMENTAL SET-UP : MEASUREMENT AND CONTROL EQUIPMENT

4.1 Overview of the whole system

The experimental set-up of the DELTA experiment is shown in Figure 4.1. Three subsystems are involved, each controlled by a PC. Their main tasks are :

- Monitoring : 50 sensors are placed in the two office rooms or on the roof of the LESO building (VNR PC) ;
- Control of blind and artificial lighting (Luxmate PC) ;
- Blind control calculation, heating control, data collection and data storage (DELTA-PC) .

The interconnection between the subsystems is made through an Ethernet bus.

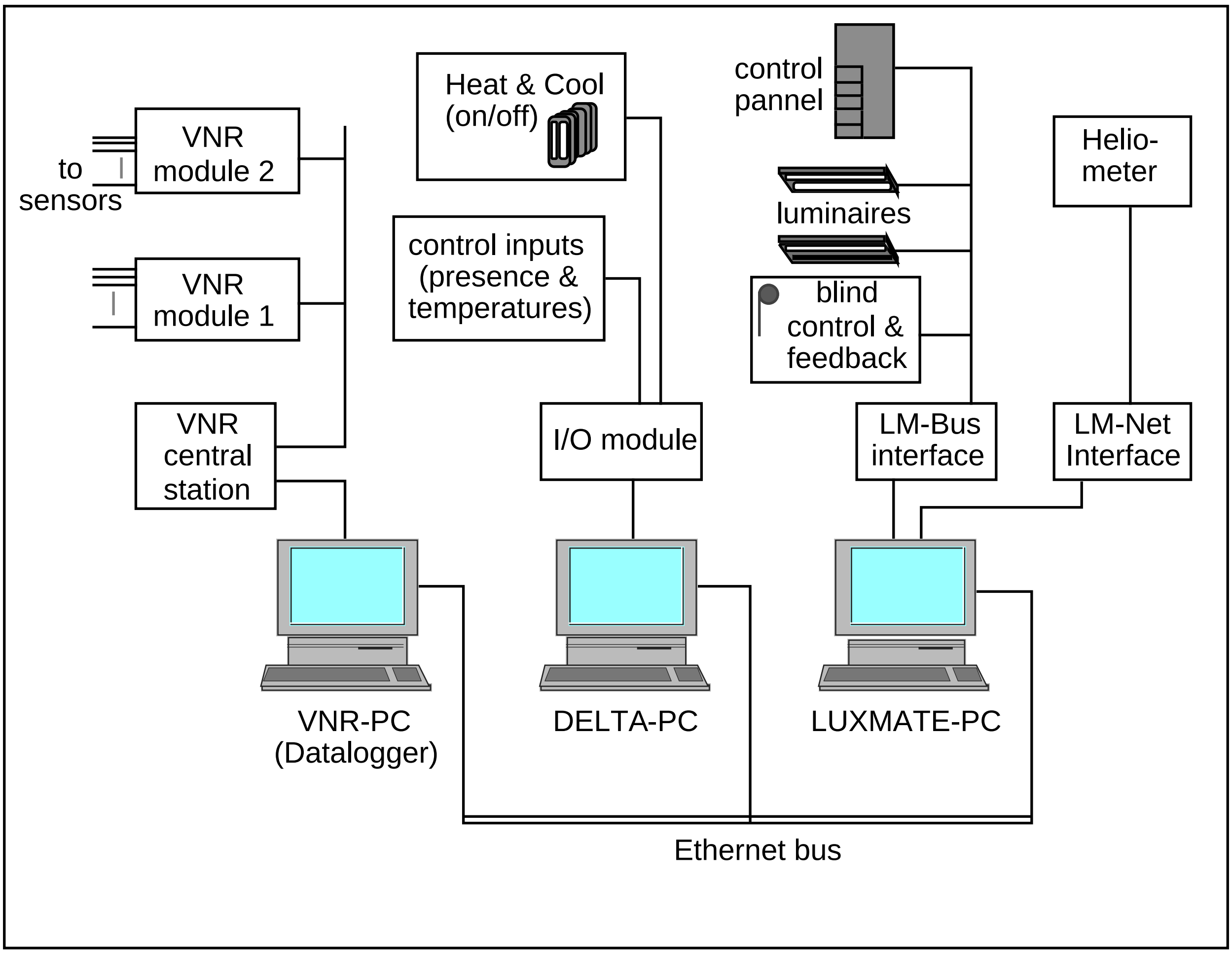

Figure 4.1 : View of the experimental set-up

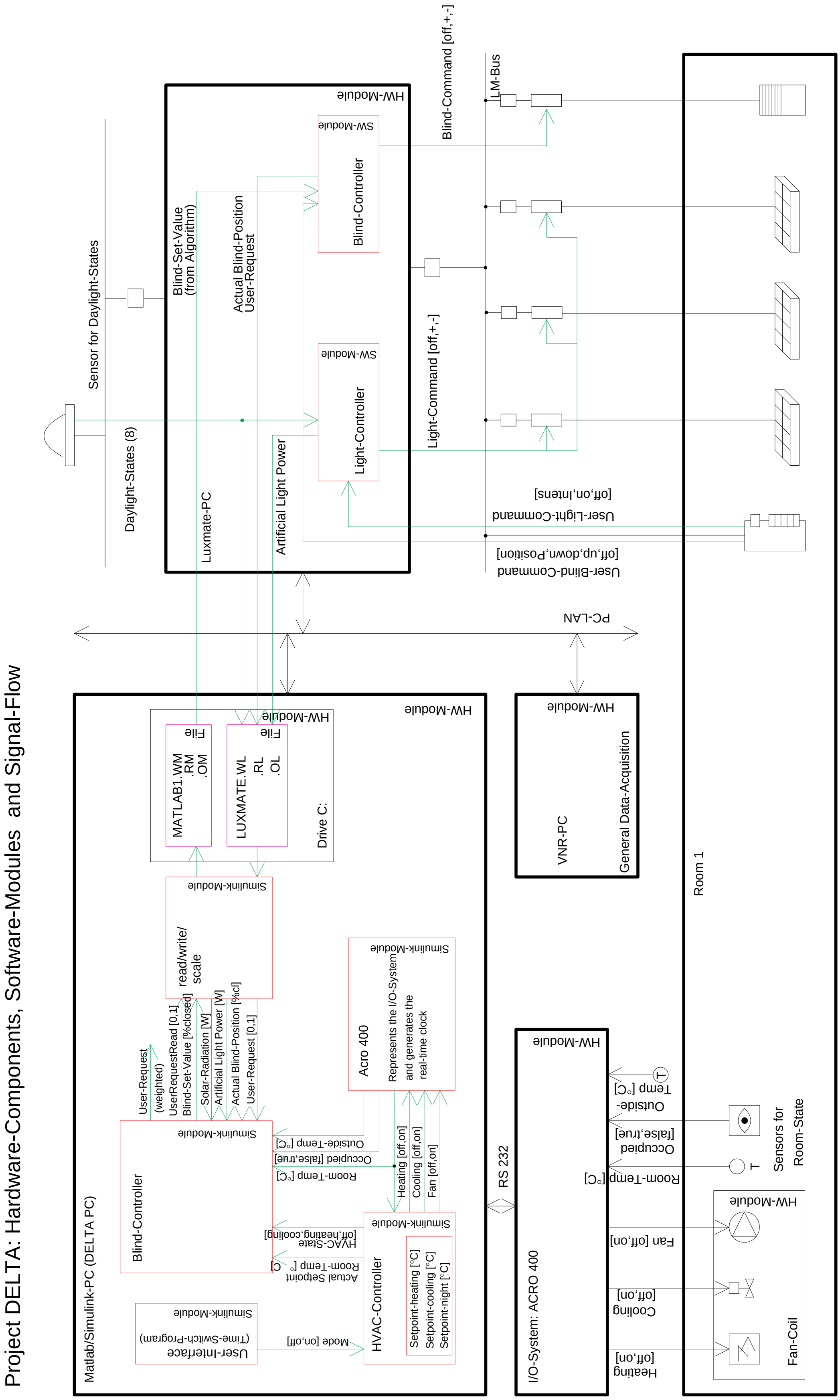

Figure 4.2 : A more detailed view of the data acquisition and control systems

4.2 Data acquisition

The data acquisition is done by a VNR DAU500/s system, which has been in use at the LESO-PB for many years already. It can be programmed and monitor data for different experiments in the building. In our case, as we were interested in meteorological data, it monitored the sensors used for the DELTA rooms and some data from adjacent rooms, including air temperatures, surface temperatures, presence detectors, blind and window position, heating power, indoor luxmeters and many others. The complete list of the monitored sensors used in the project is given in Table 4.1 :

Monitoring sensors (VNR)	Type	Accuracy
METEO		
External Temperature [°C]	Pt100/air	0.1 [°C]
Solar radiation horizontal [W/m2]	Pyranometer	3%
Solar radiation south vertical [W/m2]	Pyranometer	3%
Solar illuminance horizontal [Lux]	Luxmeter Li-50	5%
ROOM 003		
Air temperature [°C]	Pt100/ventilated air	0.1 [°C]
Air temperature down [°C]	Pt100/non-ventilated air	0.1 [°C]
Air temperature up [°C]	Pt100/non-ventilated air	0.1 [°C]
Comfort temperature [°C]	Pt100/black globe	0.1 [°C]
Floor temperature [°C]	Pt100	0.1 [°C]
Ceiling temperature [°C]	Pt100	0.1 [°C]
South wall temperature [°C]	Pt100	0.1 [°C]
North wall surface temperature [°C]	Pt100/surface	0.1 [°C]
South wall surface temperature [°C]	Pt100/surface	0.1 [°C]
People counter [-]	Light cell	20%
Opening door angle [-]	Potentiometer	5%
Opening window angle [-]	Potentiometer	5%
Opening window on/off [-]	switch	-
Opening door on/off [-]	switch	-
Indoor illuminance (window) [Lux]	Luxmeter	10%
Indoor illuminance (room) [Lux]	Luxmeter	10%
Blind position [-]	Potentiometer	5%
Passive cooling hole on/off position [-]	switch	-
Electric power (Force) [W]	Electric counter	2.5%
Electric power (light) [W]	Electric counter	2.5%
DELTA on/off signal [-]	switch	-
ROOM 004		
Air temperature [°C]	Pt100/ventilated air	0.1 [°C]
Air temperature down [°C]	Pt100/non-ventilated air	0.1 [°C]
Air temperature up [°C]	Pt100/non-ventilated air	0.1 [°C]
Comfort temperature [°C]	Pt100/black globe	0.1 [°C]
Floor temperature [°C]	Pt100	0.1 [°C]
Ceiling temperature [°C]	Pt100	0.1 [°C]
South wall temperature [°C]	Pt100/surface	0.1 [°C]
South wall surface temperature [°C]	Pt100/surface	0.1 [°C]
People counter [-]	Light cell	20%

Opening door angle [-]	Potentiometer	5%
Opening window angle [-]	Potentiometer	5%
Opening window on/off [-]	switch	-
Opening door on/off [-]	switch	-
Indoor illuminance (window) [Lux]	Luxmeter	10%
Indoor illuminance (room) [Lux]	Luxmeter	10%
Blind position [-]	Potentiometer	5%
Electric power (Force) [W]	Electric counter	2.5%
Cooling on/off [-]	switch	-
Electric power (light) [W]	Electric counter	2.5%
DELTA on/off signal [-]	switch	-
Input cooling temperature [°C]	Pt100/water	0.1 [°C]
Output cooling temperature [°C]	Pt100/water	0.1 [°C]
NEIGHBOUR ROOMS		
Corridor temperature [°C]	Pt100/ventilated air	0.1 [°C]
West room Air temperature [°C]	Pt100/non-ventilated air	0.1 [°C]
West room surface temperature [°C]	Pt100/surface	0.1 [°C]
Upper 003 Air temperature [°C]	Pt100/ventilated air	0.1 [°C]
Upper 004 Air temperature [°C]	Pt100/ventilated air	0.1 [°C]
Upper 003 surface temperature [°C]	Pt100/surface	0.1 [°C]
Upper 004 surface temperature [°C]	Pt100/surface	0.1 [°C]
Upper 003 floor temperature [°C]	Pt100	0.1 [°C]
Upper 004 floor temperature [°C]	Pt100	0.1 [°C]

Table 4.1 : List of monitored sensors in the DELTA project

4.3 Luxmate system

The artificial lighting is controlled through a standard, commercial product : The Luxmate system [Zumtobel 95]. The PC Luxmate is linked with PC-DELTA through Ethernet but it also has two other interfaces :

- The LM-Bus, to which lamps, user command panel and blind are connected.
- The LM-Net is used to read values from the Heliometer. The Heliometer is a complex sensor made of 8 luxmeters and 1 radiometer (part of Luxmate system).

4.4 Blind, heating and cooling controllers

The DELTA-PC is the centre of the experiment; its main tasks are :

- The real-time acquisition (one minute interval) of data used in the control loops (heating and blind control). The interface between the input sensors and the PC is made by an external I/O module (ACRO-400, Analogic Corporation).
- The output for heating control (I/O module interface).
- Heating and cooling loop control. It is based on a classical closed loop on the internal temperature. The heating set point is 20 [°C] with an hysteresis of ±0.5 [°C] and the cooling

set-point is 24 [°C] with an hysteresis of ±0.5 [°C]. No night setback schedules were implemented.

- The blind control loop, based on different algorithms that are described in chapter 5.3 and 6.
- Data collection from VNR, Luxmate and I/O module. Data are stored in two files (interval of 5 and 15 minutes).

Control sensors	Connection	Type	Accuracy
External Temperature [°C]	I/O Module	ventil	0.2 [°C]
Air temperature 003 [°C]	I/O Module	chrome	0.2 [°C]
Air temperature 004 [°C]	I/O Module	chrome	0.2 [°C]
Presence detector 003 [-]	I/O Module	I-R	(*)
Presence detector 004 [-]	I/O Module	I-R	(*)
Solar radiation [W/m2]	LM-net	Heliometer	10%
Solar illuminance [Lux]	LM-net	Heliometer	10%
Blind position 003	LM-bus	Zumtobel	1%
Blind position 004	LM-bus	Zumtobel	1%
User wish 003	LM-bus	Zumtobel	
User wish 004	LM-bus	Zumtobel	
Heating and cooling power 003 [W]	calculated	-	(**)
Heating and cooling power 004 [W]	calculated	-	(**)

Table 4.2 : Sensors used for control.

(*) The presence detector is switched on 30 seconds after presence detection and switched off after 15 minutes.

(**) The heating power was calculated by the PC-heat controller

All of these tasks are managed under the MATLAB/SIMULINK software. A view of the Simulink diagram is given in Figure 4.3.

The blind control algorithm is implemented in the DELTA-PC, but the control itself is done by the Luxmate system. The reason of this complex experiment set-up is the need of a data acquisition system and the use of a commercial product for artificial light and blind control. In a future practical implementation, data acquisition would not be necessary and all the software for calculation and control would fit in the same PC.

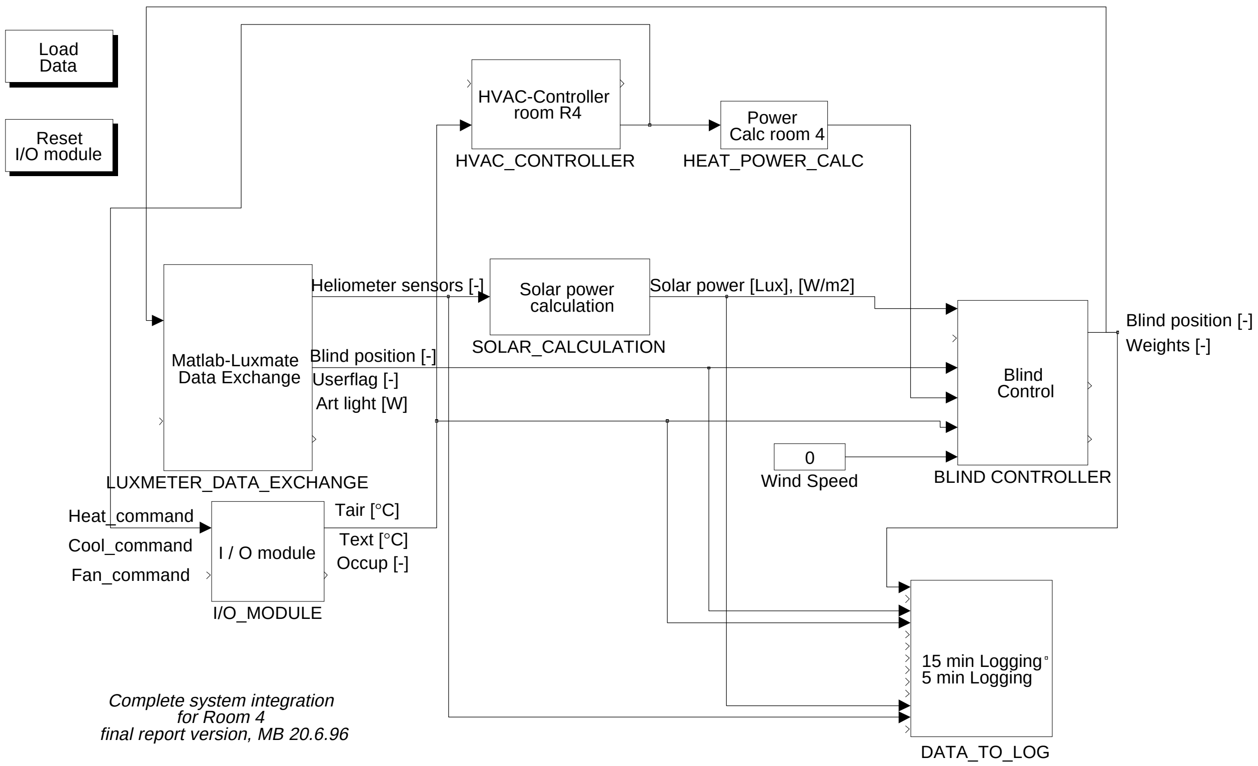

Figure 4.3 : Block diagram of DELTA-PC : software for control and data acquisition

5. THE USE OF FUZZY LOGIC FOR A CONTROLLER

5.1 Fuzzy logic

5.1.1 Fuzzy sets and subsets

Fuzzy logic is an extension to conventional (Boolean) logic. It can handle the concept of partial truth (truth values between "completely true" and "completely false"). It was first introduced by L. Zadeh in 1960's [Zadeh 65], as a means to model the uncertainty of natural language.

A fuzzy subset is characterized by a membership function defined on a fuzzy set. An example of the subset "low" of the set "external temperature" is given in Figure 5.1.

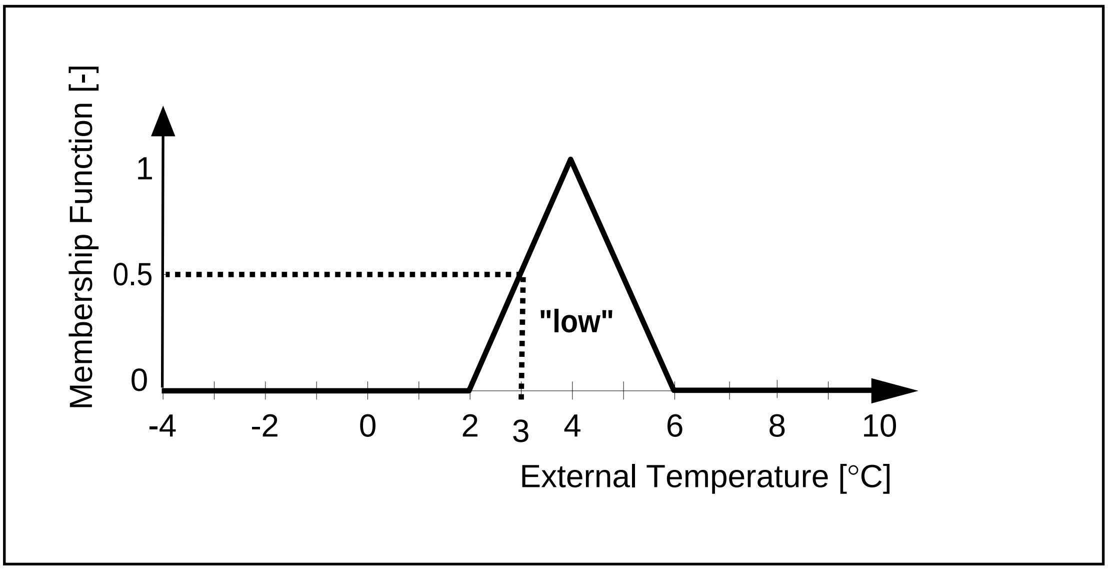

Figure 5.1: Definition of the fuzzy subset "low" for the set "external temperature"

In fuzzy expert systems, a fuzzy set is usually called a fuzzy variable and a subset, a fuzzy value (or a membership function) of this variable. A fuzzy variable can take many different values, characterised by membership functions. An example of the values of the fuzzy variable "external temperature" is given in Figure 5.2.

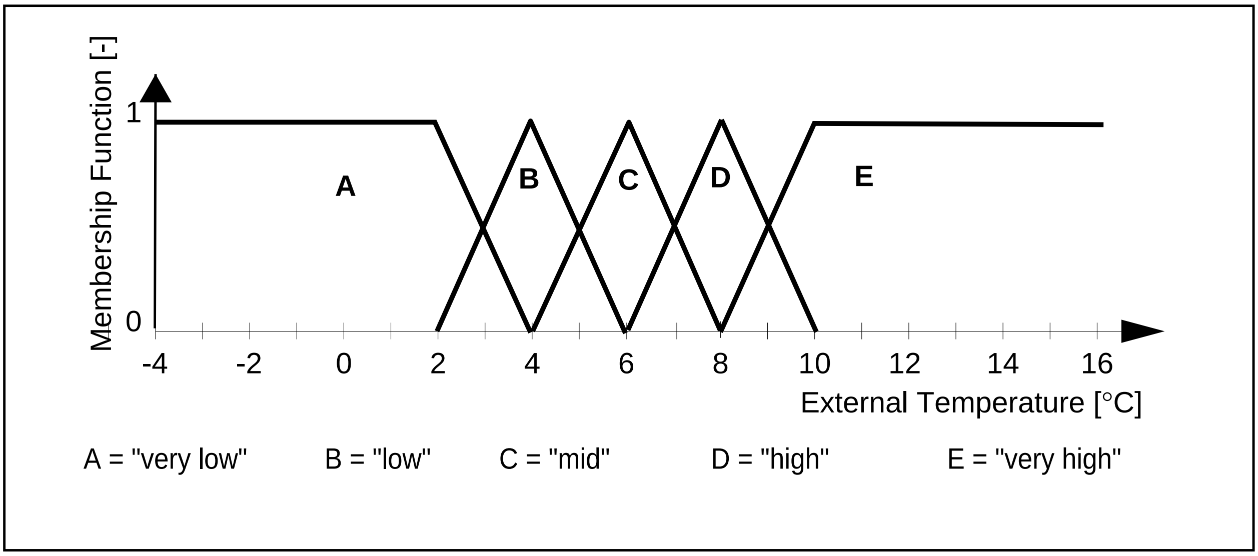

Figure 5.2: Definition of the membership functions for the fuzzy variable "external temperature". (These membership functions represent only an example and do not correspond to fuzzy logic controller used).

5.1.2 Fuzzy expert system

A fuzzy expert system (FES) contains many fuzzy variables and rules. The set of rules is known as the rule base. The rules are usually of the following form:

If x is "low" and y is "high" then z = "medium"

Where, x and y are input variables, z is an output variable. "low", "high" and "medium" are membership functions respectively defined on x, y and z.

The way to use rules with fuzzy variables is to give degrees of truth to the premise (left part) of a rule according to the actual value of the input variables. The premise "if external temperature is low" has a degree of truth of 0.5, if the actual value of the external temperature is 3 [°C] (the definition of "low" is given in Figure 5.1). The conclusion (right part of a rule) assigns a membership function to the output variable, balanced by the degree of truth of the premise.

5.2 Fuzzy logic controller

5.2.1 The inference process

Fuzzy logic can be used for control application [Bühler 94]. In this case, the value of the output variable needs to be a real number and not a fuzzy one.

The general process, which serves to determine the output of a FES using expert rules, is called the inference process; it proceeds in three steps:

a) FUZZIFICATION: the actual values of the input variables are applied to the membership functions of the input variables, to determine the degree of truth for each rule premise.

b) INFERENCE: the truth value for the premise of each rule is computed and applied to the conclusion part of each rule. This results in one fuzzy value assigned to the output variable for each rule. Then, a composition is done with all of the fuzzy values assigned to each output to form a single fuzzy subset.

c) And finally, DEFUZZIFICATION converts the fuzzy output subset to a crisp number. Usually a centre of gravity method is applied for that purpose.

Example:

Let us suppose a short rule base:

- If external temperature is "medium" then heating is "unchanged"
- If window openings are "frequent" then heating is "reduced"

Assuming the following as actual values of input variables (measurements):

Text = 5 [°C]

Number of window openings = 4 [-]

Figure 5.3 shows how the output variable (heating power supply) is determined in this case.

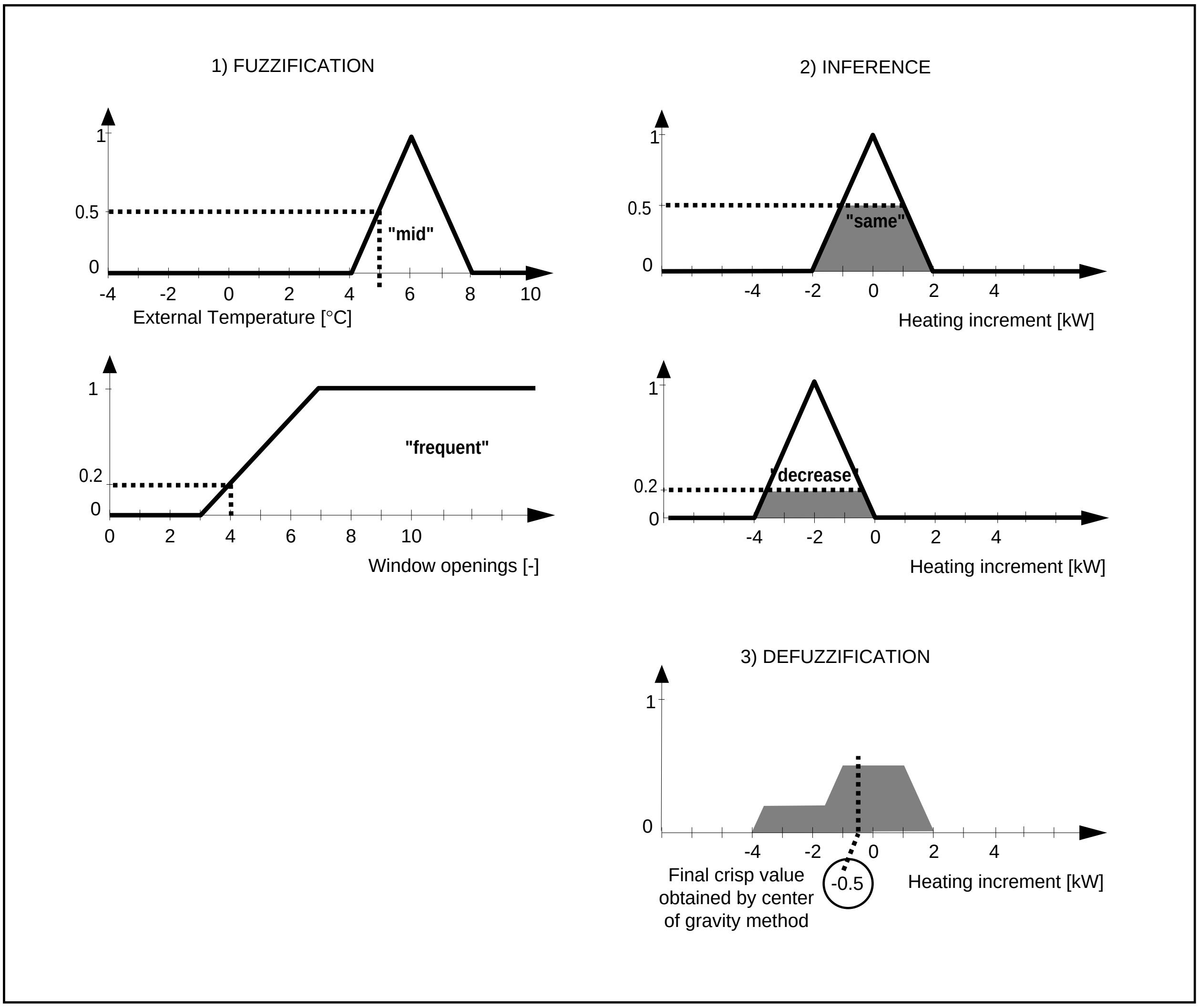

Figure 5.3: Inference process used to calculate the increment value for heating.

5.2.2 Conclusion

The fuzzy approach allows a control of non-linear systems without a deep knowledge of their mathematical model. Fuzzy rules are easily generated by imitating an expert's behaviour. However, membership functions for every input and output should be well defined.

5.3 First version of blind control algorithm

The three versions of blind control algorithms considered in the present project are given in the next table:

Versions	Authors	Comments
1	TU-WIEN/ ZUMTOBEL LICHT	Initial fuzzy algorithm
2	LESO	DELTA standard version (fuzzy)
3	LANDYS & GYR	Classical artificial intelligence algorithm

Table 5.1: The three versions of the blind control algorithm

A fuzzy algorithm applied to the blind control was first developed at TU.-WIEN [Wurmsdobler 94]. It is described in chapters 5.3.1 and 5.3.2. The initial goal of the DELTA project was to test and adapt this algorithm in a real scale experiment at LESO. Some problems of concept appear nevertheless in the TU.-VIEN program (5.3.4). For this reason new controllers based on different principles were proposed by LESO (5.4) and Landis&Gyr (5.5).

The following text is taken from [Wurmsdobler 94] and is slightly adapted to the modification proposed during the DELTA project.

The control algorithm basically consists of three parts, one calculating a blind position and a weight of the control action from the HVLK (thermal energy) point of view. A second part calculates the user wish, depending on stored wishes and user interrupts. The third part makes a synthesis of the upper ones. This is shown in Figure 5.4.

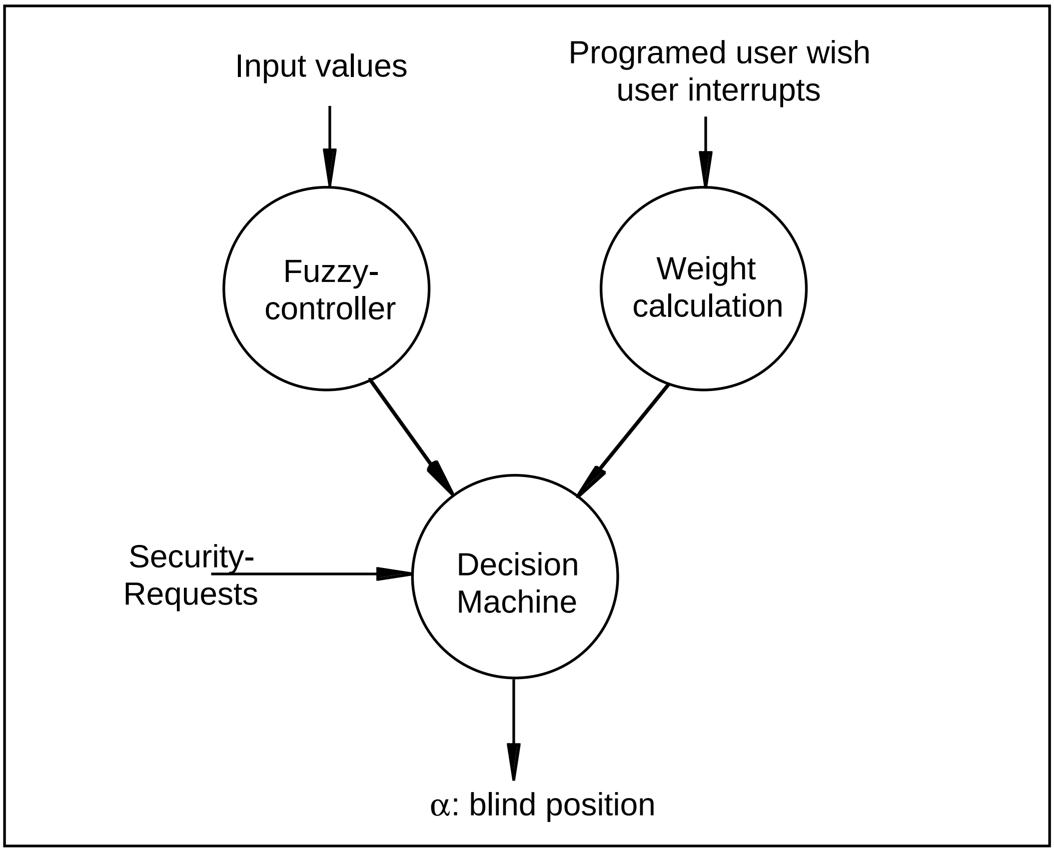

Figure 5.4: Initial structure of the control algorithm

5.3.1 Fuzzy controller

A fuzzy controller for the window blind is proposed to provide a strategy to minimise the thermal energy needs of a room. The algorithm consists in identifying the relevant input variables and then elaborate expert rules combining them and giving the blind position.

Input variables for the controller

Gv - the vertical solar radiation [W/m2], with three fuzzy sets low, middle, high
Phvac - the power for heating or cooling given by the HVAC controller, with three fuzzy sets negative, zero, positive.
Ti - the room temperature, with three fuzzy sets cold, comfortable , warm
Te - the outside temperature, with three fuzzy sets cold, middle, warm
α - the current window blind position with three fuzzy sets closed, medium, open

For all input variables, three triangular membership functions or fuzzy sets are used. This is done in order to simplify the rule base.

Since there are 5 input variables, the total number of possible rules would be 3^5=343, which is quite a lot. In this case a combination of 3 and 2 input variables are used for two separate rule bases, then the outputs are combined together.

Output of this fuzzy controller is the differential blind position (how much they should be moved), and the weight of this control output denoting the importance of the control action. For reasons of computation speed, singletons are used for the output: They are defined as:

$\Delta\alpha$ The differential blind position, with five fuzzy sets down, bitdown. equal, bitup and up.

γ The weight, with three fuzzy sets unimportant, important and most important

The fuzzy controller should be adapted by thermal physics experts to find an optimum regarding the energy consumption for the room. It does not consider any user wishes.

Rule bases for blind position

```
%    IF T_room      AND P_Sun      AND Blinds          THEN
BLINDS

RB_TS = [
     T_roomcold,    P_sunlow       Blindsclosed,       equal;
     T_roomcomf,    P_sunlow       Blindsclosed,       bitup;
     T_roomwarm,    P_sunlow       Blindsclosed,       up;
     T_roomcold,    P_sunmiddle    Blindsclosed,       bitup;
     T_roomcomf,    P_sunmiddle    Blindsclosed,       bitup;
     T_roomwarm,    P_sunmiddle    Blindsclosed,       bitup;
     T_roomcold,    P_sunhigh      Blindsclosed,       up;
     T_roomcomf,    P_sunhigh      Blindsclosed,       bitup;
     T_roomwarm,    P_sunhigh      Blindsclosed,       equal,
     T_roomcold,    P_sunlow       Blindsmedium,       down;
     T_roomcomf,    P_sunlow       Blindsmedium,       bitdown;
     T_roomwarm,    P_sunlow       Blindsmedium,       up;
     T_roomcold,    P_sunmiddle    Blindsmedium,       bitup;
     T_roomcomf,    P_sunmiddle    Blindsmedium,       equal;
     T_roomwarm,    P_sunmiddle    Blindsmedium,       bitup;
     T_roomcold,    P_sunhigh      Blindsmedium,       up;
     T_roomcomf,    P_sunhigh      Blindsmedium,       bitdown;
     T_roomwarm,    P_sunhigh      Blindsmedium,       down;
```

```
    T_roomcold,    P_sunlow       Blindsopen,         down;
    T_roomcomf,    P_sunlow       Blindsopen,         bitdown;
    T_roomwarm,    P_sunlow       Blindsopen,         equal;
    T_roomcold,    P_sunmiddle    Blindsopen,         bitdown;
    T_roomcomf,    P_sunmiddle    Blindsopen,         bitdown;
    T_roomwarm,    P_sunmiddle    Blindsopen,         bitdown;
    T_roomcold,    P_sunhigh      Blindsopen,         equal;
    T_roomcomf,    P_sunhigh      Blindsopen,         bitdown;
    T_roomwarm,    P_sunhigh      Blindsopen,         down];
```

Table 5.2: Rule base for blind position, according to indoor temperature, solar radiation and previous blind position

```
%   IF P_heat      AND T_ext      THEN BLINDS

RB_HT = [
    P_heat neg,    T_ext cold,    up;
    P_heat zero,   T_ext cold,    equal ;
    P_heat pos,    T_ext cold,    down ;
    P_heat neg,    T_ext middle,  bitup ;
    P_heat zero,   T_ext middle,  equal;
    P_heat pos,    T_ext middle,  bitdown ;
    P_heat neg,    T_ext warm,    down;
    P_heat zero,   T_ext warm,    equal ;
    P_heat pos,    T_ext warm,    up ];
```

Table 5.3: Rule base for blind position, according to external temperature and heating power.

Following the inference process described in 5.2.1, a membership function is assigned to the output variable (blind position change) for each called rule. In the present case the output fuzzy values are singletons. The min-max method [Bühler 94], a simpler method than the center of gravity method, is finally used for DEFUZZIFICATION.

Rule base for weighting

A weighting factor is attributed to the fuzzy control calculated position. It serves to choose the final value for the blind position when user wishes are added (see below).

```
%   IF P_heat      AND P_sun      THEN HVAC

RB_GW = [
    P_heat neg,    P_sun low,     important;
    P_heat zero,   P_sun low,     unimportant;
    P_heat pos,    P_sun low,     mostimportant ;
    P_heat neg,    P_sun middle,  important;
    P_heat zero,   P_sun middle,  unimportant ;
    P_heat pos,    P_sun middle,  mostimportant ;
    P_heat neg,    P_sun high,    mostimportant ;
    P_heat zero,   P_sun high,    important ;
    P_heat pos,    P_sun high,    mostimportant ];
```

Table 5.4: Rule base for the weight given to the calculated blind position considering energy efficiency.

5.3.2 User wishes

The second part of the algorithm computes the weight of the user wish depending on whether the wish is spontaneous or programmed. If there is a user interrupt, the weight is a time dependent decreasing function as defined in the next figure. It corresponds to a position manually chosen by the user. Stored programmed values (blind position and weight) are also possible.

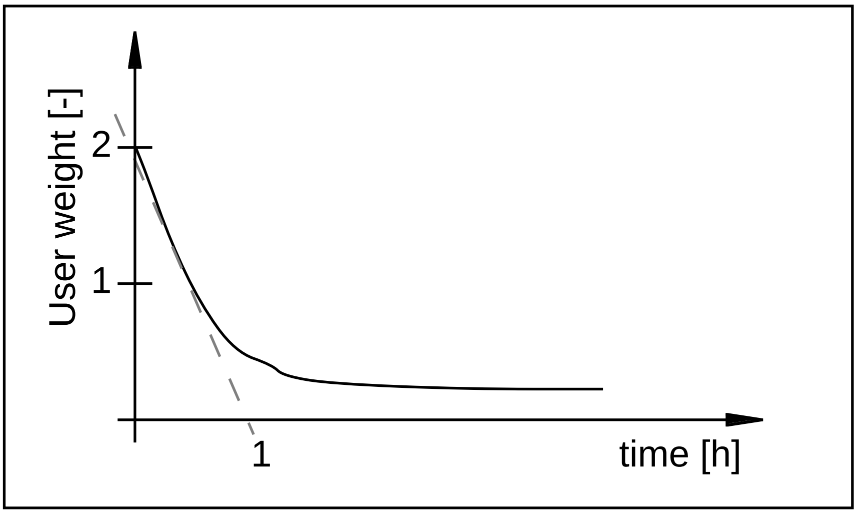

Figure 5.5: definition of the weight attributed to the user choice

5.3.3 Combination of fuzzy logic output and user wishes (final choice for the blind position)

The output weight is the maximum of both values. The blind position with higher weight is then considered for the output setpoint blind position. If the final output is the fuzzy calculated position, the commanded blind position is the nearest value between ten possible ones (to avoid too many blind changes). Otherwise (user wish), the position is kept at the value chosen by the user.

5.3.4 Problems and critics of the algorithm

The initial fuzzy algorithm proposed by TU-WIEN consists in rules combining the following fuzzy variables: internal temperature, solar radiation (orientation not specified), ambient temperature, blind position and heating power. Experts in building physics were asked to correctly define the variables so that the algorithm would give satisfactory results. The most significant variables are used to find a blind control algorithm optimising energy consumption, however, problems regarding the algorithm consistency can be noticed:

- No visual consideration is taken into account.
- The rule base implicitly includes a control of the indoor temperature (see Table 5.2). It tries to keep the indoor temperature around the « comfortable » fuzzy value. As a consequence, a rule can have an opposed effect to the HVAC controller (see below). The algorithm is therefore not efficient in optimizing the energy efficiency.
- No long term management of energy consumption is considered.
- The rule base depends on the window and the blind characteristics, which means that the complete rule base has to be adapted in every new application case.

- The rule base is too large (almost every combination of variable considered) and consequently too difficult to adjust finely even for building physics expert, because of the unclear effect of rules.

Some of these points are detailed in the following paragraphs:

A rule can make an effect opposed to a HVAC controller

The heating power is correctly considered as an input variable. The problem is that in all the rules where it is used, the blind position chosen may have the effect of heating the room when the heating system is cooling. The reverse effect is also possible. For example consider the rule:

IF P_heat is positive AND T_ext is cold THEN blind down

The action of closing the blind will often have the effect of reducing solar gains, therefore the rule will reduce the heat flow from the outside to the inside through the window. The insulation effect of closing is generally smaller. This rule clearly has an opposite effect to the heating system.

No long term saving of energy is considered (thermal inertia not considered)

The total energy supplies over a day are much more effective if they are optimised over the complete one day period [Oestreicher 95]. Instantaneous control may result in energy waste with heating and cooling during the same day. In the rule base, this aspect is not taken into account and only instantaneous control is considered.

The rule bases depend on the window and blind characteristics.

Let us for example consider the rule:

IF Ti is cold AND Gv is middle AND blinds are open THEN blind bitdown

We guess that the goal of this rule is to warm up the room (assuming that it is cold, because of a low external temperature), by reducing heat losses due to cold outside temperature. But the effect of closing the blind on the energy balance of the blind and window system is not clear. Let us suppose that the external temperature is low. If the window is a high insulation device then the room will not lose much heat through the window and the sun radiation will provide gains. In that case we should open the blind at maximum. But if the window is poorly insulated, solar gains will not be enough to compensate for the losses and we should close the blind. This clearly shows that the rules depend on the window and blind characteristics, which is a problem for any practical implementation.

5.4 A new fuzzy blind controller (version 2)

Due to the weaknesses of the initial energetic algorithm and the lack of visual comfort, a new algorithm has been proposed (a variant of that algorithm considering visual comfort was tested at Zumtobel, but not in the framework of the present project). It is based on three modules:

1) Optimised energy management: a completely new concept has been developed at LESO, based on the energy balance of the window and blind system.

2) Optimised visual comfort: this aspect is not taken into account in the initial algorithm. The proposed algorithm results from the recommendation of the CIE [CIE 83], discussions with daylighting experts, the technical manager of a large bank building, and people from industry.

3) User wishes: this part has not been modified from the initial algorithm. The opportunity to choose any blind position at any time is kept. Some new propositions concerning lighting ambiance are included.

5.4.1 Optimised energy management

A thermal model for a window with a blind

Let us consider a simple thermal static model for a window equipped with a blind system. The power balance of heat brought to building per square meter of window can be written as:

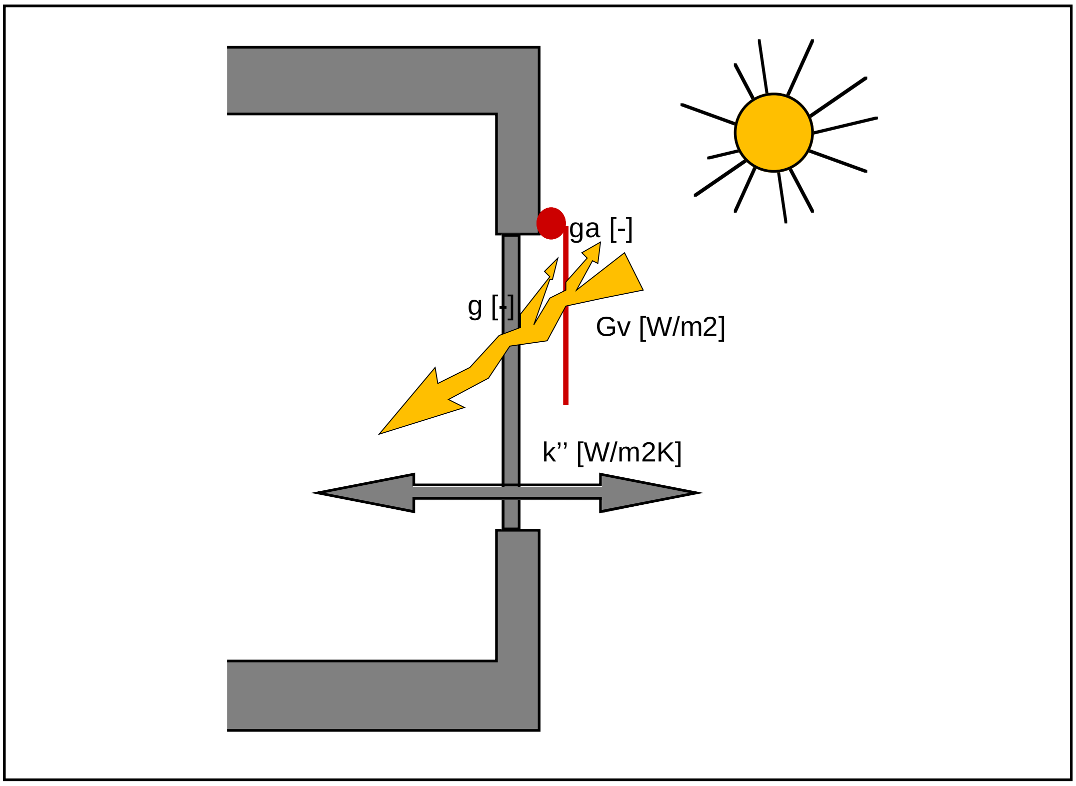

Figure 5.6: Thermal static model for a window and a blind system

$$P_s = \underbrace{G_v \cdot g \cdot \alpha}_{\text{Solar gains through open blind part}} + \underbrace{G_v \cdot g \cdot g_\alpha \cdot (1-\alpha)}_{\text{Solar gains through closed blind part}} - \underbrace{k'' \cdot (T_i - T_e)}_{\text{Heat losses through window and blind}} \qquad \text{(eq. 5.1)}$$

with

$$k'' = \underbrace{k \cdot \alpha}_{\text{Heat losses through open blind part}} + \underbrace{(1-\alpha) \cdot \underbrace{\left(\frac{k}{1 + R \cdot k}\right)}_{\text{k': k value of a window and a closed blind}}}_{\text{Heat losses through closed blind part}} \qquad \text{(eq. 5.2)}$$

where:

α [-]	- Blind position, 0≤ α ≤1 (α =1 means blind open)
k [W/m2K]	- Heat-loss coefficient of window (convective + radiative)
G_v [W/m2]	- Global vertical solar radiation
g [-]	- Solar transmission coefficient of window (energetic)
g_α [-]	- Solar transmission coefficient of blind (energetic)
R [m2K/W]	- Thermal insulation coefficient for blind

It means that if Ps>0 then solar radiation heats the building through the window and if Ps<0 then heat losses cool the building through the window. The Figure 5.7 shows the dependency of this power balance on the external temperature and the solar radiation.

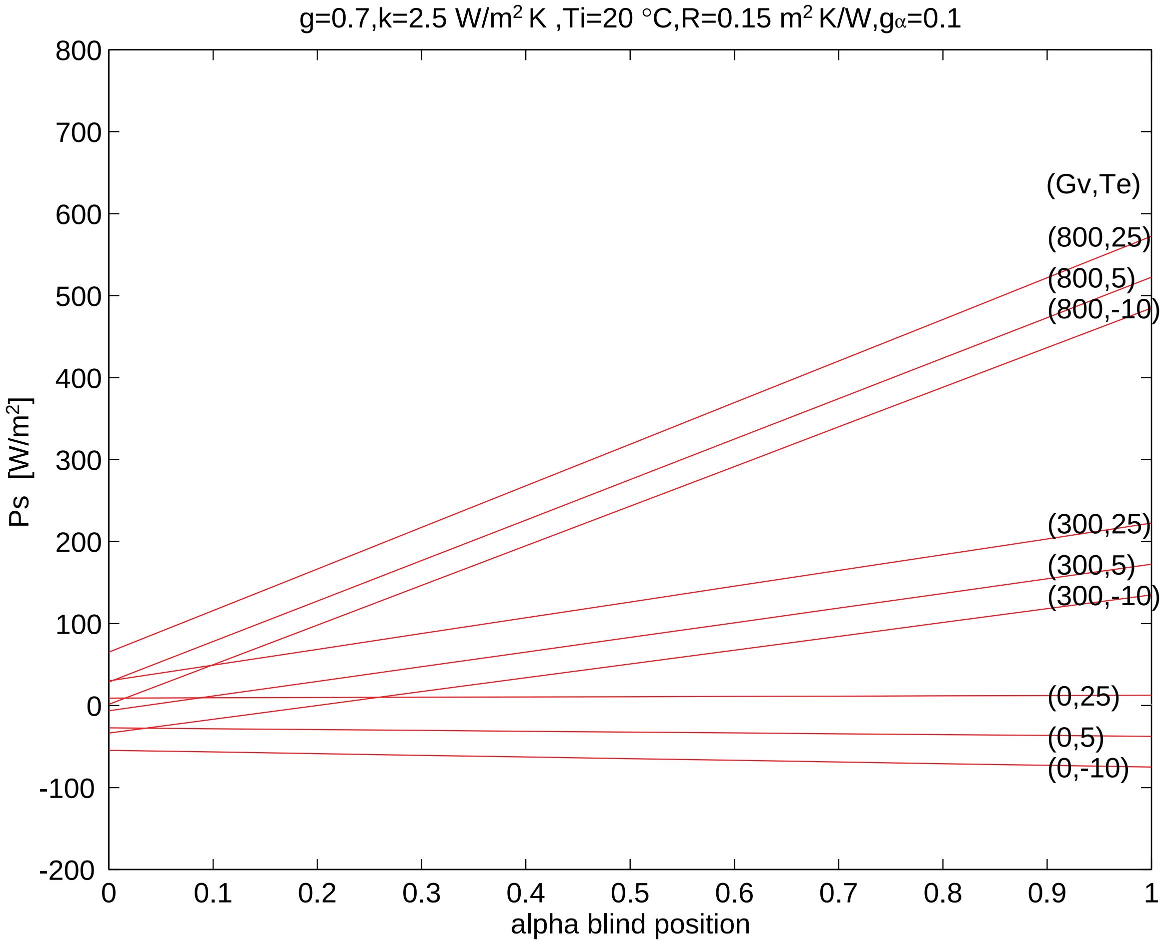

Figure 5.7: Thermal power balance of a window with solar radiation and external temperature as parameters

A new approach for the blind control

We will consider the desired window power balance Ps as the main output variable of the blind controller, as we would do with a heating system. The blind position is a consequence of the chosen Ps. This approach drastically reduces the number of fuzzy variables used and focuses on the essential.

The goals of the energy optimum algorithm are: first to calculate which power balance Ps (heating power /m2 of window) would ideally have to be brought to the room and second, to choose the blind position which results in the closest practical Ps.

The two simple basic purposes of the controller are:

- To help the heating system with the blind position, which means to try to heat the room when heating system does it and to try to cool the room when cooling system does it.
- A long term optimisation of the heating supply with a season dependency control (summer, mid-season, winter).

For the operation of the blind controller we do not consider any indoor temperature set-point, we just do what the heating system does. This approach has some advantages:

- It avoids having opposite commands due to different set-points. For example the cooling system is on and the blind lets the sun pass.
- The blind controller can adapt to any heat controller and it will always help it.
- The algorithm is portable, that is it intrinsically adjusts itself to any heating system and the model of blind and window is based on well known coefficients.

To avoid any complex modelling of the building or modelling of the heating system, expert rules are used to fulfill these tasks. As we will see, fuzzy variables are particularly adequate in our case to define the expert rules.

Definition of fuzzy variables

The season is defined according to the mean value (24h average) of external temperature. Fuzzy logic helps to pass smoothly from one season to another. The centre of the mid-season could be adapted to an estimation of the non-heating temperature of the considered building.

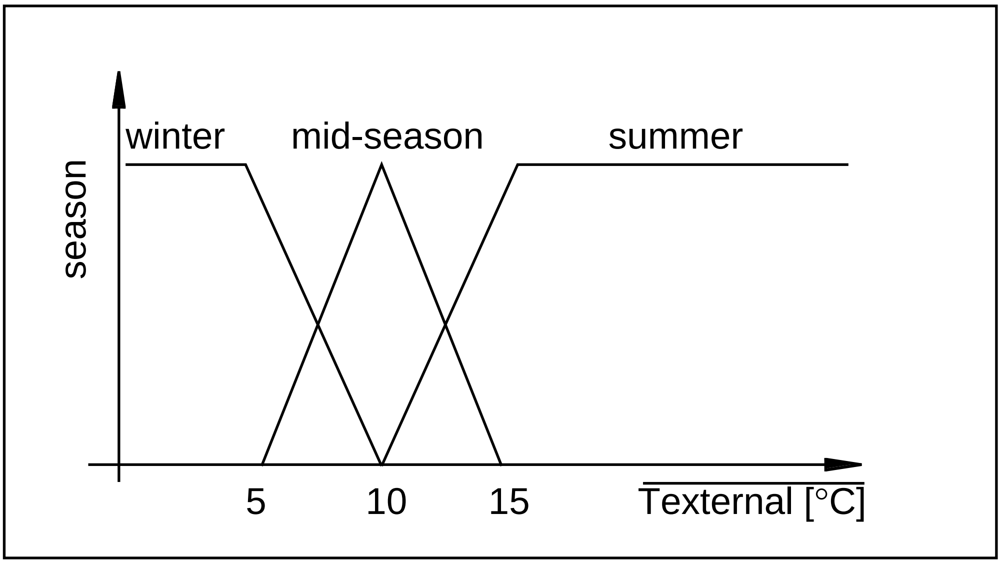

Figure 5.8: Definition of the fuzzy variable « season »

The power of the heating system is also written as a fuzzy variable, it is given in Figure 5.9 (the same definition was already used in the version 1 algorithm). Non symmetric membership functions for negative and positive values were chosen for making the system more sensitive to any negative value (cooling) than positive value (heating). The limit values (-200 W, 0 W, 500 W) should be adapted to the considered building. In our case (an office room) the maximum power of the heating system was 1000 W and the minimum around -800 W.

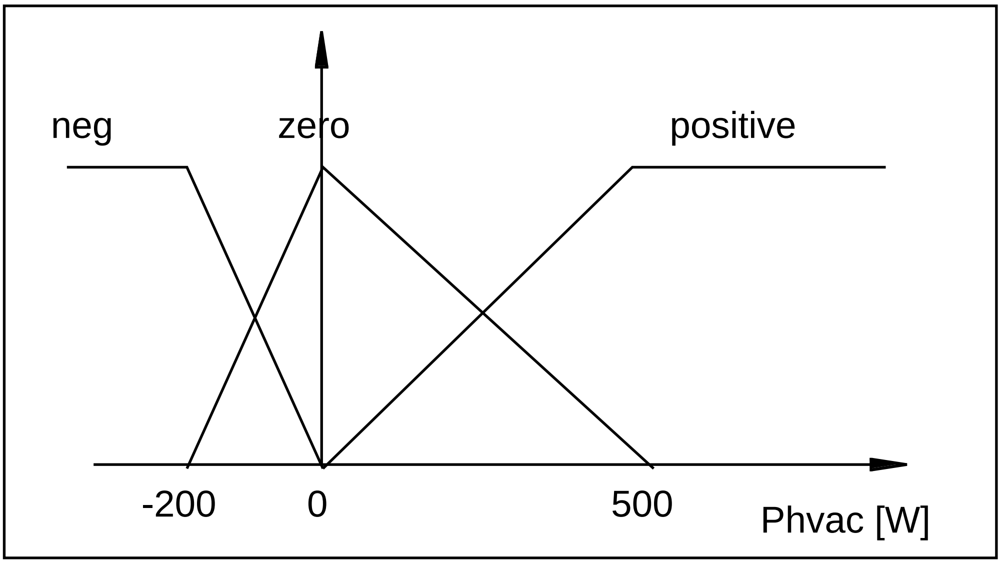

Figure 5.9: definition of the fuzzy variable « Heating power »

The desired power balance of heat brought to building per square meter of window (Ps) is also fuzzified, it will be the output of the fuzzy controller. The values chosen are actually not fuzzy, this choice allows faster computer calculation in the inference process [Bühler 94]. The response surface of the system is not much different with fuzzy values. The limit values chosen are given per square meter of window, and therefore there is no need for any adaptation to the particular building considered.

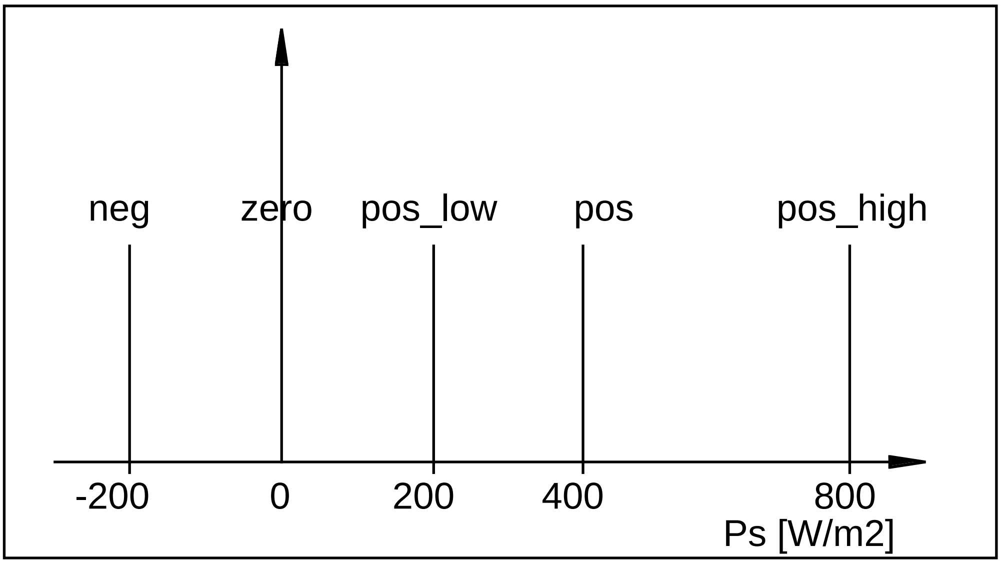

Figure 5.10: Definition of the fuzzy variable « power balance of window »

A simple rule base

The rule base of the fuzzy expert system is given in Figure 5.11. It gives, according to the two inputs (Season and Heating power) what the power balance of window (Ps) should ideally be. We have for example the following two rules:

- if Season is « winter » and Phvac is « positive » then Ps is « positive high »
- if Season is « mid-season » and Phvac is « zero » then Ps is « positive low »

The two principles described over are applied to fulfill the rule base:

- to help the heating system,
- to achieve a long term optimisation according to the season.

Such a rule base can be easily completed by a building physics expert. It is completely general. It is the translation in fuzzy language of the two concepts discussed before.

		Heating power		
	Ps	**neg**	**zero**	**pos**
season	winter	neg (+)	pos	p_high
season	mid-season	neg	p_low	pos
season	summer	neg	zero or neg	p_low (+)

Figure 5.11: Rule base of the fuzzy « energetic » expert system , the cases with a (+) should normally not occur for an energy efficient heating system

Surface response

A fuzzy controller is nothing more than a multivariable non linear function. Figure 5.12 shows the surface response of the energetic fuzzy expert system, after defuzzification (using the Min-Max method):

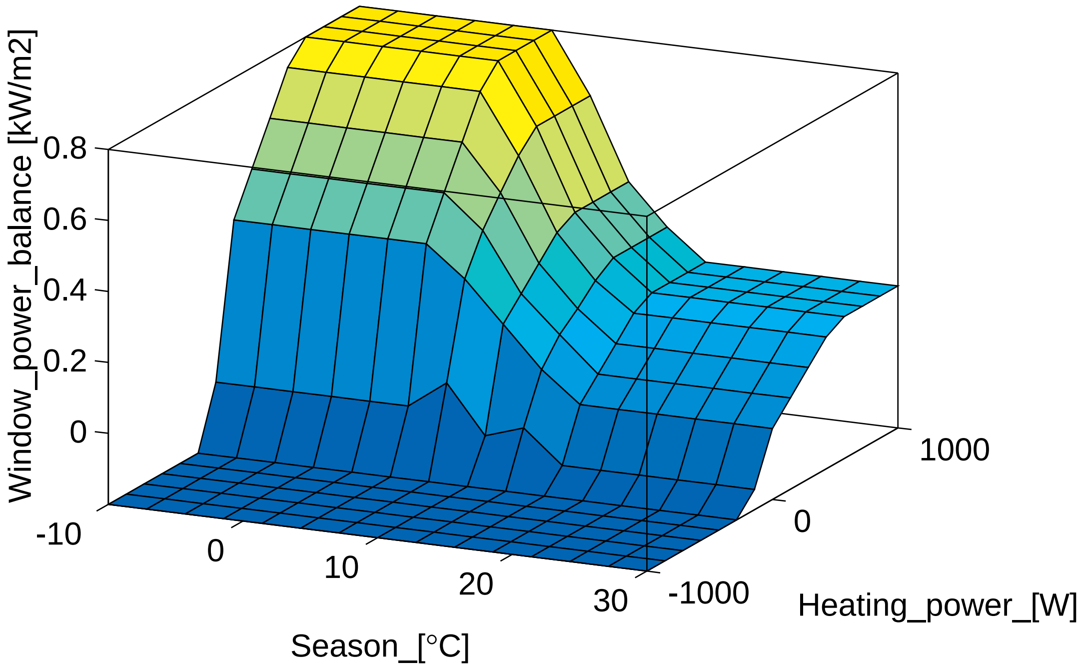

Figure 5.12: Surface response of the fuzzy controller

Choice of a blind position

The blind position chosen by the control system is the inverse function of (eq 5.1)

$$\alpha = \frac{P_s - g_\alpha \cdot g \cdot G_v + \frac{k}{1+R\cdot k}\cdot(T_i - T_e)}{G_v \cdot g \cdot (1-g_\alpha) - \left(k - \frac{k}{1+R\cdot k}\right)\cdot(T_i - T_e)} \qquad \textbf{(eq. 5.3)}$$

with the physical limitation of:

$$\alpha < 0 \Rightarrow \alpha = 0$$
$$\alpha > 1 \Rightarrow \alpha = 1$$

The value desired for Ps sometimes cannot be achieved by any blind position. This can, for example, happen in summer during daytime if the desired Ps is less than zero. The equation 5.3 would give $\alpha<0$. In such a case the chosen blind position is the best possible, which means in our example that the blind is closed ($\alpha=0$).

Impact of energy-optimised control

The question to be answered here is: does the chosen blind position have a large impact on the power balance of the window. In other words can the blind be opened (or closed) without Ps being too much affected ? In order to be able to answer this question, we need to add a weighting factor to the calculated blind position. It can be given by the derivative of Ps versus blind position.

$$\frac{\partial P_s}{\partial \alpha} = G_v \cdot g \cdot (1 - g_\alpha) - \left(k - \frac{k}{1 + R \cdot k}\right) \cdot (T_i - T_e) \qquad \textbf{(eq. 5.4)}$$

Fuzzy logic is used here to calculate a weighting factor (0 or 1), according to the possible values of (eq. 4).

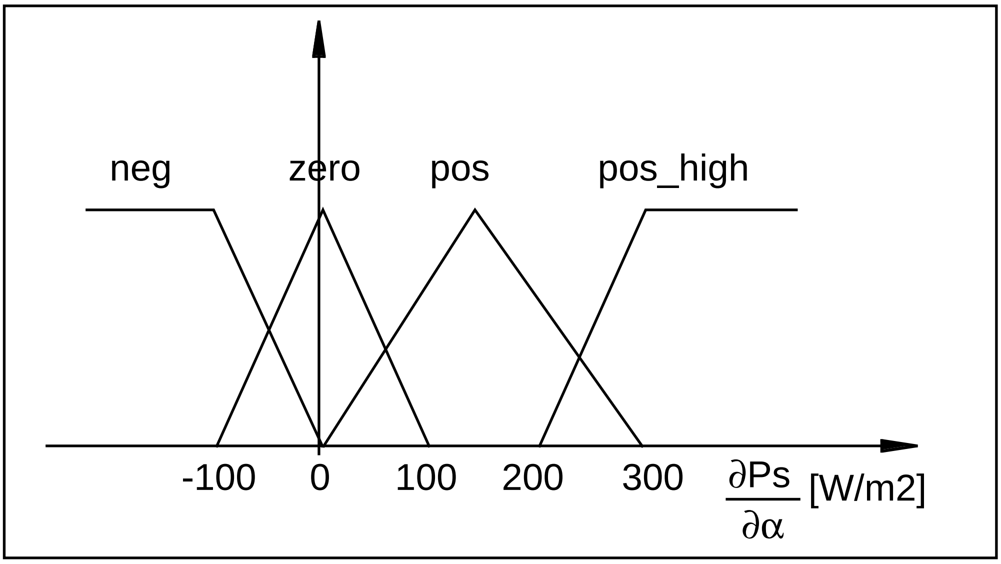

Figure 5.13: Definition of the fuzzy variable window power balance derivative

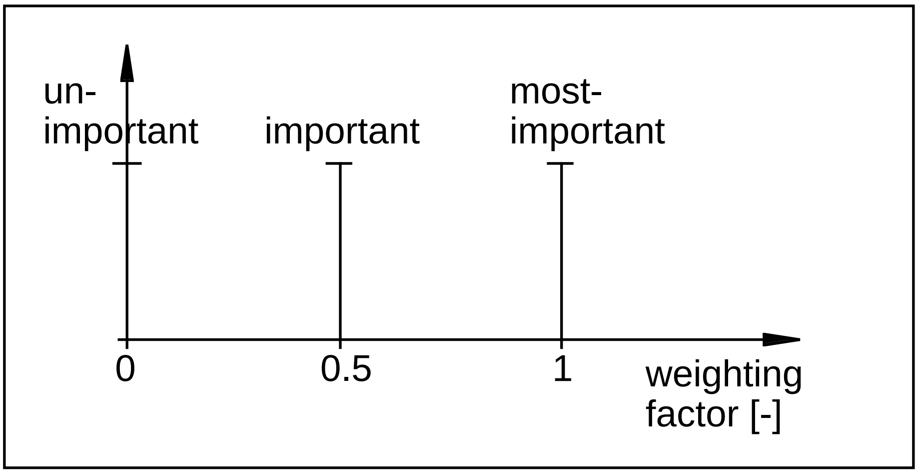

Figure 5.14: Definition of the weighting factor

The following rule base is based on the idea that when the window power balance changes much with the blind position then the energy control is sensitive to the blind position, thus it can be considered important.

$\frac{\partial Ps}{\partial \alpha}$	neg	zero	pos	p_high
energy weight	important	un-important	important	most-important

Table 5.5: Rule base for weighting factor calculation

This energy weight was not used in the final DELTA algorithm (see 5.4.4), because the energy optimum had always been used when the rooms were unoccupied, and never during occupancy. But, in a more general case, for example with a venetian blind, where special blind positioning allows solar gains without glare, a combination of visual and energy optimised control become possible. Weighting factors then become more interesting.

5.4.2 Visual aspect

This chapter discusses different aspects that need to be taken into account to obtain a visual comfort optimum in an office room according to the recommendation of the CIE [CIE 83], discussions with daylighting experts, the technical manager of a large bank building, and people from the industry.

A control algorithm for visual aspects is then proposed.

Visual comfort assumptions

1. *Avoid glare*. All the comfort indexes provided in the CIE documentation are related to the luminance contrasts in the vision angle. To avoid too large contrasts, direct sunlight should be avoided. The two main variables are: the incident solar illuminance and the solar angle related to the window.
2. *Always keep a minimum of blind aperture*. That recommendation comes from the technical manger of a large bank building equipped with automatic blinds. It has been confirmed by the people in the LESO rooms used for the DELTA project.
3. *Without a risk of glare, allow as much daylight as possible*.
4. When people are in their office, *visual quality has priority over energy saving*.
5. *The number of unexpected blind movements should be as low as possible* (it disturbs people at work).
6. *The visual comfort of people is necessary only when office rooms are occupied*. This trivial assumption allows the automatic system to save heating energy when people are not in their offices.

Automatic control algorithm

A fuzzy rule base has been established. It includes rules on direct illuminance and the incidence angle of solar radiation. The diffuse illuminance is also taken into account to avoid glare when the sky is very clear, but without direct illuminance. The rule base should provide a « standard » comfort for an office room. A « clear » or « dark » ambiance could be easily derived from the « standard » rule base. For example a « dark » ambiance could be obtained by shifting all the blind positions to a more closed position.

Definition of fuzzy variables

A value of 40 [klux] for outside illuminance is considered by daylighting experts as a standard threshold for a bright sky. This assumption, and the physical limits (the global horizontal illuminance is <120 klux) were used to define the membership function for the direct and diffuse illuminance.

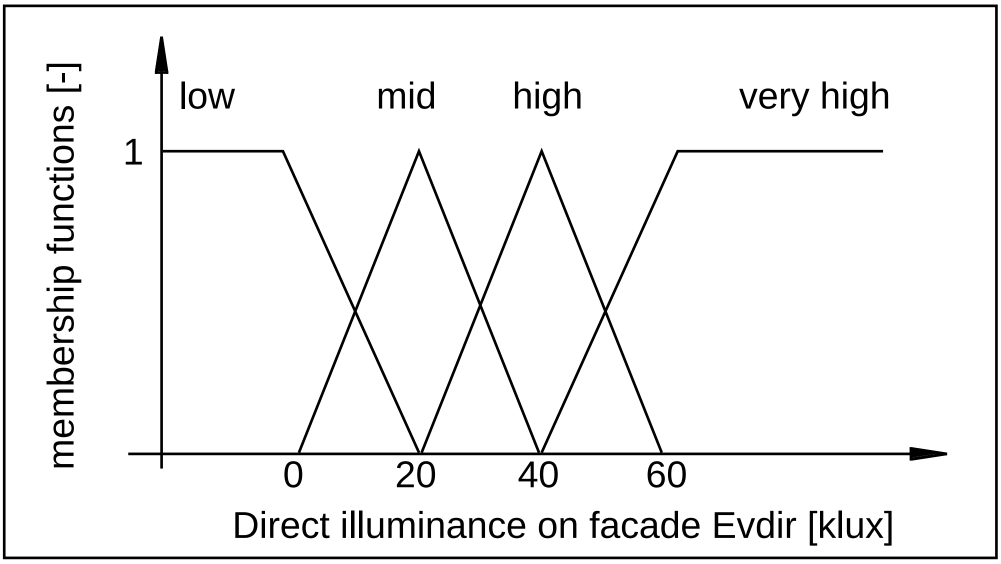

Figure 5.15: Fuzzy definition of the direct illuminance

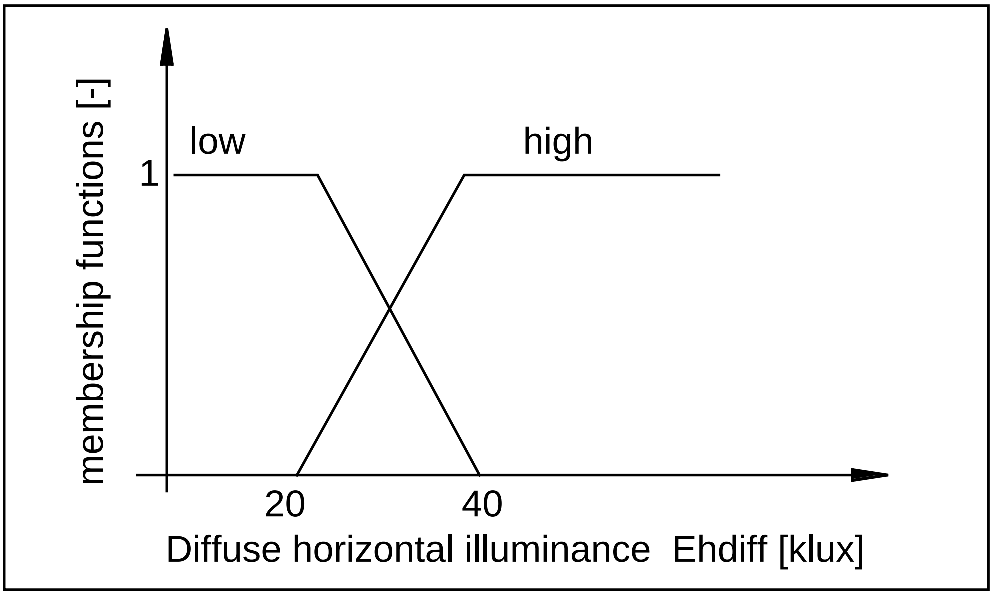

Figure 5.16: Fuzzy definition of the diffuse illuminance

The solar incidence angles are defined on the following base:

- One meter or more of direct solar penetration in the room is considered as very disturbing. For the LESO building (window height is 2.7 m), this corresponds to an incidence angle of 70° or less. This value was attributed to the « low » value for the solar incidence angle.
- An incidence angle of more than 80° corresponds to less then 50 cm of solar penetration. It is considered as non disturbing and set as the « high » value for the solar incidence angle.

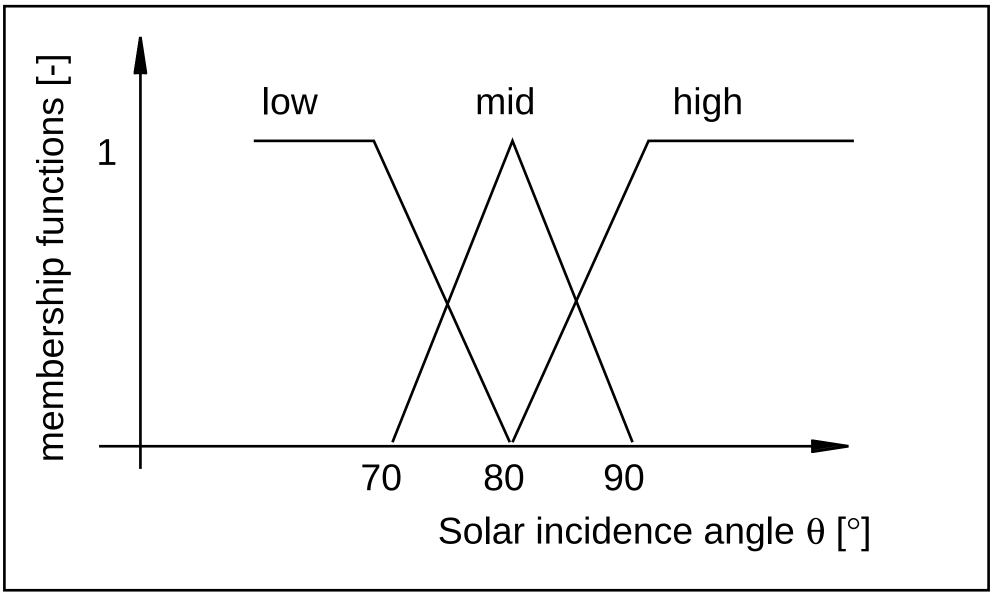

Figure 5.17: Fuzzy definition of the solar incidence angle

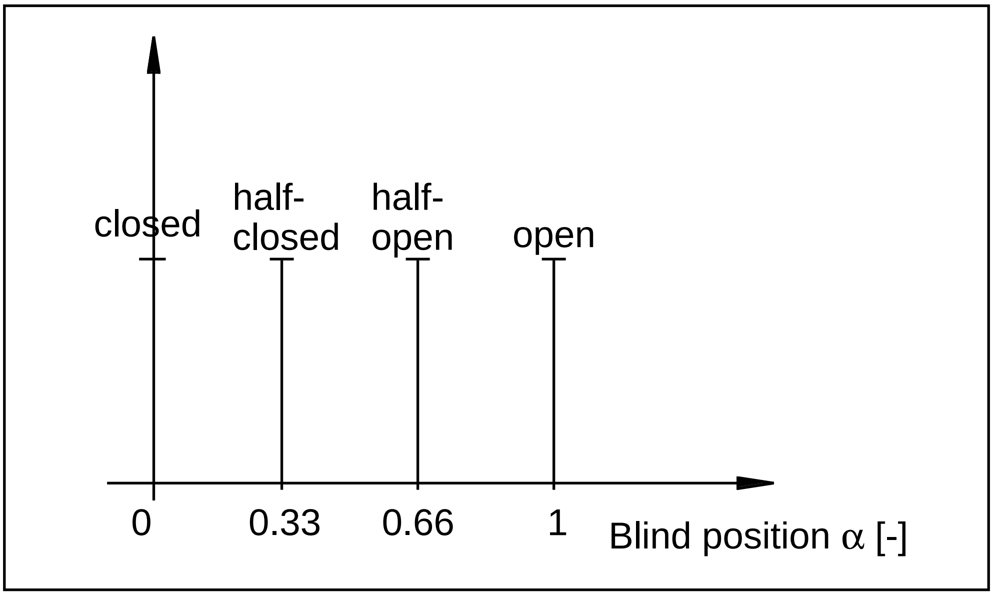

Figure 5.18: Definition of the blind position as an output

Visual rule base

Ehdiff = low

θ \ Evdir	low	mid	high	very high
low	open	half closed	closed	closed
mid	open	half open	half closed	half closed
high	open	open	open	open

Ehdiff = high

θ \ Evdir	low	mid	high	very high
low	half closed	half closed	closed	closed
mid	half closed	half closed	half closed	half closed
high	half closed	half closed	half closed	half closed

Figure 5.19: Visual comfort rule bases (θ is the solar incidence angle, Evdir is the direct vertical illuminance, Ehdiff is the diffuse horizontal illuminance)

These rule bases can be adapted to other ambiances: For example, a dark ambience could be obtained by shifting all the blind positions to a closer position.

Importance of visual control

A weight is attributed to the calculated blind position. It is simply set to 1 (maximum value) during occupancy and to 0 (minimum value) without occupancy. For an office equipped with a presence detector the weight corresponds directly to the output of the sensor. Without presence detectors available, a deterministic occupancy schedule (office hour) can be set.

5.4.3 User wishes

Energy optimised control regulates the blind position to minimise the heating and cooling energy needs. Visually optimised control provides standard visual comfort by maximising daylighting and preventing glare when offices are occupied. Now we will consider user wishes. Two points are considered:

- The user always has the opportunity to choose the position of the blind. That position is kept during a time of ~30 min. The decreasing weighting function is assumed identical to the one in Figure 5.5.
- Another opportunity for the user (but not yet implemented in the DELTA project) is to choose between different ambiances for visual comfort (dark, clear, blind open or blind closed).

5.4.4 Final choice for the blind position

The final position is chosen by a ‘decision machine’. It is slightly different from the one in the TU-WIEN algorithm (section 5) because of the presence of a new term for visual comfort during occupation:

1) If the room is not occupied then the blind position is the position calculated by the energy optimum controller.

2) If the room is occupied then the blind position is the one (between user chosen position and visual comfort optimum) with the higher weight.

In automatic mode (all the time except when the user regulates the blind position), only 4 output values are possible. This choice allows a drastic reduction of the number of blind movements.

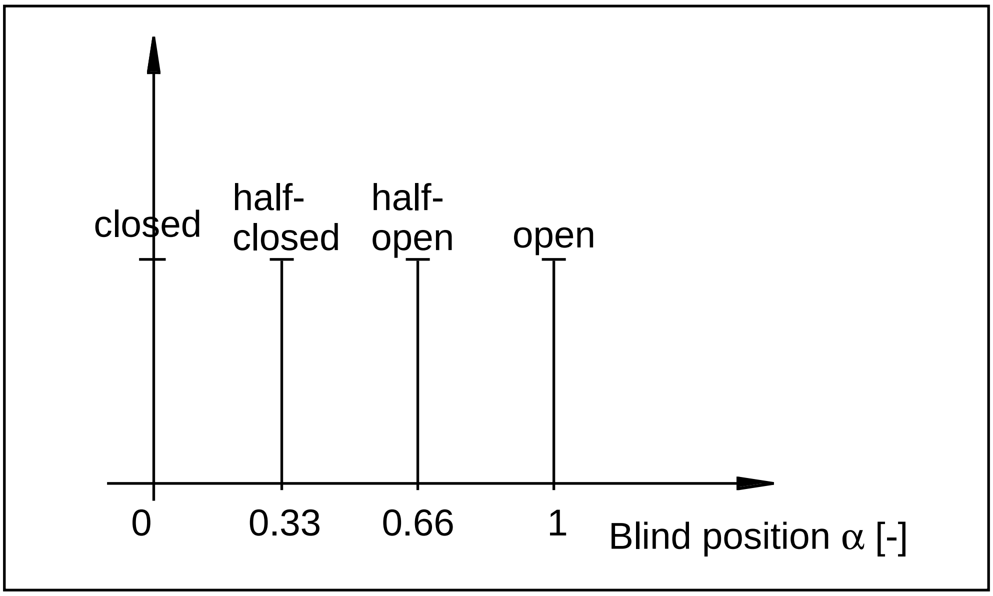

Figure 5.20: Possible blind positions in automatic mode

5.5 Classical artificial intelligence controller (algorithm version 3)

This controller variant is based on classical logic (non fuzzy). The main concepts are the same as in version 2 (see section above). A comparison of the two variants should allow a quantification of gains related to the use of fuzzy logic as compared with a conventional intelligent controller.

The algorithm is based on logical decisions, depending on various conditions, given by: Environment, Room, User.

A set of decision rules defines the state of the blinds, which has to be expressed in an appropriate blind-position, depending on the type of blinds. For the desired visual comfort and energy gain, a given static position is defined, which has to be adjusted (e.g. every 15 minutes, or more frequently, if significant changes in the system state variables occur).

Stepwise control of the blinds:

When a room is occupied, blind moves are strongly restricted so as not to disturb the users. This offers the following possibilities: Large pauses (15-60 minutes) between two movements of the blinds or very slow and quiet movements (like the sun), in a way the user does not take notice.

4 basic states:

Closed :	Minimum Energy and Illumination Transfer
Open:	Full Illumination, Full HeatGain, No GlareProtection in case of direct SunRadiation
AntiGlareWithoutHeatGain:	closed with indirect IlluminationGain but no HeatGain
AntiGlareWithHeatGain:	closed with indirect IlluminationGain and HeatGain

These are the basic states. For every type of blind, appropriate positioning has to be defined for every state. The AntiGlare positions may not be static, depending on the angle of the direct sun radiation.

Definition of a set of states for the room and the environment

- Room States:	Occupancy , Visual Comfort, Thermal Comfort
- Environment of the building:	Outside Temperature, Outside Illumination, Global Sun Radiation, Direct Sun Radiation, Wind-Velocity

These states are relevant for the definition of the actual blind position.

The needed states depend on continuous signals and are defined by comparison of the measured values with one or two thresholds which give a two or three-state decision.

Wind-Velocity [Low,TooHigh]:	Important for certain blind-constructions: When the wind is strong,, the blinds must always be open with highest priority, because of potential mechanical damage.
Room-Occupied [No,Yes]:	Important basic information. When a room is occupied, visual and thermal comfort have to be maintained. Visual c. has priority over thermal c. When the room is not occupied, the blinds can be fully used to optimise the energy-consumption of the building.

UserWishBlind [Inactive,Active]:	A user-wish for a blind-position has absolute priority over system-commands (except wind-emergency). For a given time after the last interaction the blinds are not moved. Criteria: time since user request, change of outside lighting.
Daylight-State [Dark,Bright]:	When it is dark, can blinds be closed ?
HVAC_Season [Heat,Neutral,Cool]:	Helps to decide if solar heat-gain is useful or not. During the cooling season SHG is never desired.
ComfortRoom [TooCold,Comfort,TooWarm]:	Helps to decide if SHG is useful or not. When it is too warm, SHG is never desired.
WindowHeatFlow [Negative,Positive]:	Indicates if heat-gains through window are possible or not.
DirectSunRadiation [No,Yes]:	Helps to decide if glare-protection is needed. A possible additional function is the control of the blind-position by the elevation-angle of the sun.

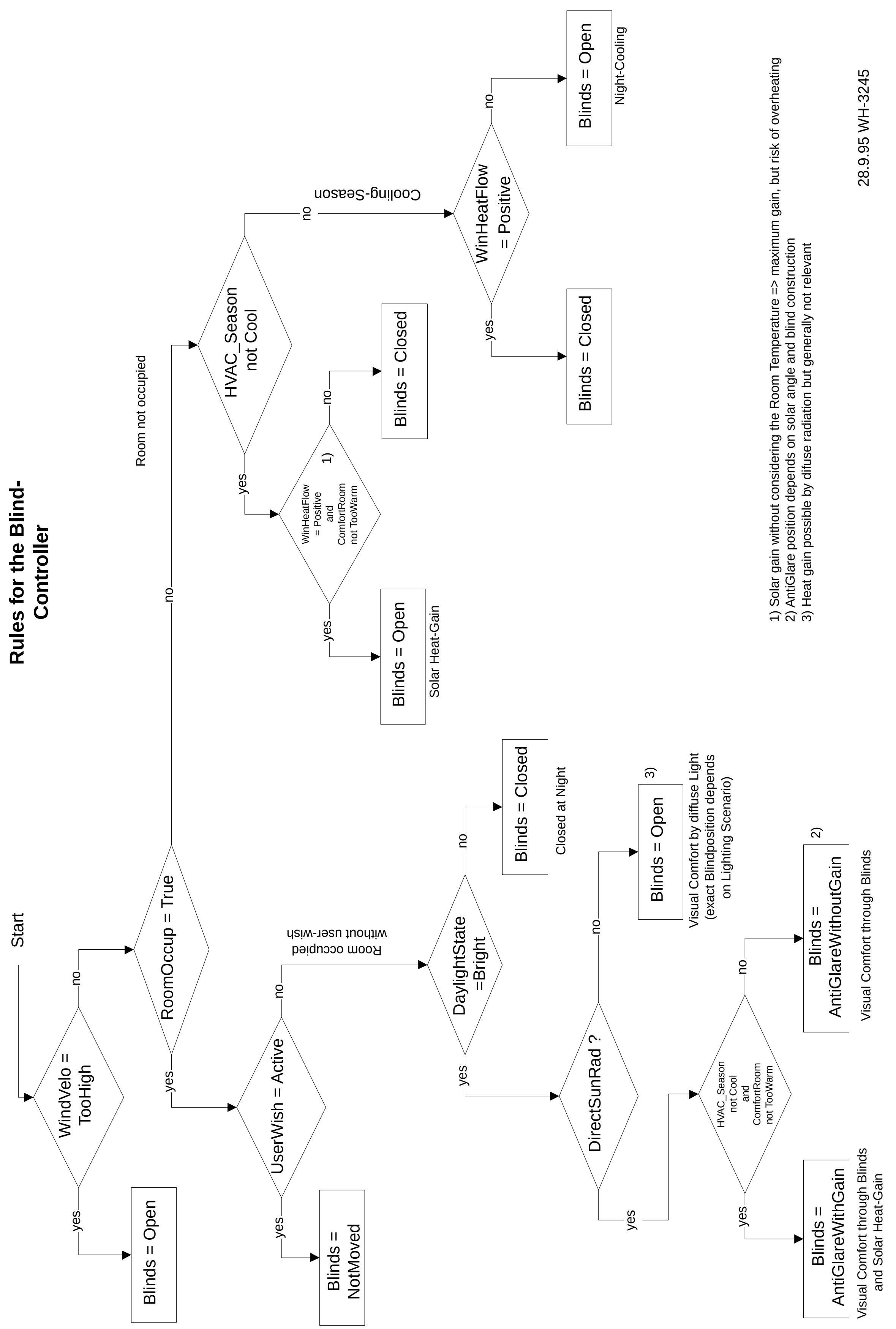

Figure 5.5.21: Rules for the Blind-Controller

6. THERMAL MODEL AND SIMULATION PROGRAM

In order to be able to simulate the controller algorithm, a model of the room described briefly in section 3.1 was made. The model was checked both by a comparison of calculated and simulated response to simple excitation functions (section 6.3), and by a comparison of measured and simulated response to real climate (section 6.5).

The detailed thermal characteristics of the rooms have already been explained in section 3.1.

6.1 Nodal network description

The thermal model was limited to the thermal masses inside the boundary surface. The boundary was defined as the insulation layer for the inside walls and the outside surface for the outside wall, the window and the window frames (South facade).

Preliminary tests have also been carried out with the inclusion of more wall layers, i.e. including fixed temperature nodes for the adjacent indoor spaces. Since these account for a very small fraction of the global heat losses, they were dropped in order to make the simulation faster. This simplification does not limit the generality of the conclusions that can be drawn from the simulations when comparing various blind control algorithms.

The thermal model used for the simulation is a classical nodal network model. The nodes are either floating temperature nodes (i.e. their temperature is the solution of the differential equation system), or assigned temperature nodes (i.e. their temperature is assigned to a fixed or tabulated variable value as a function of time).

There is one floating node corresponding to the inside room air, and several floating nodes for the building elements. For the heavy structure elements, one node has been placed at the interface between each layer. For the glazing, there is one node for each glass layer.

The system therefore consists the following nodes:

node description	node #	thickn. [m]	area [m2]	mat.	λ [W/mK]	ρ [kg/m3]	Cp [J/kgK]
room air, 43.8 m3	1			air		1.2	1000
South wall							
inside coating	2-3	0.01	3.55	coating	0.7	1800	920
concrete	3-4	0.14	3.55	concrete	0.7	1500	1000
insulation	4-5	0.10	3.55	glassw.	0.04	80	920
air ventilation	5-6	0.24	3.55	air			
alu prot.foil	6	0.01	3.55	alu	200	2700	1000
North wall							
inside coating	7-8	0.01	9.5	coating	1.4	1800	920
concrete	8-9	0.12	9.5	concr.bri	0.18	600	1000
East wall							
plaster	10-11	0.015	14.6	plaster	0.5	1200	830
cavity	11-12	0.048	14.6	air			
plaster	12-13	0.015	14.6	plaster	0.5	1200	830
West wall							
inside coating	14-15	0.01	14.6	coating	1.4	1800	920
concrete	15-16	0.12	14.6	concr.bri	0.18	600	1000
Ceiling							
inside coating	17-18	0.01	15.6	coating	1.4	1800	920
concrete slab	18-19	0.20	15.6	concrete	1.8	2400	1000
Floor							
rubber coating	20-21	0.01	15.6	rubber	0.6	1000	920
screed	21-22	0.05	15.6	concrete	1.4	2200	920
Window							
inside glazing	23	0.004	3.77	glass	1.15	2530	840
middle glazing	24	0.004	3.77	glass	1.15	2530	840
outside glazing	25	0.004	3.77	glass	1.15	2530	840
Window frame							
inside	26-27	0.03	2.85	wood	0.12	500	2500
outside	27-28	0.01	2.85	alu	200	2700	1000

Table 6.1*:* Layers and nodes

The following figure shows the nodal network of one of the test rooms.

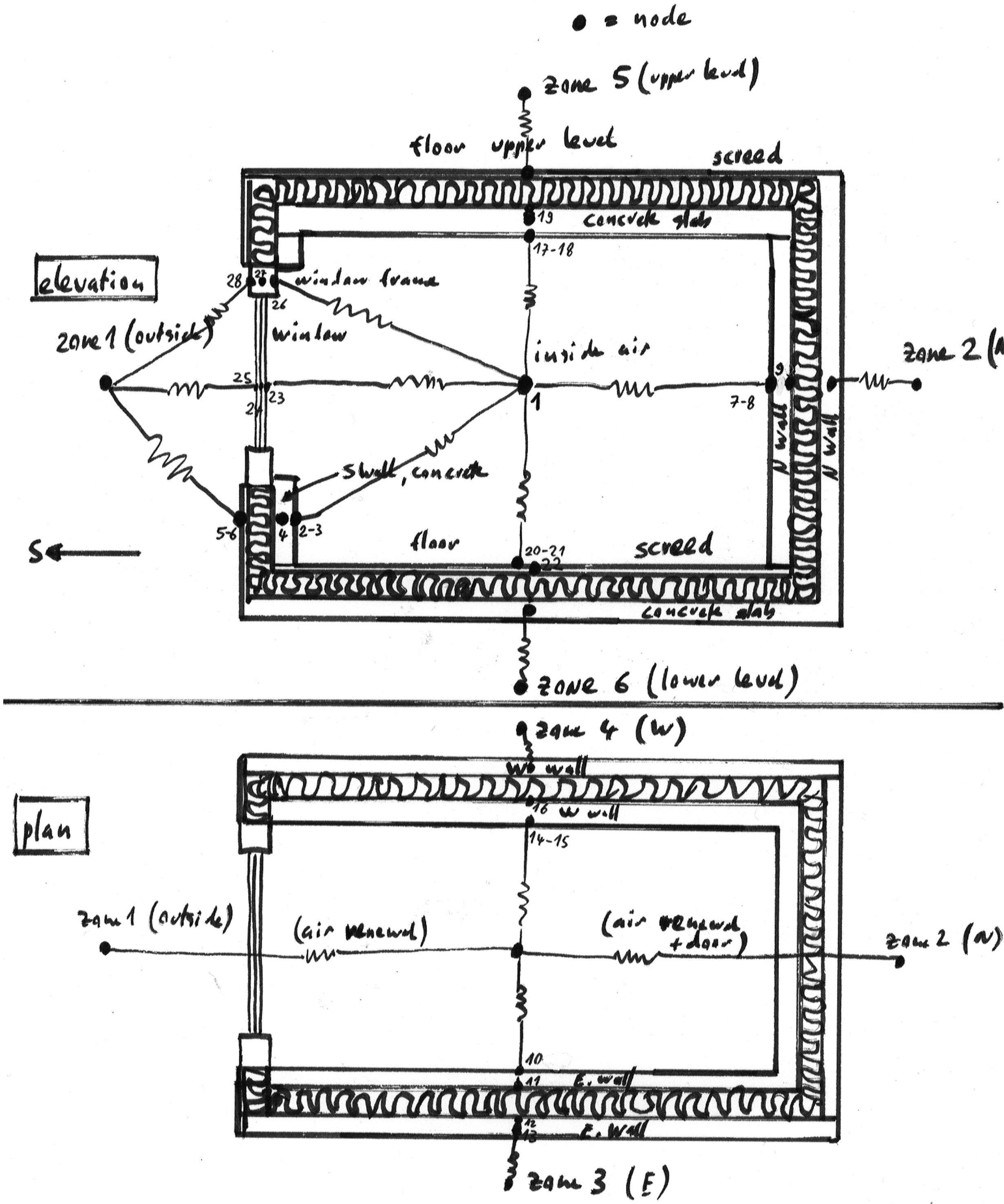

Figure 6.1: Thermal model of the test room; the numbers are node numbers.

The following assigned temperature nodes have been considered:
- outside air (temperature assigned to the value given by the available weather data tabulation);
- sky (temperature given by a simple correlation model as a function of the sky cloud cover derived from the direct/global solar radiation ratio) [Ineichen 83]. The nodes are connected either by simple conduction (e.g. when there is a connection between structure nodes), or by conduction/convection (when there are air layers between the window panes), or by radiation (e.g. between inside surfaces, or between outside surfaces and sky).

6.2 The simulation program

A first version of the simulation program was developed by the TUW (Technical University of Vienna) [Wurmsdobler 94]. The program has been corrected and completed by LESO-PB. It is written in the MATLAB language, which is very convenient for such a matrix handling in a nodal network equation system, although much slower than a purely compiled language like C or Fortran.

Basically, the program first reads two files, one describing the physical system and the other the simulation conditions. Then it displays a graphical user interface, with several quantities drawn as a function of the elapsed time while the simulation is carried out. The user can start or stop the simulation, and during the simulation he can change some conditions relative to the behaviour of the blinds. In the end, all the system temperatures and other variables can be displayed graphically as a function of time or tabulated to a disk file (as instant or integrated values). All the graphic displays can be also printed.

The following two figures give the block diagram of the simulation code and an example of the graphical interface seen by the user.

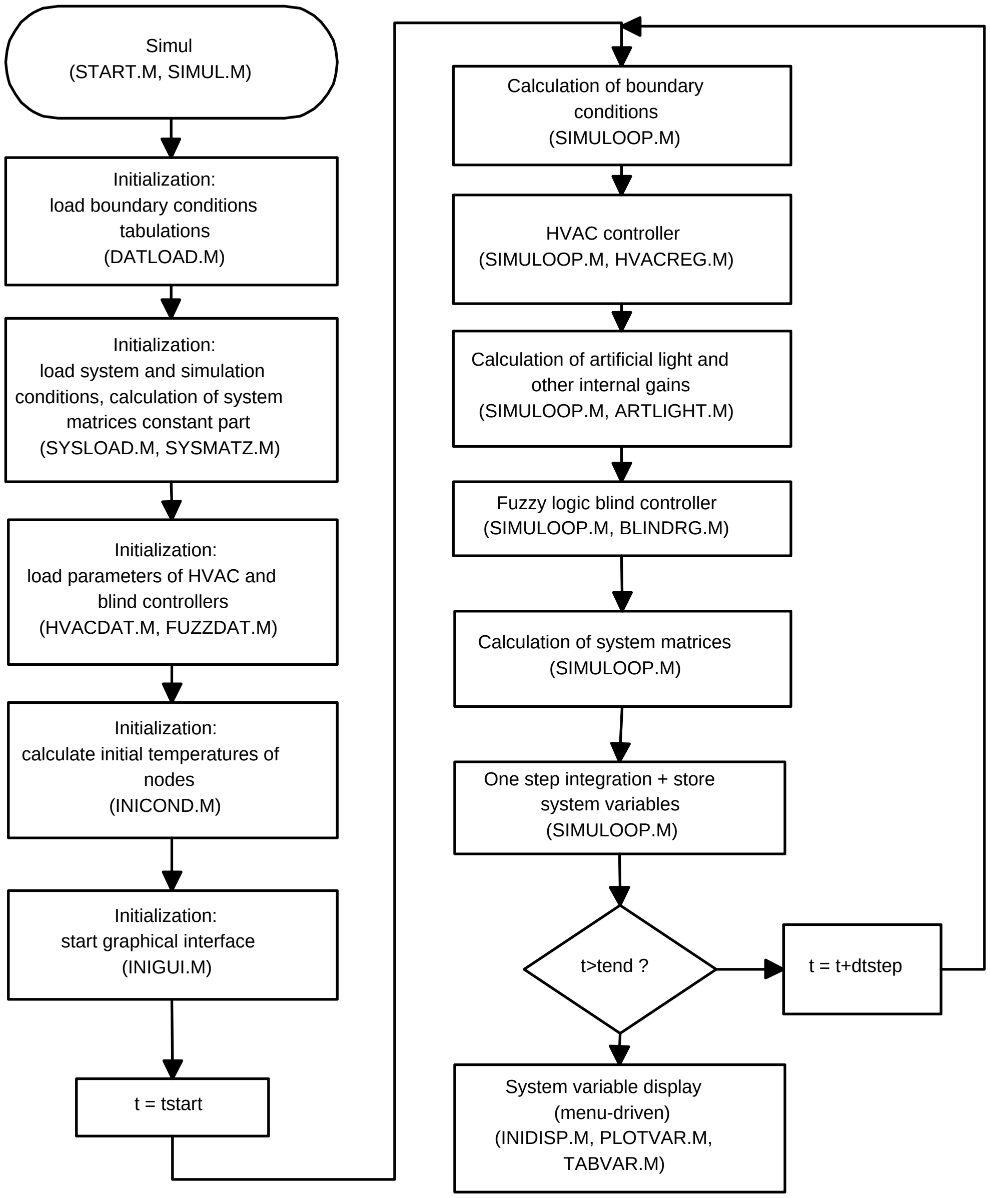

Figure 6.2: Block diagram of the simulation code (the names in parentheses are those of the m-files of the Matlab program code; each m-file represents a routine).

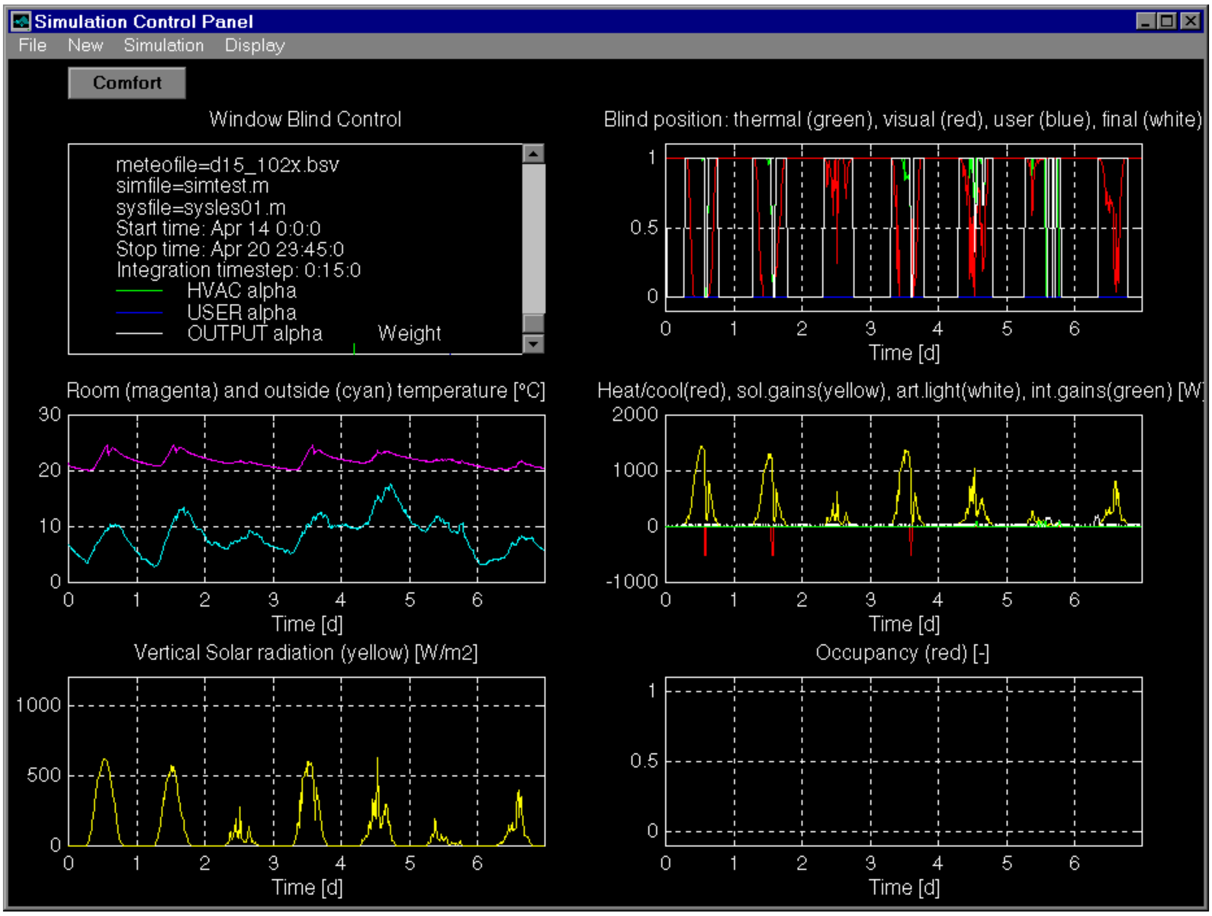

Figure 6.3: The graphical user interface of the simulation code

The simulation itself corresponds to the iterative resolution, with a given time interval, of the equation system given below:

$$dT/dt = A \cdot T + B \cdot U$$

where T is the floating nodes temperature array (size 28 elements), U is the external excitation functions array (it contains assigned temperature nodes, solar radiation components, internal and heating/cooling gains, and user behaviour relative to the blind if applicable), and A and B are the system matrices.

The heating control algorithm is a simple on/off controller; it will be discussed in section 8.3.

The solar radiation on any incident surface is calculated using a 'solar generator' which, starting from the global horizontal radiation at a given time, breaks it into its two direct and diffuse components using a classical Liu and Jordan correlation (see [Ineichen 83] or [Perez 87]). The two components are then transposed to the surface on which we need to calculate the global incident solar radiation are then summed up.

6.3 First check of the thermal model: response to simple excitation functions

In order to check the simulation program, the response of the inside temperature to simple excitations functions (either outside temperature or solar radiation) has been studied. Both cases without and with auxiliary heating have been simulated. The check has allowed a correction of several programming errors, which would have been much more difficult to track down if we had not gone through this step.

Most cases have been simulated over the first 30 days of the year, i.e. well beyond the room time constant (about 7 days, see below).

The following cases have been investigated:

- response to an outside temperature step (from 20 °C to 0 °C, day #3 at 00:00), no auxiliary heating;
- response to a heat gain step (from 0 to 100 W/m2 of window, day #3 at 00:00), no auxiliary heating;
- response to an outside temperature step (from 20 °C to 0 °C, day #3 at 00:00), with auxiliary heating;
- response to cyclic heat gains, everyday 100 W/m2 of window from 6 am to 6 pm, with auxiliary heating;
- response to cyclic heat gains, everyday 200 W/m2 of window from 6 am to 6 pm, with auxiliary heating.

The first two cases can easily be compared with the analytical response of the room. The last three cases have been used to check the correct behaviour of the heating controller, in particular the absence of uncontrolled oscillations.

6.3.1 Simplified model of the room

In order to be able to check the validity of the simulation, the results have to be compared with analytical temperature behaviour. For this, a simplified model was established.

The simplified model includes only one equivalent node for the inside, connected to the outside by equivalent conductances, and with a total capacitance equal to the sum of all massive parts which are effective for thermal storage, plus various less important parts also contributing to thermal storage.

The figure below gives an idea of such a model.

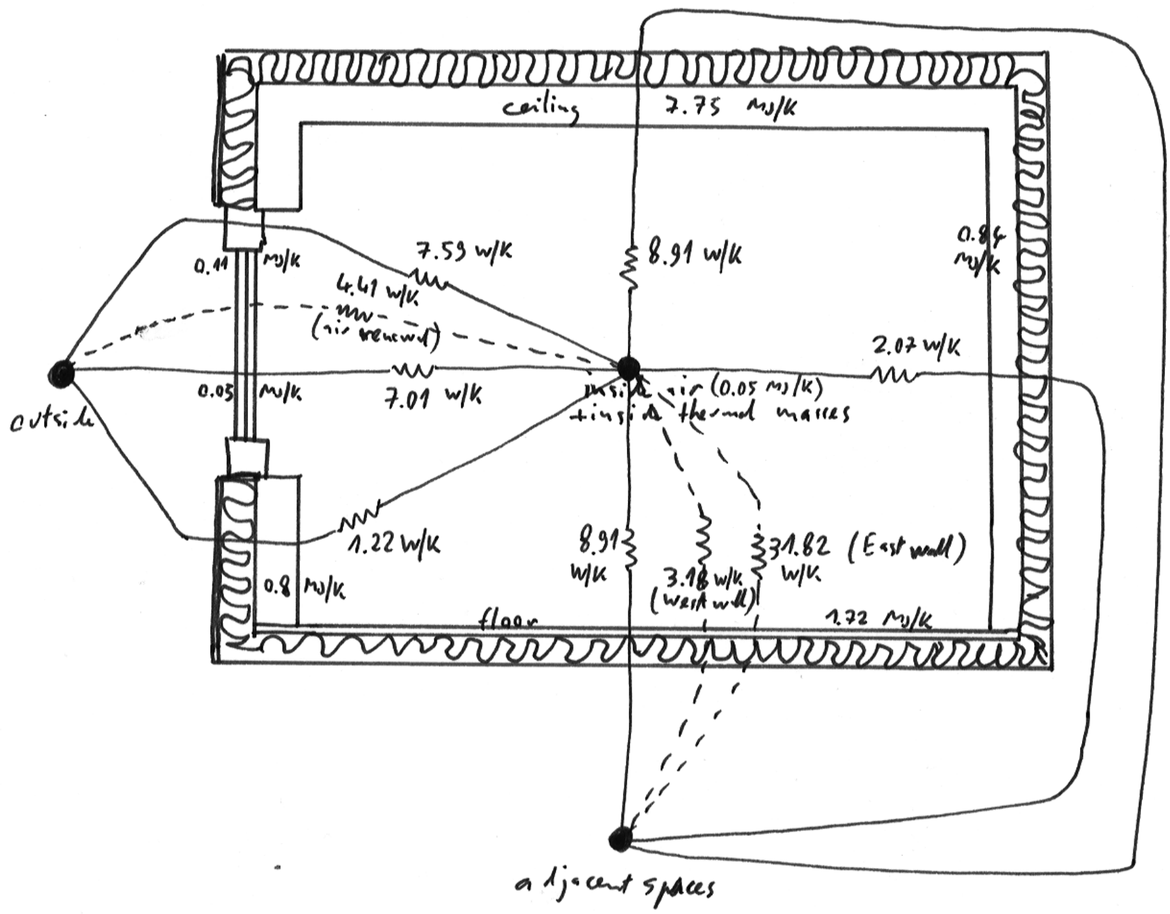

Figure 6.4: Simplified thermal model of the test room.

The thermal masses and conductances which have to be considered are the following:

	conductance to outside [W/K]	effective capacitance [MJ/K]
South wall	1.22	0.80
window	7.01	0.05
window frame	7.59	0.11
air / air renewal	4.41	0.05
North wall	-	0.84
East wall	-	0.14
West wall	-	1.29
ceiling	-	7.75
floor	-	1.72
total	20.23	12.75

Table 6.2: The characteristics of the simplified model (one node, test room isolated from adjacent spaces)

When considering the response to a step excitation, the temperature behaviour will be exponential with a time constant equal to:

tc = C / G = 12.75 MJ/K / 20.23 W/K = 7.29 days

When applying an outside temperature step, since there is no connection to spaces at other temperatures, the asymptotic value reached by the inside air temperature, when starting from initial conditions of 20 °C, will be equal to the outside temperature after the step jump, i.e. 0 °C.

When applying a solar radiation step of 100 W/m2 of window, the power delivered to the inside will be given by the approximated expression:

$$P = Ivs \cdot (t + a/2) \cdot Aw = 302 \text{ W}$$

where Ivs is the vertical south radiation (100 W/m2), t is the glazing transmission coefficient (0.70), a the absorption coefficient in glazing (0.20), and Aw the glazed area (3.77 m2). The resulting equilibrium temperature is then 302 W / 20.23 W/K = 15.0 °C.

This behaviour applies when the room is considered isolated from the adjacent spaces, i.e. when the temperatures of the adjacent spaces are considered to behave exactly the same way as those of the test room. Another hypothesis is to consider that the adjacent spaces are kept at a fixed temperature (for instance 20 °C), and the step excitation is applied to the test room. In such a case, the conduction to the adjacent spaces should be considered, and
Table 6.2 has to be modified as follows:

	conductance to outside or to adjacent spaces [W/K]	effective capacitance [MJ/K]
South wall	1.22	0.80
window	7.01	0.05
window frame	7.59	0.11
air / air renewal	4.41	0.05
North wall	2.07	0.84
East wall	31.82	0.14
West wall	3.18	1.29
ceiling	8.91	7.75
floor	8.91	1.72
total	75.12	12.75

Table 6.3: The characteristics of the simplified model (one node, test room connected to adjacent spaces)

The time constant expression becomes then:

tc = C / G = 12.75 MJ/K / 75.12 W/K = 1.96 days

Assuming an outside temperature step from 20 to 0 °C, starting from initial conditions of 20 °C and keeping the adjacent spaces at 20 °C, the asymptotic value reached by the inside air temperature will equal 14.6 °C.

When the outside temperature is kept at 0 °C, but the room is subjected to a solar radiation step of 100 W/m2 of window, the response can be analysed the same way as before as the same power is delivered to the inside. The resulting equilibrium temperature will be 4.0 °C if the adjacent spaces are kept at 0 °C, and 19.0 °C if they are kept at 20 °C.

6.3.2 Simulated response to an outside temperature step (20 °C to 0 °C)

For the adiabatic case, where the room is considered to be isolated from the adjacent spaces, except for the outside air through the South facade and air renewal (i.e. when the adjacent spaces' temperatures behave like those of test room), the air and mean radiant temperatures have been plotted in the Figure 6.5 below. The mean radiant temperature is near the average temperature of all surrounding surfaces, and therefore gives an idea of the thermal mass temperatures. Moreover, the "comfort temperature" (i.e. the temperature which is felt by a person in the room), when there is no draft, is a weighted average of the air and the mean radiant temperature.

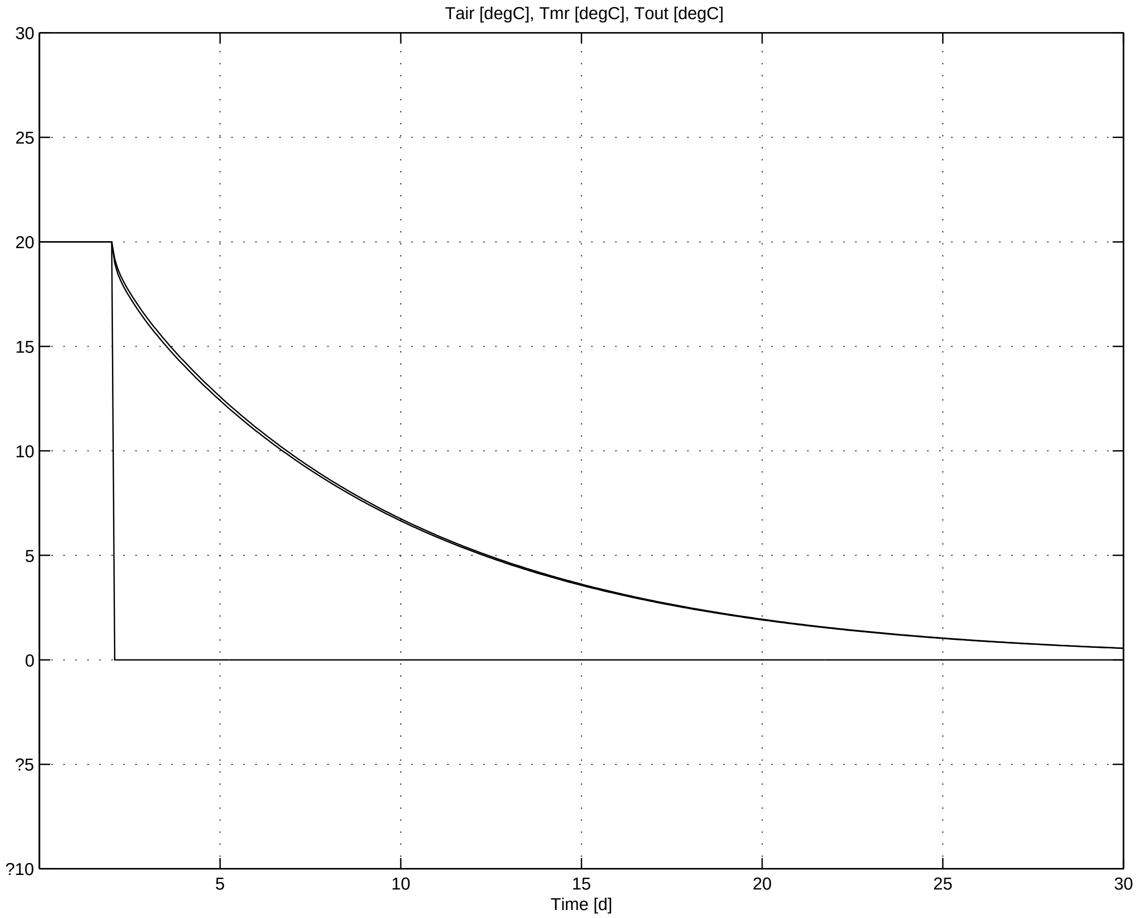

Figure 6.5: Tair, Tmr and Toutside for an outside air temperature step of 20 °C to 0 °C, test room insulated from adjacent spaces

The time constant measured on the plot is 7.3 days, in good agreement with the value predicted by the simple model (7.29 days).

If the other situation is simulated, i.e. the test room is connected to adjacent spaces which are kept at 20 °C, the temperature behaviour is given in the figure below.

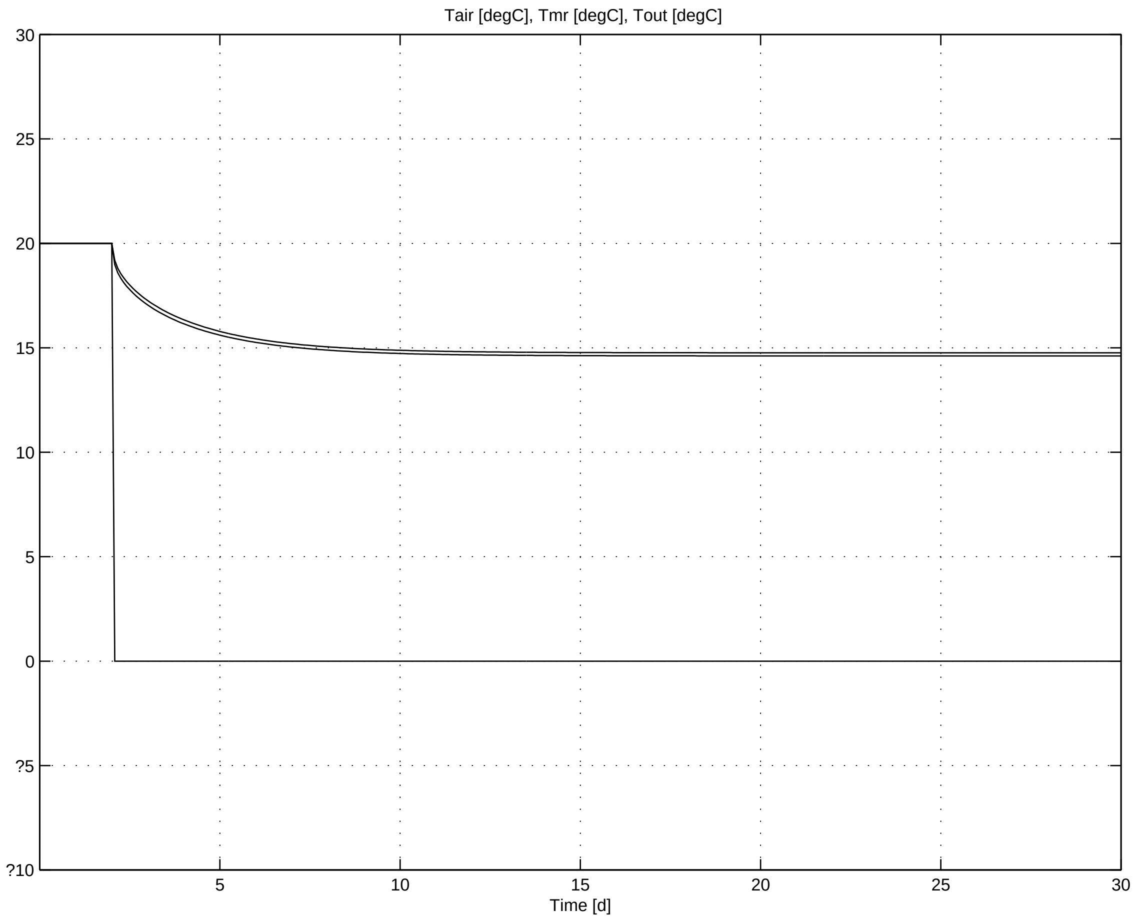

Figure 6.6: Tair, Tmr and Toutside for an outside air temperature step of 20 °C to 0 °C, adjacent spaces kept at 20 °C permanently

The time constant then becomes 1.8 days, and the equilibrium temperature 14.9 °C, again in good agreement with the values predicted by the simplified model (respectively 1.96 days and 14.6 °C).

6.3.3 Simulated response to a solar radiation step (from 0 to 100 W/m2 of window)

The room response to a "solar radiation" step also allows a check of the model. The radiation step the room is subjected to is represented in Figure 6.7. It corresponds to a step of 0 to 100 W/m2 of window area. Only the transmitted radiation is represented (which accounts for 264 W), an additional component is absorbed in the window panes and also contributes (partly) to the room heat gains.

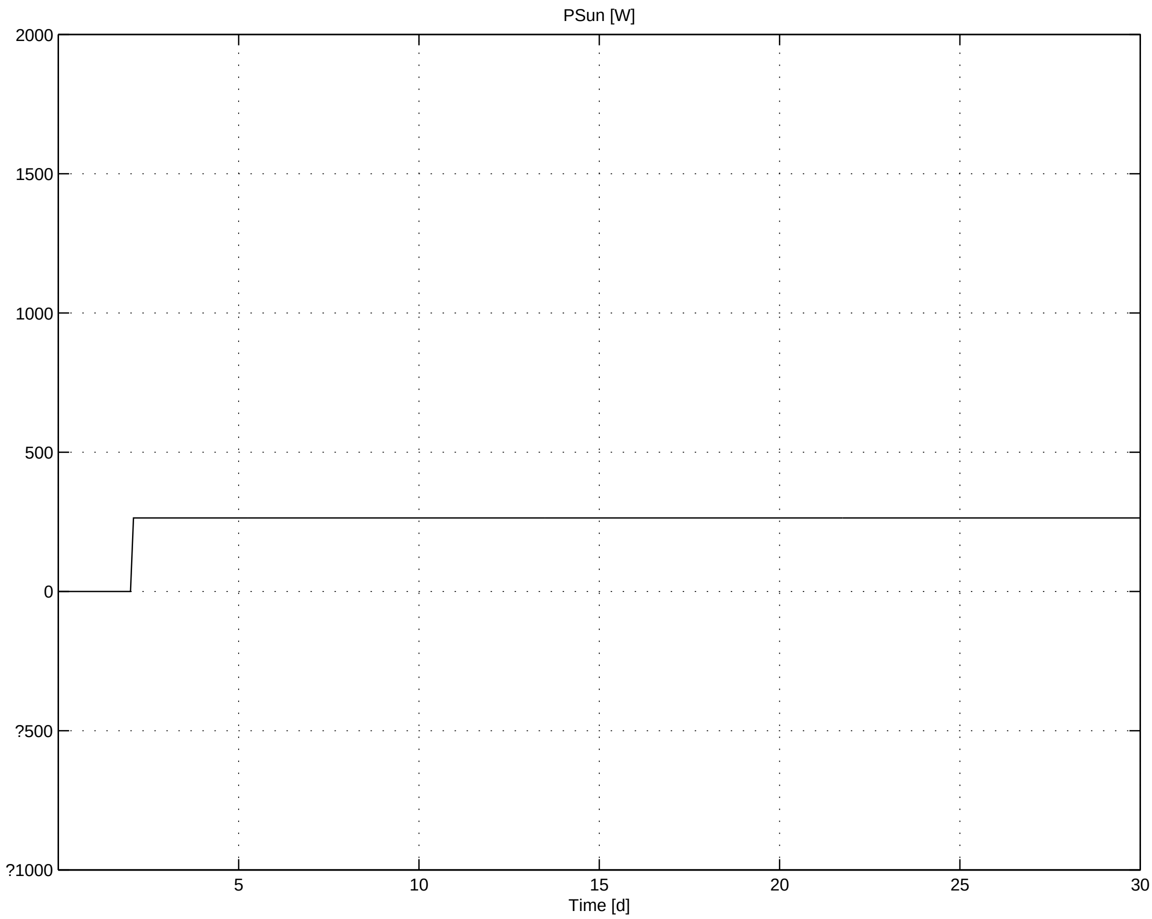

Figure 6.7: Transmitted solar heat gains, "solar radiation" step

As before, the adiabatic case and the case where the adjacent space temperature is kept constant at 0 °C give a different response. For the adiabatic case, the inside temperature is plotted in the figure below. The time constant measured on the plot is 7.2 day, in good agreement with the simple model value of 7.29 days. The asymptotic value of the inside temperature is 16.5 °C on the plot, again in rather good agreement with value predicted by the simple model (15.0 °C).

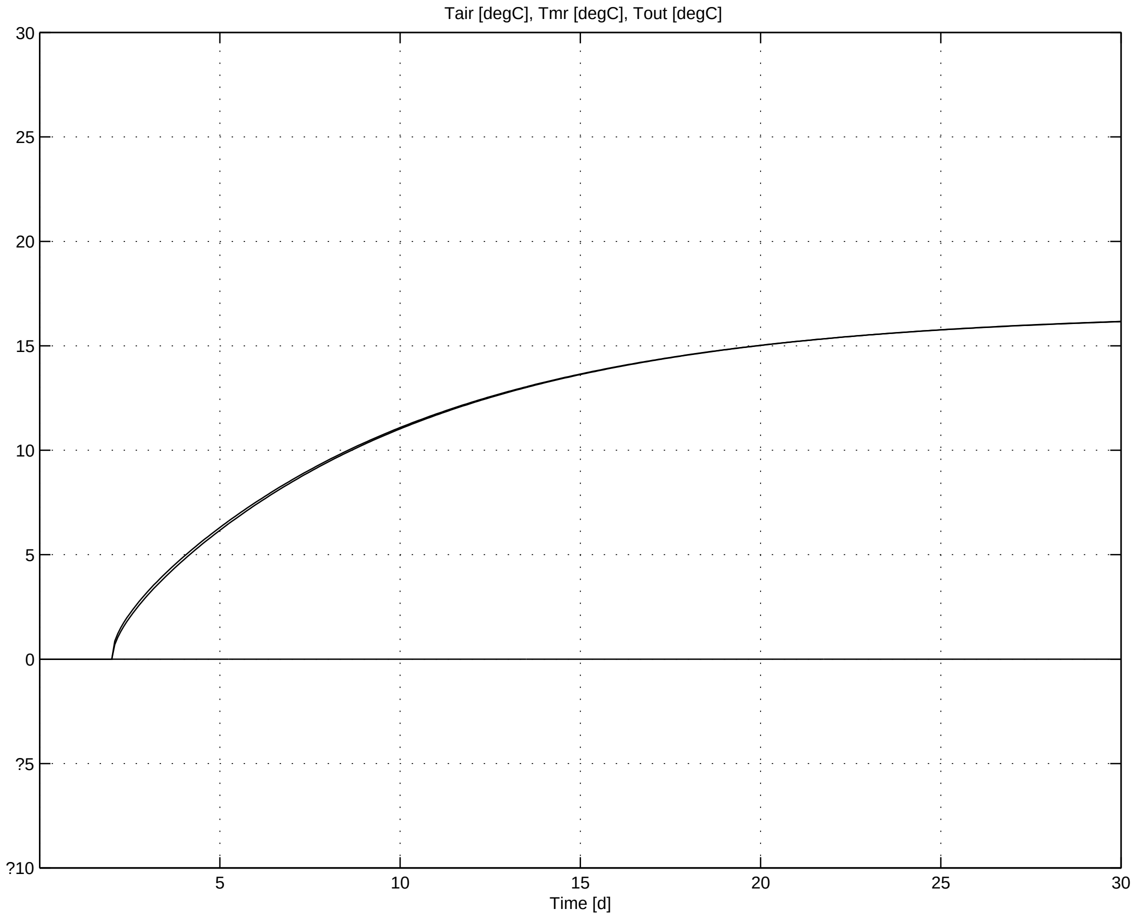

Figure 6.8: Tair, Tmr and Toutside for a solar radiation step from 0 to 100 W/m2 of window, outside temperature kept at 0 °C, adiabatic case

For the case with a connection to the adjacent inside spaces, supposed to be kept at a constant temperature of 0 °C, the temperature behaviour is given by Figure 6.9.

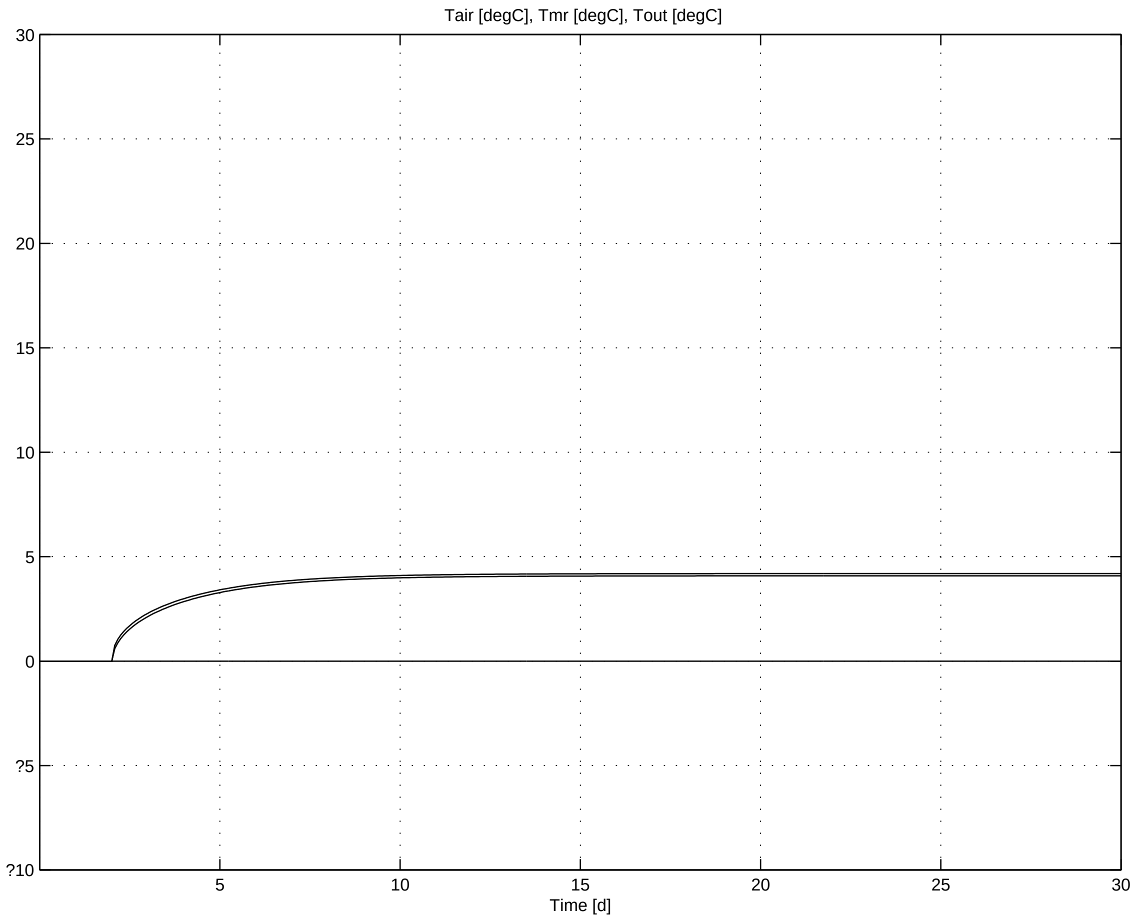

Figure 6.9: Tair, Tmr and Toutside for a solar radiation step from 0 to 100 W/m2 of window, outside temperature and adjacent spaces kept at 0 °C

The time constant then becomes 1.6 days, and the equilibrium temperature 4.0 °C, again in reasonable agreement with the values predicted by the simplified model (respectively 1.96 days and 4.0 °C).

6.3.4 Heating demand for steady-state condition

A simulation has been done, without any solar or internal gains, in order to check the heating demand at a constant outside temperature (0 °C). The heating setpoint was 20 °C. In these conditions, and for the adiabatic case (no conduction towards adjacent spaces, except to the outside), the heating demand, after stabilization, is 405 W.

This number is in good agreement with the result given by a simple calculation, taking into account equivalent conductance from the inside to the outside (including air renewal):

Pth = Gequ · (Tin - Tout) = 20.23 W/K · 20°C = 405 W

6.3.5 Simulated response to cyclic conditions and heating behaviour

In order to investigate and check the heating controller, several simulations have been carried out with cyclic excitations (either outside temperature or solar heat gains) and the auxiliary heating working. All the results show a good behaviour of the inside temperature after an adjustment of the heating controller algorithm. Only two cases will be shown here. In the first one, the solar power was 100 W/m2 of window from 6 am to 6 pm ("day"), and 0 from 6 pm to 6 am ("night"). The second case is similar, except that the solar power was set to 200 W/m2 of window during the "day". In both cases, the outside temperature was kept at a constant value of 0 °C. These values were chosen so that the solar power was not enough to heat the room in the first case, and just a little more than enough to heat the room completely during the day but not during the night, in the second case.

The four figures below show the response of the system. No direct comparison with a simplified model can be done easily, but the heating controller reacts correctly to these strongly varying conditions.

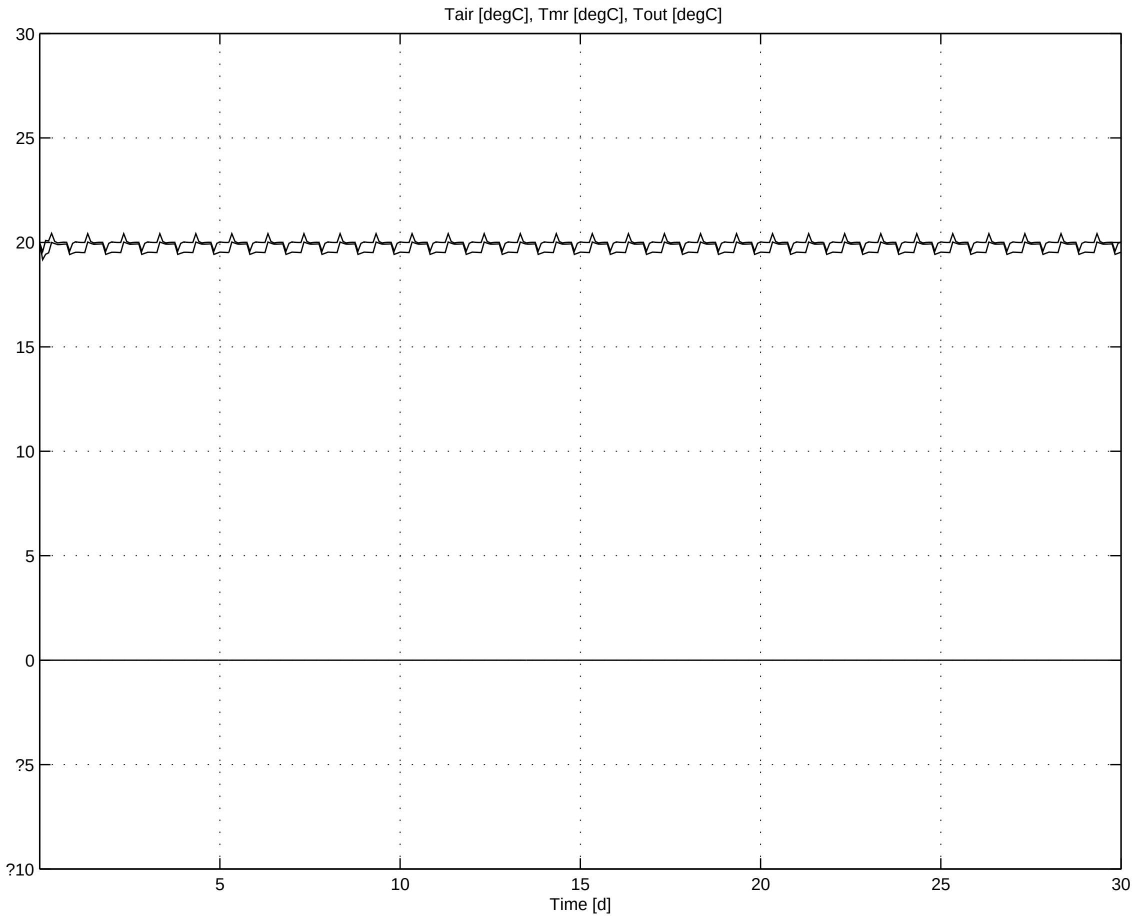

Figure 6.10: Tair, Tmr and Toutside for a cyclic variation of Psun, first variant (100 W/m2 of window from 6 am to 6 pm)

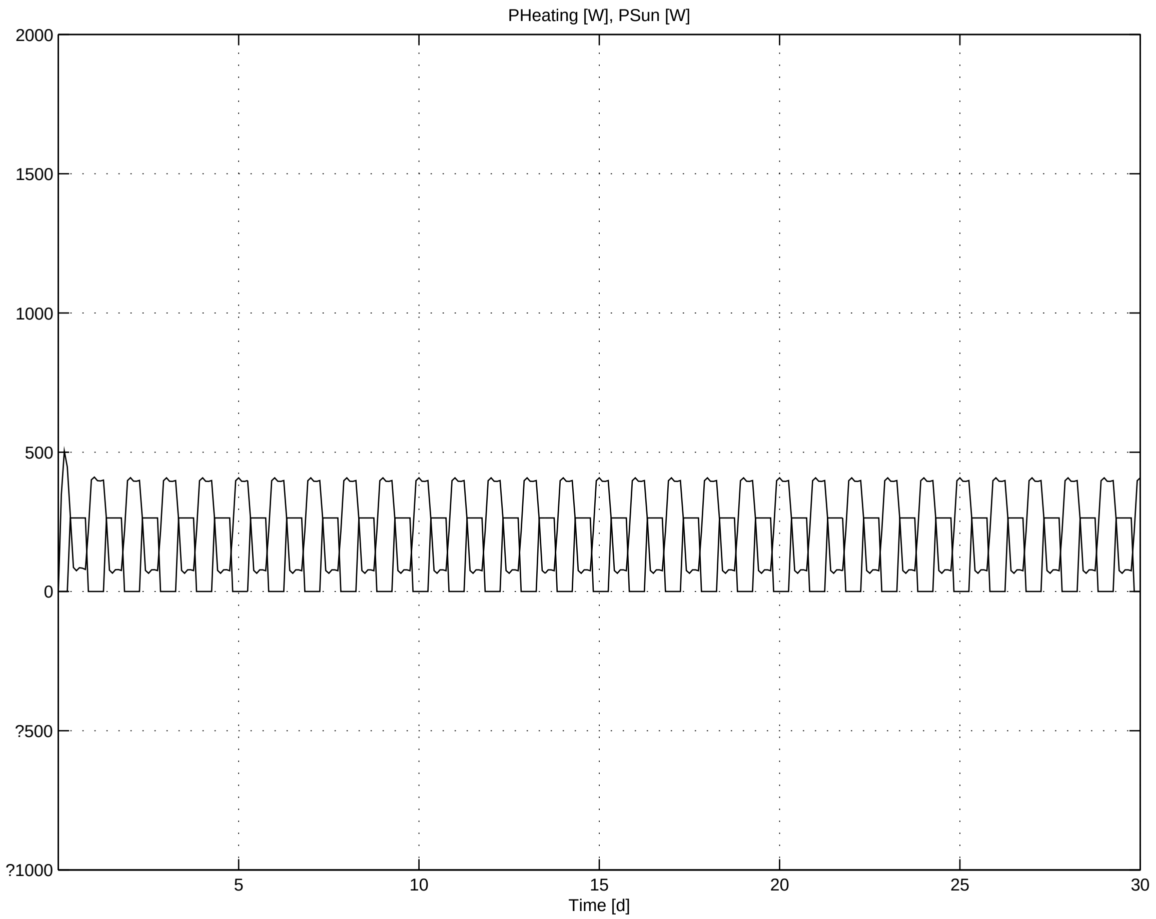

Figure 6.11: Pheating and Psun for a cyclic variation of Psun, first variant (100 W/m2 of window from 6 am to 6 pm)

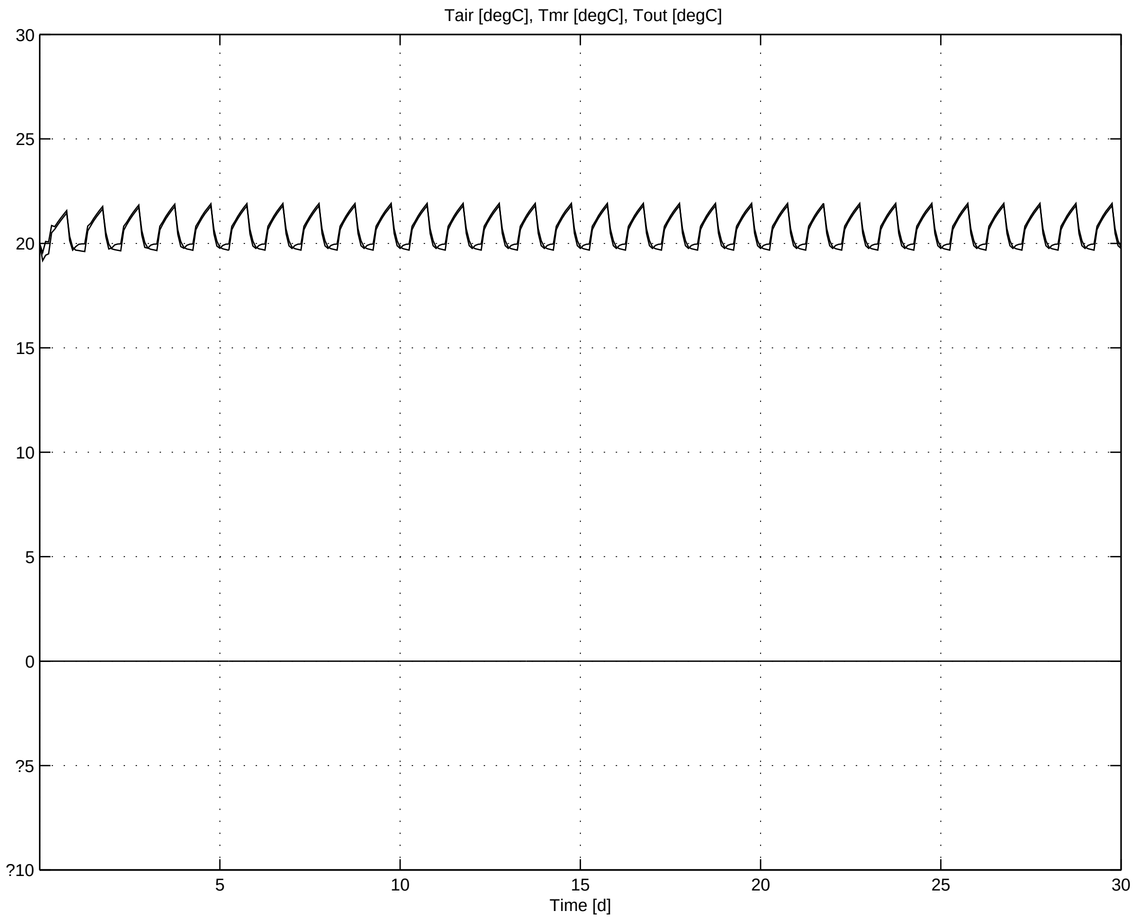

Figure 6.12: Tair, Tmr and Toutside for a cyclic variation of Psun, second variant (200 W/m2 of window from 6 am to 6 pm)

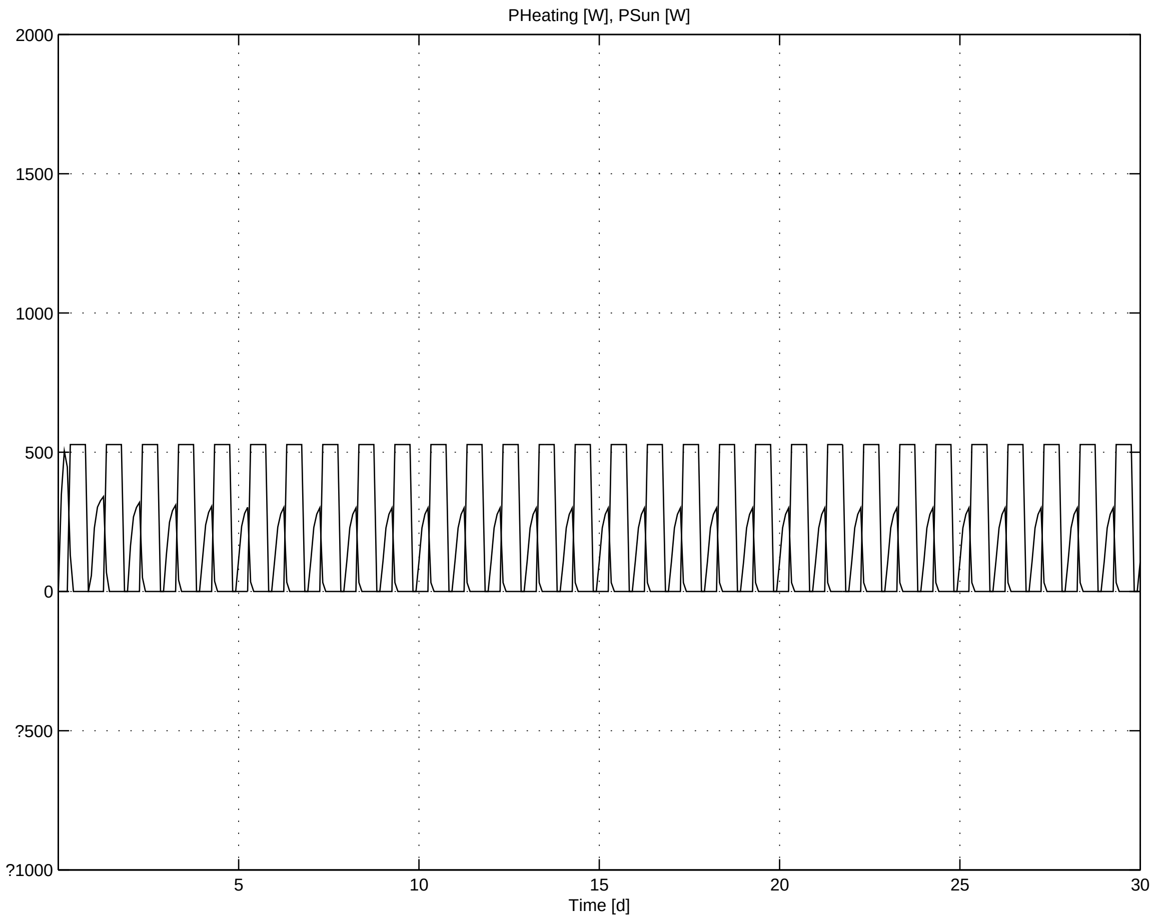

Figure 6.13: Pheating and Psun for a cyclic variation of Psun, second variant (200 W/m2 of window from 6 am to 6 pm)

6.4 Another check of the simulation code: thermal balance calculation

As a rather simple check of the code, the thermal balance can be evaluated over a rather long period. This check does not give conclusive proof that the physical phenomena are simulated correctly, but it can help to debug the program code and show the self-consistency of the calculation.

In order to establish a heat balance, the physical system which is considered has to be defined carefully. Then we can calculate:
(a) the whole energy which goes through the system border during the test time interval (with a positive sign for the energy going in, and a negative sign for the energy going out);
(b) the difference of stored energy in the system, between the beginning and the end of the test time interval.

The two figures should be as close as possible. The energy disclosure is a measure of the numerical accuracy. In order to do a valid comparison, this energy disclosure should be compared to something significant: we choose to relate it to the total heat gain (solar, heating equipment and internal gains) during the considered period.

In order to make the calculation easy, the border of the physical system was as follows:

- for all the walls, the ceiling and the floor, the middle of the first inside layer (i.e. the conductive connection between the first and the second nodes, starting from the inside surface);
- for the window, the gap between the innermost pane and the middle pane (i.e. the connection between the first two panes, starting from the inside pane);
- for the window frame, the middle of the first inside layer (i.e. the conductive connection between the first and the second nodes, starting from the inside surface);
- for the air renewal, through the equivalent conduction from inside air to outside air (only the air renewal towards outside was considered in the simulation).

Two cases were considered: without air renewal, and with a 0.3 vol/hour renewal. The table below gives the result, for the base case (see section 8.2) and for the first 6 months of one year of simulation.

	no air renewal		air renewal 0.3	
	energy [GJ]	fraction of gains	energy [GJ]	fraction of gains
gains	36.828		44.208	
losses	35.983		43.679	
heat stored	0.820		0.575	
difference	0.025	0.0007	-0.045	-0.0010

Table 6.4: heat balance for two cases (no air renewal and 0.3 vol/hour air renewal), over a 6 months period (January-June)

As we can state from the table, the heat balance is quite satisfactory, i.e. the energy disclosure is small enough to be negligible (less than 0.1 % of the total gains to the room).

6.5 Experimental validation of simulation program

The measurements taken during the experiment allowed a validation of the thermal simulation program. Three measurement periods (without window openings) were chosen for that purpose.
Winter: 14 to 20 of April (colder available period)
Mid-season: 10 to 15th of June.
Summer: 8 to 14 of August.

6.5.1 Simulated and measured indoor temperature comparison

As a first comparison, all gains (solar, internal and heating) were entered in the simulation program. The simulated temperature could then be compared with the real one. The following figure shows a comparison of the measured and simulated indoor temperature during the winter period.

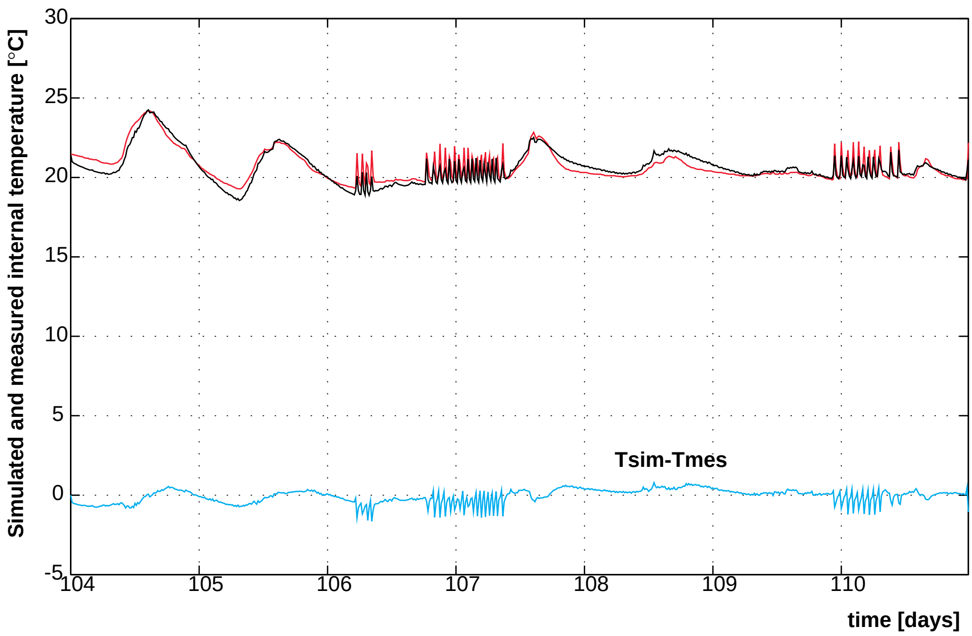

Figure 6.14: Comparison of measured and simulated indoor temperature during winter period.

The difference between the measured and the simulated indoor temperature is in every case less than 1 degree. The measurements and simulated internal temperatures were analysed through a χ^2 statistical test. It is assumed (hypothesis) that Tmes follows a normal distribution over Tsim, with a σ standard deviation due to measurement errors. With this assumption, the statistic

$$Q = \sum_{i=1}^{N} \left[\frac{T_{mes,i} - T_{sim,i}}{\sigma_i} \right]^2 = \frac{1}{\sigma^2} \sum_{i=1}^{N} \left[T_{mes,i} - T_{sim,i} \right]^2$$

follows a χ^2_υ distribution that can be calculated with υ being the number of degrees of freedom (equal to the number of measurements minus the number of adjusted parameters).

The comparison between Q and $\chi^2_{\upsilon,\alpha}$ (with α the significance threshold) gives a good indication of whether or not measured and simulated temperatures can be considered the same. To avoid any bias due to a difference in the initial conditions, the first two days are dropped for the comparison.

Q	σ=0.4 [°C]	σ=0.5 [°C]	σ=0.7 [°C]	σ=1 [°C]
winter period	583	374	191	93
mid season period	399	256	130	64
summer period	751	481	245	120

Table 6.5: T values for different standard deviation

$\chi^2_{,\alpha}$	α=0.95	α=0.975	α=0.99
winter period	529	539	552
mid season period	326	335	345
summer period	481	489	501

Table 6.6: $\chi^2_{\upsilon,\alpha}$ values for different significance threshold

If σ is assumed equal to 0.5°C, $Q < \chi^2_{\upsilon,\alpha}$ in every case. Therefore our hypothesis can be accepted as reasonable. Our measurements are compatible with the simulations when the standard deviation on the air temperature is 0.5 °C. The deviation can be explained by measurement errors and the stratification of temperature within the room (the temperature sensor is not representative of the whole room due to stratification).

6.5.2 Heating demand

In this comparison, the heating energy consumption is compared over the whole period considered. Internal and solar gains are identical in measurements and simulations. The internal temperature is not directly compared.
The difference between measured and simulated heating demands is compared to other heat flows in the room (see table).

	Heat (MJ)	Cool (MJ)	Internal gains (MJ)	Solar gains (MJ)	Heating+cooling difference (simulation-meas.) (MJ)	% of total heat balance
Winter (7 days)	23.4	0	15	65.9	-4.9	4.7%
Mid-season (5 days)	1.8	0	10.2	22	1.2	3.5%
Summer (6.5 days)	0	-16.9	8.7	26.5	-7.9	15%

Table 6.7: Comparison between the measurements and the simulation for heating and cooling needs

The difference between simulated and measured heating and cooling needs represents in winter and mid season about 5% of the total heating and cooling loads in the building and in the summer period about 15%. The difference, which is very reasonable, can be explained by :

- the very short time periods considered. This type of comparison is normally valid for long periods only.
- the fact that even a small difference in simulated measurements of the internal temperature can result in the heating or the cooling system being switched on. This effect is weighs quite heavily when short periods are considered.

6.5.3 Heat loss coefficient

To obtain a long term comparison of heating and cooling needs, the heat loss coefficients of the simulated system were taken from H-m [LESO 85] diagrams over the whole season and compared to the coefficient obtained from the previous general measurements carried out on the LESO building.

Ho (W/K)	
19 ±0.2	Simulation: blind open
17.1 ±0.2	Simulation: blind 1/2 open
13.6 ±0.2	Simulation: blind closed
19.3 ± 1.1	LESO measured reference [LESO 81]

Table 6.8: Overall heat loss coefficient of the office room, simulated and measured values

Because of the blind isolation system effect (see 5.4.1), the heat loss depends on the blind position. For an open blind, Ho is very similar to the measured value. With a half closed or closed blind Ho decreases down to 13.6 (W/K).

The comparison of simulated and measured temperatures shows a good correspondence and the comparison of heating needs shows little difference. The simulation model can therefore be considered sufficiently representative of real offices rooms.

7. MEASUREMENTS

7.1 Monitoring campaigns

The following table gives the dates of the monitoring campaigns. The first periods were mainly used to debug the complex experimental system (data-acquisition, heating and cooling control, blind control). These measurements were not very interesting with regard to the automatic blind control algorithm efficiency, but have been used for the validation of the simulation program. We consider three periods here, one for each automatic controller type, to check their performance in reality. A long term comparison of these options based on measurements was not possible within the time allocated for the project. The diagrams in this chapter only give a qualitative judgement of their performance. You will find a detailed discussion of energy-related and visual performance results of different algorithms from simulation in Chapter 8.

Begin of measurements	End of measurements	Algorithm
12.4.95	21.4.95	version 1
23.5.95	1.6.95	version 1
8.6.95	15.6.95	version 1 (*)
3.8.95	14.8.95	version 1
4.10.95	16.10.95	version 2
24.10.95	31.10.95	version 3 (*)
6.11.95	23.11.95	version 2 (*)

Table 7.1: Measurement periods. (*) results presented in the report

7.1.1 Version 1 (TU-WIEN algorithm)

The seven-day period considered (from 8.6.95 to 15.6.95) corresponds to summer and mid season weather conditions (see Figure 7.1). Figure 7.2 shows the occupancy, the user requests (manual blind changes), the user chosen position, the energy-optimised blind position and the final blind position. Figure 7.3 shows lighting gains, heating gains and inside illuminance.

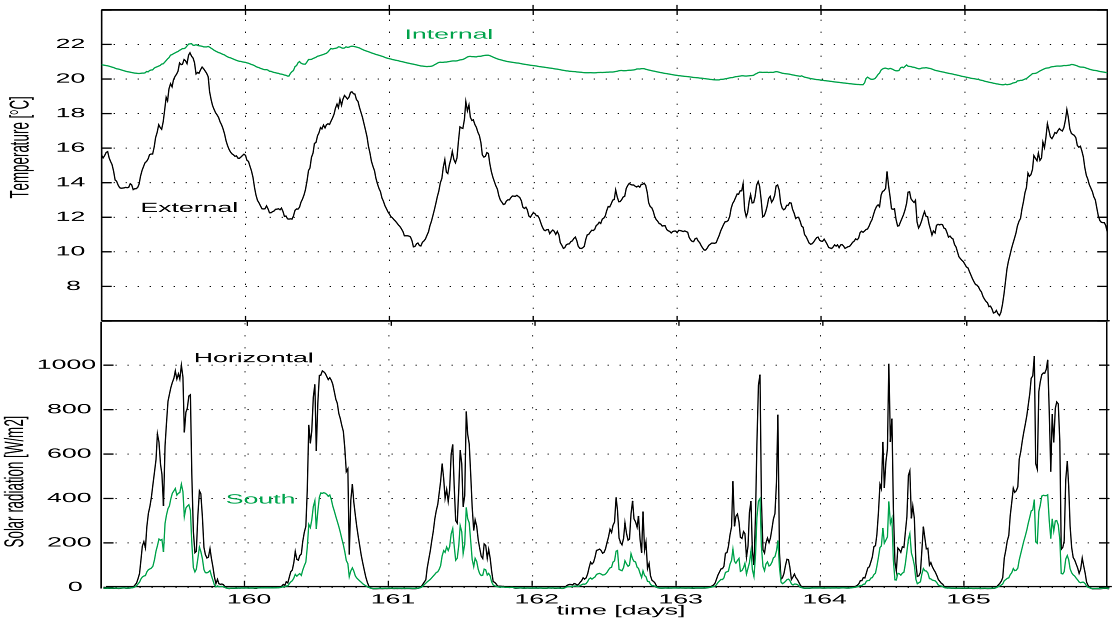

Figure 7.1: Blind control algorithm version 1: meteorological situation

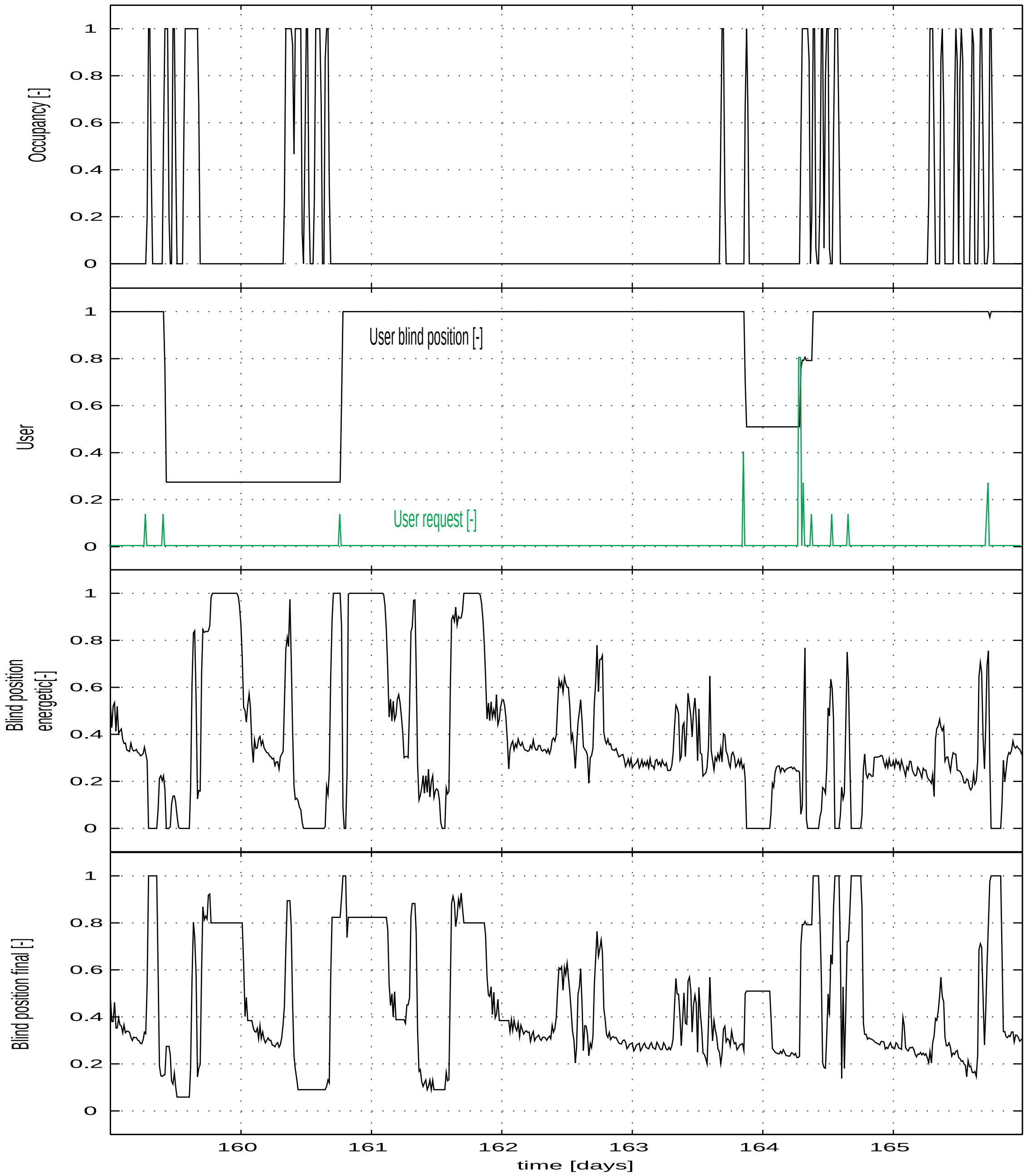

Figure 7.2: Blind control algorithm version 1: occupancy, user wishes and blind positions (a blind position=1 means 'blind is open'; occupancy=1 means 'room is occupied')

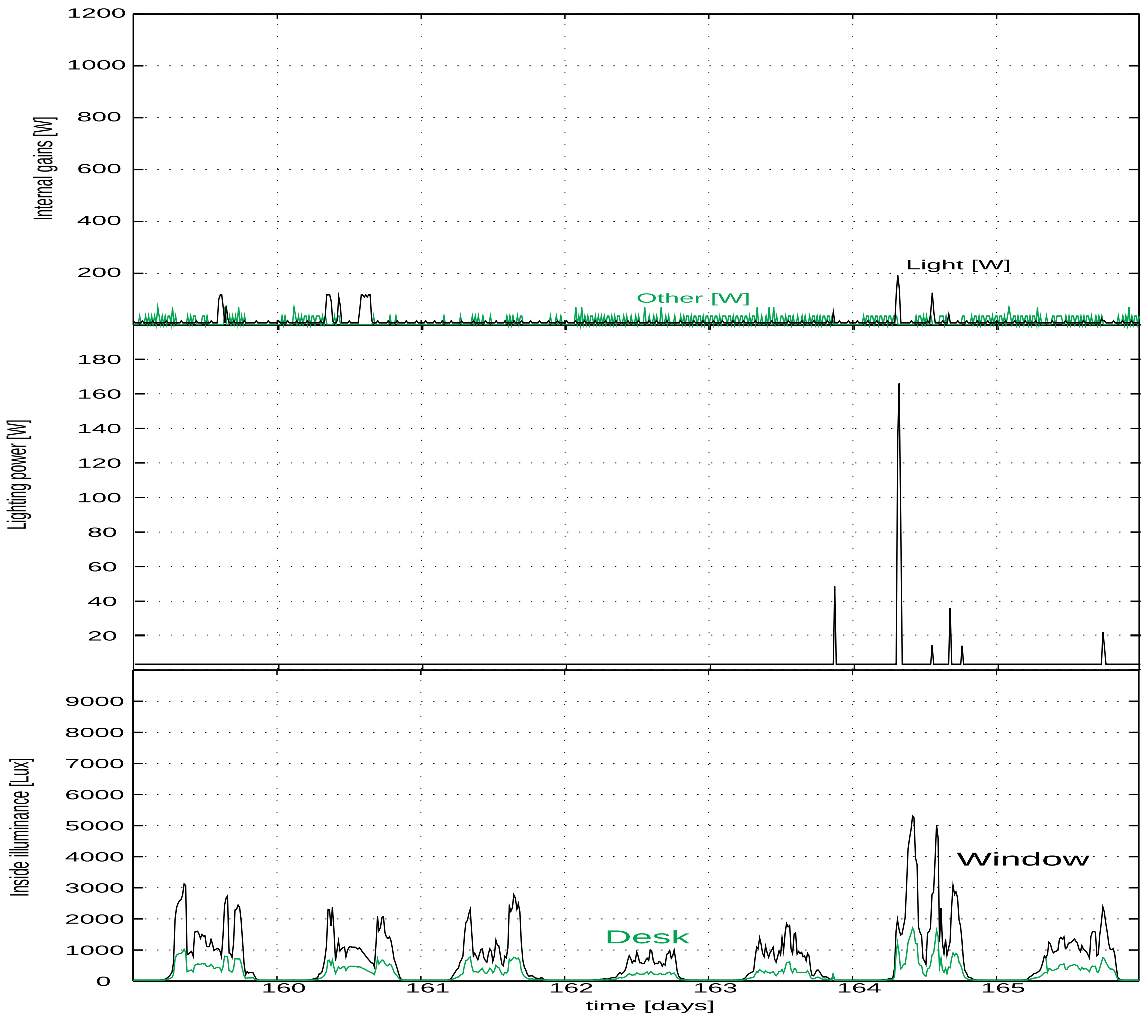

Figure 7.3: Blind control algorithm version 1: heating, internal, lighting gains and inside illuminance.

Heating [MJ]	6.7
Cooling [MJ]	0
Solar gains [MJ]	33.5
Internal gains [MJ]	4.6
Artificial lighting [MJ]	2.2
Total blind moves [1/day]	70.5
Blind moves with occupancy [1/hour]	2.3
User blind moves [1/hour]	0.9
Hour of occupancy per day [1/day]	1.9

Table 7.2: Gains and blind moves for version 1

Thermal energy observation

During days 159 and 160, summer conditions can be observed; thus solar gains should be cut during the day to avoid cooling loads. This is only approximately done by the system (the blind moves too often).

During the night, the blind is open to increase heat losses, but only half the possible time. It has no energy-related consequences in this case (there is no cooling during that period), but during a hotter period, the insufficient blind opening during the night could increase cooling needs.

Daylighting supplies

During days 161 and 162, with a low solar irradiation, the blind is almost closed. This behaviour is generally not efficient from a daylighting point of view because it increases the artificial lighting needs.

Considering both thermal energy and daylighting supplies, the algorithm seems to be inefficient. However, this result needs to be confirmed over longer periods (see the simulation section).

User wishes and blind movements

The total number of blind movements is 70 per day. This high value is explained by the very high complexity of the rule base and by the fact that when there is no occupant, the blind movements are not restricted to 6 possible positions. During occupancy, the number of blind movements remains rather high (2.3 per hour) and user moves up to 0.9 per hour.

7.1.2 Version 2 (DELTA Standard algorithm)

This algorithm was tested during a winter period (November). Various climate conditions occurred during this period, as can be seen in the next figure:

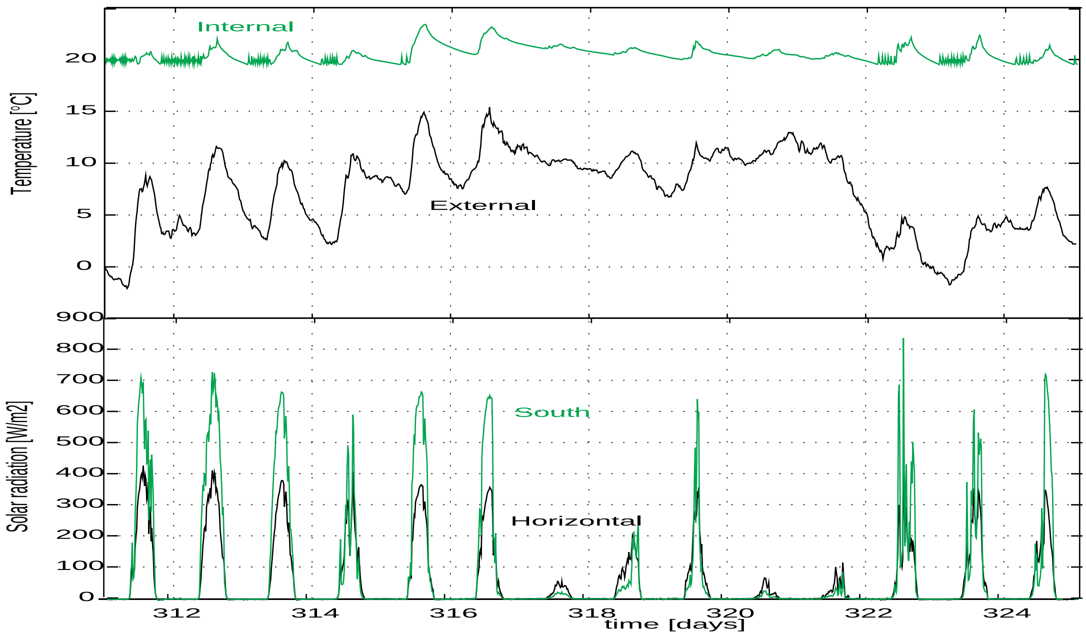

Figure 7.4: Blind control algorithm version 2: meteorological situation

The occupancy and the blind positions are given in the following figure; the visual position is not represented here, but can be deducted from the difference between the final position and the energy-optimised and user-chosen positions.

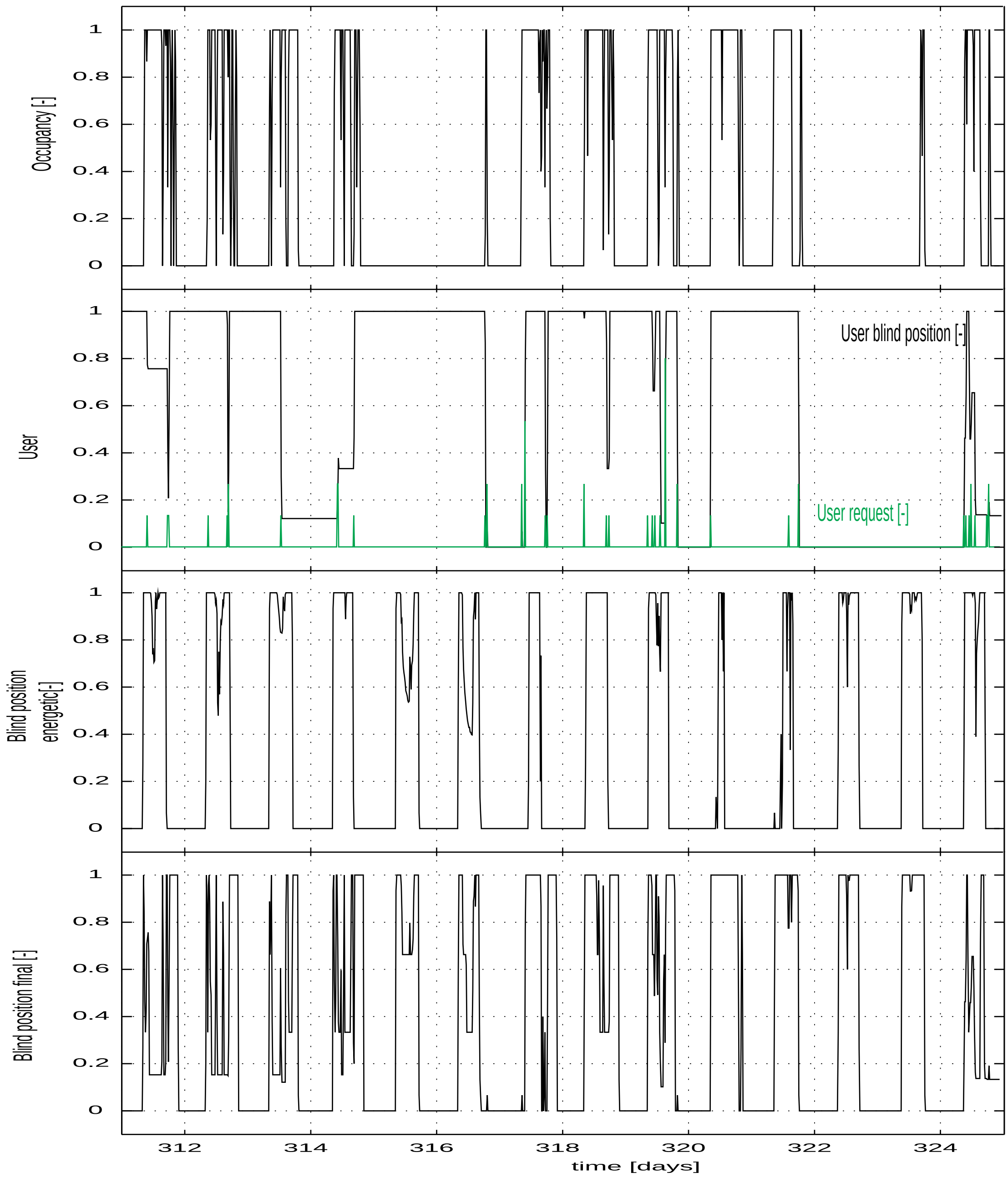

Figure 7.5: Blind control algorithm version 2: occupancy, user wishes and blind positions

The next figure shows the different gains in the room.

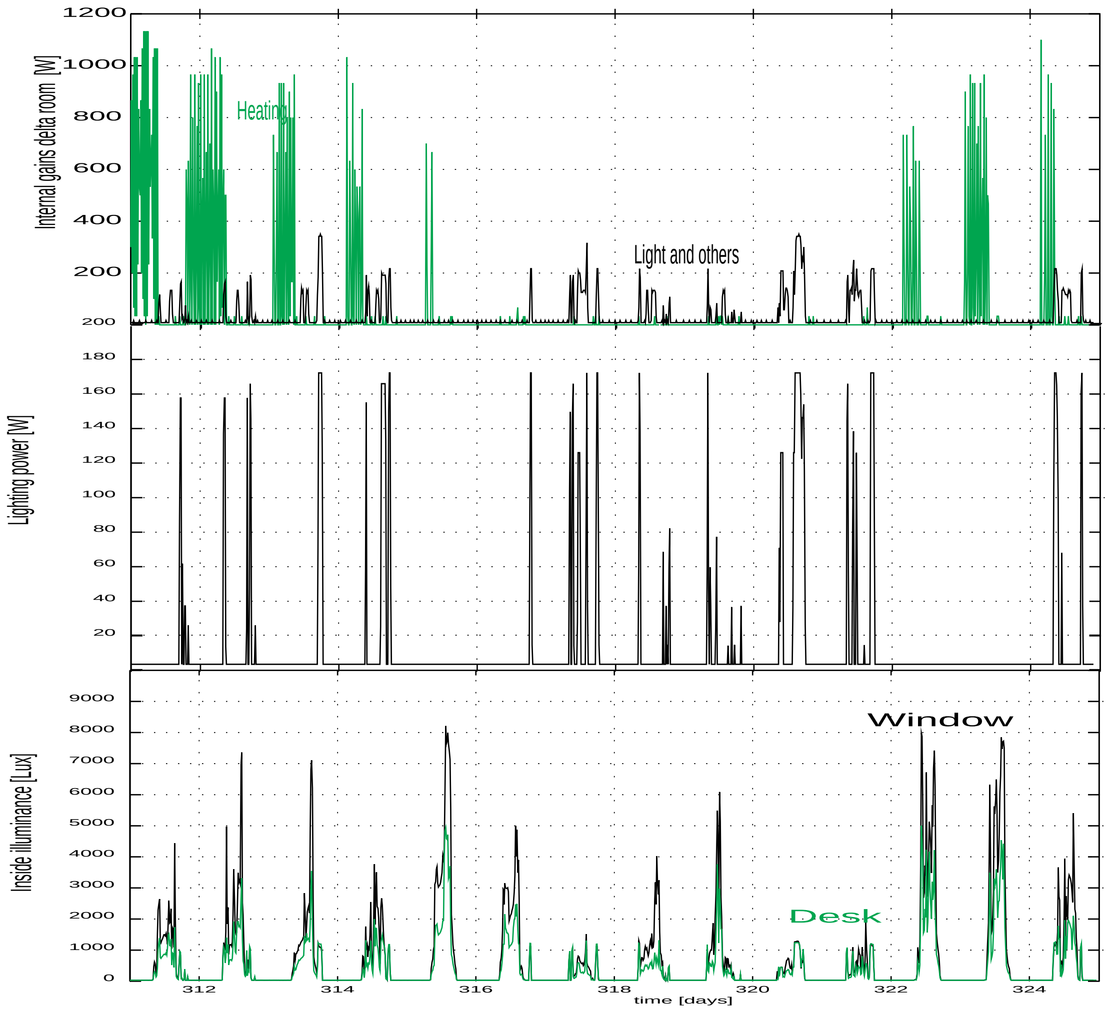

Figure 7.6: Blind control algorithm version 2: heating, internal, lighting gains and inside illuminance.

Heating [MJ]	52.9
Cooling [MJ]	0
Solar gains [MJ]	117.4
Internal gains [MJ]	17.4
Artificial lighting [MJ]	17.9
Total blind moves [1/day]	15.4
Blind moves with occupancy [1/hour]	1
User blind moves [1/hour]	0.4
Hour of occupancy per day [1/day]	5.7

Table 7.3: Gains and blind moves for version 2

Thermal energy observation

The period was characterized by cold days and high heating needs (days 311 to 315 and 322 to 324). Under such conditions, the optimal strategy for the blind control system is to maximise solar gains and minimize losses during the night.

The real behaviour of the algorithm can be observed directly from the energy-optimised blind position (the final blind position depends on visual and user aspects, too). Roughly speaking, the blind is closed during night and open during the day, following the time schedule of the window power balance sign change. If we look more in detail, however, the blind is not completely open during the very sunny periods. This behaviour reduces solar gains and avoids overheating in mid-season (days 315, 316)

Lighting consideration

During occupancy, for example days 320 and 321 (cloudy days), the blind is open to maximize daylighting even if this is not very efficient from a thermal energy point of view (heat losses). During high irradiation periods (days 311, 312 and 313), the blind position is kept down to avoid glare when the room is occupied.

User wishes and blind movements

The total blind movements (automatic + user) equals 1 per hour of occupancy, thus user requests are frequent (0.4 changes per hour). Most of them occur just when people enter the room (the occupancy changes from 0 to 1). But some changes also occur during occupancy periods, which indicates that the standard visual condition does not always correspond to user wishes.

7.1.3 Comparison of version 2 with the reference room

The following two figures are taken from the reference room in which the blind control was in manual mode all the time. This room is occupied by another person and the occupancy schedule is different. The blind position is not often changed during the period as can be seen is the next figure.

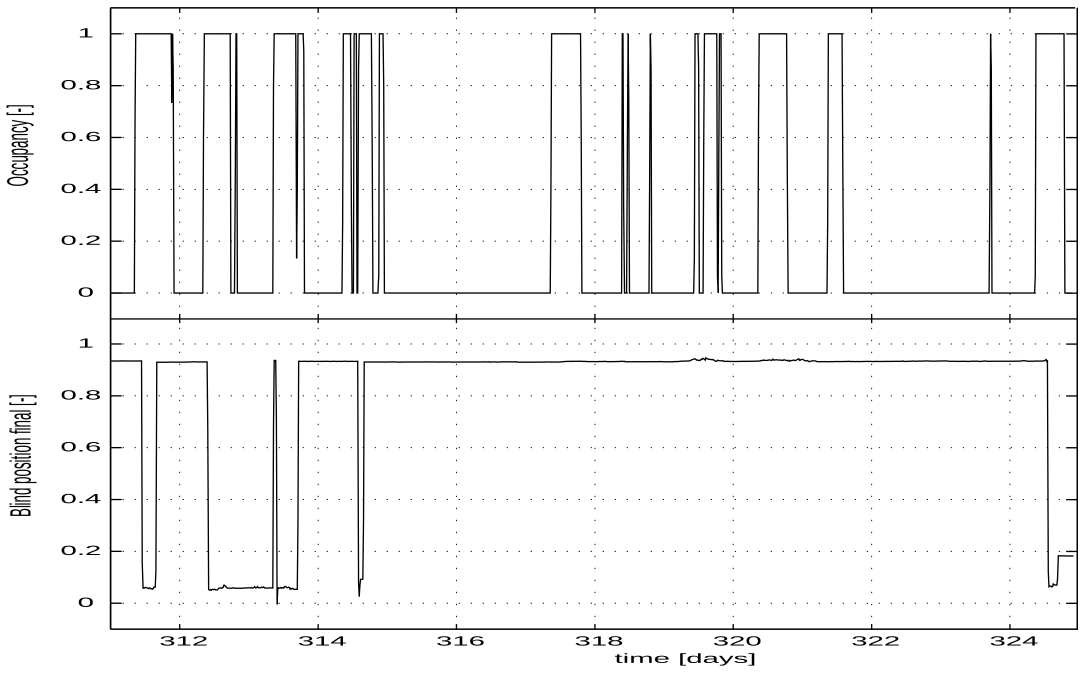

Figure 7.7: Reference case (manual control): occupancy, and blind positions

Figure 7.8 shows the heating energy consumption, the lighting gains and the indoor temperature obtained during the monitoring period (heating gains are more continuous than in the DELTA room because the heater has no air convector and the heat diffuses more slowly).

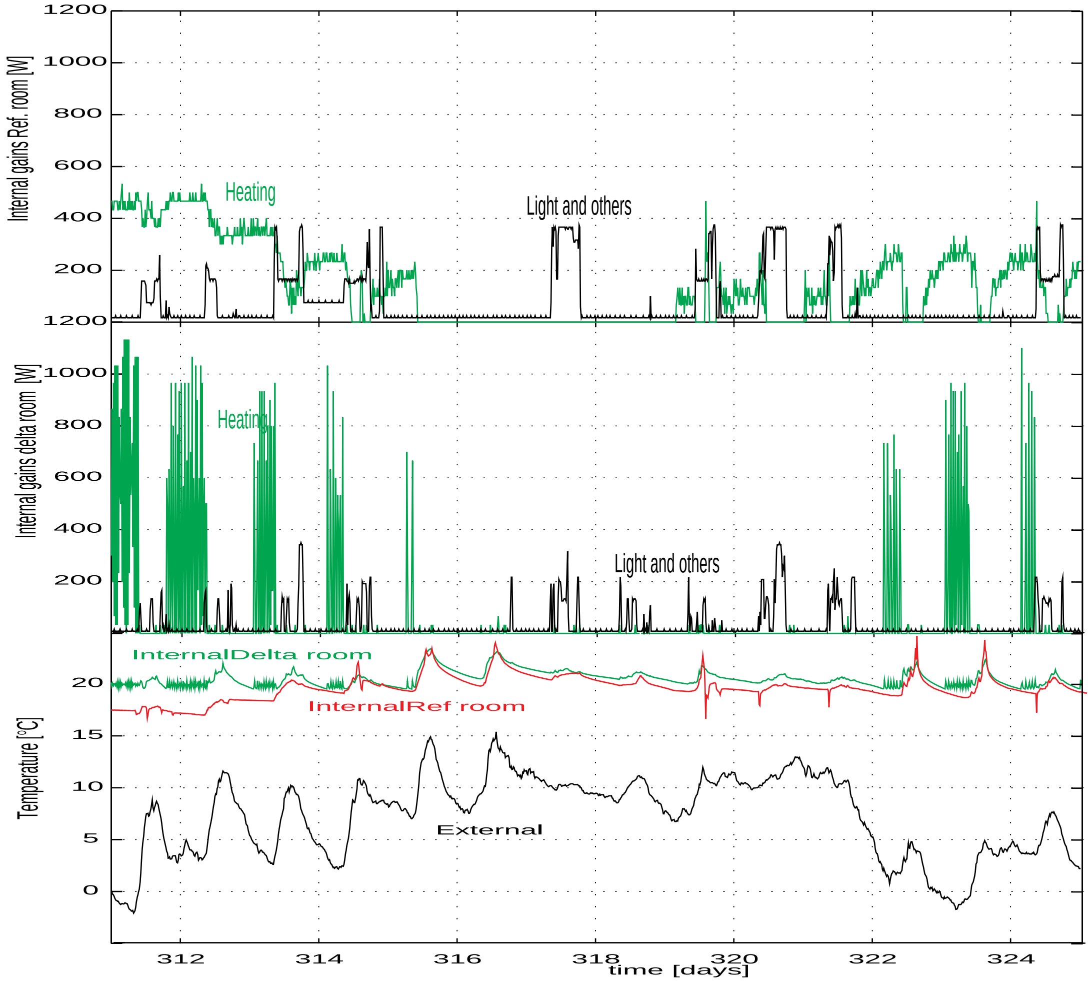

Figure 7.8: Comparison between the reference case (manual control) and the blind control version 2: heating and internal gains, inside temperatures

	Reference room	DELTA room, version 2
Heating [MJ]	132.5	52.9
Cooling [MJ]	0	0
Solar gains [MJ]	122	117.4
Internal gains [MJ]	52.4	17.4
Artificial lighting [MJ]	27.4	17.9
Total blind moves [1/day]	0.5	15.4
Blind moves with occupancy [1/hour]	0.1	1
User blind moves [1/hour]	0.1	0.4
Hour of occupancy per day [1/day]	5.5	5.7

Table 7.4: Gains and blind moves for the reference and the DELTA room (controller version 2)

Figure 7.9 shows the opening occurrences for the window and the door in the two rooms. It allows to control non measured heat losses. Normally the door should be kept closed all the time (except for entering and leaving). The long periods where the door was open at the beginning of the measurements (days 311 and 312) for the reference room, and during the night 320-321 for the DELTA room, show that even when people are asked not to keep the door open, they still do it.

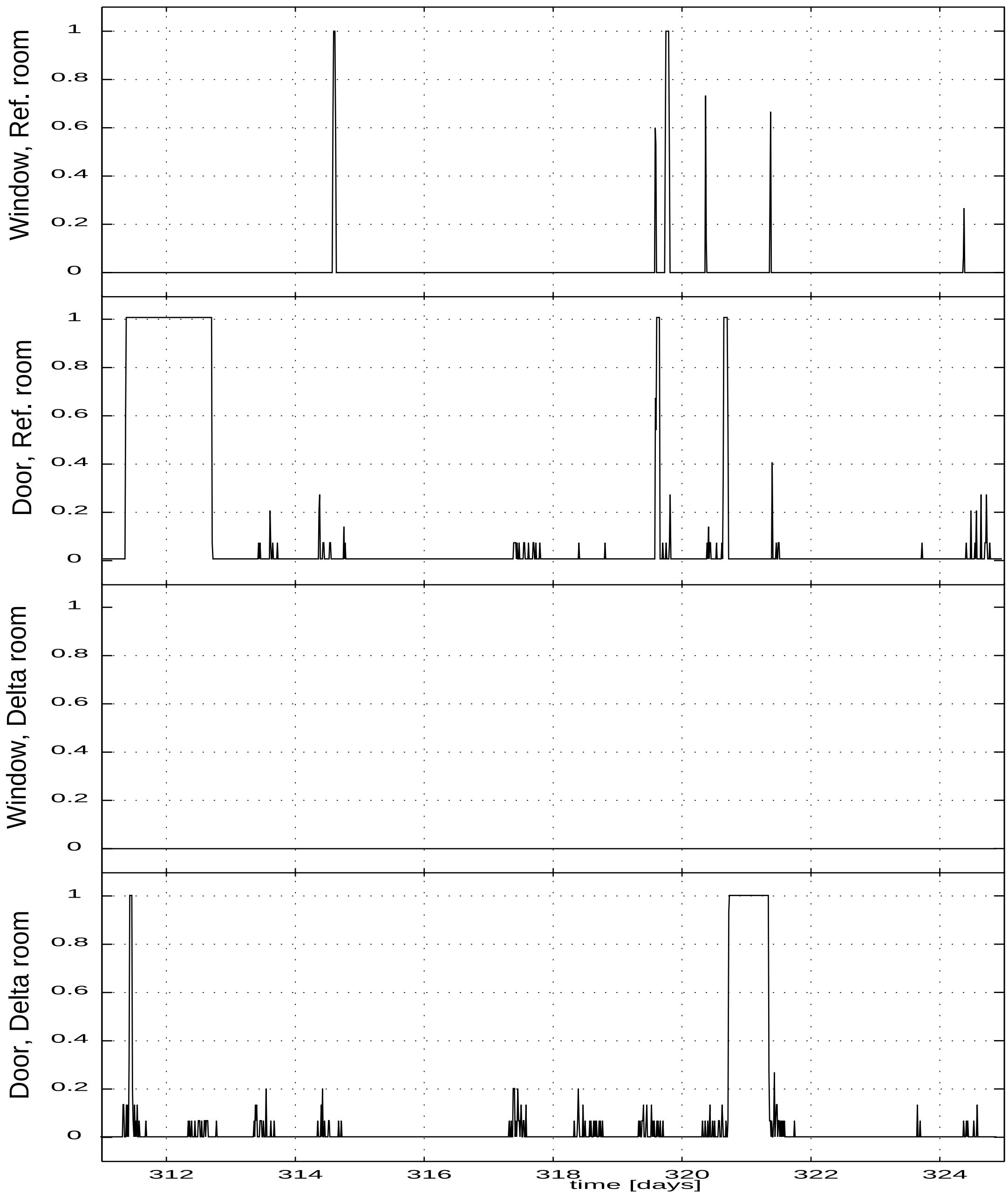

Figure 7.9: Door and window opening statistics for reference and DELTA rooms

Observations

Energy supplies

The total heating supplies during the period amount to 132 MJ for the reference room and 53 MJ for the controlled room. This large difference can be explained by:

- a start-up period for heating in the reference room. The heater was switched on only one or two days before the experiment started. Therefore, the heating system had to provide much heating energy to increase the indoor temperature (days 311 to 315).
- a better night insulation with the DELTA control algorithm. In the reference room, the user typically left the blind during the night in the same position as it was set during the day (i.e.

open) which resulted in higher heating needs than with the DELTA system, especially when it was cold outside (days 322, 323).

Internal gains and lighting gains

The artificial light gains during the monitoring period represent 27 MJ in the reference room and 17 MJ in the DELTA controlled room. The difference depends mainly on the behaviour of two different users and cannot be attributed, over such a short period, to higher artificial lighting needs in the reference room.

User and blind movements

In the reference room, the blind position was changed quite rarely (only 0.1 changes per occupied hour) whereas in the DELTA controlled room, manual changes occurred up to 0.4 times per hour. Users are different and this result cannot be generalised, but it seems to indicate that the visual comfort position was not satisfactory for the user so that he needed to change the position himself more frequently (in any case when entering the room).

7.1.4 Version 3 (Artificial intelligence algorithm)

This algorithm was tested in October, without having extreme weather conditions.

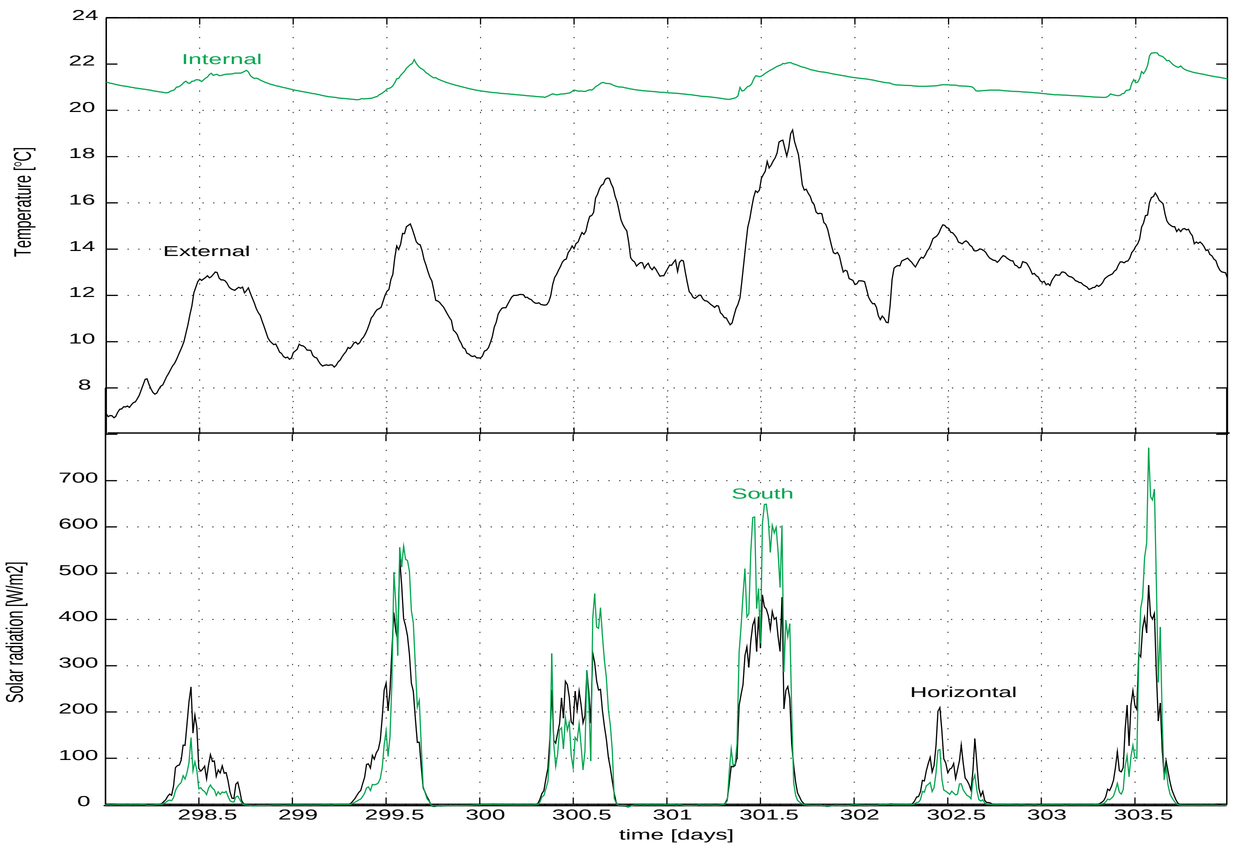

Figure 7.10: Blind control algorithm version 3: meteorological situation

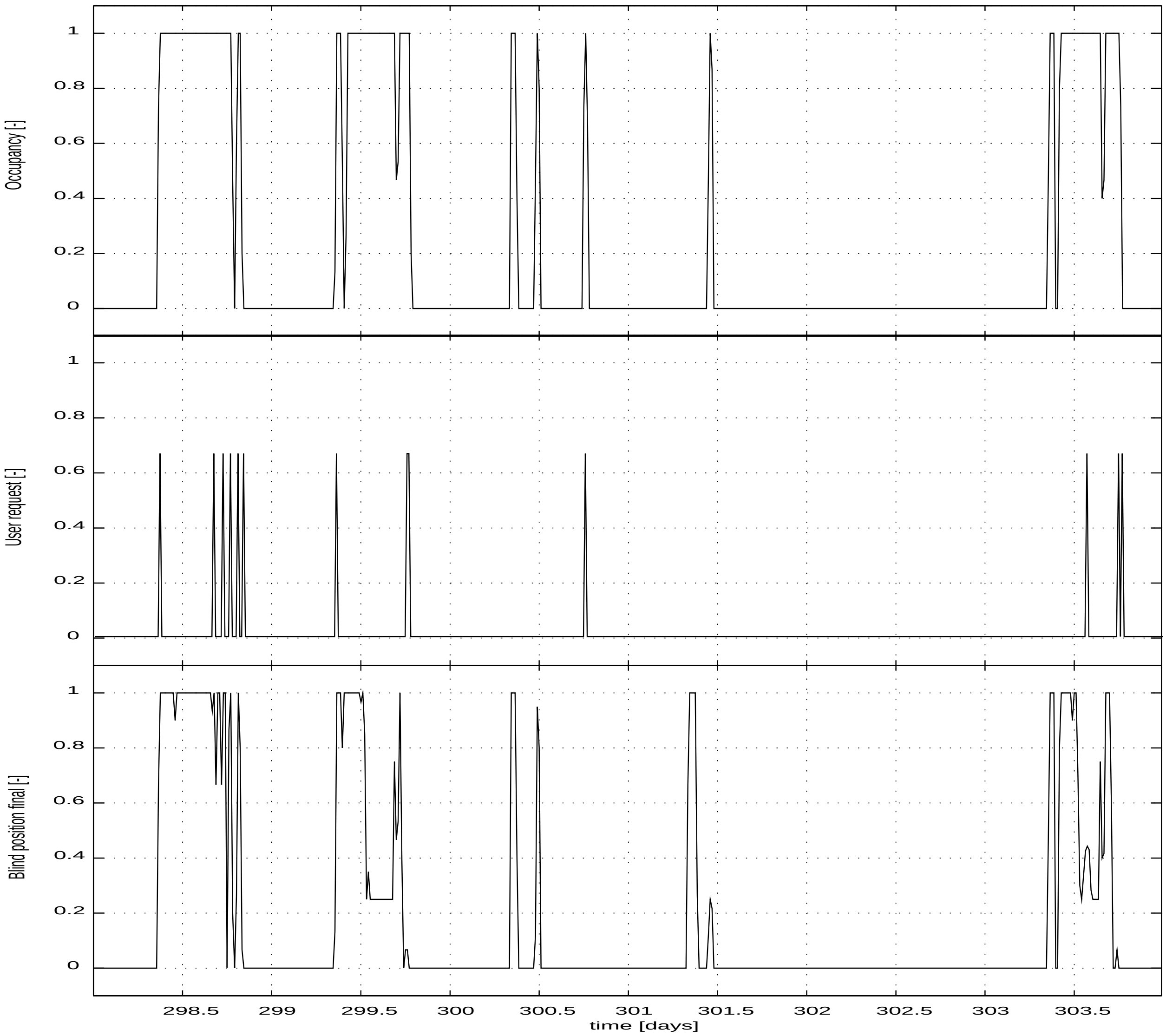

Figure 7.11: Blind control algorithm version 3: occupancy, user wishes and blind positions

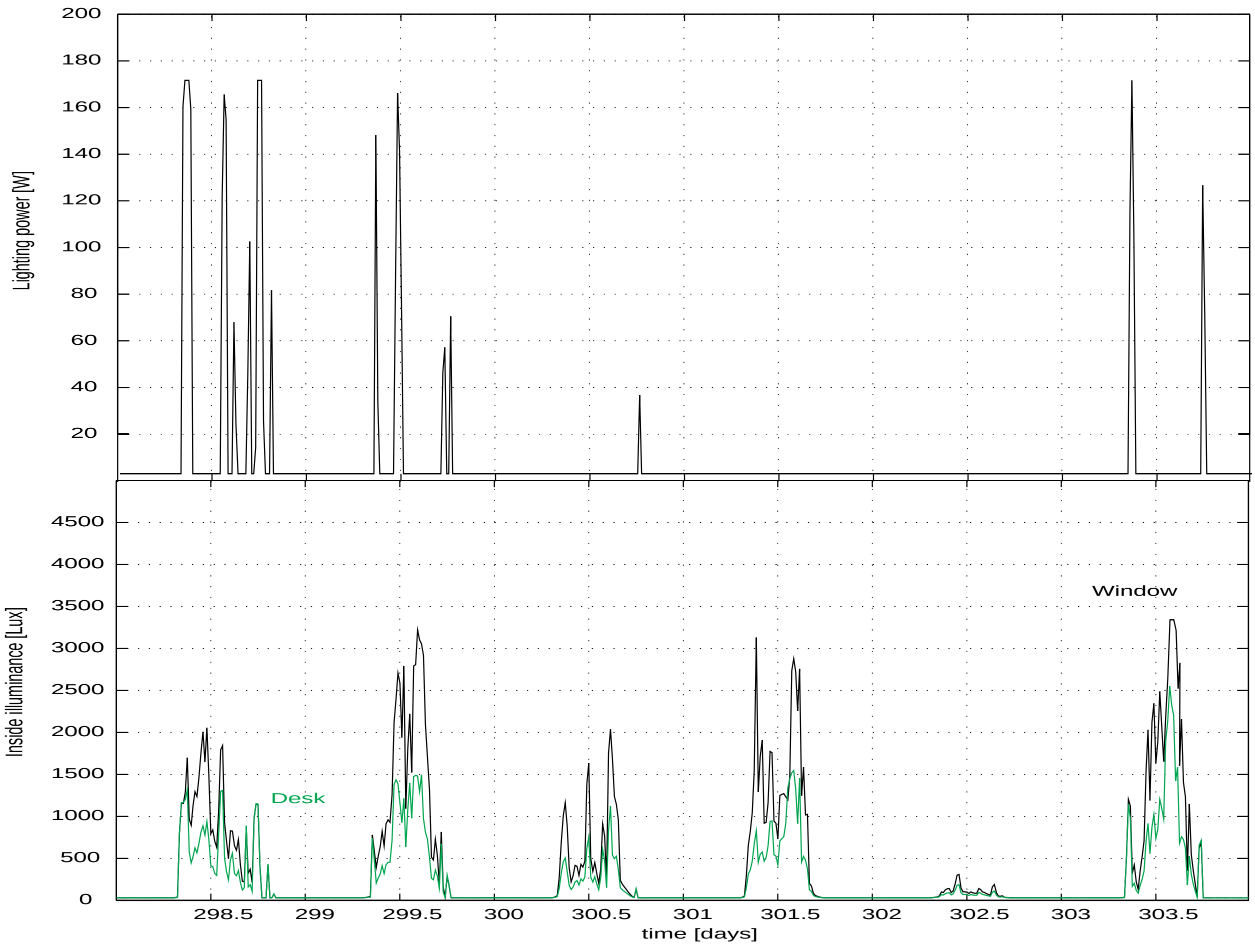

Figure 7.12: Blind control algorithm version 3: heating, internal, lighting gains and inside illuminance.

Heating [MJ]	0.7
Cooling [MJ]	0
Solar gains [MJ]	31.7
Internal gains [MJ]	5.1
Artificial lighting [MJ]	3.9
Total blind moves [1/day]	14
Blind moves with occupancy [1/hour]	1.8
User blind moves [1/hour]	0.5
Hour of occupancy per day [1/day]	4.7

Table 7.5: Gains and blind moves for version 3

Thermal energy observation

The weather conditions were typical of summer and mid-season and the heating and cooling needs close to zero.

The blind was always closed during the night to reduce heat losses, but during day 302, the blind was closed around the clock (day included) which is not efficient in the heating period. The strange behaviour is due to a previous version of this algorithm that systematically closed the blind when there was nobody in the room. Now this does not occur any longer and the opening/closing times are set based on the window power balance value as in the algorithm version 2. For this reason , the reader should only consider the results during occupancy.

Daylighting

During day 298, the solar radiation was very low and the blind open to increase daylighting during occupancy. It may be noticed that the user changed the blind position very often to close it (problem of glare ?). The blind moves during occupancy amount to 1.8 per hour which is a midrange value between algorithm version 2 and 1.

7.2 User's response and satisfaction

The user response to the different automatic blind control systems was analyzed by way of a questionnaire that people had to fill in twice a day. There were two people in the DELTA room and only one person in the reference room. The following results cannot be considered as statistically significant but give interesting qualitative results.

An example of such a questionnaire can be seen in Figure 7.13. The questions concern:

1. window opening (specify if the window has been opened and how often),
2. manual blind opening or closing (specify frequency of manual openings),
3. thermal comfort (give a vote on Fanger's scale [Fanger 70]),
4. visual comfort (give a vote on CIE scale [CIE 83]),
5. operation of the automatic controller,
6. other remarks of the users concerning the system.

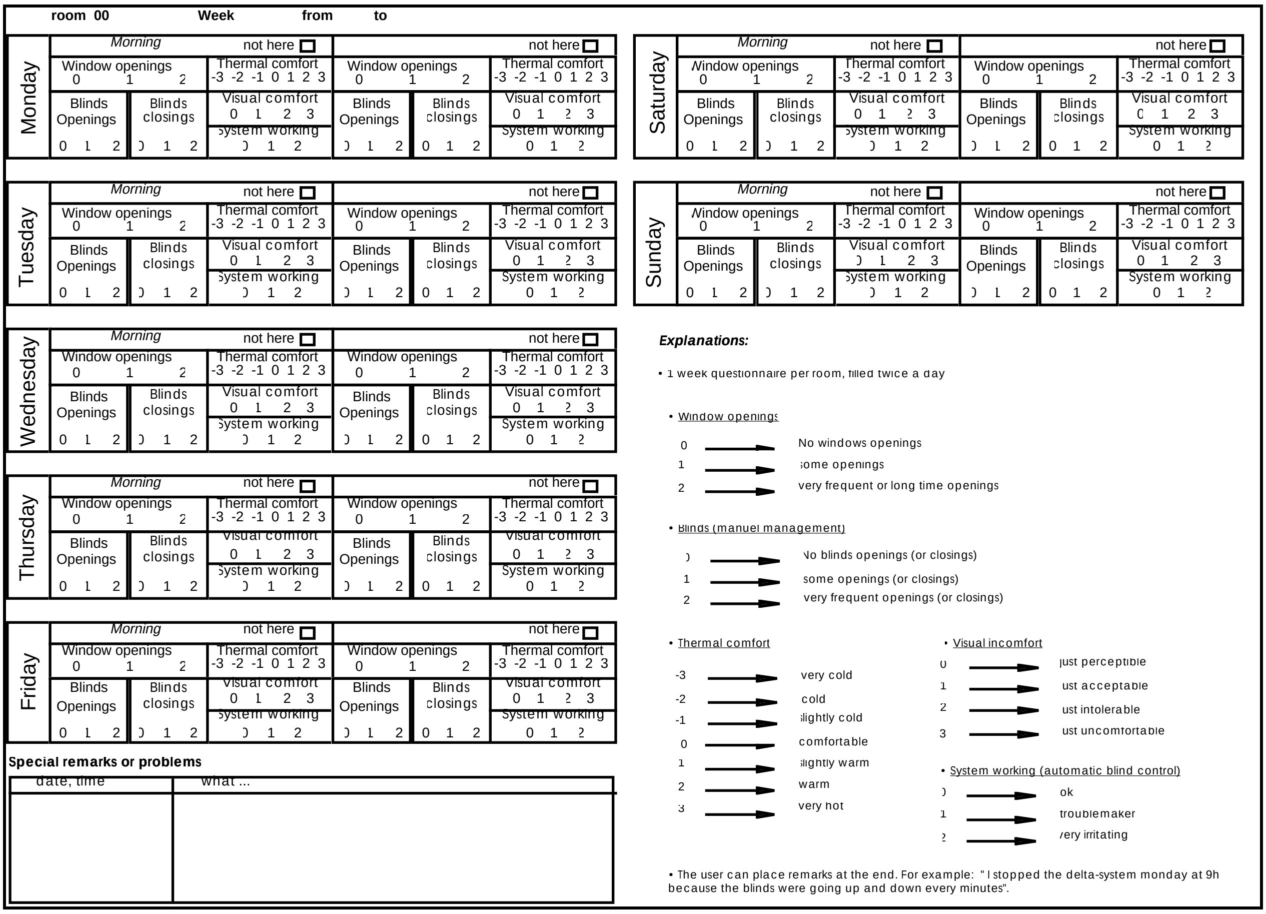

Figure 7.13: Example of one week DELTA-questionnaire

One of the goals of questions 1 to 4 was to produce some statistics and compare them for automatic and manual mode. This idea had to be dropped because there were not enough measurement periods. The user remarks regarding the behaviour of the system were more interesting. They can be sorted into four different categories:

- remarks that allowed an improvement of the system
- problems related to the DELTA system in normal operation

- problems related to a malfunction of the DELTA system
- experimental constraints

7.2.1 Remarks that allowed an improvement of the system

When clouds are passing, the blind moves too often.

This problems generally occurs in automatic blind control system based on a instantaneous measurement of solar radiation. The correction, implemented in the DELTA system, consists in moving down the blind immediately, according to the visual comfort algorithm, but opening it back only after 15 minutes of continuous opening commands of the system. People were satisfied with this solution.

The blind position changes too often

This is a general remark (not specially when clouds are passing). People proposed to restrict the number of possible blind positions. Nevertheless they expect from the automatic control system a fine tuning. A compromise with four possible positions was finally chosen (completely open, 1/3 closed, 2/3 closed, completely closed).

I would appreciate a darker ambiance when working on my PC.

The visual comfort algorithm provides standard visual comfort conditions. But for the user, the wished lighting ambiance depends on the work to be accomplished: dark ambiance for work on the computer screen, clear ambiance without glare for desktop work and a very clear ambiance is sometimes desired when no writing or reading activity takes place. Programmed ambiance should be obtained by shifting the rule base of the standard visual comfort. An example of a darker ambiance is given in Figure 7.14:

Standard visual comfort

θ \ Evdir	low	mid	high	very high
low	open	half closed	closed	closed
mid	open	half open	half closed	half closed
high	open	open	open	open

dark ambiance

θ \ Evdir	low	mid	high	very high
low	half open	closed	closed	closed
mid	half open	half closed	closed	closed
high	half open	half open	half open	half open

Figure 7.14: Rule base for blind position in a dark ambiance (low diffuse radiation) obtained by shifting the rules of the standard visual comfort algorithm

Some possible programmed ambiances and their applications are given in Table 7.6.

Ambiance	Possible applications
Standard	Desktop work
Dark	PC working
Clear	Non desktop work, discussions
Closed	Slide presentation
Open	Outside contemplation, leisure time activities
Manual (no automatic intervention)	Automatic-systems allergic users

Table 7.6: Possible ambiances and their applications

The implementation of the variants to the standard ambiance has not been tested in the DELTA experiment. Practically, it should be possible to program the control panel of the Zumtobel system (five button can be programmed). The user just has to press the button that corresponds to the desired ambiance.

The weather is nice, I would prefer to see outside

One solution to this problem consists in programmed ambiances, in this case a clear or open ambiance. But people may be working on the desktop (problems of glare etc.). The solution adopted here consisted in always keeping a minimal aperture of 10% so that people could always have a look outside when they wanted.

7.2.2 Problems related to the DELTA system in normal operation

There is no sun but the blind is down.

The offices are located on the first floor of the LESO building, but the solar sensors are on the roof, 15 meters higher. In this case, the sun was still shining on the roof, but not on the ground level (late in the afternoon). This problem could be solved by taking into account complex geometrical assumptions between room and sensor position. But the problem occurs only a couple of minutes a day and can be considered as the price to pay for a simpler system.

The blind is closed when I arrive in the morning; it looks strange

This is due to energy-related considerations in the winter period. The insulation of the room is better with the blind closed at night (5.4.1). It had to be explained to the office user that this function is completely normal.

People enter the room: the sun shines, the blind is up, it is too hot inside

This is also due to energy-related considerations. During the winter period, the system tries to accumulate solar gains (season dependency: 5.4.1). This also had to be explained to users.

7.2.3 Problems related to a malfunction of the DELTA system

These remarks are reported here because they were the main cause of the users' irritation against the DELTA system. They are all due to malfunction of the prototype software, problems with the sensors or communication problems between the PC’s. In a real application they would not occur.

Sometimes artificial light suddenly switches on.

Some user-chosen positions are not taken into account and the system changes the blind position after one minute only.

The sun is shining and the blind does not move down.

7.2.4 Experimental constraints

One main remark concerns an experimental constraint: the door of the room had to be maintained closed during the experiments. This way, the heat flows between the rooms and the rest of the building were close to zero and the rooms could be considered as independent buildings. It was particularly irritating for users who usually keep their door open at all times.

7.2.5 Other remarks

Another questionnaire [Högskolan 95] was filled in by the users two months after the end of the DELTA experiment. They expressed themselves about their general feeling of the system. We group in positive and negative remarks:

Positive feelings about DELTA blind control

- The management of solar and thermal losses when nobody was in the room was very much appreciated. This new possibility offered by an automatic system represents an interesting feature since user-control cannot achieve the same.
- The standard visual comfort was moderately appreciated. People like to have the possibility to move the blind themselves, but they find they have to do it almost as often as in manual mode.
- As to the blind-motor noise and the unusual feeling of seeing the blind move by itself, people say that after an adaptation phase it is acceptable (the motors used in the DELTA experiment were very noisy, normally motors would be much less of a nuisance).
- The cooling system was much appreciated in summer. Usually the rooms are not cooled, but because of the high ratio of window area per heated volume and the relative transparency of the blinds to solar radiation, the indoor temperature can be very high in summer.

Negative feelings about DELTA blind control

- Users feel that blind movements occur too soon after a manual change, in normal function mode, the blind should not move before a delay of 30 minutes (§ 5.3.2), but in some cases even after this interval it can be uncomfortable because users find the manually chosen position is still the right one.
- In automatic mode, the user still has to change the blind position himself. He appreciates in some cases to have glare avoided automatically, but often, the user adjusts the position more finely by himself so that it is optimally adapted to his current work.

7.2.6 Conclusion regarding user satisfaction

Users - appreciate: the possibility of manual regulation, energy management.
- do not like: the automatic position often does not fit the needs exactly.
- but would need: programmed ambiances (dark, clear, fixed position,...).

8. SIMULATION RESULTS

8.1 Aim of simulations

We were interested in comparing the energy efficiency of the proposed blind control algorithms related to reference situations. Simulation allowed testing the systems over a whole year of operation. All possible meteorological situations and winter, summer as well as mid-season could thus be covered and compared. We were particularly interested in the following topics:

- energy consumption for heating and cooling,
- thermal comfort,
- artificial light needs,
- the effect of users on the consumption,
- evaluation of the effect of the blind isolation coefficient value
- evaluation of systems' performances in non heated or non cooled buildings.

8.2 Studied variants

To achieve these goals, we needed to define the simulated blind control algorithms. Reference cases and automatic algorithms were considered.

8.2.1 Reference cases

The reference cases represented standard situations to which the automatic systems could be compared. Three fix situations were considered: blind always open, blind half-open, blind always closed. Then we considered the blind open during daytime (7h to 19h) and closed during night-time (19h to 7h), which maximises solar gains during daytime and minimises heat losses during night-time and is particularly efficient in winter. The opposite case, i.e. closed during the day and open during the night, efficient in summer, was also considered. A combination of these two kinds of regulation (open during the day, closed at night in the winter period (October 1 to April 30) and inversely in summer time) is called «efficient user» and results in a very efficient use of thermal energy. But such an energy-optimized system does not fulfill visual comfort criteria: first, glare will occur with the blind completely open in the winter period and second, the blind is always closed during the day in summer periods; few users would accept this.

Blind control type	Remarks
closed	blind always closed
half-open	blind half closed
open	blind always open
economic winter	closed at night open during day
economic summer	closed during day, open at night
energy efficient user	economic winter and summer combination

Table 8.1: Simulation reference cases

8.2.2 Automatic algorithms

In this section, we discuss all the automatic blind control algorithms: the initial algorithm from TU-WIEN, the fuzzy standard system and the classical artificial intelligence system. Some possible variations of the DELTA system are also considered: e.g. energy optimum only, which may be applied in an unoccupied building.

Blind control type	Remarks
version 1	original algorithm of TU-WIEN
version 2, energetic DELTA	LESO algorithm, only energetic optimum
version 2, visual DELTA	LESO algorithm, only visual optimum
version 2, standard DELTA	LESO algorithm, standard system
version 3	Classical artificial intelligence algorithm, proposed by Landis & Gyr

Table 8.2: Automatic blind controller algorithms

8.2.3 User effects

The exact effect of the users on the system is impossible to evaluate. It depends on:

- the people concerned (different users show different behaviour)
- the type of work the user has to accomplish
- environmental variables (for example, solar radiation and indoor temperature)
- subjective feelings of the users

To test the user effect, experimental testing is best. However, simulation can also give some indications as we are going to see.

8.3 Simulation assumptions

8.3.1 Meteorological data

The meteorological data used for the simulation were generated by the Meteonorm Swiss program [MET95]. Data were generated for the village of Ecublens and a horizon specific to the LESO building was introduced to take into account shadows due to surrounding buildings. The time interval of data is one hour. Meteorological data were interpolated to a 15 minute interval to fit the simulation time interval. The generated data include date, time, external temperature, global horizontal solar radiation, diffuse horizontal solar radiation and global south solar radiation. The other variables were directly calculated in the simulation program through the solar generator; they include: solar incidence angle, direct and diffuse radiation on a vertical plan as well as direct and diffuse illuminance on a vertical and a horizontal plan.

8.3.2 Heating control system

The heating control consists of an on/off controller closed loop on the internal air temperature. It has a hysteresis of ±0.5 °C and the heating and cooling set-points are respectively 20°C and 24°C. No night setback schedule is considered. This is a very simple control system, but much more efficient than an open loop on the external temperature (most common system) with regard to the large solar gains of the building.

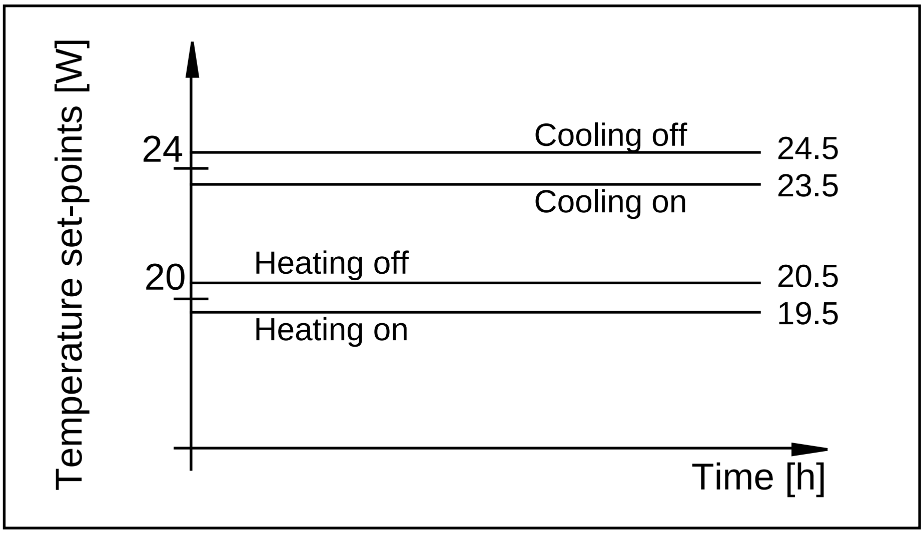

Figure 8.1: Set-points for heating and cooling

8.3.3 Artificial light calculation

The artificial lighting power is calculated on the basis of the inside horizontal illuminance at the user's work place (2.5 m from the window). The inside horizontal illuminance is calculated from the external horizontal illuminance, the blind position and two measured daylight factors (one with the blind open, the other with the blind closed).

$$E_{inside} = E_{outside} \cdot \left[DF1 \cdot \alpha + DF0 \cdot (1-\alpha) \right]$$ **Equation 8.1**

with:

α	the blind position [-] (α=1 $\Rightarrow$ blind open, α=0 $\Rightarrow$ blind closed)
DF1:	the daylight factor [-] with blind open
DF0:	the daylight factor [-] with the blind closed
E_{inside}:	the inside horizontal illuminance [Lux]
$E_{outside}$:	the outside horizontal illuminance [Lux]

The artificial lighting system has to deliver 500 Lux for the minimum inside illuminance in the room during occupancy. The installed light power was calculated to achieve 500 Lux without daylighting. It corresponds to an electric consumption of 192 Watts. Then the Luxmate system linearly reduces the electric consumption when daylighting increases, so that the total (daylighting+artificial lighting) always reaches 500 Lux. Then, for a higher level of daylighting illuminance, the electric power is equal to a base power of 25 W. When nobody is in the room, the light is switched off completely and the base power falls to 3 W.

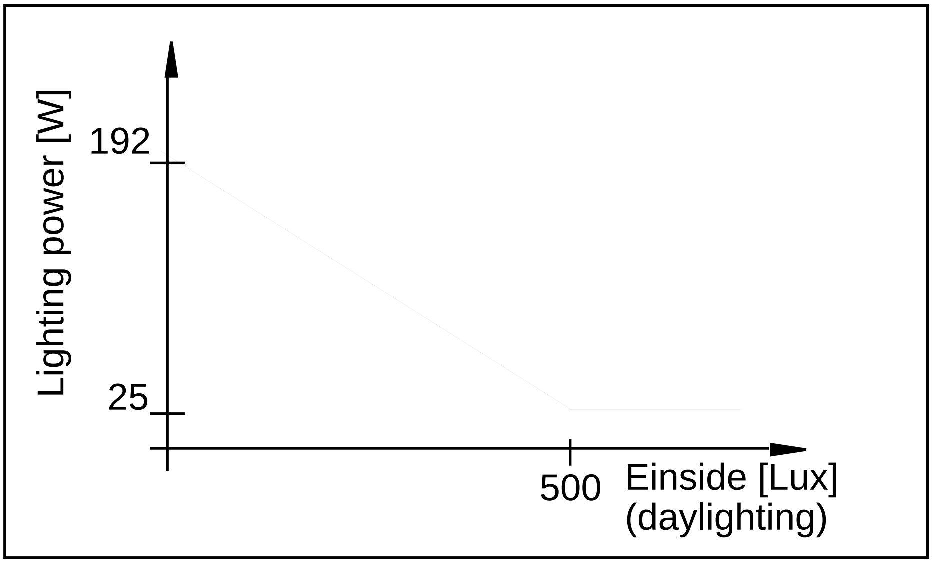

Figure 8.2: Lighting power as a function of inside daylighting illuminance

The relation used for calculating the inside illuminance is only valid for a diffuse sky and is not correct in the presence of direct illuminance. But we assume that in such cases the inside illuminance due to daylight is larger than 500 Lux; thus the lighting power is not affected.

8.3.4 Other aspects

Air renewal

Constant air renewal of 0.3 [h^{-1}] from the outside is assumed. We suppose that no window opening occurs and that the air exchange with other rooms is set to zero.

Internal gains due to people

During occupancy, 100 W are taken into account for internal gains (to be added to the lighting power). This figure accounts for one person in the room and no additional gains through appliances (except for artificial lighting).

Occupancy schedule

A standard office schedule of 8h to 12h and 14h to 18h is considered in the simulation. In some special variants, the occupancy is supposed to be zero all the time.

8.4 Qualitative comparisons

Some qualitative comparisons are performed over a few short periods. They give an idea of the performance of the blind controllers in some typical situations. After checking the weather file, we considered the following two cases:
Winter periods: 24 February to 6 March
Summer: 16 June to 29 June
The winter period also includes typical mid-season days.

8.4.1 Winter period

The period considered goes from 24 February to 6 March. It includes cold days and mid-season days (-10 [°C]≤Text≤15 [°C]). The solar radiation changed much from one day to another (100 [W/m^2]≤Gh(max)≤600 [W/m^2]). The occupancy schedule includes a week-end and days with office hour times.

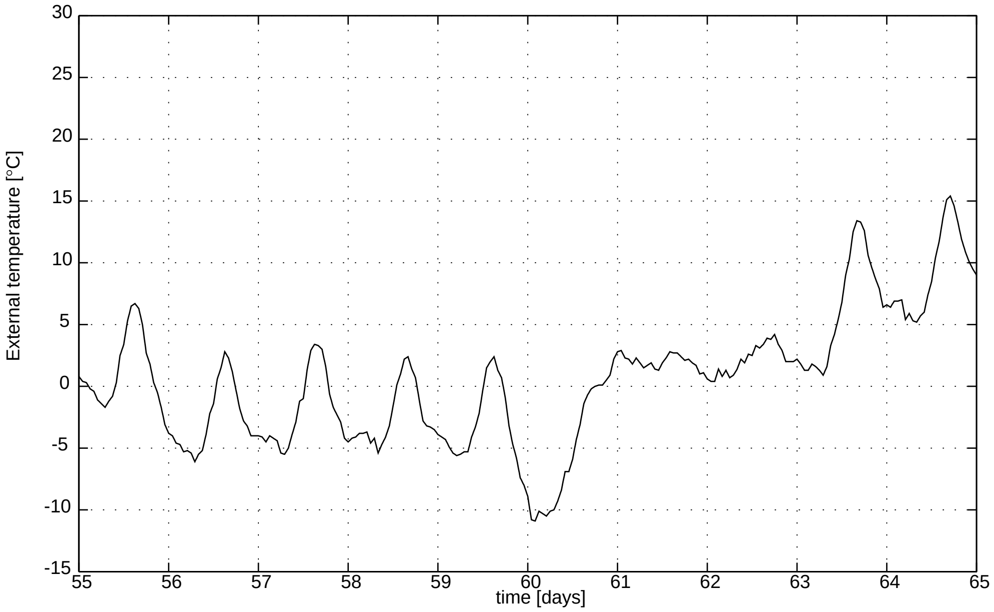

Figure 8.3: External temperature of the winter period

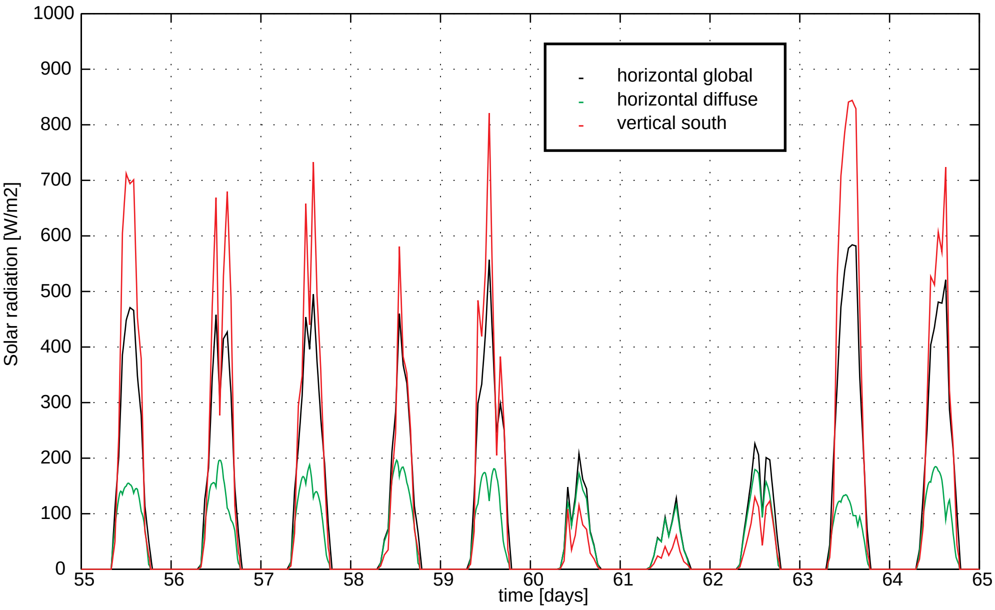

Figure 8.4: Solar radiation of the winter period

For the winter period, four different blind control algorithms are analysed in detail in the next sections; the next figure shows the tabulated gains obtained by the different versions.

	version 1: TU-Wien	version 2: DELTA std	version 3: AI algorithm	energy efficient user
Heating [MJ]	126	95.4	147	77.4
Cooling [MJ]	0	1.8	0	23.6
Direct solar gains [MJ]	92.8	169.7	79	236.7
Artificial lighting [MJ]	25.9	14.5	13.6	11.1
Internal gains [MJ]	20.2	20.2	16.4	20.2

Table 8.3: Tabulated gains for four different blind control algorithms in the winter period

TU-Wien system (version 1)

The TU-Wien system does not seek to offer a visual optimum, only energy efficiency and thermal comfort are taken into account (see 5.3).

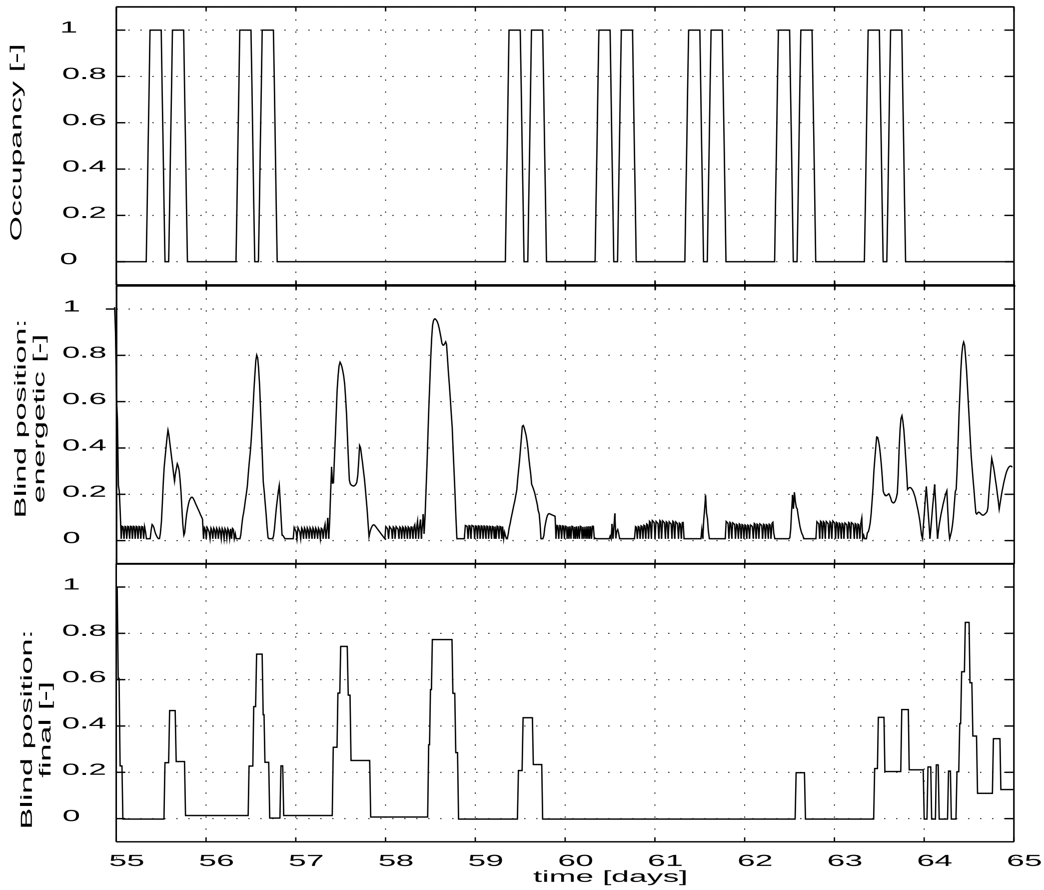

Figure 8.5: Occupancy and blind position (energy-optimised, final) for the TU-Wien algorithm in winter.

Its main characteristics are the following:

- the blind is closed during the night
- the blind is closed during the day when the solar radiation is very low (days 60, 61).
- the blind is 'almost' open when the solar radiation is high (days 57, 58)
- during days 63 and 64, with a very changing external temperature, the blind position behaviour is not explicable. It is the consequence of a very complicated rule base.

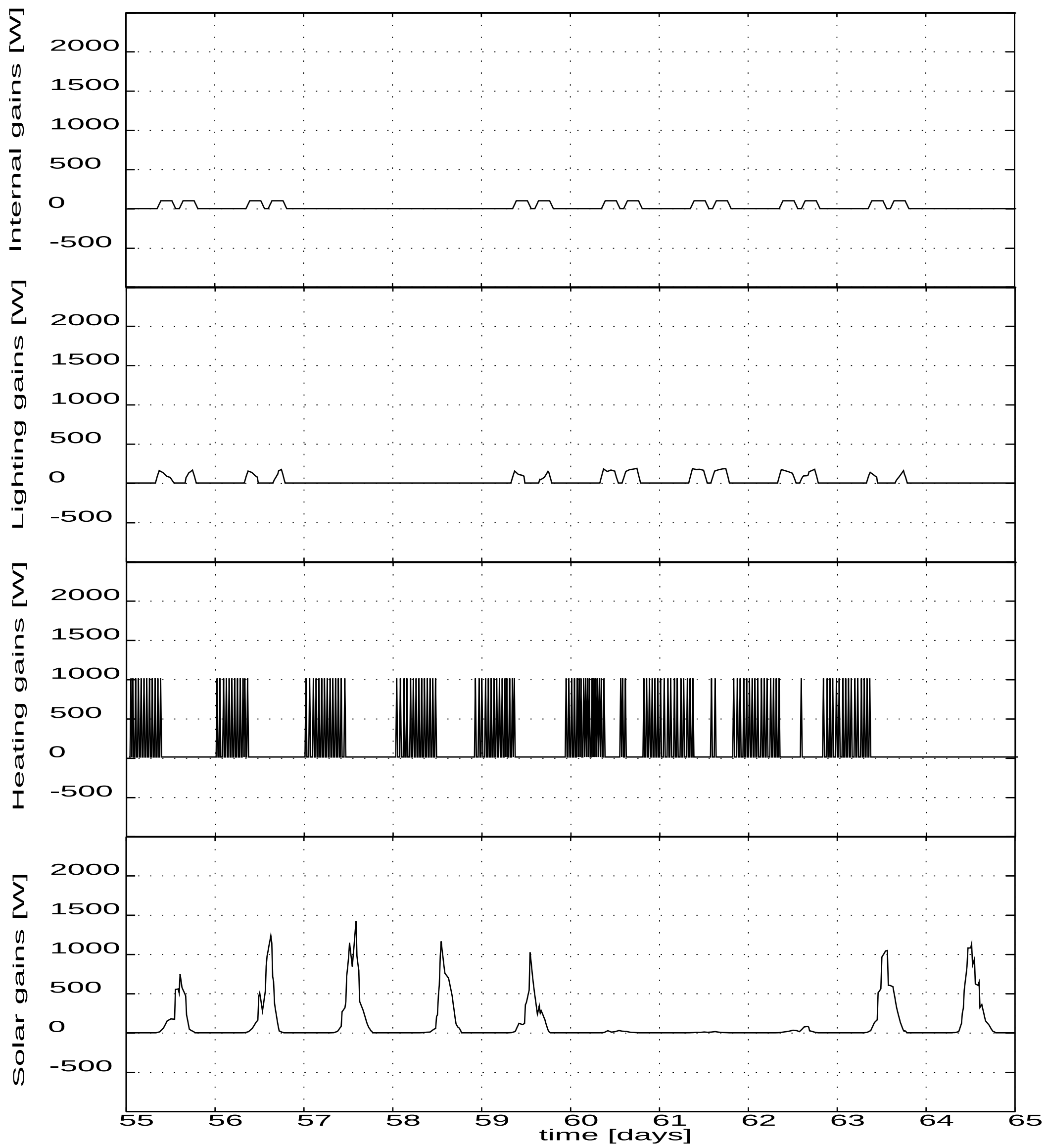

Figure 8.6: Gains (solar, heating, lighting, internal) for the TU-Wien algorithm in winter (the integrated values can be found in Table 8.3).

Daylighting is lower than with version 2 which results in higher lighting needs (26 MJ vs 14.5 M). This is not efficient, but explicable by the fact that this algorithm does not take into account visual comfort. Less explicable is the fact that this algorithm is not energy-efficient. The heating energy amounts to 126 MJ over the monitored period (95 MJ with the DELTA standard system). The fuzzy rules are not efficient to optimise the window power balance (see 5.3.4). The only positive point in this example is the lack of cooling during days 63 and 64. Unfortunately, the annual results will not confirm that interesting behaviour, which is only a matter of chance.

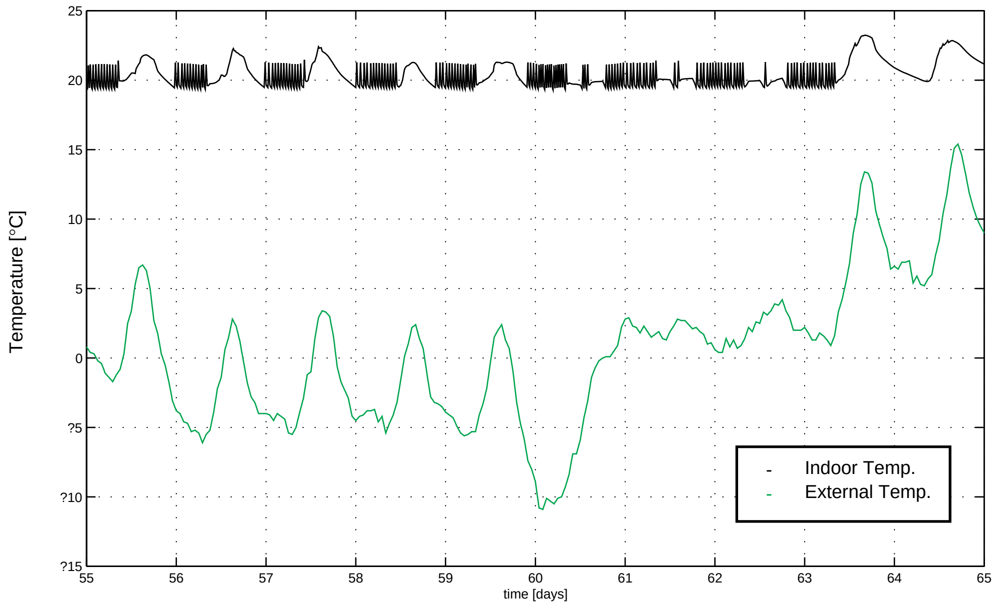

Figure 8.7: Internal temperature for the TU-Wien algorithm in winter.

Standard DELTA system (version 2)

The system chooses the final position according to visual criteria, energy efficiency and occupancy (see 5.4).

Figure 8.8 shows that during occupancy, the visual aspect is taken into account but not the energy efficiency aspect. On the opposite, when there is nobody in the room, only the energy efficiency aspect is taken into account.

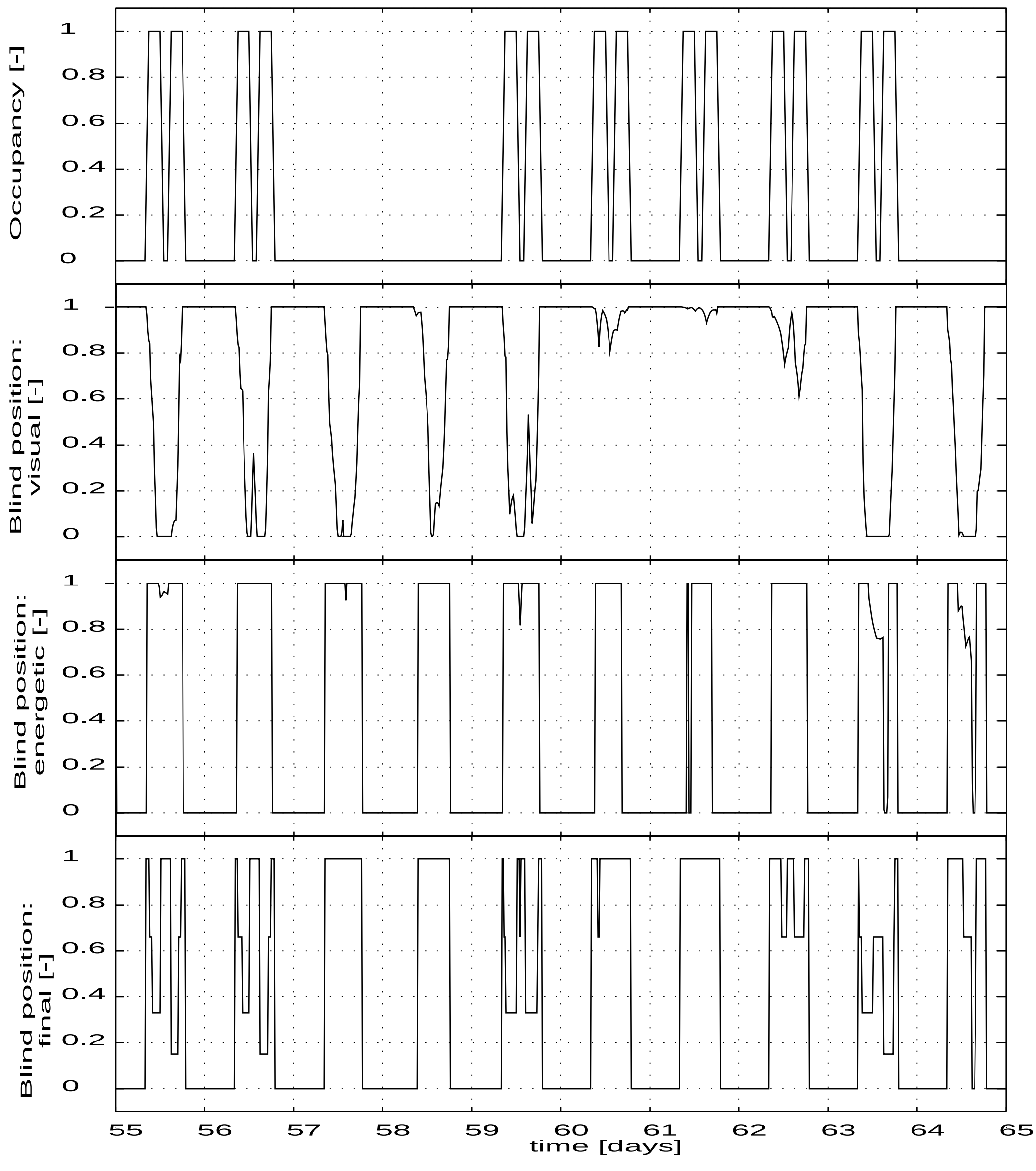

Figure 8.8: Occupancy and blind position (energetic, visual, final) for the DELTA standard algorithm in winter.

During mid-season and winter, some general characteristics are pointed out :

- The blind is closed at night which reduces the heat losses during the heating season.
- The closing and opening schedule varies slightly from one day to another, depending on the moment when the window heating power balance changes its sign.
- During occupancy, the blind is closed when the solar radiation is high to avoid glare, but it is open with little radiation to supply as much daylighting as possible.
- During mid-season days with high solar radiation (days 63, 64), the solar gains are reduced to avoid overheating.

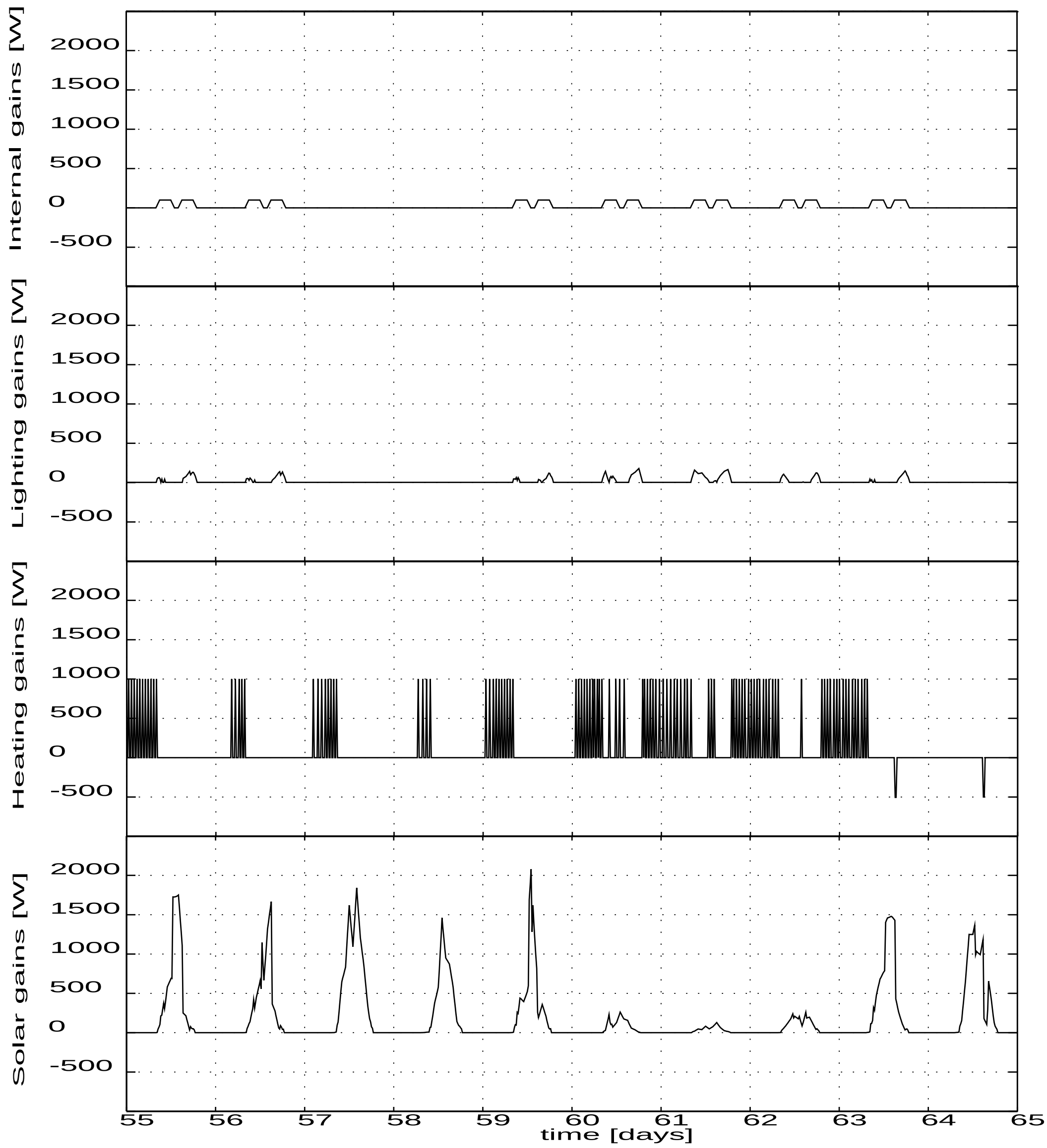

Figure 8.9: Gains (solar, heating, lighting, internal) for the DELTA standard algorithm in winter (the integrated values can be found in Table 8.3)

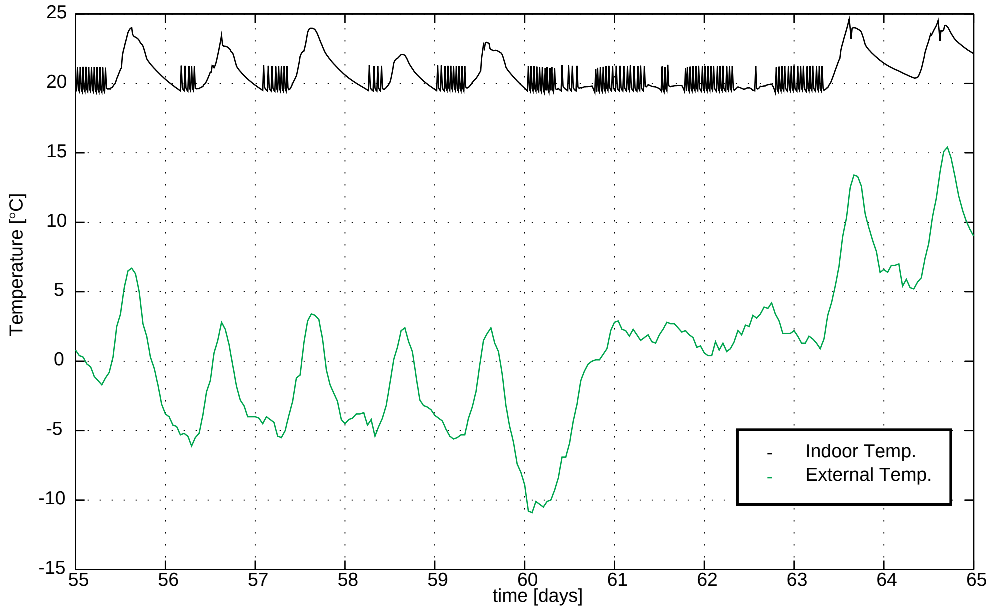

Figure 8.10: Internal temperature for the standard DELTA algorithm in winter.

The heating system was switched on during the first cold days. Afterwards (days 63, 64), typical mid-season days with sunny days and cold nights occurred.

The HVAC system had to cool slightly during the last two days, to reduce overheating. During these cooling periods, the blind system helped by closing the blind and reducing the solar gains.

We notice that the HVAC system is not optimal in such cases because it heats during the night and cools during the day (day 63). This behaviour is usual with conventional heat controllers because they do not include any prediction on solar gains and building behaviour [Oestreicher 95]. It is important, as can be observed, that the blind control system does not interfere with the HVAC system.

As to the artificial lighting needs, it can be seen that they (14.5 MJ) are kept low because of high daylighting supplies (the blind is up whenever possible).

Artificial intelligence algorithm (version 3)

The blind position chosen by this algorithm is given in the next figure.

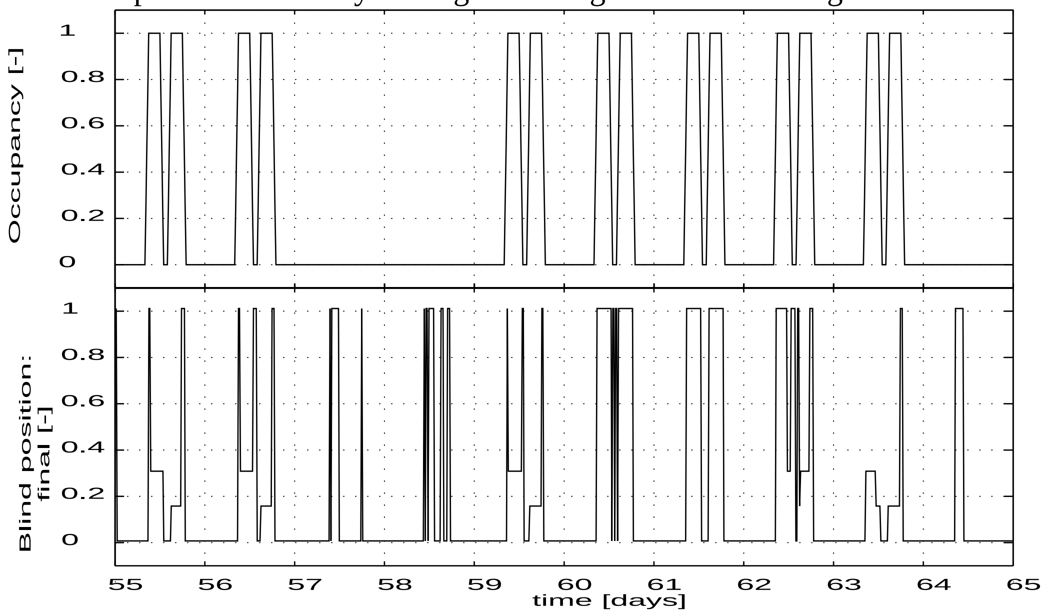

Figure 8.11: Occupancy and blind position (energetic, final) for the version 3 algorithm in winter (the integrated values can be found in Table 8.3).

The main characteristics of this control algorithm during the monitored period are the following:

- The blind was systematically closed during the night.
- During occupancy visual comfort had priority: the blind was closed to avoid glare but open with low solar radiation. The blind position during occupancy was very similar to that in version 2 (see Figure 8.8). Therefore, artificial lighting gains (13.6 MJ) were kept low because of high daylighting supplies. The differences in lighting gains and internal gains between version 2 and 3 are explained by a different way of counting the gains during occupancy in the simulation program (different versions of the simulation program). To have comparable values, the internal gains and lighting gains should be increased by 20% for version 3.
- When there was nobody in the room, the blind was closed much longer than with version 2. The energy optimum seems not to be well adjusted. For example, during day 58, the blind moved a lot instead of being open to benefit from solar gains which resulted in a high heating demand (147 MJ vs. 95 MJ for version 2).

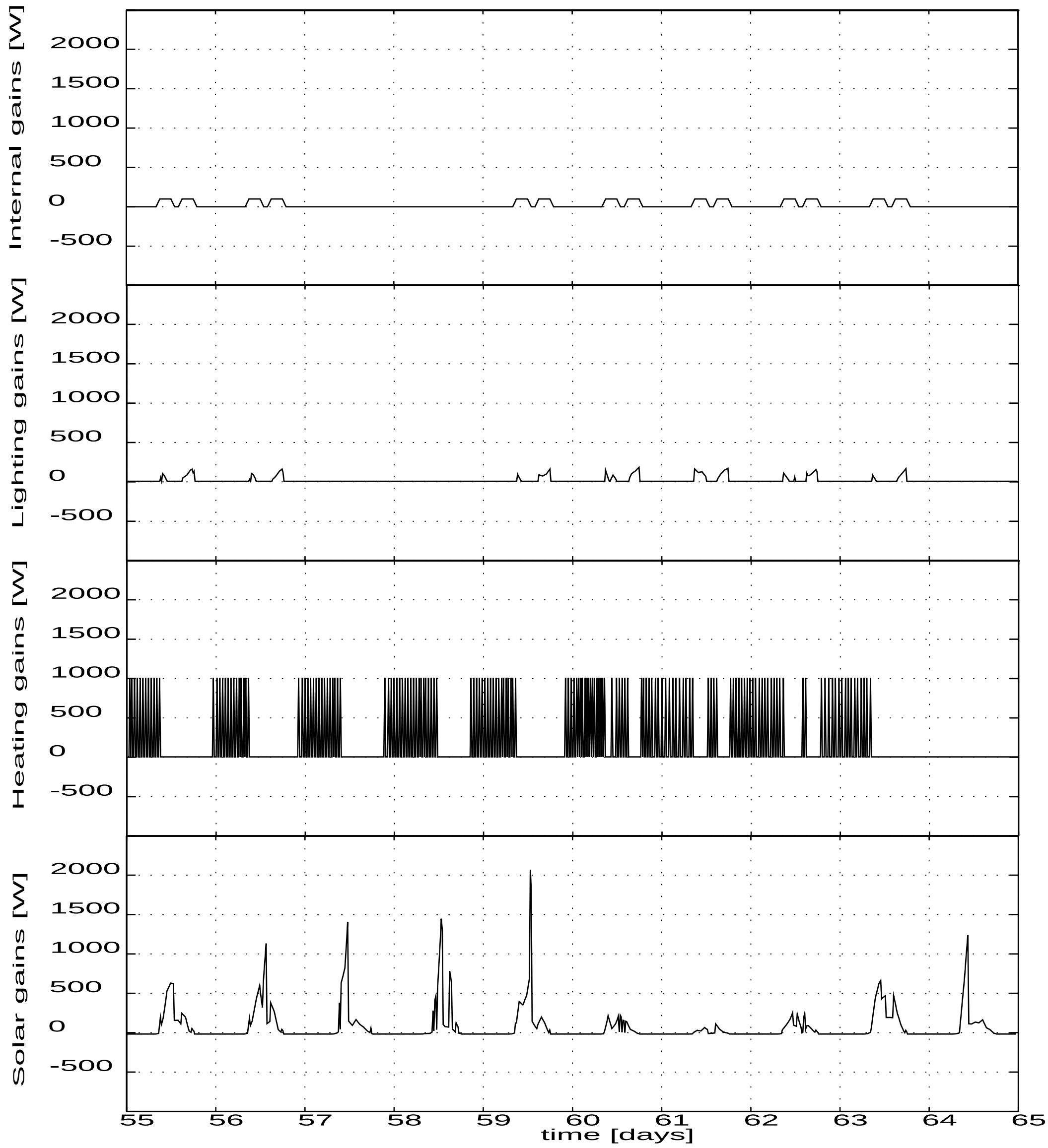

Figure 8.12: Gains (solar, heating, lighting, internal) for the version 3 algorithm in winter.

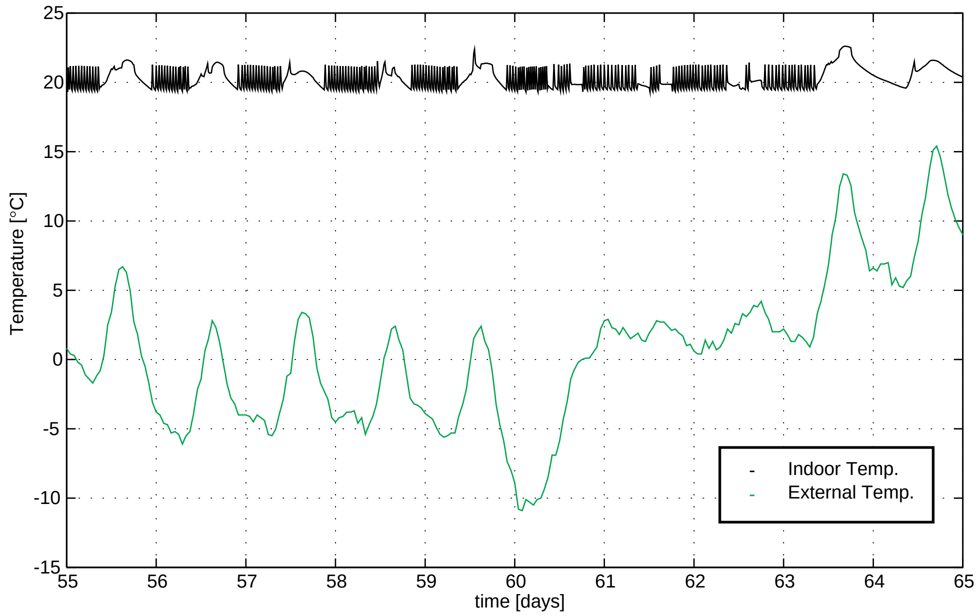

Figure 8.13: Internal temperature for the version 3 algorithm in winter.

Energy-efficient user

During the winter and mid-season period, the efficient user closed the blind during the night and opened it during the day.

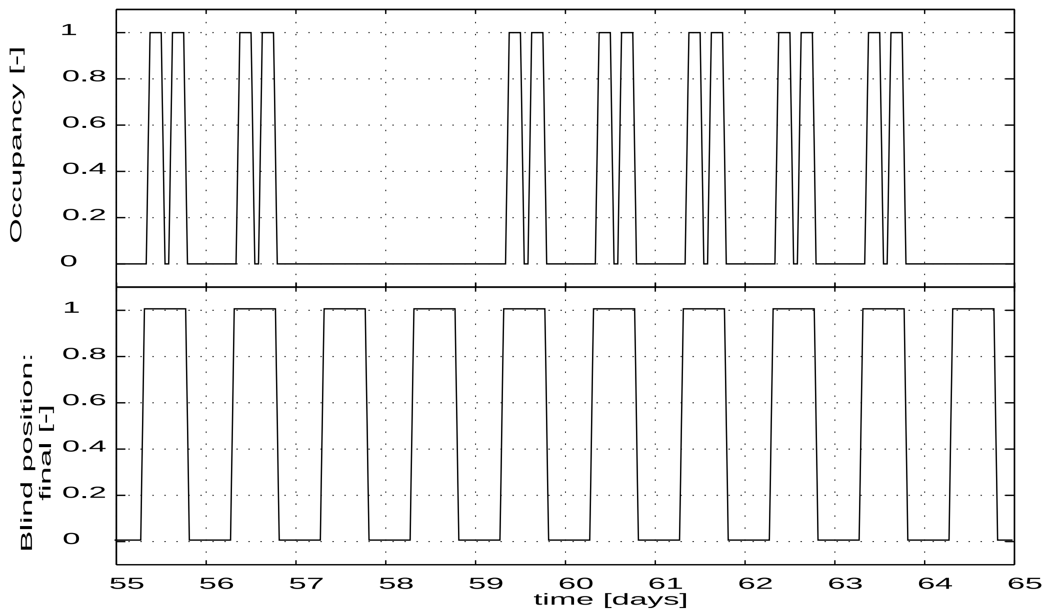

Figure 8.14: Occupancy and blind position for the energy efficient user algorithm in winter.

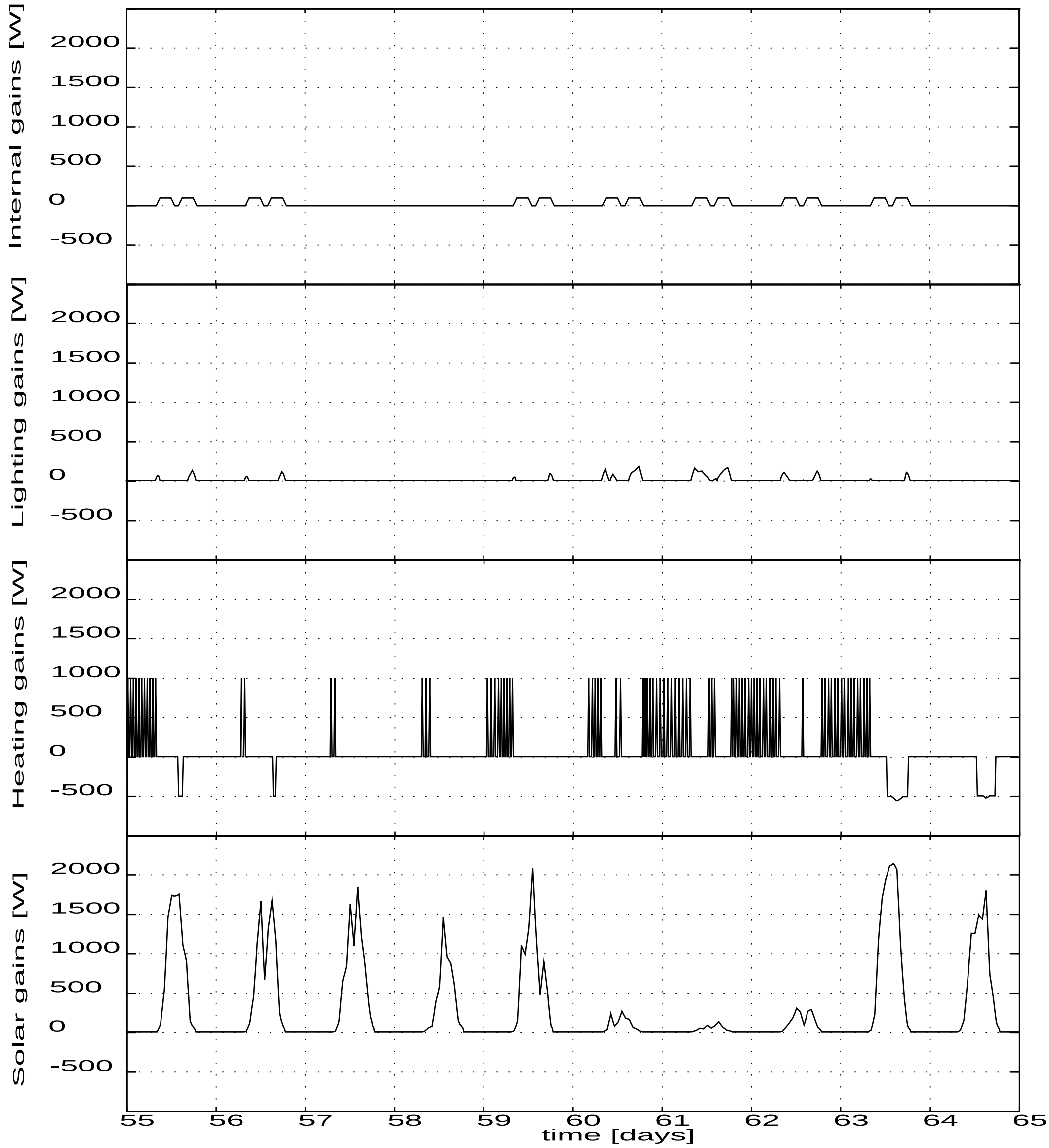

Figure 8.15: Gains (solar, heating, lighting, internal) for the energy efficient user algorithm in winter.

This strategy compared to the standard DELTA system results in:

- less heating supplies (77 MJ), due to a solar gains (237 MJ) maximisation.
- less electric lighting demand (11 MJ, DELTA standard: 14.5 MJ).

But some problems occur:

- some overheating which results in a rather high cooling demand (-24 MJ).
- glare problems are suspected during occupancy.

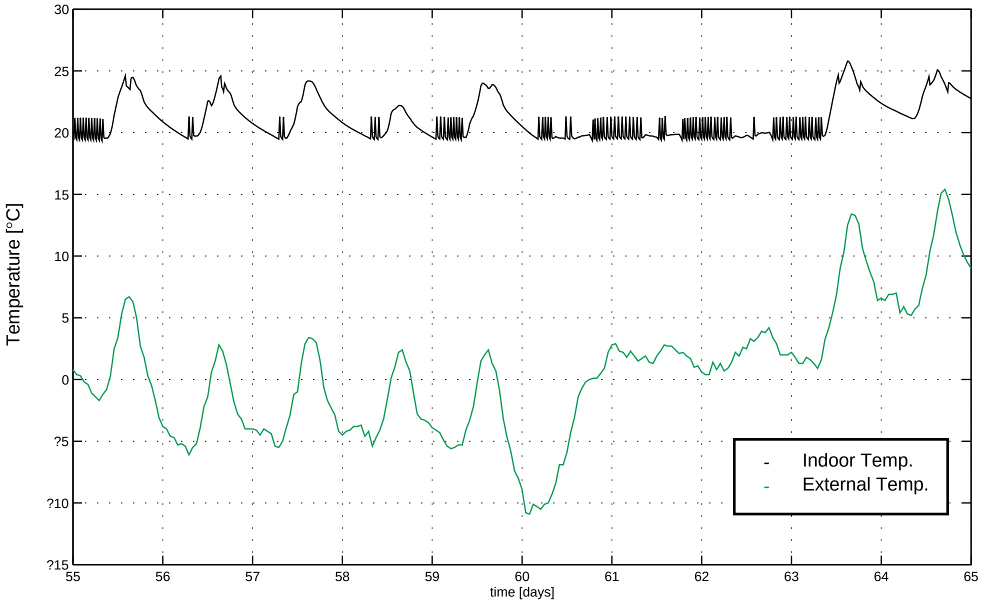

Figure 8.16: Internal temperature for the energy efficient user algorithm in winter.

8.4.2 Summer period

The main functions of the different blind control algorithms have already been shown in the winter period section. For this reason, the only example presented here in detail is the standard DELTA system. For the other algorithms,
Table 8.4 shows the tabulated gains; the graphics can be found in appendix.

The period considered (end of June) is typical of a summer period. The temperature is rather high (15 [°C] at night and 25 [°C] during the day), the solar radiation varies from low values to higher ones (100 [W/m^2]≤Gh(max)≤550 [W/m^2]).

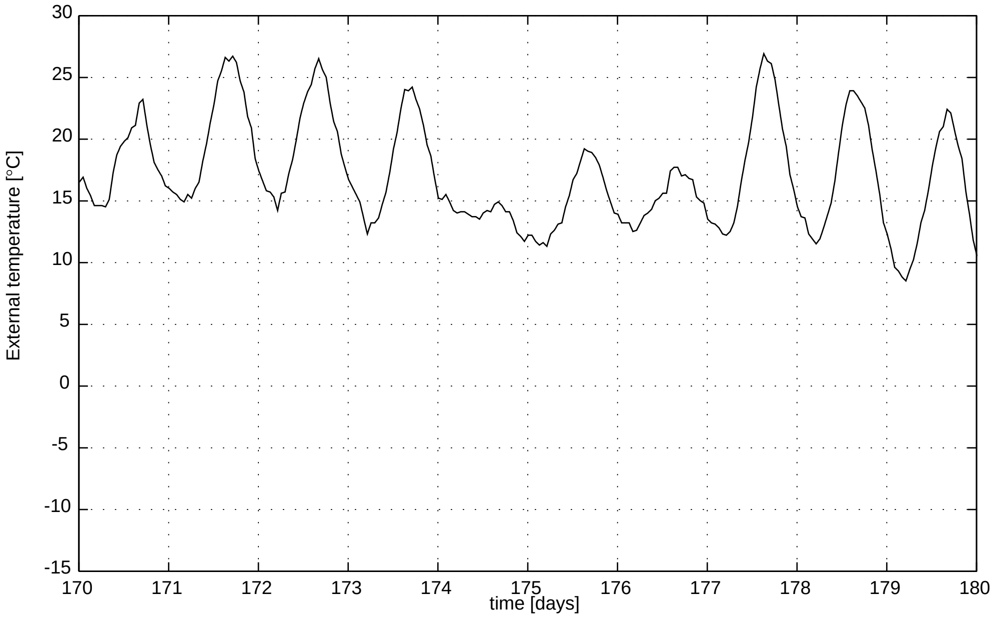

Figure 8.17: External temperature in the summer period

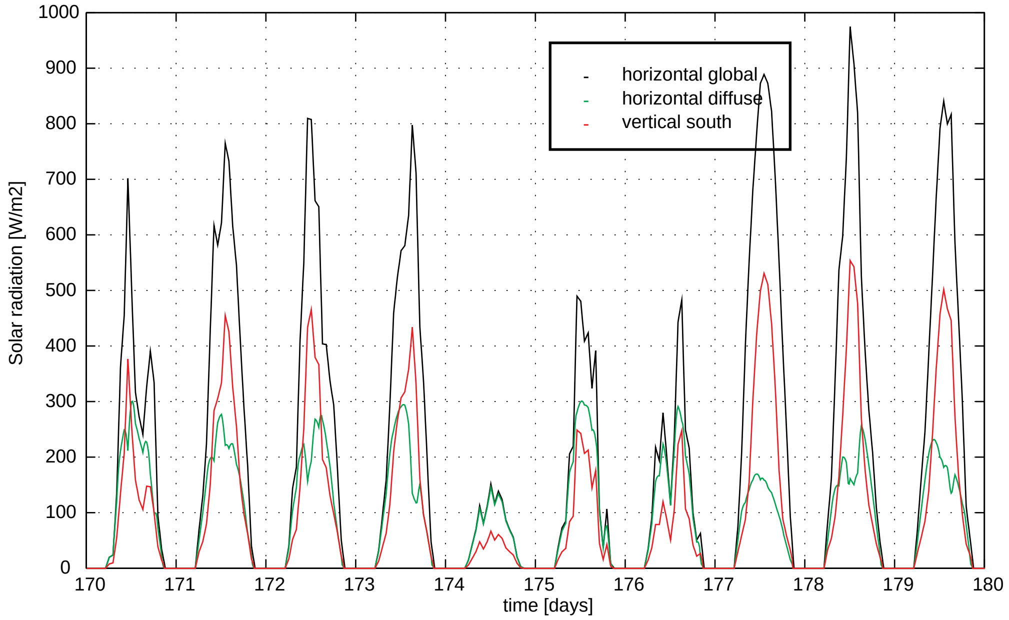

Figure 8.18: Solar radiation in the summer period

An example for the summer period: Standard DELTA system (version 2)

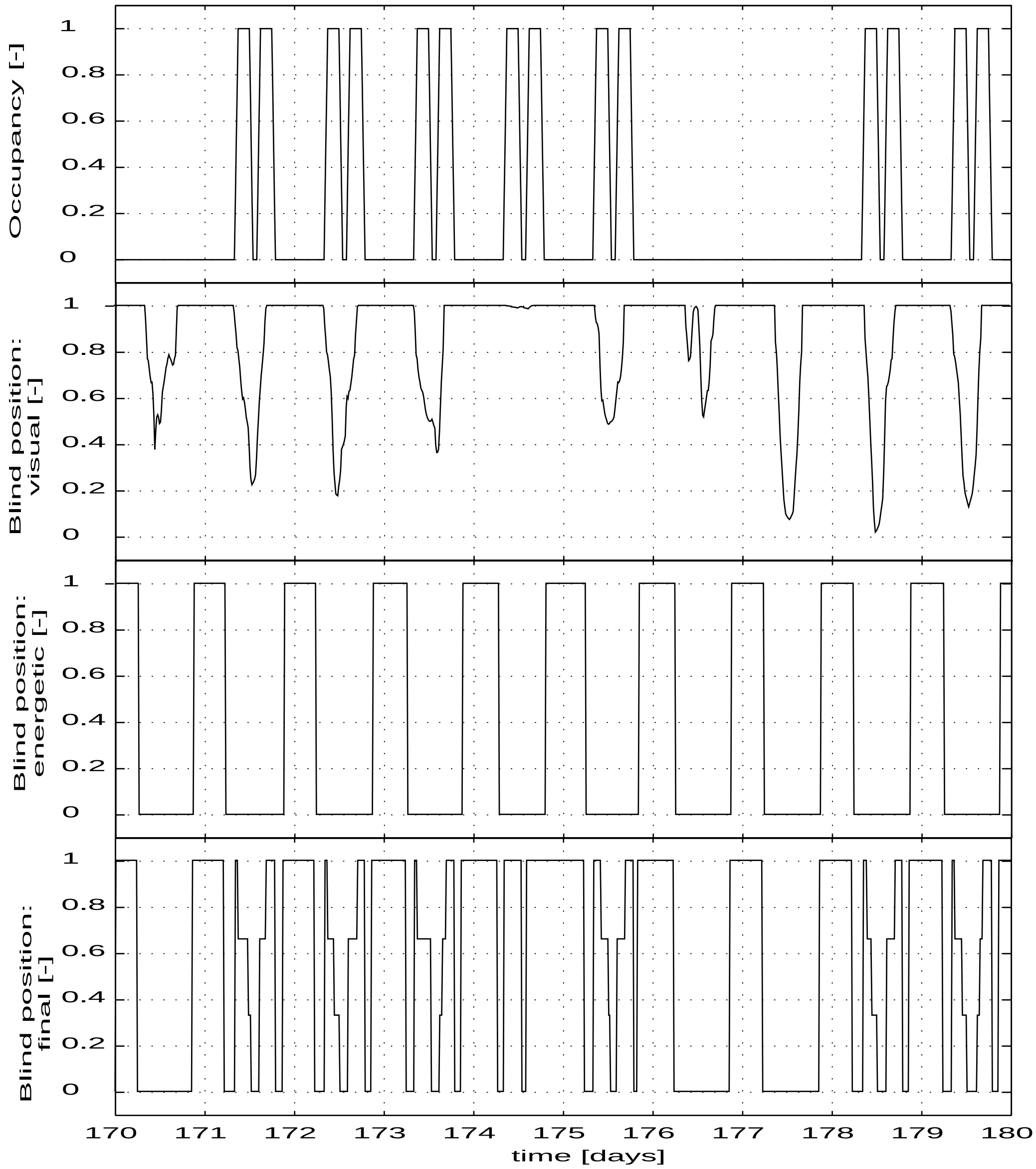

Figure 8.19: Occupancy and blind position (energy-optimised, visual, final) for the standard DELTA algorithm in summer.

The general characteristics of the standard DELTA system in summer are:

- The energy-optimised algorithm closes the blind during the day and opens it at night to minimise solar gains and maximise night cooling.
- Visual comfort optimisation is obtained by closing the blind with a high solar illumination (avoid glare) and opening it to maximise daylighting in other periods.

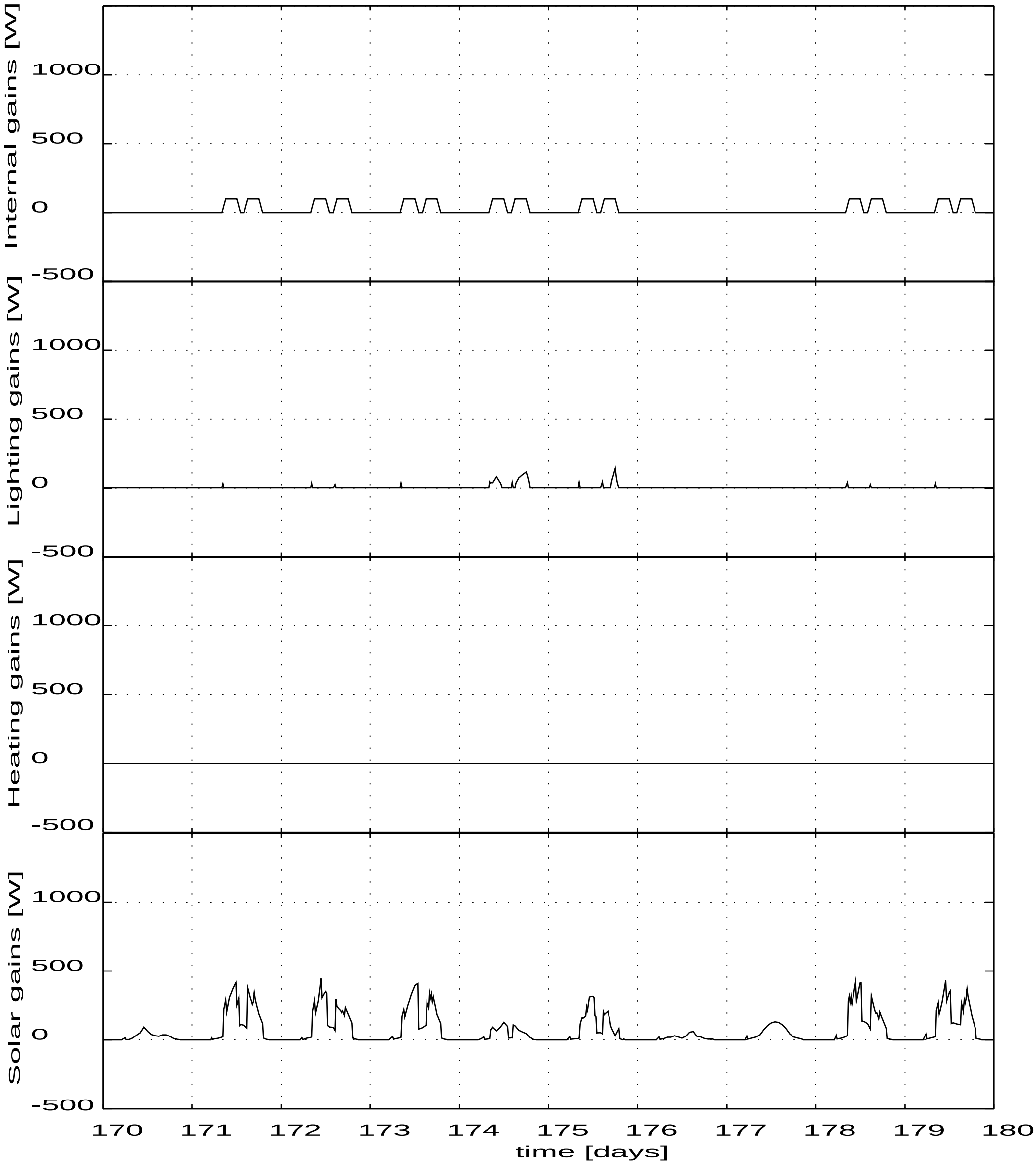

Figure 8.20: Gains (solar, heating, lighting, internal) for the standard DELTA algorithm in summer.

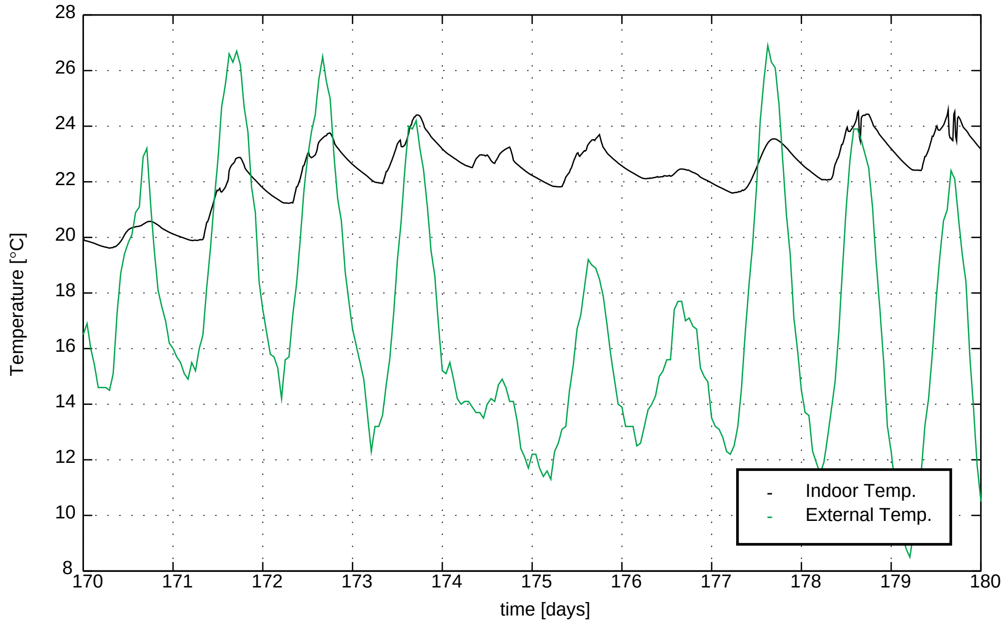

Figure 8.21: Internal temperature for the DELTA standard algorithm in summer.

General discussion for the summer period

Table 8.4 shows the main results for some of the considered algorithms.

	version 1: TU-Wien	version 2: DELTA std	version 3: AI algorithm	energy efficient user
Heating [MJ]	0	0	0	0
Cooling [MJ]	0.9	0	0	0
Direct solar gains [MJ]	63.1	60.2	50.7	27.5
Artificial lighting [MJ]	7.5	5.1	4.3	17.9
Internal gains [MJ]	20.2	20.2	16.4	20.2

Table 8.4: Tabulated gains for three different blind control algorithms in the summer period

The best results with regard to energy-efficiency are obtained by the standard DELTA algorithm and the artificial intelligence algorithm (version 3) (no heating or cooling needs, 5.1 MJ and 4.3 MJ of artificial lighting). The small differences in artificial lighting and internal gains is explained by the different way the simulation program counted these gains (different versions: see previous section). Version 1 has some cooling loads and the artificial lighting needs amount to 7.5 MJ. The energy-efficient user algorithm closes the blind during the day. It is efficient from a thermal but not from a visual comfort point of view. Because of that, the artificial lighting needs amount to 17.9 MJ.

8.5 Thermal energy consumption results (heating and cooling)

The heating system's energy consumption was determined with the different blind control algorithms over a whole simulated year. The Table 12.1, Table 12.2 and Table 12.3 in the appendix show the direct and indirect solar gains as well as the internal, lighting, heating and cooling gains obtained with all the reference and automatic blind control systems.

Figure 8.22 focuses on the heating and cooling energy needs.

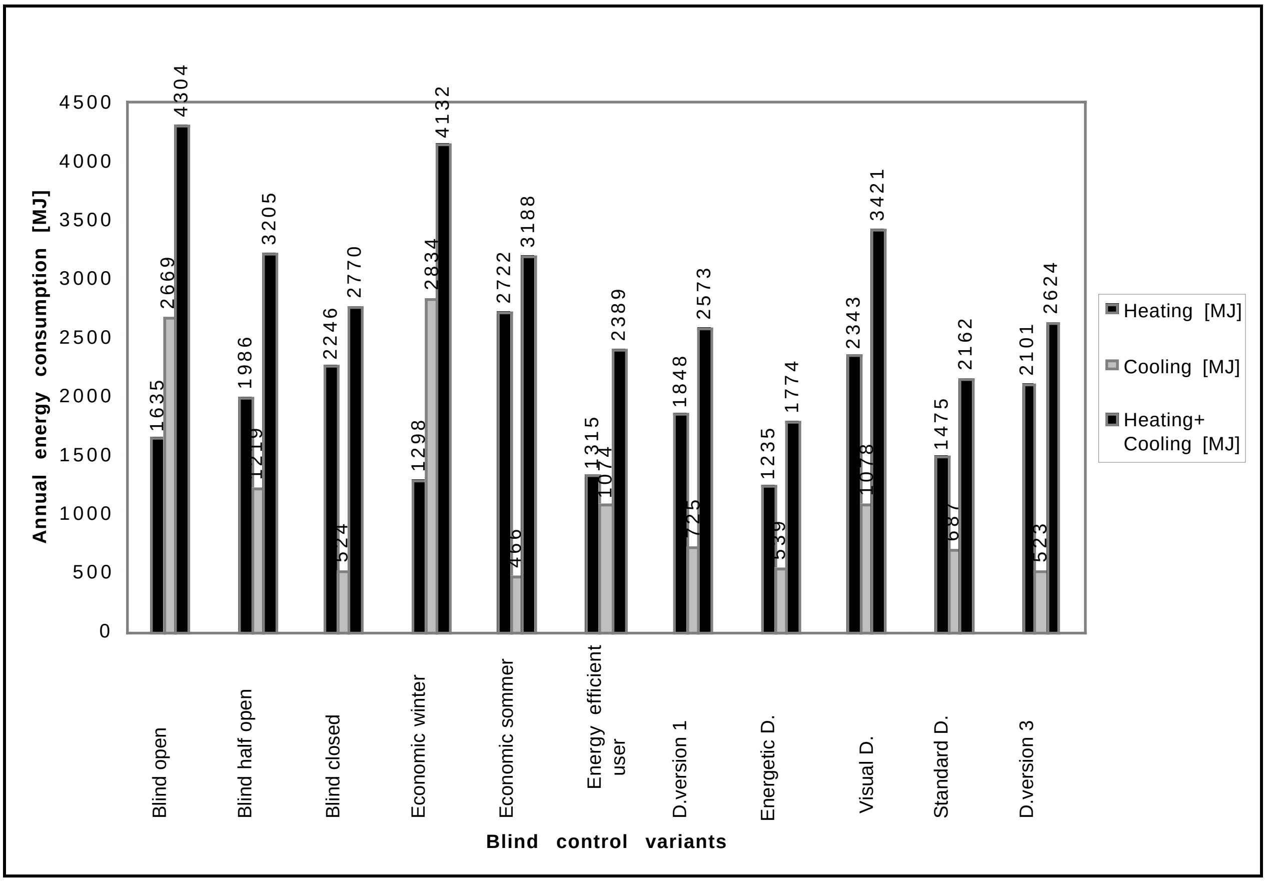

Figure 8.22: Heating and cooling annual energy needs for different blind control variants (reference floor area=16.7 m2)

Some interesting results can be pointed out:

The thermal optimum with the DELTA energetic-only algorithm is very efficient when compared to the reference cases:

- 59 % of global energy saved (heating and cooling) compared to the case where the blind is always open, which can be explained by a smaller heating demand due to a better night insulation, and secondly by a smaller cooling need in mid-season and summer (overheating is reduced).
- 36 % of thermal energy saved compared to the case where the blind is always closed, which can be explained by a much smaller heating demand in winter (more sunlight enters the room).
- 26 % of thermal energy saved compared to the energy-efficient user setting, which is obtained by reducing the heating and especially the cooling needs through a more accurate definition of the season (based on the external temperature and not the Julian calendar).

The energy-optimised DELTA control can be applied to unoccupied buildings, but during occupancy, people want to have visual comfort in their offices. The standard DELTA system (version 2) and version 3 (thermal optimisation and visual comfort) correspond to that situation. Version 2 energy consumption results show that:

- large savings are obtained in comparison to fixed settings (22 % vs blind closed, 50 % vs blind open).
- 9 % savings are obtained compared to the ‘energy efficient user’ setting. This result shows that the DELTA system can be very efficient regarding the energy consumption even when providing visual comfort during occupancy.

Version 3 is not very efficient in winter (2100 MJ for heating), and comparable to the fixed half-open setting. However, it is very efficient in terms of cooling needs (523 MJ). Basically, the system closes the blind too often and should be better tuned to avoid this situation.

The version 1 algorithm is not particularly efficient; it gives results comparable to the fixed half open position.

In all the simulated cases, the user does not change the blind position manually. In versions 2 and 3, the automatic visual comfort algorithm is supposed to simulate an already very strict user behaviour relative to the visual comfort.

To try to quantify the effect on a realistic user behaviour’s energy consumption, some random behaviours were tested.

Three users with various probabilities to change the blind position within one hour were tested. The chosen position is randomly uniformly distributed between 0 and 1. Table 8.5 shows the effect on consumption.

Whole year consumption	***Heating energy [MJ]***	***Cooling energy [MJ]***
Standard DELTA	1475	-687
Standard DELTA, proba=0.2	1464	-868
Standard DELTA, proba=0.4	1442	-908
Standard DELTA, proba=0.6	1439	-925

Table 8.5: User behaviour effect on thermal energy consumption. Proba=probability that the user changes the blind position within the hour.

It can be seen that :

- the total consumption is very similar with or without user perturbation (the fluctuation on energy needs is less than 3% in the worst case).
- the users' changes reduce heating needs and increase cooling needs. We can deduce that they let more solar radiation enter by opening the blind. (The DELTA system strictly cuts direct gains).
- a non-random user with a systematic behaviour could of course modify those results by increasing or reducing the thermal needs of the room.

8.6 Thermal comfort

The thermal comfort was analysed using the Fanger [Fanger 70] model. The considered variables are the radiant temperature in the room and the room’s air temperature. The comfort parameters used for winter and summer periods are given in the next table.

Comfort parameters	Summer season	Winter season
activity [W/m2 of body area]	75	75
clothing [clo]	0.5	1.1
air velocity [m/s]	0.1	0.1
relative humidity [-]	50 %	50 %
optimal operative temperature [°C]	~24	~20

Table 8.6: Comfort parameters used in the Fanger's model

The comfort histograms for the PMV (predictive mean vote) were calculated. Figure 8.23 to Figure 8.28 show histogramms for a few simulated cases.

In any case, the PMV fits in the -1, +1 interval, i.e. in reasonable comfort conditions. The heating and cooling system prevents uncomfortable situations. Without a cooling system, which is the most usual case in our country, uncomfortable situations due to overheating would have been obtained in mid-season or summer for non-efficient blind control systems (blind open in summer, 'efficient user' in mid-season). It can be seen that slight occasional overheating observed in winter in the next diagrams is not really disturbing, because it is obtained with a clothing of 1.1 clo. If the user feels too hot, he will reduce his clothing level down to the summer value (0.5 clo). Similarly, a slightly cool feeling in summer is not important, for symmetric reasons.

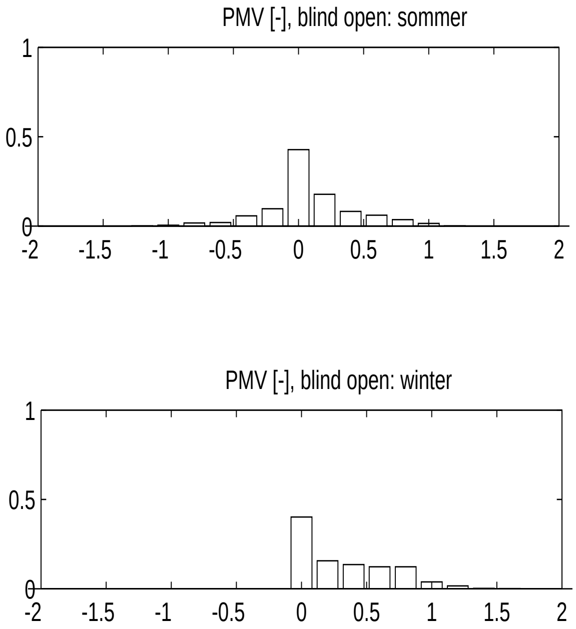

Figure 8.23: Summer and winter PMV with an opened blind

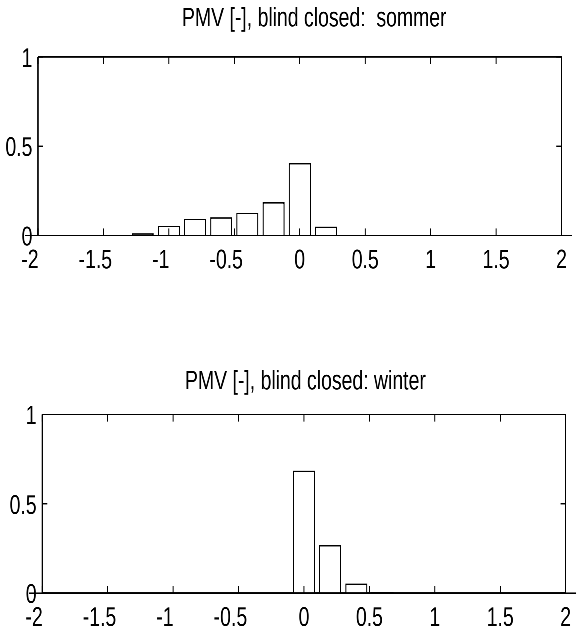

Figure 8.24: Summer and winter PMV with a closed blind

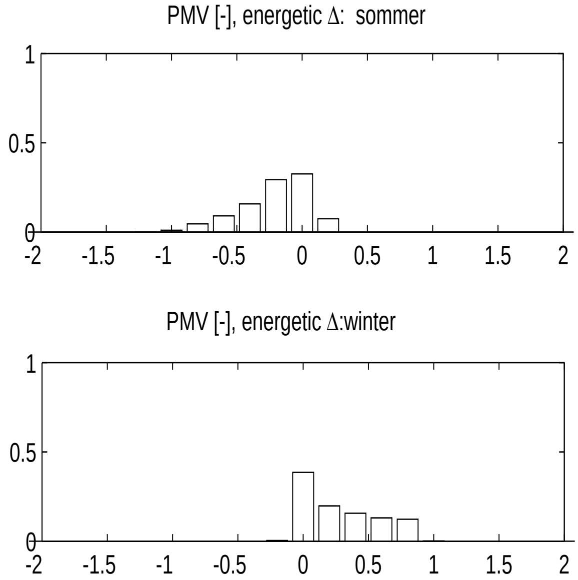

Figure 8.25: Summer and winter PMV with 'energetic DELTA' blind control system

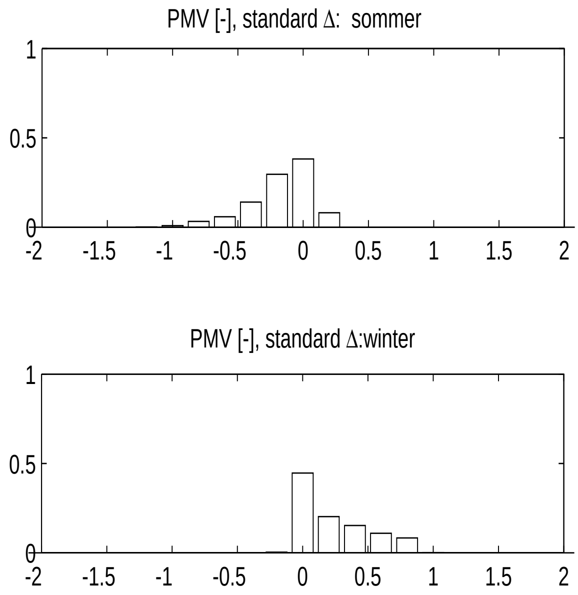

Figure 8.26: Summer and winter PMV with 'standard DELTA' blind control system

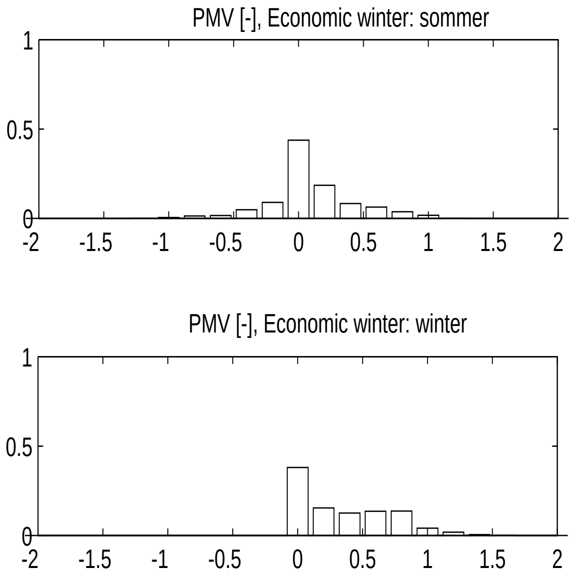

Figure 8.27: Summer and winter PMV with an 'energy efficient winter user'

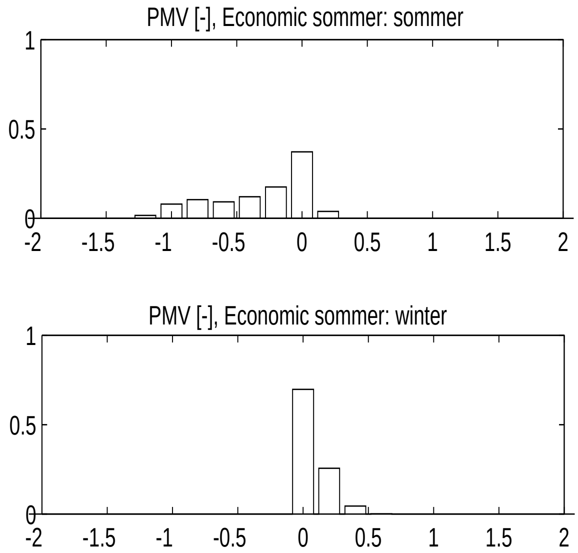

Figure 8.28: Summer and winter PMV with an 'energy efficient winter user'

8.7 Lighting aspects

8.7.1 Artificial lighting needs

The daylighting supplies of the different blind control systems can be determined by comparing the electric energy needed to insure a minimum inside illumination of 500 lux on the desktop during occupancy. Figure 8.29 shows the results obtained in winter, summer and the whole year.

The standard DELTA system shows results very close to when the blind is open all the time (maximum daylighting supplies). Most of the time, the DELTA system supplies enough daylight without artificial light. Nevertheless, in some situations, the artificial lighting was switched on in standard DELTA mode, when the blind was not completely open, which can happen to avoid glare with low solar illuminance.

Energy-optimised systems (DELTA, efficient user, and TU-Wien) are not especially efficient systems from a daylighting point of view, comparable to a permanently half-closed position.

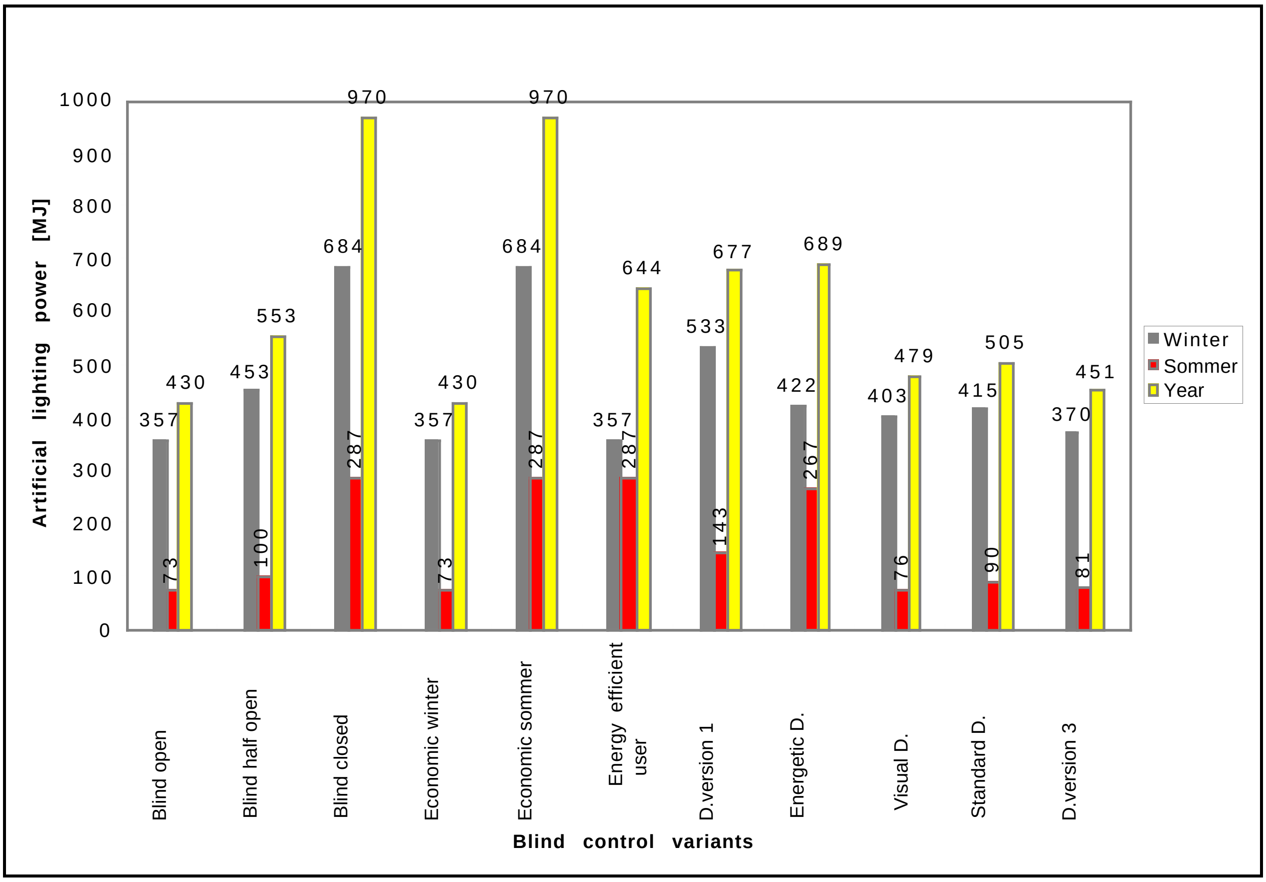

Figure 8.29: Energy consumption for artificial lighting for different blind control algorithms

8.7.2 Glare

The DELTA system seems to be efficient if we consider the artificial lighting needs. What about its anti-glare efficiency ?

The existing glare comfort indexes [CIE 83] are all based on luminance proportions between the visual observer position and the environment. The simulation program developed in the project is not able to calculate the luminances in the room. As an extension to the project it is proposed to use a specialised tool like Radiance [Ward 94] to quantify the visual comfort obtained by the DELTA blind control systems. Nevertheless we can list the blind control systems that will certainly *not* avoid glare:

- blind open
- economic winter
- energy-efficient user
- DELTA version 1 (most of time)
- energy-optimised DELTA

8.8 Global energy consumption overview

In this section a global view of the energy needs (heating, cooling and lighting) as well as the free gains (internal and direct solar gains) is given for the different blind control algorithms.

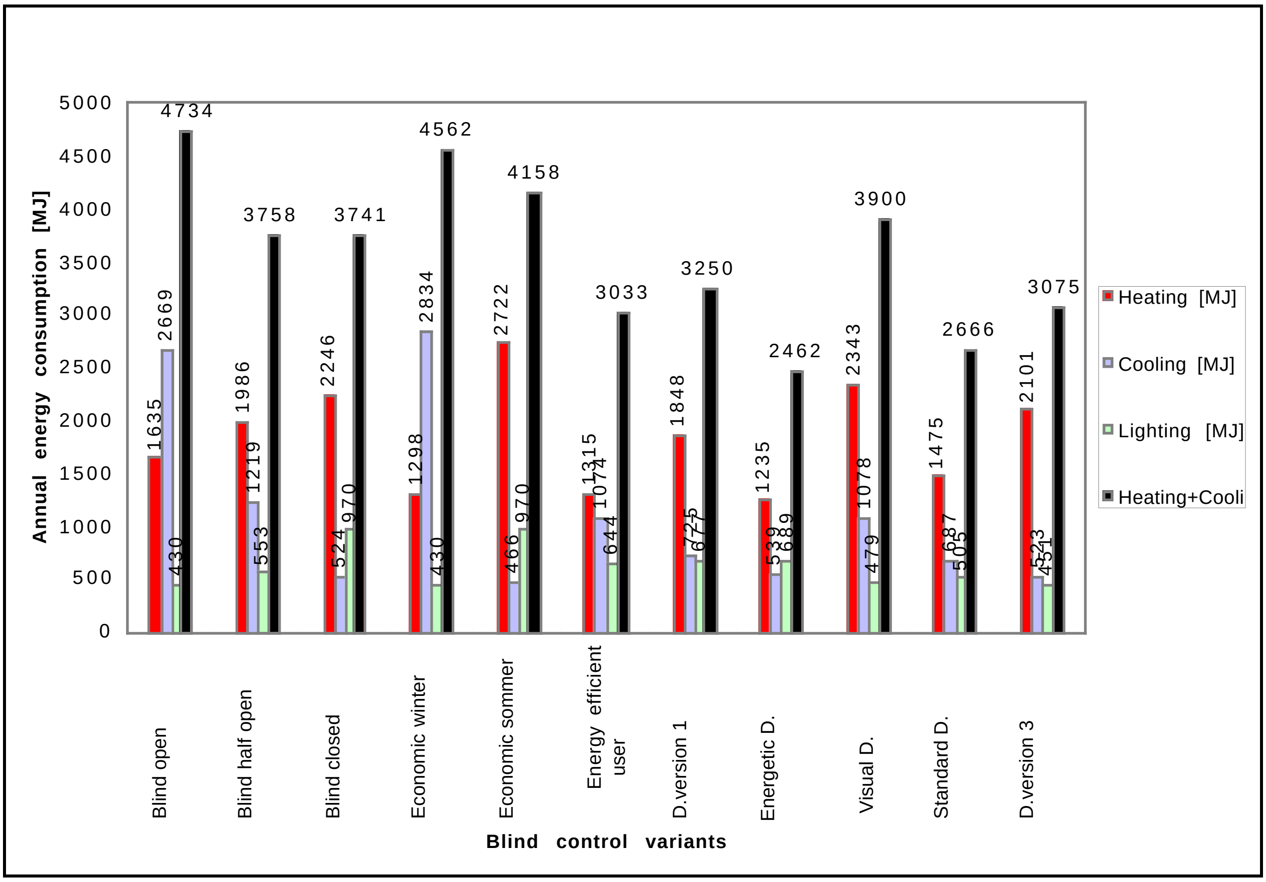

Figure 8.30: Thermal and artificial lighting energy consumption for different blind control algorithms

The above figure shows that the lighting part represents between 10% (blind open) and 26% (blind closed) of the global energy consumption. Figure 8.31 shows all energy flows (heating, cooling, lighting, direct solar gains and internal gains) in the office rooms.

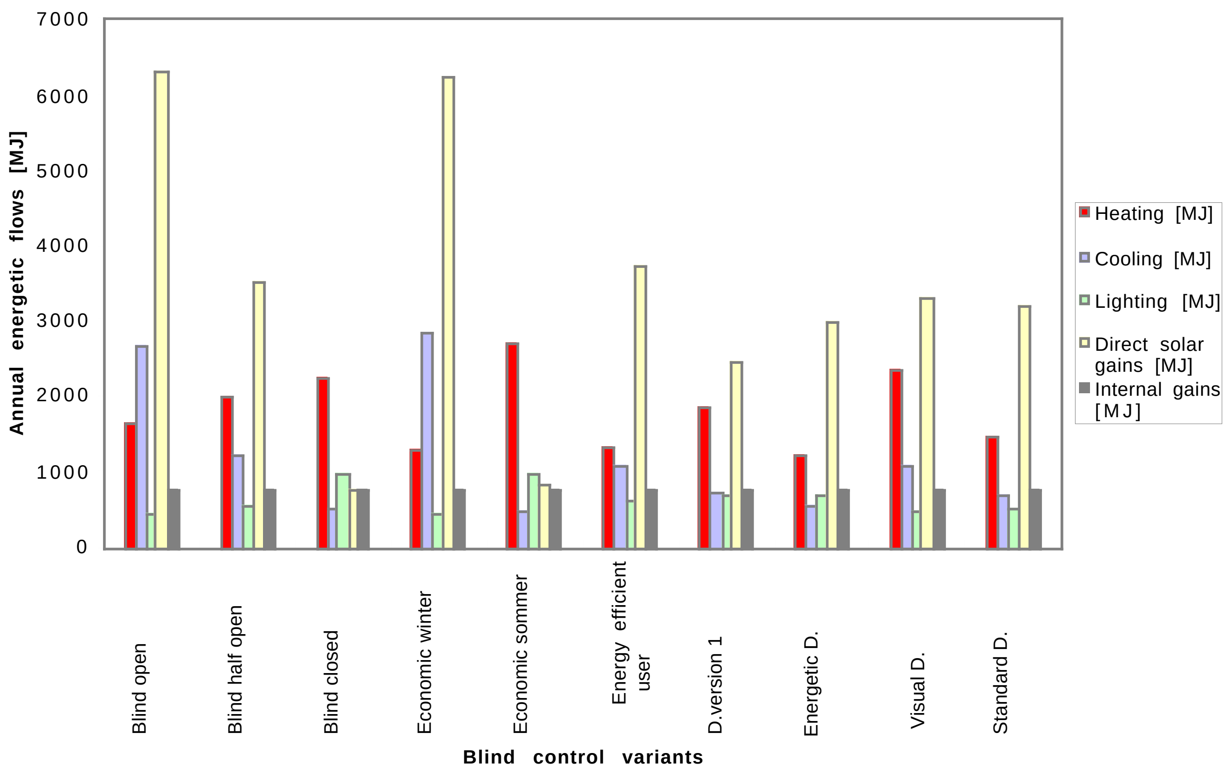

Figure 8.31: Energy flows for different blind control algorithms

9. CONCLUSION AND PERSPECTIVES

The goal of the project DELTA was to check a fuzzy logic algorithm for a blind controller, and the elaboration of alternative algorithms which could make the original controller better and more efficient, from the viewpoints of both energy consumption and user comfort (thermal and visual).

9.1 Original algorithm

The original algorithm, elaborated by the Technical University of Vienna (see reference [Wurmsdobler 94]), aims at minimizing the thermal and artificial lighting energy demand in the building. It is based on several input variables: the vertical solar radiation incident on the window, the outside temperature, the heating or cooling power, the room temperature, and the current blind position. After fuzzification of the input variables, a rule base evaluates a fuzzy value for the blind position; after defuzzification, the blind position is combined with other values given by the user or the security system in order to give a final blind position setpoint. The combination takes into account a relative priority for the user (with a weight decreasing with time), and an absolute priority of safety aspects (e.g. too strong wind triggers rolling-up of the blind).

The algorithm does not directly take into account thermal and visual comfort; only the energy consumption is considered. The level of thermal comfort provided is satisfactory mainly due to the possibility of cooling. Otherwise, severe summer overheating would occur. The rather high cooling energy demand is an indication of this problem.

It has been shown in the present report that the results of the original algorithm are interesting, but not particularly exceptional. The heating, cooling and artificial lighting demands are still rather high when compared to more "optimal" control algorithms: for instance, the heating + cooling consumption is 2573 MJ for the whole test year, compared to 2770 MJ for the case where the blinds are always kept closed, and 4304 MJ where the blinds are always kept open, but 2389 MJ for a hypothetical "energy-efficient user" (who would always optimize the blind position relative to heating and cooling energy, without any consideration for the comfort).

Moreover, the rule base needs to be adapted to the particular room considered (building characteristics) and to the heating/cooling equipment used (heating, cooling, controller).

Alternative algorithms have been elaborated in order to cure these problems, and to try to find a controller algorithm which would be very energy-efficient and optimizing both thermal and visual comfort.

9.2 Alternative algorithms

Two alternative algorithms have been elaborated. The first one takes into account the visual comfort of the user, and the second is an adaptation with a classical artificial intelligence rule base without fuzzy logic.

9.2.1 First alternative algorithm

The first algorithm is based on two principles. The first principle is the reconsideration of the aspect of energy-efficiency: the controller should try to always complement the heating/cooling system (avoiding to go in the opposite direction), and aim at a long term optimization of energy supplies depending on the season; it is based on the window heat balance. The corresponding rule base is reduced to 9 easy general rules. The second principle is the optimization of visual comfort, which is evaluated with an equally simple rule base.

When there is nobody in the room, only the first principle applies (visual comfort does not need to be considered, only thermal optimization) but when the user is present in the room, the second principle takes precedence.

The principle of energy optimization used by this algorithm has several advantages:
- easy adaptation to any heating and cooling equipment whose power is approximately known (should be accessible to the controller);
- the thermal characteristics of the room do not need to be known, only the window type (U-value of glazing, U-value of blind, g of glazing, g of blind);
- the only other parameter to be adjusted is the threshold for the "season" parameter fuzzification, which should be centred on the value for the "no-heating temperature" transition, for the building considered.

9.2.2 Second alternative algorithm

The second alternative algorithm is based on a classical artificial intelligence approach. The same variables and essentially similar principles are considered, but no fuzzy logic is used. The rule base corresponds to a decision tree, and takes into account all possible aspects, including thermal and visual comfort. Four different blind positions are possible (e.g. "antiglare without heat gain"), which are basic for any blind type (textile or venetian).

Both of these alternative algorithms consider user wishes and safety requirements in a similar way as the original algorithm.

9.3 Comparison of the algorithms checked (simulated energy and comfort)

The energy consumption corresponding to the three considered algorithms is given in the table below (the settings "blind permanently half-open" and the so-called "energy-efficient user" algorithm have also been reported as a comparison):

variant	Heating [MJ]	Cooling [MJ]	Artificial lighting [MJ]	Total [MJ]
Blind permanently half-open	1986	1219	553	3758
Energy efficient user	1315	1074	644	3033
Original TUW algorithm (version 1)	1848	725	677	3250
First alternative LESO algorithm (version 2)	1475	687	505	2667
Second alternative L&G algorithm (version 3)	2101	523	451	3075

Table 9.1*: Energy consumption values for the blind controller algorithm variants*

This table shows the interesting improvement with regard to energy efficiency resulting from the alternative algorithm developed at the LESO (visual comfort with fuzzy logic rules) and from the algorithm developed by Landis & Gyr (visual comfort with a decision tree).

Moreover, the artificial lighting requirements are lower, which is also an indication of better visual comfort (most users prefer daylighting to artificial lighting !).

The increase of thermal comfort has been discussed in the text (see section 8.6), using Fanger's Predicted Mean Vote (PMV) histograms. It has been shown that the various algorithms give satisfactory thermal comfort, partly due to cooling. The visual comfort is better with the alternative algorithms than with the original TUW algorithm, because they were developed keeping visual comfort as a significant parameter in the rule base.

9.4 Experimental results

The experiment has essentially been performed for two purposes: validating the simulation program used for the detailed comparison, and getting an idea of user satisfaction and acceptance of the various algorithms (the results rely on the three users of the monitored office rooms; they give an indication of user acceptance but have no real statistical signification). The validation has been carried out successfully, and will not be discussed here.

The user satisfaction data have shown the importance of allowing the user to change the blind position by himself. Some minor experimental problems have led to complaints, and some of the remarks have allowed us to improve the algorithm (for instance, less blind movements, minimal blind aperture). Nevertheless, the main conclusions are good acceptance by the users of the management of solar gains when they are not in the room and moderate acceptance of the visual comfort standard (the users still frequently needed to adapt the blind position to their activity since the position calculated by the controller did not always fit their needs).

Concerning that last point, the inclusion of "predefined ambiances" (dark for working at a computer screen, bright for discussion with other people, manual adjustment for the people allergic to automatic controller systems, etc.) would be a real improvement on the algorithm. Although not very difficult to implement, this possibility has been checked neither by simulation nor by direct user satisfaction enquiry.

9.5 Possible improvements of the blind controller algorithm

Some possible improvements have already been discussed above, e.g. the implementation of "predefined ambiances". Another important issue is the evaluation of visual comfort.

The evaluation of visual comfort is necessary for a good blind control algorithm. A first version of such an algorithm, using a simplified evaluation of visual comfort, has already been tested in the DELTA experiment. It takes into account the solar incidence angle and the illuminance on the facade to avoid glare for a person located at one meter from the window and also includes functionalities for maximising daylighting without glare, avoiding too many blind movements and keeping a minimal aperture.

The estimation of the visual comfort in a room relies on the luminance of all surfaces. Several visual comfort indexes have been proposed. In order to be able to know the luminances of all surfaces in the considered room at any moment, they can be calculated for typical daylighting situations, for instance using a ray-tracing software like Radiance (available at LESO-PB). Afterwards, an interpolation can be performed to get the visual comfort at any value of the parameters characterizing the daylighting situation.

Basically, the daylighting situation can be described by the following parameters:
- the solar radiation intensity (or the illuminance on a horizontal plane, in Lux);
- the diffuse/global radiation ratio;
- the position of the sun in the sky;
- the blind position;
- the room characteristics.

Currently, the evaluation of visual comfort could fulfil two separate needs:
(a) the establishment of statistics of visual comfort for the various simulated controller algorithms, in order to make a comparison using visual comfort as a criterion;
(b) the consideration of visual comfort in the controller algorithm itself, in a more detailed way than the rules currently implemented.

Considering the second goal (b), if we calculate the visual comfort index for a large enough number of typical situations in order to be able to do an interpolation, we will get the visual comfort index for any possible situation. In order to establish the minimum number of representative situations (or parameter set values), we can use the "design of experiments" method, which was used widely at LESO-PB for thermal experiments (see for instance [Goupy 88]).

Another issue is the test for the user acceptance of the blind control system. During the DELTA experiment, because of a practical limitation to two office rooms, there were only two users in the DELTA room and one in the reference room. They had to test a system over a one or two-week period. The results show interesting issues but for a realistic statistical validation, the IEA [Högskolan 95] recommends to have a few people in an office, testing the same new system during a complete year or to have many people testing the system over a shorter period.

9.6 Significance of the results in practice

The study reported here essentially concerns office buildings. At present, these are practically the only buildings equipped with blinds that can easily be controlled electrically. They also represent the largest part of the buildings in which significant energy savings and comfort improvements can be carried out using sophisticated controller algorithms.

A better management of energy in buildings is highly desirable. A significant part of building energy consumption can be saved by using better controllers, without sacrificing at all the users' comfort. The market for controllers is therefore likely to grow considerably, including "intelligent" systems (which adapt themselves to the conditions or to the users), integrated control systems (for all appliances in the building), or controllers using new technologies.

The integration of a blind controller such as the ones discussed here implies the use of several sensors: for instance a presence detector or an inside thermometer. With the Luxmate system from Zumtobel Licht, the integration of such sensors is not difficult, installing a presence detector in each room is currently rather expensive; nevertheless, such equipment will certainly be much more common in the future. When the occupancy schedule is rather repetitive and regular, a simple fixed schedule could be used instead of a presence detector.

The project DELTA is part of a research effort to produce innovative algorithms for the control of building appliances. The participation of two leading companies in the domain (Landis & Gyr, active in the building equipment controller market, and Zumtobel Licht, active in artificial lighting systems) shows the interest of the branch for the development of new algorithms. The participants have filed a patent for the protection of the main results of the project including the preliminary results of the collaboration between Zumtobel Licht and Technical University of Vienna.

10. ACKNOWLEDGEMENTS

The present project has been supported by the Swiss Federal Office of Energy (OFEN/BEW), to which we would like to express our gratitude and thanks for the financial effort which was devoted to DELTA.

We would also like to thank the people at LESO and EPFL who helped us to carry out the project: installing the needed electric appliances and helping to cable sensors, and last but not least, the users of the two rooms who served as guinea pigs for the fuzzy logic blind controller acceptance, and sometimes had to support rather disturbing conditions due to malfunctions in the system.

Also all our thanks go to the collaborators of the industrial partners (Zumtobel Licht and Landis & Gyr) for their help and participation in the project.

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12. APPENDIX: FURTHER SIMULATION RESULTS

Whole year	Heating energy [MJ]	Cooling energy [MJ]	Direct solar gains [MJ]	Intern. gains [MJ]	Artif. lighting [MJ]	Blind changes [/day]	Blind changes occup. [/day]	Tint [°C]	Text [°C]
Blind Open	1635	-2669	6315	752	430	0	0	22.32	10.29
Blind Half-open	1986	-1219	3536	752	553	0	0	21.85	10.29
Blind Closed	2246	-524	756	752	970	0	0	21.32	10.29
Economic winter (19h to 7h)	1298	-2834	6238	752	430	8	0	22.44	10.29
Economic summer (19h to 7h)	2722	-466	833	752	970	8	0	21.23	10.29
Energetic DELTA/office hour occupied	1235	-539	2974	752	688.7	3.3	1	21.86	10.29
Visual DELTA/office hour occupied	2343	-1078	3306	752	479	3.4	1.7	21.68	10.29
Standard DELTA/office hour occupied	1475	-687	3213	752	505	6.3	2.1	21.81	10.29
TU-WIEN (version 1)	1848	-725	2464	752	677	6.5	1.6	21.64	10.29
Artif. intelligence algor. (version 3)	2101	-523	1985	608	451	4.6	1.25	21.59	10.29
Standard DELTA, proba =0.2	1464	-868	3363	752	519	10.6	4.5	21.94	10.29
Standard DELTA, proba =0.4	1442	-908	3410	752	544	14.6	7.6	21.96	10.29
Standard DELTA, proba =0.6	1439	-925	3441	752	546	17.7	10.1	21.99	10.29
Energ.DELTA, no occupancy	1775	-268	3353	0	95	4.6	0	21.66	10.29
Energ.DELTA, no occup (a=8W/m2K)	2050	-148	3376	0	95	4.5	0	21.44	10.29
Energ.DELTA, no occup (a=3W/m2K)	1471	-487	3312	0	95	4.7	0	21.88	10.29
Energ.DELTA, no occup (no cooling)	1655	0	3557	0	95	4.5	0	22.27	10.29
Energ.DELTA, no occup (no heat, no cool)	0	0	3551	0	95	4.6	0	19.47	10.29

Table 12.1: Annual simulation results of blind control variants (energy, blind change occurrences and temperatures). The direct solar gains are the those entering the room directly without the reemitted part by the window and the external wall, the internal gains are counted without the artificial lighting and the temperatures are mean values

Winter season	Heating energy [MJ]	Cooling energy [MJ]	Direct solar gains [MJ]	Intern. gains [MJ]	Artif. lighting [MJ]	Blind changes [/day]	Blind changes occup. [/day]	Tint [°C]	Text [°C]
Blind Open	1629	-538	3297	432	357	0.0	0.0	21.24	5.18
Blind Half-open	1979	-75	1827	432	453	0.0	0.0	20.72	5.18
Blind Closed	2237	0	357	432	684	0.0	0.0	20.22	5.18
Economic winter (19h à 7h)	1292	-608	3288	432	357	8.0	0.0	21.38	5.18
Economic summer (19h à 7h)	2699	0	366	432	684	8.0	0.0	20.20	5.18
Energ.DELTA/off.hour occupied, new alg.	1230	-73.5	2414	432	421.5	3.9	1.60	21.04	5.18
Visual DELTA/office hour occupied	2336	-10	1605	432	403	3.2	1.5	20.51	5.18
Stand.DELTA/off.hour occupied, new alg.	1469	-34.1	2131	432	414.9	5.7	1.7	20.84	5.18
TU.-WIEN (version 1)	1841	-3.6	1400	432	533.3	5.3	1.3	20.59	5.18
Artif. intelligence algorithm (version 3)	2095	0	1219	351	369.7	5.2	1.5	20.32	5.18
Standard DELTA, proba =0.2	1459	-63	2171	432	428	9.3	4.3	20.93	5.18
Standard DELTA, proba =0.4	1436	-70	2190	432	443	13.0	7.4	20.96	5.18
Standard DELTA, proba =0.6	1433	-72	2192	432	445	16.2	9.9	20.98	5.18
Energ. DELTA, no occupancy	1768	-51	2625	0	55	3.5	0.0	20.87	5.18
Energ. DELTA, no occup. (a =8W/m2K)	2030	-40	2652	0	55	3.4	0.0	20.79	5.18
Energ. DELTA, no occup. (a =3W/m2K)	1466	-74	2582	0	55	3.6	0.0	20.98	5.18
Energ. DELTA, no occup. (no cooling)	1649	0	2816	0	55	3.0	0.0	21.20	5.18
Energ.DELTA, no occup.(no heat, no cool)	0	0	2812	0	55	3.0	0.0	16.47	5.18

Table 12.2: Winter simulation results of blind control variants (energies, blind change occurrences and temperatures). The direct solar gains are those entering the room directly without the reemitted part by the window and the external wall, the internal gains are counted without the artificial lighting and the temperatures are mean values.

Summer season	Heating energy [MJ]	Cooling energy [MJ]	Direct solar gains [MJ]	Intern. Gains [MJ]	Artif. lighting [MJ]	Blind changes [/day]	Blind changes occup. [/day]	Tint [°C]	Text [°C]
Blind Open	6	-2131	3018	320	73	0.0	0.0	23.81	17.32
Blind Half-open	7	-1144	1709	320	100	0.0	0.0	23.39	17.32
Blind Closed	9	-524	399	320	287	0.0	0.0	22.83	17.32
Economic winter (19h à 7h)	6	-2226	2950	320	73	8.0	0.0	23.90	17.32
Economic summer (19h à 7h)	23	-466	468	320	287	8.0	0.0	22.65	17.32
Energ.DELTA/off.hour occup.,new algo	4.5	-464.9	560	320	267.3	2.6	0.2	22.98	17.32
Visual DELTA/office hour occupied	7	-1068.1	1701	320	75.6	3.7	1.9	23.28	17.32
Standard DELTA/off.hour occup,new algo	6.3	-652.5	1082	320	89.9	7.2	2.5	23.13	17.32
TU.-WIEN (version 1)	7	-721.6	1063	320	143.3	8.2	2.1	23.08	17.32
Artif. intelligence algorithm (version 3)	6.3	-522.5	766.2	257.4	81	4	1.0	22.9	17.32
Standard DELTA, proba =0.2	5	-805	1192	320	91	12.4	4.8	23.33	17.32
Standard DELTA, proba =0.4	6	-838	1220	320	101	16.8	7.9	23.35	17.32
Standard DELTA, proba =0.6	6	-852	1249	320	101	19.8	10.4	23.38	17.32
Energ. DELTA, no occup.	7	-217	728	0	40	6.1	0.0	22.75	17.32
Energ. DELTA, no occup. (a =8W/m2K)	20	-108	724	0	40	6.0	0.0	22.33	17.32
Energ. DELTA, no occup. (a =3W/m2K)	5	-413	730	0	40	6.2	0.0	23.12	17.32
Energ. DELTA, no occup. (no cooling)	6	0	741	0	40	6.6	0.0	23.74	17.32
Energ.DELTA, no occup. (no heat, no cool)	0	0	739	0	40	6.7	0.0	23.61	17.32

Table 12.3: Summer simulation results of blind control variants (energiy, blind change occurrences and temperatures). The direct solar gains are the those entering the room directly without the reemitted part by the window and the external wall; the internal gains are counted without the artificial lighting and the temperatures are mean values

Simulation results: summer period, TU-Wien algorithm (version 1)

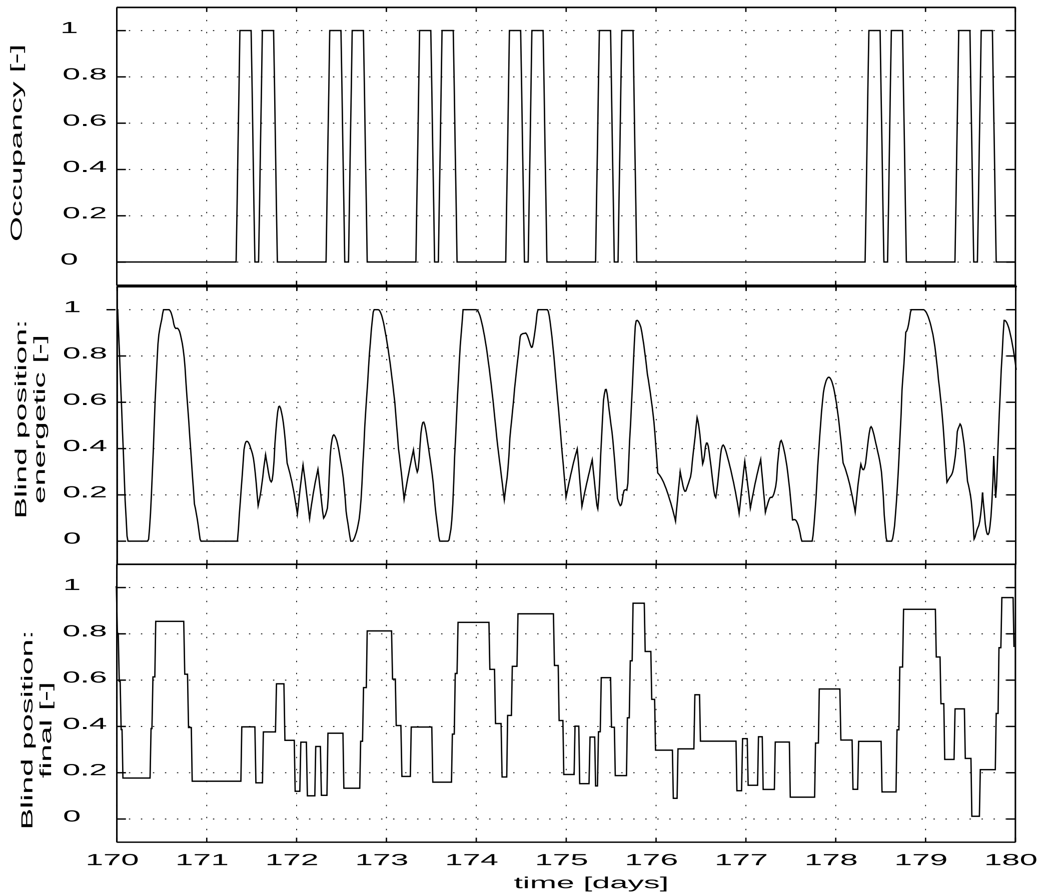

Figure 12.1: Occupancy and blind position (energetic, final) for the TU-Wien algorithm in summer.

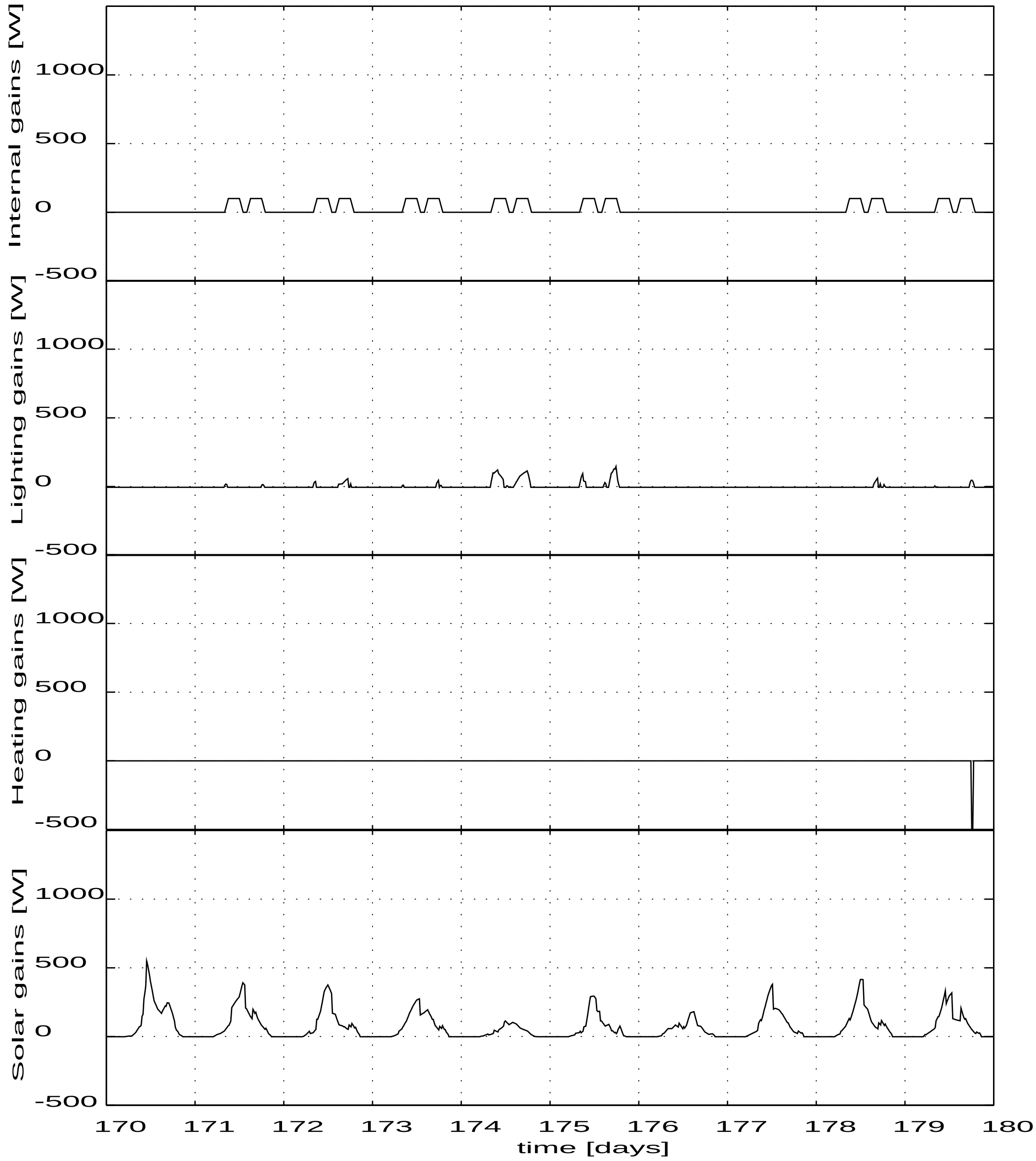

Figure 12.2: Gains (solar, heating, lighting, internal) for the TU-Wien algorithm in summer.

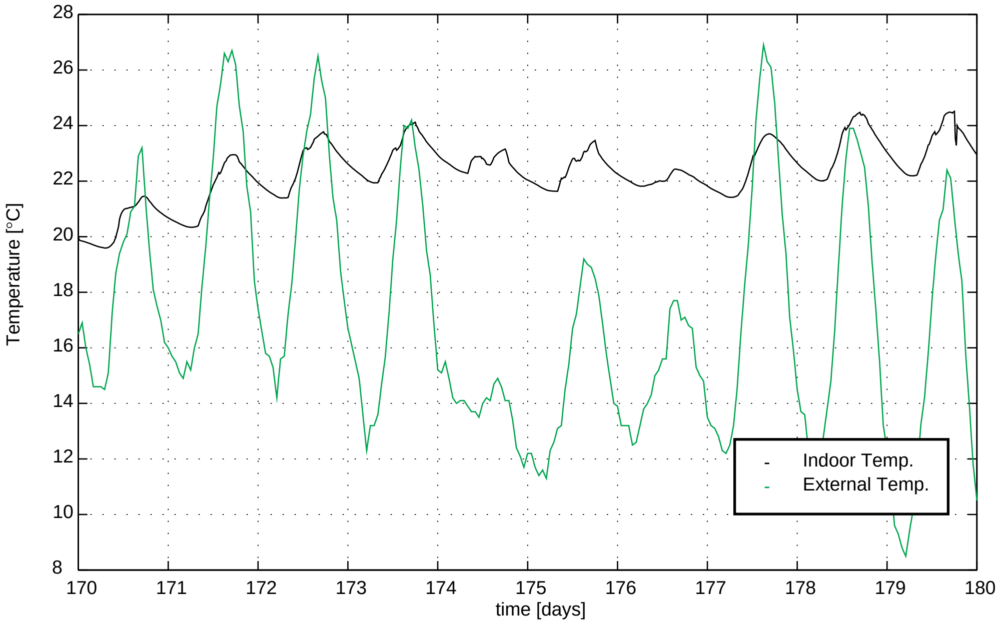

Figure 12.3: Internal temperature for the TU-Wien algorithm in summer.

Simulation results: Summer period, artificial intelligence algorithm (version 3)

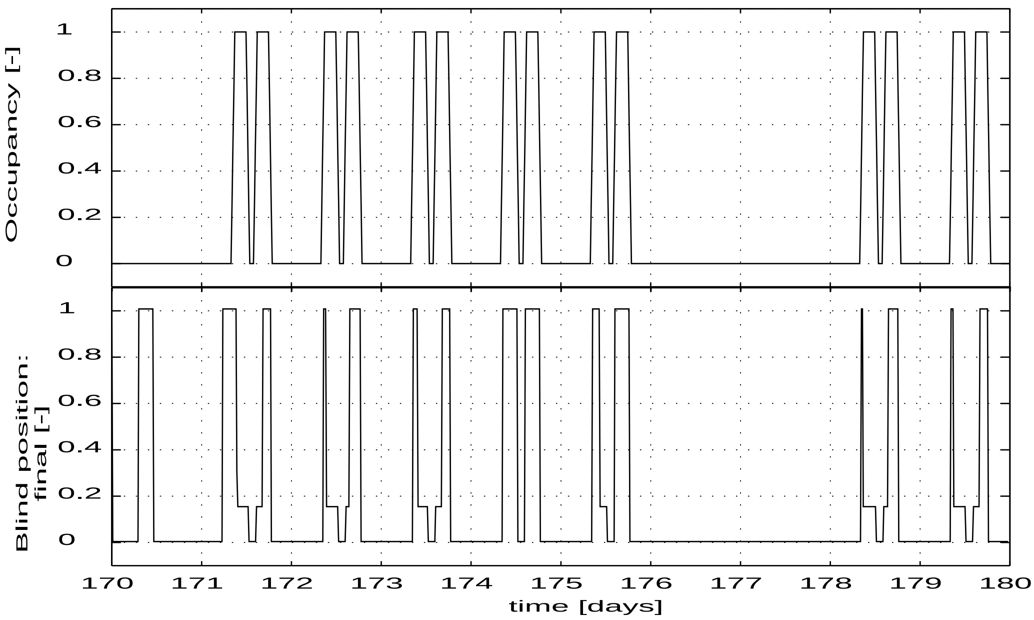

Figure 12.4: Occupancy and blind position (energetic, final) for the version 3 algorithm in summer.

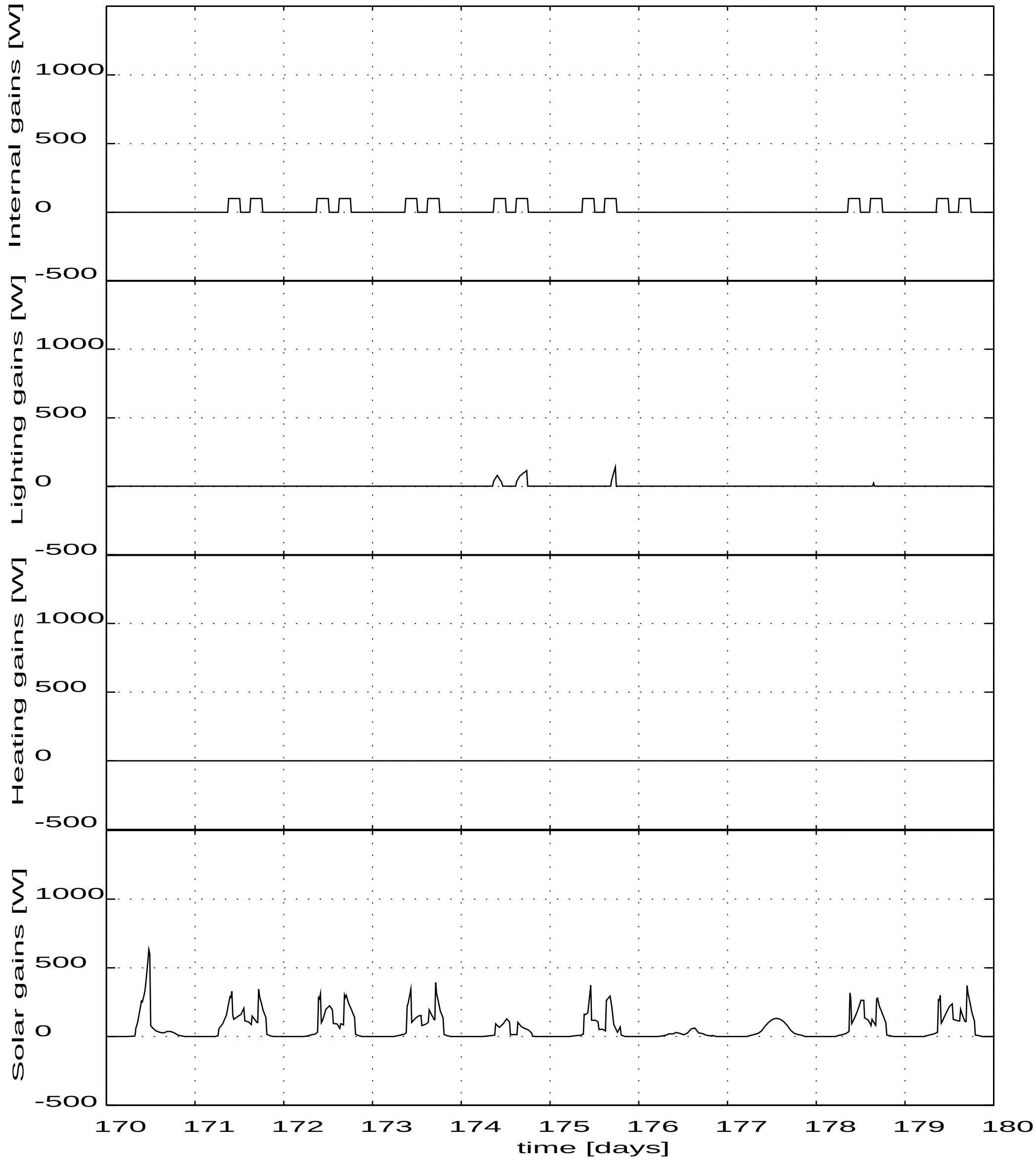

Figure 12.5: Gains (solar, heating, lighting, internal) for the version 3 algorithm in summer.

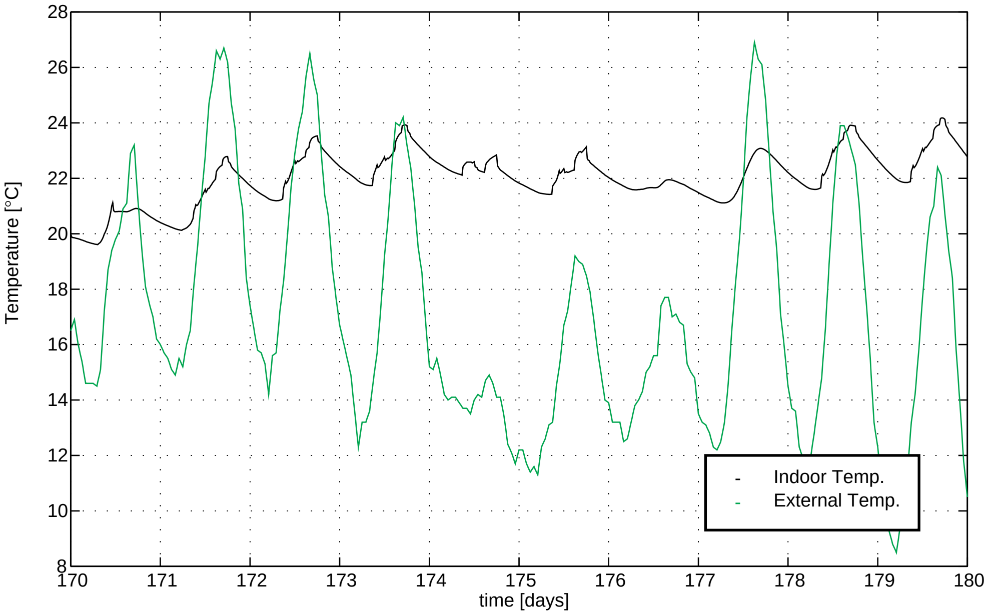

Figure 12.6: Internal temperature for the version 3 algorithm in summer.

Simulation results: summer period, Energy efficient user algorithm

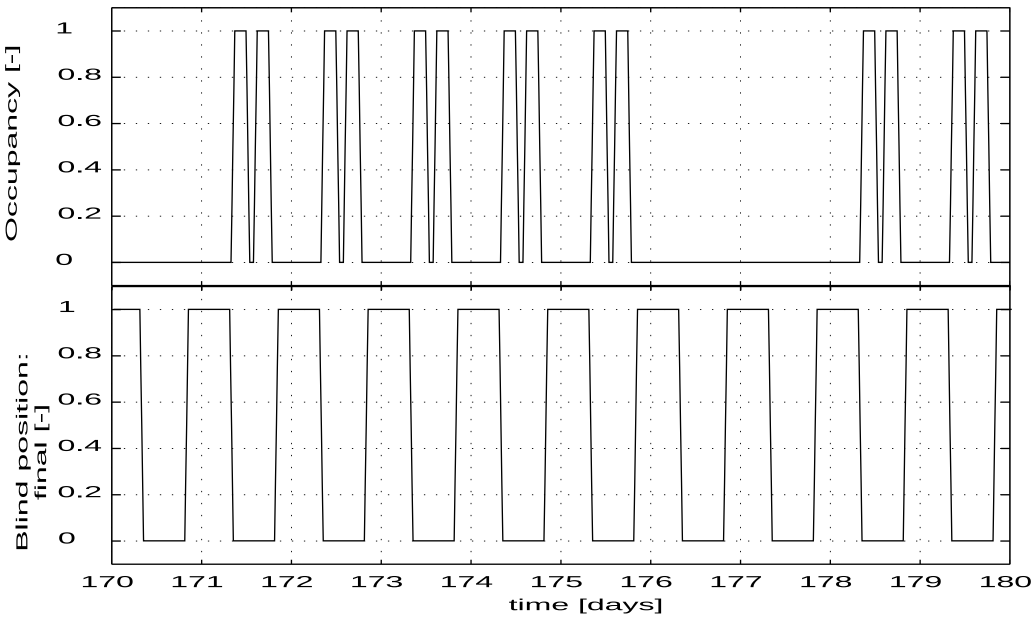

Figure 12.7: Occupancy and blind position for the energy-efficient user algorithm in summer.

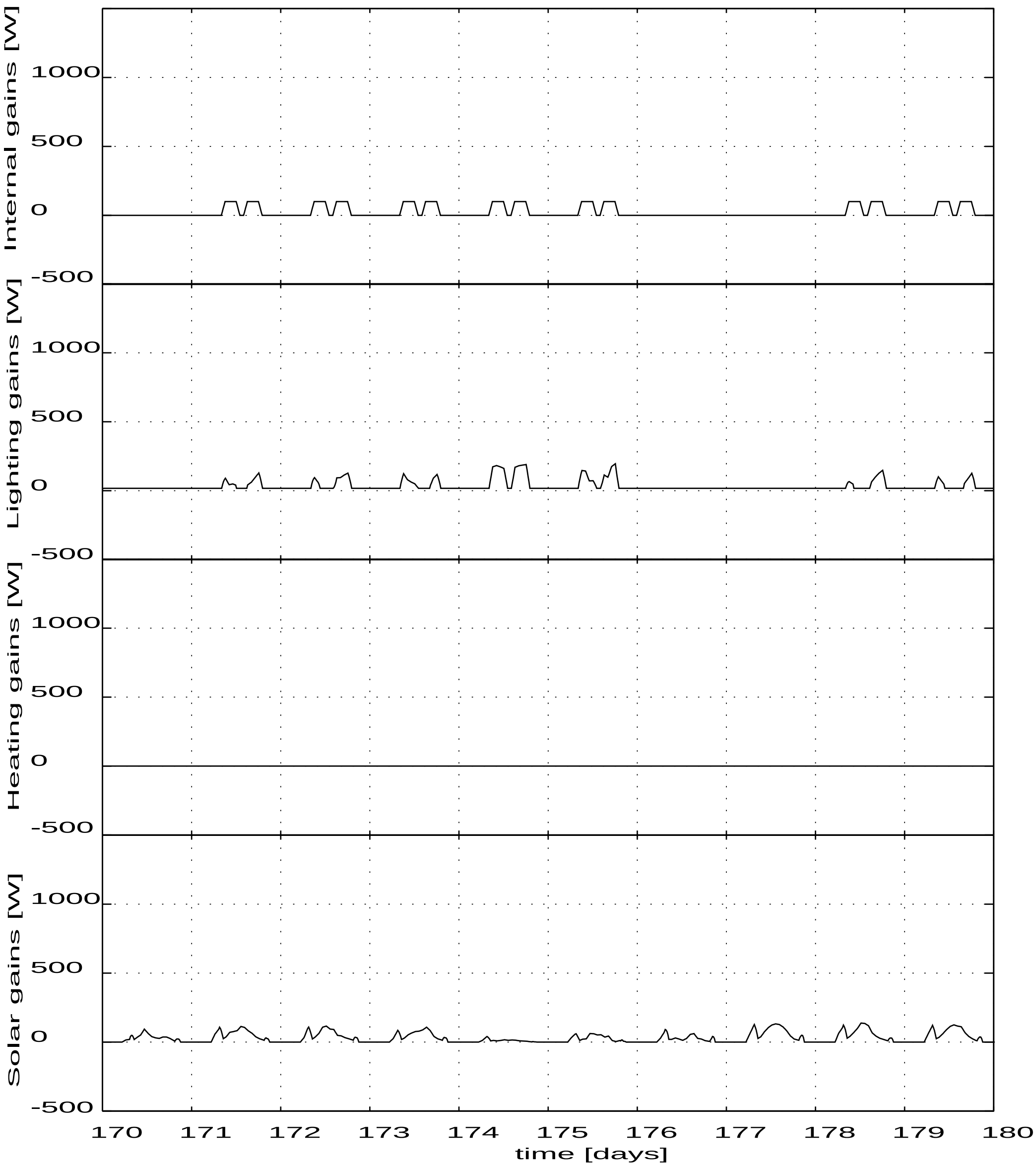

Figure 12.8: Gains (solar, heating, lighting, internal) for the energy-efficient user algorithm in summer.

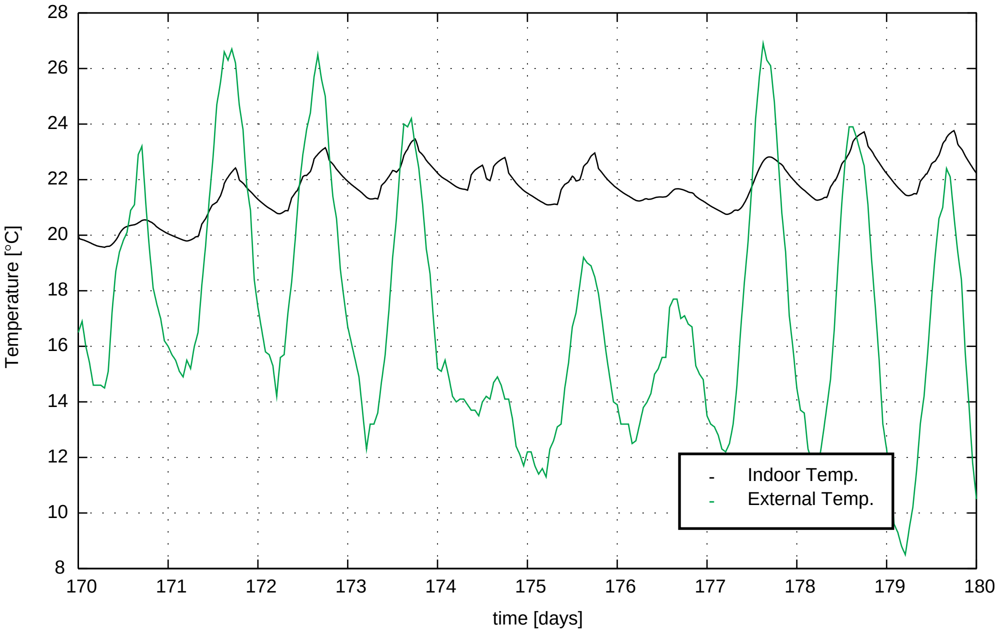

Figure 12.9: Internal temperature for the energy-efficient user algorithm in summer.