



Efficient Design Incorporating Fundamentals Improvements for Control and Integrated Optimisation

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1. EXECUTIVE SUMMARY

The project EDIFICIO (Efficient Design Incorporating Fundamental Improvements for Control and Integrated Optimisation) has the main objective to develop innovative integrated control systems to improve the performance of energy management systems and indoor comfort in buildings.

The project have seen the participation of eight partners, having different role and background:

- CONPHOEBUS (I), research centre for energy saving and renewable energy, as Co-ordinator
- CSEM (CH), expert in control sector and microtechnology
- EPFL-LESO (CH), expert in solar energy and building physic laboratory
- ST-THOMSON (I), microelectronics industry
- TNO-BOW (NL), research centre on smart control and energy management
- VTT (FI), research centre in building technology
- SENAMION AUTOMAZIONE (I), real-time systems and building automation
- IMPA (A), Technical University of Vienna

The activities have been subdivided into four main task areas: control assessment, algorithms development, experimental tests and dissemination, giving a total project duration of 33 months.

The final products of the project have been mainly:

- a PC-based Neural-Fuzzy integrated control system;
- a fully dedicated Integrated Room Controller (IRC);
- a new communication protocol between the IRC and the LonWorks technology, that accomplishing a new typology of BEMS network.

The potential customers for the project products, to which the exploitation strategy is addressed are engineering companies, installers of building automation and manufacturers of control systems.

In the following chapters the complete scientific and technical description of the project is reported.

2. OBJECTIVES OF THE PROJECT

The EDIFICIO project had the goal to develop innovative, adaptive, integrated smart control systems to improve the overall performance of the energy management systems and the indoor comfort in buildings. This is achieved by using Soft Computing Techniques (SCT), specially Fuzzy Logic (FL), Artificial Neural Networks (ANNs) and Genetic Algorithms (GAs).

Being the result of recent developments in computer science, SCT are already adopted in various industrial processes and are widely recognised to open very promising possibilities with respect to complex integrated and adaptive control problems, such as encountered in the building energy sector.

The main objectives of the EDIFICIO project were:

1. development of individual smart control algorithms of the following building functions:
 - lighting (artificial and natural);
 - heating and cooling;
 - indoor air quality and ventilation.
2. Development of new integrated and adaptive control strategies, based on SCT techniques, in order to obtain a more efficient building energy system management through a more consistent process co-ordination;
3. integration of the individual control modules to create a multi-functional control system;
4. implementation of the innovative control system into an IRC (Integrated Room Controller) coupled to PC;
5. implementation of the Fuzzy Logic procedures into a Building Management Network, using the LonWorks technology.

The products of the project have been:

1. a PC-based Neural-Fuzzy integrated control system, incorporating algorithms for heating/cooling, ventilation and lighting control;
2. a hardware prototype of the IRC which is essentially a new LonWorks device;
3. a new I/O protocol to communicate between the IRC and building network using LonWorks technology.

A preliminary estimate of existing BEMS control systems led to the conclusion that, by using SCT, important improvement could be reached in the following key areas:

1. HVAC and ventilation systems: the air flows are controlled by valves which often have non-linear characteristics; these non-linearity cannot adequately be handled by conventional control strategies, leading to errors in resulting flows;
2. Adaptive control strategies make possible to create self-tuning building energy management systems, solving the practical problems of badly tuned building installations, improving the indoor climate and the performance of the system, while saving on commissioning costs;
3. Short-term weather prediction and forecasting capabilities of the energy management system could be directed to anticipate delay and building plant response time. These predictions could

be utilised as input for the individual controls or could be combined in a more sophisticated integrated control strategies;

4. Integration of control modules - such as heating, cooling, lighting and ventilation - avoid possible conflicts between individual controllers and lead to reduce internal gains or overheating (seasonal strategies);
5. Possibility to reduce the number of sensors and connections, preserving or improving the performances of the control strategy, is a cost reducing activity that has not yet investigated;
6. Human-presence, user-behaviour and room-occupancy are to be considered variables of the control strategies are to be evaluated together with the physical parameters in order to obtain a combination of energy efficiency and optimal individual comfort;

The expected benefits achieved by the EDIFICIO project have been demonstrated and quantified in terms of:

1. Energy saving, by increasing efficiency of building energy management system;
2. Comfort improvement, by combining the control actions with the human presence;
3. Reliability of the building management network.

The main economic and scientific benefits the project leaded are:

1. Innovation and efficiency in building energy management;
2. A new methodology for industries willing to adapt predictive controls for the overall management of the building services;
3. Prospects of commercialisation of hardware/software products and selling of licences.

3. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE PROJECT

The project has been developed following some phases, within these phases have been developed some tasks. The initial one was the task Control Assessment (CA), then, on the basis of results achieved, algorithms development took place. Indeed algorithms development proceeded during all the project duration due to the necessity to tune up continuously developed automatic procedures. This happened particularly, during the most important phase of the project, namely Experimental phase (ET). Project ended with the Dissemination phase (DI) which, apart some actions took along the project, still is actual. In fact, the most important project's documentation has been planned to be published (after the final acceptance by the European Commission) on web pages hosted nearby web servers of some project's partners. In the following paragraphs, each task will be described rather in detail. For further information one can refer to the very large documentation produced by project's partner and delivered to the Commission.

3.1 TASK CA: CONTROL ASSESSMENT

Task leader of Control Assessment was VTT. This task was carried on taking advantage of contribution of all project's partners. In fact there was the necessity to assess, on country bases, specification for control algorithms to be implemented at software level. It was also needed to achieve a complete survey of standards, guidelines and codes relevant to application of BEMS (Building Energy Management System).

Main topics of this task were:

- Survey of standards, guidelines and codes of practice applicable to BEMS;
- Survey of existing building control strategies and control system;
- Performance criteria;
- Definition of operating condition;
- Impact of human presence on the control algorithms;
- Benefits, costs and evaluation of the market potential.

The following paragraphs deal with the items above.

3.1.1 SURVEY OF STANDARDS, GUIDELINE AND CODES

Just on the beginning of the project a lot of Bodies have been identified in the aim to have a complete frame of available information world-wide, in the following a list of them.

The list can be used to fetch information of HVAC system, building ventilation, control systems and so on.

In terms of specific BEMS application more in deep information can be retrieved looking at the following publication, code and/or guidelines.

AIST	Agency of Industrial Science and Technology, Tokyo, Japan
ANSI	The American National Standards Institute, New York, USA
AMEV	Arbeitskreis Maschinen und Elektrotechnik Staatlicher und Kommunalen Verwaltungen, Bonn, Germany
ASHRAE	The American Society of Heating, Refrigeration and Air-conditioning Engineers, New York, USA
BRE	Building Research Establishment, Watford, United Kingdom
BSI	The British Standards Institution, London, United Kingdom
BSRIA	The Building Services Research and Information Association, Berkshire, United Kingdom
CCITT	Consultative Committee of International Telephone and Telegraph, Milton Keynes, United Kingdom
CEN	Comité Européen De Normalisation, Brussels, Belgium
CENELEC	Comité Européen de Normalisation Electrotechnique, Brussels, Belgium
CSA	Canadian Standards Association, Ontario, Canada
DIN	Deutsches Institut für Normung, Berlin, Germany
DS	Dansk Standardiseringsrad, Hellerup, Denmark
EIA	Electronics Industries Association, Washington, USA
FSA	The Finnish Standards Association, Helsinki, Finland
IBM	International Business Machines Corporation, London, United Kingdom
IEC	International Electrotechnical Commission, Geneva, Switzerland
IEEE	The Institution of Electrical and Electronics Engineers, London, United Kingdom
ISO	International Standards Organisation, Geneva, Switzerland
ITU	International Telecommunications Union, Geneva, Switzerland
NNI	Netherlands Standardization Institute, Delft, The Netherlands
ON	The Austrian Standards Institute, Vienna, Austria
SS or SIS	Standardiseringsen i Sverige (SIS), Stockholm, Sweden
UNI	Italian National Standards Body, Milano, Italy
VDE	Verband Deutscher Elektrotechniker, Germany
VDI	Verein Deutscher Ingenieure, Düsseldorf, Germany

Table 1: possible relevant organisation in BEMS specification

105-1984 (RA 90)	Standard Methods of Measuring and Expressing Building Energy Performance
114-1986	Energy Management Control Systems Instrumentation
135-1995 & 135-1995R BACnet	A Data Communication Protocol for Building Automation and Control Networks (Awaiting publication)
140P	Standard Method of Test for the Evaluation of Building Energy Analysis
GDL 8-1994	Energy Cost Allocation for Multiple-Occupancy Residential Buildings

Table 2: ASHRAE - some BEMS relevant standards

3.1.2 SURVEY OF EXISTING BUILDING CONTROL STRATEGIES

Building Management System (BMS), comprises a lot of functionality. Apart energy control, in more general way, such system consists of physical devices (hardware), functions performed by software, field devices and services achieved by engineering. A BMS may be individually designed by the combination of (CEN TC247):

- Standard computer hardware
- Manufacturer specific hardware
- Standard software (e.g. operating system, database management system)
- Manufacturer specific application software (e.g. engineering tools)
- Project specific application software (e.g. functions that have been engineered)

Usually building automation systems are divided in subsystems of three different levels, namely: field level, automation/control level, and management level (see Figure 1). In addition, remote monitoring and servicing is a feature utilized in some special application areas when supervised systems are geographically scattered.

In the field level, sensing elements detect and measure the controlled variable giving the output mainly in analog, pulse, or binary form. Based on these messages control of actuators, operating final control elements (e.g., valves and dampers), is made. For data transfer the mentioned signals has to be converted to a digital form. There are various, non-standardized solutions for connecting a field device into a data communication network. The field network connects the field devices and the automation stations that control the devices. The network takes care of the transmission of the traditional I/O-signals from a sensor to the automation station and from the station to the actuator. In addition, the field panels include message (or signal) handling, control algorithms, and self-test routines. In this case, the automation station gives the set-points, possibly alternative control algorithms and methods, and registers status data from field devices. The field network must nearly always work in real time.

The field level consists of devices that interface mechanical and electrical plant to the functional units within a BMS (CEN TC247). The sensors, actuators, and other field devices provide the necessary information about the conditions, states and values of the processes in the plant and enable them to effect the programmed operations.

Specifically, the field level within a BMS consists of (CEN TC247):

- Sensors for plant operation measuring, signalling and limiting;
- Actuators for switching and positioning;
- Devices for automatic safety functions;
- Controllers for zones / single room controls;
- Information exchange with Control level and Management level;
- Units for manual control override (service operation).

Safety functions shall be performed at field level. Service Operation Devices may be provided at field level. Devices for monitoring and manual operation may be provided at field level.

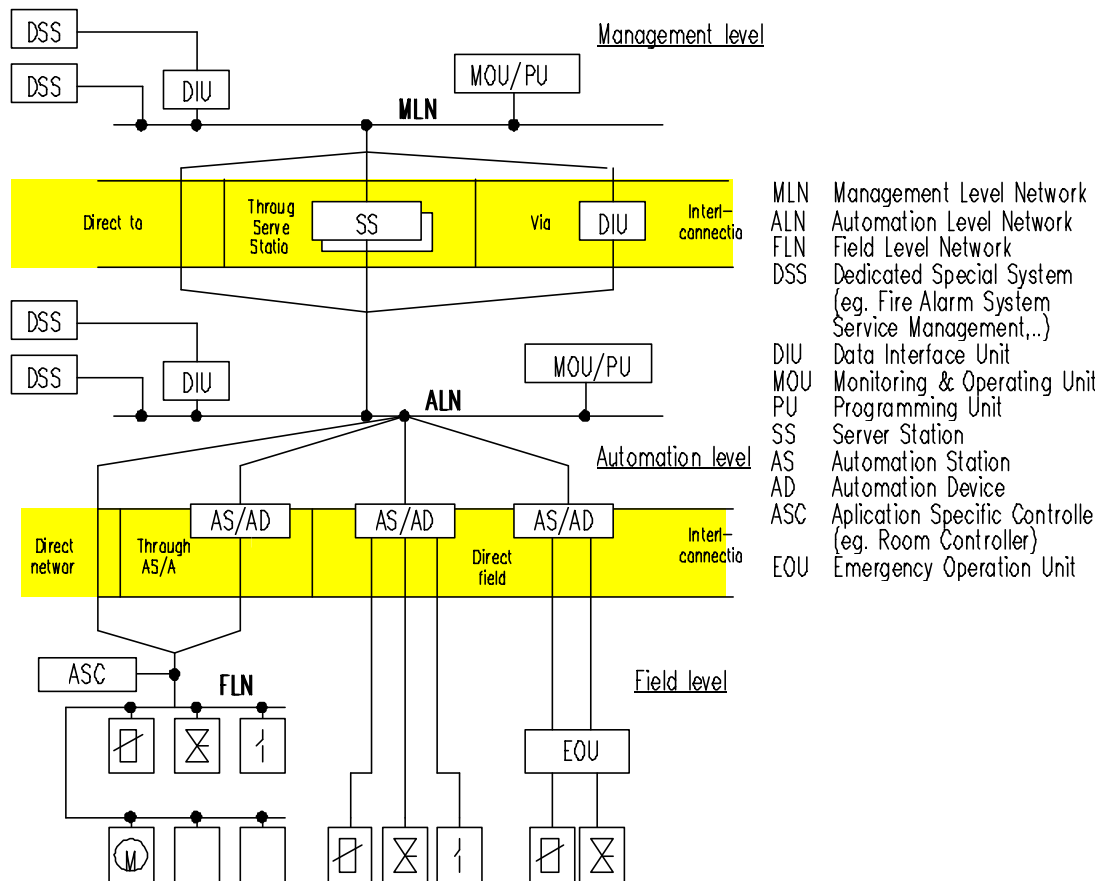


Figure 1: Data communication levels according to CEN TC247.

An automation network is a communication channel for automation systems of a building. It handles data transfer between the field level and the management level. The transferred data can be divided to transient state data, and statistics for optimization and decision making. Typically an automation station includes application software for: system security, system penetration, data formatting, data segregation, custom programming, graphics, standard reports, custom reports, maintenance management, site-specific customization, and system integration HVAC management. The personnel that operate and manage the building, or facility, interact the automation/control level on a day-to-day basis. The data transfer solution of an automation network should be relatively quick though it doesn't have to work on real-time.

The Control Level is where the plant oriented functions of a BMS are normally executed. The hardware may vary according to specific solutions (CEN TC247):

- Devices for monitoring and manual operation may be provided at Control level;
- Service Operation Units can be provided at field level;
- Devices for safety functions belong to field level, they do not need to be performed within Control level;
- Field devices may initiate Control functions (e.g. limiting, 2-point control etc.);
- Co-ordinating automatic management functions may be allocated to computers at the management level.

The stations, devices, units and control peripherals at the Control level provide the environment for following main tasks of building Control (CEN TC247):

- Direct Digital Control;
- Energy and operations optimisation;
- Automatic and manual control (service operation excluded);
- Plant operation monitoring;
- Provide data for statistics and analysis of values and states;
- Provide alarm, fault, maintenance and operations information;
- Information exchange within Control level and with field and management level.

The primary function for the management level is the facility management or the real estate management. Typical management level functions include: management of space usage, management of services, investment planning, assignment of operators and operator authority, report output of operator changes to the building management system or Display Data Channel (DDC) software operating parameters, plant efficiency and utilization summaries, reports, and alarms, energy cost/usage reports, allocations, and accounting, historical storage of all alarm and return-to-normal activity, data base archives of all automation level DDC programs for backup, daily reports of failed, engineering tools to monitor and tune major and critical systems, special critical alarm monitoring. Typically, large amounts of data is transferred in the management level, so it does not need to function in real time.

Remote monitoring and servicing does not necessarily form an own functional unity. It means control and supervision of running of technical systems outside of a single building based on data systems. It may decrease maintenance or running costs of a building but on the same time it often weakens services when compared to services got from in-building management systems. Typically remote monitoring systems consist of a subset of normal management functions. The subset provides the operator with critical and/or essential systems status information.

Looking at the three level subdivisions, within this project these concepts have been extensively applied as well. It must be pointed out that, so far, we spoke about BMS, but the same concepts can be applied to BEMS which can be seen as a sub set of the more general Building Management System.¹

3.1.3 PERFORMANCE CRITERIA

One of the most important target of BEMS system is to perform energy saving in building management acting on thermal, lighting, ventilation devices. Some information on the expected improvement in energy management came from experiences had by EPFL-LESO.

In general, two criteria have to be considered for quantifying the performance of the control system:

- Energy consumption for the considered technical equipment (heating/cooling equipment, fans, and artificial lighting devices);
- Level of user's comfort which can be obtained.

Additional criteria may include cost (controller and installation), and how easily the controller can be installed and commissioned. When trying to get an energy saving potential, one has to consider a base situation, and evaluate how much one can save by using a smart controller algorithm. In order to get a realistic potential, the base situation chosen should be rather representative of the average

¹ In the following pages, we refer always to BEMS system since its design was just the aim of the EDIFICIO project.

building equipment and use. In general, we consider for that evaluation the most up-to-date controllers (without using smart algorithms), good technical equipment (heating, cooling, ventilation, artificial lighting), and the average user's behaviour (which can be sometimes rather bad, like for instance for the artificial lighting which is frequently left on even when not necessary). The EDIFICIO team had the necessity to build up an whole BEMS system implementing smart controls whenever energy saving potential was foreseen. To do that, some experiences on already completed projects were used as starting point for further improvements. This is the case of the NEUROBAT project². The main achievement from this project was that in term of performances gains a significant heating energy saving has been recorded, both with experiment (between 15 % and 20 % when comparing the NEUROBAT controller with the advanced traditional controller) and with simulation (11 % in the same conditions). The comfort level was always similar or better when using the NEUROBAT controller. Actually, the NEUROBAT controller allows more stable temperature conditions than the traditional controller, due to its predictive behaviour. An important aspect is the commissioning: traditional controllers need to be adjusted carefully in order to allow good energy and comfort performances. In the reality, it has been shown that very often the commissioning is not done carefully, or sometimes not done at all. The result is of course a significant loss both in energy and comfort. A self-adaptive algorithm such as the one used in the NEUROBAT controller allows a very simplified commissioning procedure. The controller's parameters adjust themselves to the building characteristics, the local weather conditions, and the heating equipment characteristics, during the first months of function. In the case of the NEUROBAT controller, both experimental and simulation tests have shown that this adjustment needs a limited time, between one and three months.

In term of global energy saving about 15% has been shown realistic by using a smart predictive heating controller instead of an advanced traditional controller, for office buildings with individual controls at the room level. Such a good result cannot be expected for an office building with a centralised controller. Minor experiences were available for smart control of cooling system. For the ventilation system a good starting point for further investigation was the project proposal SMARTIS³ which wasn't financed by the European Commission. Improvements for ventilation system devices described in that project represented the starting point for the EDIFICIO project.

Concerning lighting performance (day light) the project DELTA⁴ carried on at EPFL (Switzerland) and funded by the Federal Office of Energy, has allowed to investigate the use of fuzzy logic to control a blind, both by experiment and by simulation. Two categories of considerations must be taken into account when controlling blinds: thermal and lighting. For the thermal control point of view, a maximum amount of solar gains must be allowed in winter (avoiding of course too high overheating), and a minimum in summer. Additionally, during the night, the blinds should be closed in winter (to increase the effective insulation of the system window + blind) and kept open in summer (to maximise the heat losses during the night). On the other hand, for the day lighting viewpoint, the effective use of day lighting should be maximised, in order to minimise the needed complement by artificial lighting, without impairing the visual comfort (avoid glare).

Two rule bases have been elaborated for the thermal and visual control, and the combination of both outputs is based on the presence of the user: when the user is present, the lighting aspect has the priority; when the user is not present, thermal optimisation is considered. It has to be noted that the

² NEUROBAT Pre-study, CSEM - LESO-PB/EPFL, April 1995; NEUROBAT, Annual Report 1996, CSEM - LESO-PB/EPFL, December 1996; NEUROBAT, Annual Report 1997, CSEM - LESO-PB/EPFL, October 1997; NEUROBAT, Final Report, CSEM - LESO-PB/EPFL, to be published in April 1998.

³ Smart Controllers to Improve the Overall Performance of Ventilation Systems (SMARTIS), Joule-Thermie proposal, January 1997

⁴ DELTA, Final Report, LESO-PB/EPFL - Zumtobel Licht - Landis & Gyr, November 1996; DELTA, un contrôleur de stores intelligent à logique floue, N.Morel, J.Geiginger, G.Sejkora, W.Hegetschweiler, P.Wurmsdobler, CISBAT'97 Conference, Lausanne, October 1997

user always keeps the highest priority: when he/she decides to change the blind position (using the usual up/down press-buttons), that decision is immediately taken into account by the system.

For blind control, performances can be discussed in terms of thermal performances, and artificial lighting needed to complement the day lighting when the latter is not sufficient. Of course, both aspects are important, but the emphasis can be put either on saving the most heating and cooling energy, or saving a maximum of artificial lighting energy. Both are interrelated, therefore increasing one generally decreases the other one (for instance, in summer, trying to use a maximum of day lighting could lead to overheating risks and thus additional cooling demand when a cooling equipment is provided).

A comparison of various controller strategies has been done during the DELTA project. In order to show the whole picture, the energy consumption for heating, cooling and artificial lighting, as simulated in the Lausanne climate for one year, is displayed in the table below (floor area 15.6 m², heavy construction, artificial light dimming control using standard Luxmate algorithm).

Variant	Heating [MJ/m ²]	Cooling [MJ/m ²]	Artificial lighting [MJ/m ²]	Total [MJ/m ²]
Blind always open	105	171	28	304
Blind always half-open	127	78	35	240
Blind always closed	144	34	62	240
Optimal thermal saving	84	69	41	194
DELTA algorithm with optimal thermal saving	79	35	44	158
DELTA algorithm with optimal visual comfort	150	69	31	250
DELTA algorithm with standard conditions (*)	95	44	32	171

(*) the DELTA algorithm with standard conditions uses the DELTA optimal thermal saving when the user is not present in the room, and the DELTA visual optimum when the user is in the room.

Table 3: comparison of control strategies according to the results of the DELTA project.

The experimental test data are not complete enough to get the statistical view over one full year, but it has allowed to assess the simulation model on the one hand, and the good acceptance of the system by the user on the other hand. By Table 3 it can be seen that using a smart algorithm for blind control would allow a small artificial light energy saving (around 8 %) when compared to a user who always keep the blind half-open. The saving would be much higher when comparing with a rather "badly-behaving" user who keeps the blind always closed (nearly 50 %). Of course, considering only artificial lighting demand, the "best" strategy is to keep the blind always open, but this does not consider the resulting glare. Using a smart algorithm (DELTA standard) which allows a good visual comfort does not make the artificial light demand much higher, only about 11 % (but the artificial lighting is still a very small fraction of the total energy need, i.e. only 18 %). On the other hand, a smart blind controller allows a very significant saving for heating and cooling (better use of passive solar gains in winter, and avoiding too much solar gains in summer). When compared to rather bad strategies like keeping the blinds at a fixed position, the heating + cooling energy saving can be between 20 and 50 %. From the numbers quoted above, the energy saving associated to the use of smart algorithms for controlling shading devices can reach nearly 50 % (summing up heating, cooling and artificial lighting), when such a controller is compared to a user who does not use the blind smartly at all. Nevertheless, most users behave a little better, and the energy saving potential would be smaller than such an amount. From our experience, we realise that the user's

behaviour is still far from perfect, and that a smart controller would probably allow to save between 10 and 20 % of global energy need (heating, cooling and artificial lighting summed up).

In terms of artificial lighting there is the need to control it in a smart way as well. Actually, a significant proportion of office buildings have no automatic control of artificial lighting, relying on the users to switch on and off the lighting devices. There are two important drawbacks with this procedure:

- An on/off switching is not adequate, because it is not always necessary to use the whole installed artificial lighting power;
- Very often, the users switch the light on when they need it (for instance in the morning when they arrive), but they never switch it off because they forget to do it.

The situation is a much less important with residential buildings, because most of the people feel more concerned about their electricity bill and more responsible about what they do during their private life than at work.. Controlling the artificial lighting smartly is not too difficult. There are already such controllers on the market (for instance, the Luxmate system of Zumtobel Licht⁵). Basically, such a smart controller does a measurement of day lighting outside illuminance on an horizontal plane (in Lux), and takes into account the daylight factor of the room and the blind obstruction factor to derive the day lighting level which is expected at the control point in the room. The controller adjusts then the artificial lighting at a level just sufficient to complete the day lighting and to reach the requested lighting level. Some improvements can be added to that simple algorithm: for instance, taking into account the presence of the user to avoid using the artificial lighting when he/she is not present, or introducing various requested lighting levels, depending on the user's occupation. For the office buildings, an energy saving of 50 % or even more can be obtained when compared to the situation where the artificial lighting is kept on during all the time the people are present in their office rooms (or worse, during all the day long). The energy saving is less significant for residential buildings, but could still justify the use of simple and smart artificial lighting control systems. Globally, we can probably expect between 10 and 50 % of saving for artificial lighting energy demand. Considering the proportion of artificial lighting energy relative to the whole energy used in the building (in Europe, that fraction is around 20 % for office buildings, much less for residential buildings), the energy saving is not very important, but still interesting, especially for office buildings where it can reach 10 %.

Table 4 gives a brief summary of the possible improvements which can be obtained by the use of more intelligent controllers.

Equipment	Reference projects and/or Industrial products	Possible (realistic) improvement (decrease of energy consumption)
Heating	NEUROBAT	10 - 20 %
Cooling	-	10 - 20 %
Ventilation	SMARTIS Indoor Air Quality Audit IEA/ECB Annex 18 (Demand controlled ventilation)	10 - 30 %
Day lighting	DELTA	10 - 20 %
Artificila light	Zumtobel Luxmate Daylight Europe	10 - 50 %

Table 4: Summary of the possible energy savings.

⁵ Luxmate System User's and Installation Manual, Zumtobel Licht, 1995

Globally, using all intelligent controllers together, we might theoretically expect an energy saving of 40 to 80 %.

On the basis of these experiments and studies, further implementation and brand new concepts have been introduced in EDIFICIO project.

3.1.4 DEFINITION OF OPERATING CONDITIONS

The objective of this section is to define a "standard" set of operative conditions⁶ (climates, buildings and building installations) for design, evaluation and testing of control strategies to be developed in the EDIFICIO project. Generally there are four types of operating conditions to which one can refer for control strategies.

- **Climate:** the most important variable is the outdoor dry-bulb temperature. Other variables are humidity, wind speed, and direct and diffuse solar radiation;
- **Passive Building Properties:** these passive building properties determine the response of the building to the climate such as outdoor temperature, internal and solar gains, sky conditions and solar position. Important variables are thermal mass, transmission/infiltration resistance, window properties, geometry and colours of internal spaces, and "ventilation paths". For indoor air quality aspects the air polluting sources of the building (and sometimes outside) are relevant;
- **Building Systems (Building Services):** these are the active systems in the building which respond both to the indoor and outdoor climate and to the occupants (settings or actions). Important variables are for example HVAC system type, HVAC system capacity, air flow rates, ventilation/infiltration openings, solar shading systems together with the control system;
- **Building Use:** these variables reflect how a building is used. Two similar buildings may be used very differently. Variables are: the number of occupants, internal gains (e.g. lights and equipment) and occupation patterns.

The following sections specify a possible set of operative conditions for the design, validation and rating of the control algorithms used/developed within the EDIFICIO project. Choices for climate, building properties and building system are considered.

Concerning climate it must be said that weather represents the most difficult condition to select. Referring specifically to EDIFICIO project, due to the large differences in geographical position of sites under test, performances of BEMS system have to be carried out considering large range of climates typology. The following Figure 2 shows the temperature's daily variation versus site's latitudes along the period January – July.

Task ET has been carried on three different sites: Catania (I), Lausanne (CH), Espoo (FI) for each of these sites extensive climate analysis have been carried on by project's partners.

Referring to building properties its response to the environment conditions characterise its own typology. The conditions can be divided into those describing the building shell, internal building structure and those describing the active building systems as the HVAC system, shading control system, electrical lighting system.

⁶ Kelly, G.E. 1993. Guidelines for Evaluating the Performance of BEMS Using Emulators. In: Kärki, S. (ed.) Development of emulation methods. Espoo: VTT, Laboratory of Heating and Ventilation. P. 90 - 118. (VTT Research Notes 1514). ISBN 951-38-4448-X

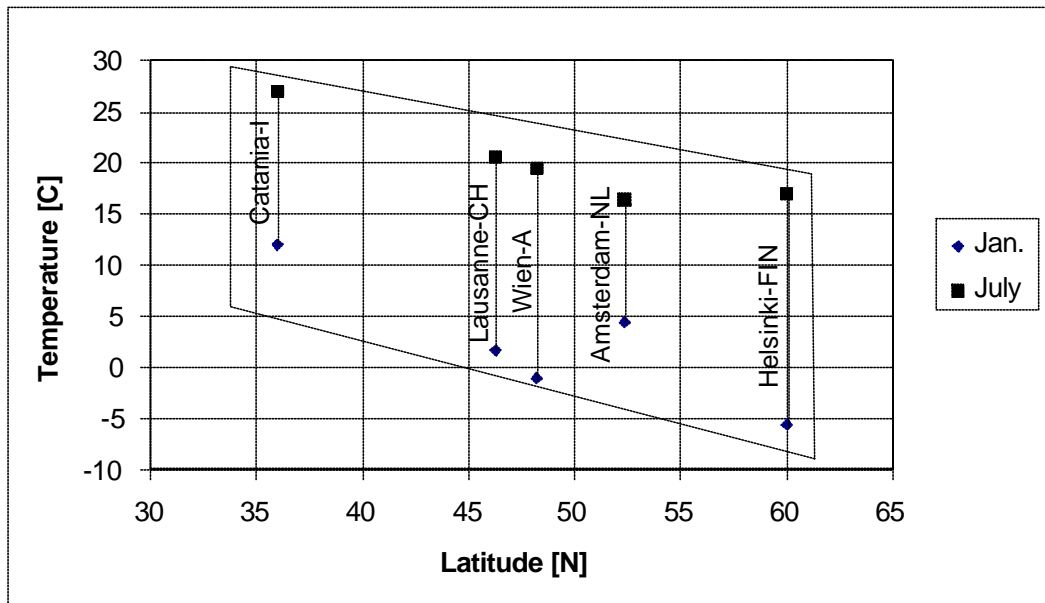


Figure 2: Average daily ambient temperatures (1961-90) for the locations of the EDIFICIO partners

The conditions for these two types can be decoupled to some extent, since different active building systems could be installed in various buildings. The building shell characteristics include resistance to thermal heat transfer, resistance to infiltration, thermal capacity (mass), and transparent system properties as total solar transmittance, visual transmittance, colour rendering index, colour temperature, and building/zone volume and also geometry of the windows and rooms, used colours (wall, ceiling, floor), specific light deflecting properties of window systems or passive shading systems.

If the algorithms being evaluated are to be installed in a variety of building types, then tests may have to be conducted in a number of different buildings with a range of characteristics. However, it would probably be undesirable to use a very large selection of characteristics. Instead, it may be preferable to limit the number of building shell types to something like three, which might be called heavy, medium, and light structures. The exact properties for a certain building type might also vary with the climate choice, since for example a medium building in a warm climate might have less insulation than a medium building in a very cold climate.

One possibility to characterize heavy, medium and light buildings is to use building time constants, for example 96, 48, and 24 hours correspondingly. Just to give examples of possible buildings in each category: in heavy buildings the external and internal walls might be made of stone, in medium buildings the external walls might be made of stone but the internal walls would be light, and in light buildings the external walls might be made of wood and the internal walls would be light.

Alternatively, many detailed tests could be done using one particular building type and a limited number of tests done on a range of other building types to determine if different building characteristics significantly effect the results. For example, the major portion of the tests (e.g., evaluating different application algorithms) could be performed on medium buildings (medium mass, medium insulation, medium glazing ratio).

Building types may also be categorised based on the building usage. However, there rarely exists a building which has only one type of activities. For example in an office building there may be inside parking spaces, canteens, gyms etc. which often have different operating times than normal office-hours.

3.2 TASK AD: ALGORITHMS DEVELOPMENT

Algorithms development took a large implementation time and continued also during the experiments since there was the necessity to tune up behaviour of software. This task, due to its complexity have been divided into different subtask, namely:

- AD1: Thermal control;
- AD2: Ventilation Control;
- AD3: Lighting Control;
- AD4: Software integration;
- AD5: Software Tools;
- AD6: Feedback from experiments.

The following paragraphs will describe each task rather in details.

3.2.1 TASK AD1: THERMAL CONTROL

3.2.1.1 INTRODUCTION

Task leader of Thermal Control was CSEM. The thermal controller (heating/cooling) has been developed to fulfil two main objectives:

- Provide the required level of comfort to the user when he is present.
- Minimise the energy costs.

In the most general case of a building with several rooms and several users, three basic levels of control have been considered:

- *Thermal plant control*: a central heater/cooler, which delivers a constant fluid flow at a controlled fluid temperature, normally constrained in a range of values to give the optimum thermal efficiency of the heater or cooler.
- *Group control*: usually with a three way valve, which controls the fluid temperature delivered to a group of rooms.
- *Local control*: today mostly achieved with thermostatic valves or direct manual control by the user.

From task CA emerged that, in practice, there were two possible scenarios for the implementation of an intelligent thermal controller in a multiple room commercial building:

- with controllers for each room, independent from each other;
- with a two-stage controller: first stage at room level, second stage at building(or zone) level.

This distinction is important in so far as energy cost optimisation for a whole building is concerned, therefore it is relevant for thermal and ventilation control, where optimisation can be local (for a room) and/or global (for the whole building). In the case of lighting energy costs, the local optimisation is sufficient. The integrated control system architecture, consisting of a 3 nested levels control loop allows for both implementation scenarios. However, in the EDIFICIO project the case of a "room controller" for level 2 was considered as agreed between the various partners. The added complexity which may result from an optimisation scheme for the thermal plant (e.g. fluid

temperature) can be taken into account with the level 3 control loop. What follows describes the proposed strategies to build up an efficient thermal controller.

3.2.1.2 PROPOSED CONTROL STRATEGIES

3.2.1.2.1 General consideration

The internal climate of a room is influenced by external and internal disturbances, such as the external temperature, the solar radiation, the free/internal gains, the temperature of adjacent rooms and the users. The random nature of these disturbances, especially the solar radiation and the user actions (window openings, manual blind control, room temperature setpoint etc.) makes an optimal control of the delivered heating/cooling power difficult. Therefore the thermal comfort of the user may be sub-optimal (overheating, low room temperatures at the beginning of comfort periods) and the energy consumption excessive. These type of problems can be stated especially for well isolated buildings and buildings with important passive solar gains, as can be seen in Figure 3.

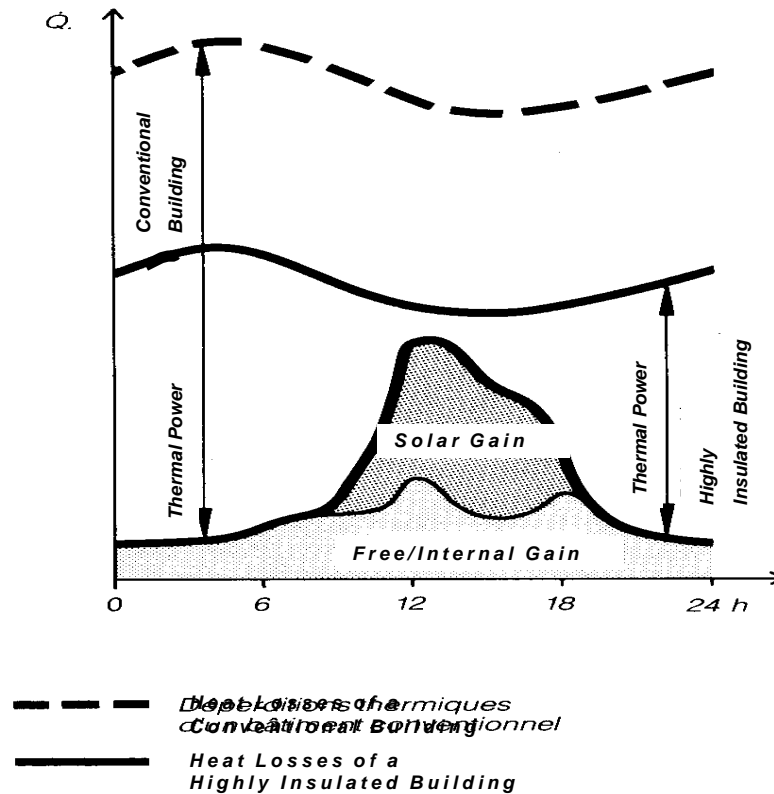


Figure 3: Heat losses and free/internal gains for a conventional and a highly insulated building.

It has been highlighted, during task CA, that existing room control and thermal plant control systems are not able to adjust the thermal power to take maximum benefit from the free energy. This is because of the relatively high thermal inertia of the building, where heating or cooling at a given time has an effect over a several hour period. Therefore, a smarter control system has to anticipate and take account of several factors:

- The future climatic conditions, in particular the external temperature and the solar gains;
- The presence or absence of the user;
- The user interaction with the system (set-point requests);
- The amount of energy which should be supplied over a given time horizon.

The problem of energy optimisation is therefore highly complex because one has to search over an enormous amount of possible future states, even when the climate and user presence can be predicted with reasonable accuracy. Two possible solutions are a-priori possible and are detailed in the following section:

- Optimal control of thermal power at each control step in a closed loop with a dynamic programming algorithm;
- Adaptive control of the so-called "power profile" with a predictive-fuzzy algorithm.

The second solution has been selected for the EDIFICIO controller and it is showed in the next paragraph. This solution reply some choices done within the NEUROBAT project (see note 2).

3.2.1.2.1.1 Optimal control with dynamic programming

The control strategy of the optimal control is based on the dynamic behaviour of the building and enables a correct optimisation of the thermal comfort with regard to the user schedule. This is the control concept of the NEUROBAT controller.

The optimal control receives the information from the building and climate models to elaborate an optimal heating command (the output of the user block model corresponds for the herein presented work to the room temperature set point). At each time step (15 min), the following information is available:

- The current state of the building: air temperatures $T_i(k)$ and $T_i(k-1)$.
- The predicted profile of the vertical solar radiation for the 6 next time steps ($G_v(k+1) \dots G_v(k+6)$).
- The predicted profile of the outside air temperature averaged on the last 24 hours ($T_e(k+1) \dots T_e(k+6)$).

At each new time step k , the optimal command U_k^* is the command which minimises the cost on the time horizon:

$$U_k^* \text{ such as } H = \min (\sum J(u_m, T_{m+1}))$$

the sum being taken from $m = k$ until the time horizon.

The calculation of U_k^* uses the dynamic programming algorithm⁷. The method presents the following characteristics:

- Global minimum: the algorithm allows the determination of the global minimum of the cost function. If the prediction models are correct, then the method allows the optimisation of heating and thermal comfort over the whole time horizon;

⁷ M. Bauer, Y. Oestreicher, J.-L. Scartezzini: Régulation prévisionnelle appliquée à une installation solaire active, Rapport final OFEN, Série de publications du CUEPE, Université de Genève, 1994 ; D. Bertsekas: Dynamic programming and stochastic control, Academic press, New York, USA, 1976.

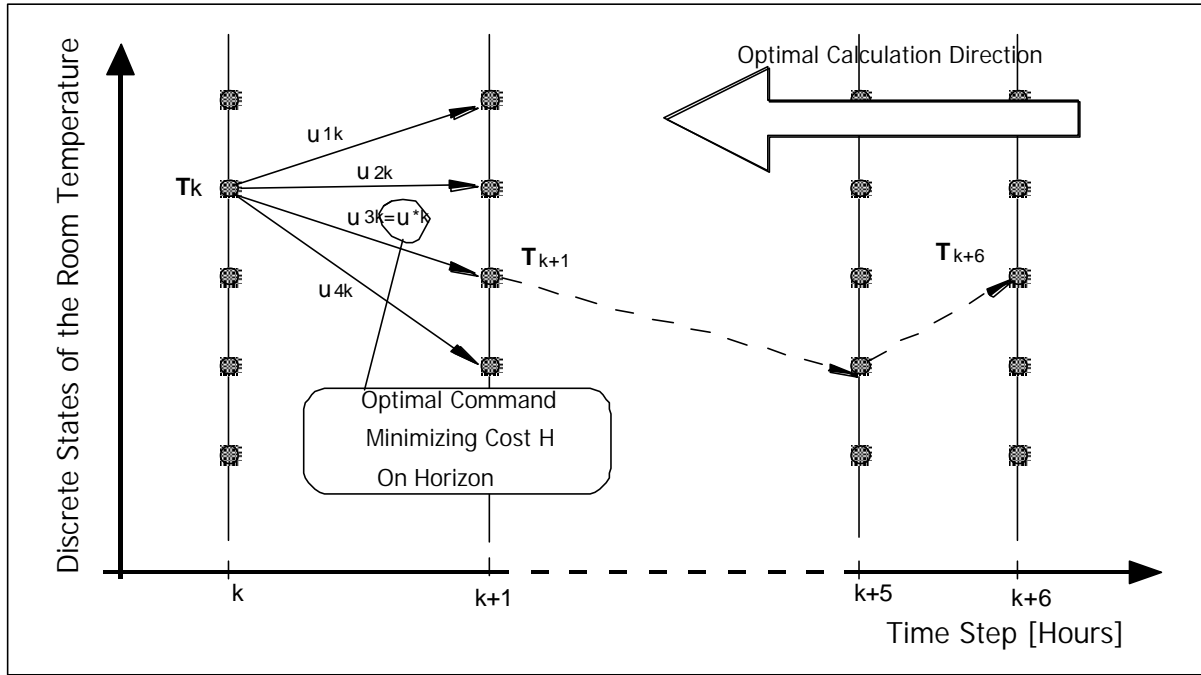


Figure 4: Calculation of the optimal command by minimising the cost on a time horizon.

- Optimisation time horizon: the time horizon has been chosen equal to 6 hours. The farther the horizon the better the optimisation of heating commands. Nevertheless, it is reasonable to say that the effect of a heating command is not longer than the building time constant. A second practical limit arises from the decreasing prediction quality of the models, especially the solar radiation prediction that degrades quickly after some predicted hours. A third practical limit is the calculation CPU time, proportional to the time horizon. The chosen value of 6 hours represents a compromise between all these considerations;
- Floating horizon: the 6 hours time horizon is floating, i.e. it is always counted from the current time. The optimal command is repeated every 15 minutes, in order to take into account sudden variations of the perturbations (solar radiation, window opening, blind handling);
- Dynamic programming algorithm: this technique has been chosen because of the non-linearity of the models, which makes impossible the analytical resolution of the problem⁸ and because it allows to find a global minimum instead of being trapped in a local minimum like it can happen with other techniques. The dynamic programming requires a discretization of the state variables and of the heating command. The following discretisation has been used in the NEUROBAT project (see Table 5).

	$T_i(k)$ [$^{\circ}$ C] (current Air Temperature)	$T_i(k-1)$ [$^{\circ}$ C] (previous Air Temperature)	Heating Command [W]
Number of discrete states	141	61	5
Interval	0.035	0.035	$P_{max}/4$
Domain considered	[-2.45, +2.45]	[-1.05, +1.05]	[0, P_{max}]

Table 5: Variable discretization

⁸ K. J. Aström, B. Wittenmark: computer controller systems, Prentice Hall, 1990

The discretisation used is very fine, since it allows to distinguish a temperature difference of 0.035 °C and a heating power difference of 250 W (with reference to a maximal heating power of 1000 W, as it was used for the NEUROBAT test phase) during one hour. Such a fine discretisation is required for a good functioning of the controller, but is very demanding for calculation time. This approach has not been adopted for the EDIFICIO project for the following reasons:

- Optimisation and control are done simultaneously, which would mean, for the EDIFICIO project to include lighting and ventilation in the dynamic programming search algorithm. Obviously, the amount of computation time required would be unrealistic;
- For the same reason, this approach is not in line with the three nested control loop concept and does not integrate easily with ventilation and lighting control.

3.2.1.2.1.2 Predictive-fuzzy control

Such a control strategy is depicted in the diagram below (level 1 and 2 only). As stated above, a major unknown variable for the prediction of building behaviour in the following hours is the amount of energy supplied either for heating or for cooling. Therefore, the only way to avoid the complexity of dynamic programming is to assume a given energy input distribution (power profile) over the required time horizon and to calculate the resulting future room temperature which would result from this distribution. The goal of the controller is in this case to correct the power input at each control step in order to achieve optimal comfort for the user.

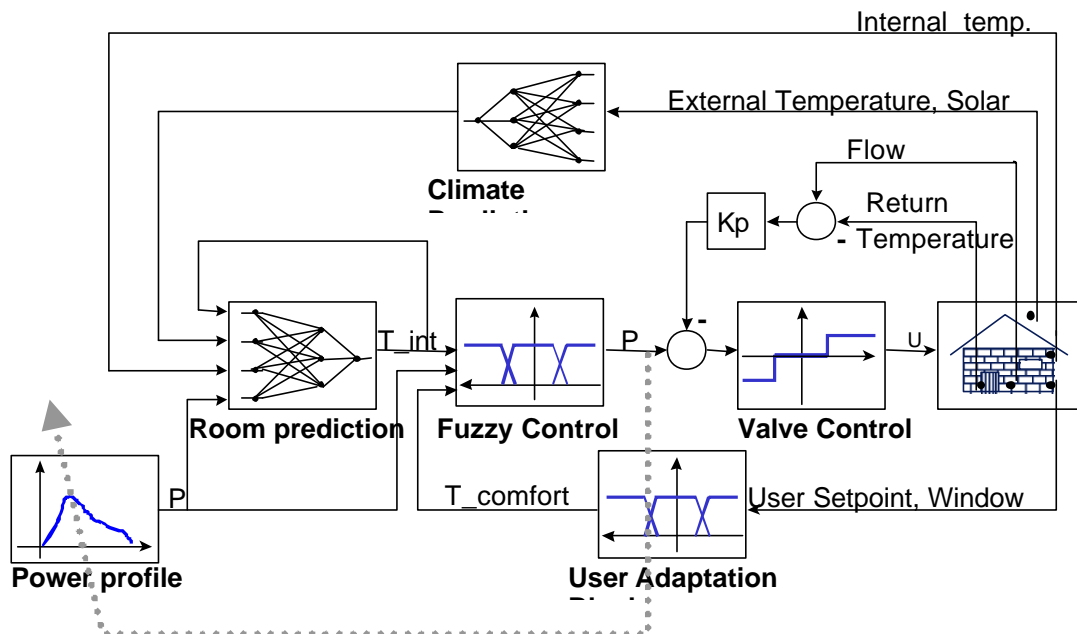


Figure 5: Adaptive control with a predictive-fuzzy algorithm

The level 1 controlled variable is the three-way valve position based on the temperature difference of the cooling/heating fluid (Inflow temp. - Return temp.) which is a direct measure of the energy utilisation (with a constant fluid flow). It could be replaced by any other level 1 controller provided that the input to level 1 (output of level 2) is the same, i.e. the power input.

The required power input is determined by a fuzzy algorithm which minimises overheating and overcooling over a time horizon. This is done by a set of rules which take account of the current comfort level and the predicted future comfort level. The algorithm takes care of:

- Climate: the *climate prediction module*, developed using ANNs, predicts external temperature and global solar radiation for a further time horizon⁹, based over a set of actual and past meteo measurement;
- Room prediction: the *prediction of room temperature*, developed using ANNs, provides the evolution of internal room temperature, receiving as input the previous states of the building and predicted climate data. Both Radial basis function and back-propagation have been considered for ANN training;
- User behaviour: time schedule room occupancy and modification of user's temperature set-point determine prediction of comfort temperature, which corresponds to the output of the *user adaptation block*.

The choice to adopt predictive control strategy, combined with non-linear modelling of building, user's behaviour, and weather prediction, allows the thermal controller to achieve energy consumption optimisation while ensuring thermal comfort. Adaptation of the fuzzy parameters is done in an external loop (level 3), not shown in the above figure. This will be done in a way as to optimise the cross-coupling with lighting control and ventilation control in order to produce further energy savings. In case of a several room buildings, the same concept can be used at the local level and/or group level, provided there is one actuator (i.e. valve) at the level to be controlled and at least a temperature measurement or estimation. In such cases, there will be a single module for climate prediction. The *room predictor* module will need to be revised to incorporate the several controlled zones.

3.2.1.2.2 Input and output variables

Hereafter the relevant input and output variables which are needed by the control algorithm are reported. Not all of them need to be measured by sensors: some may be derived from another measurement, or just calculated.

Input variables for each controlled zone:

User's presence (if available; otherwise fixed comfort schedule and/or switch operated by the user);

User's input for comfort adjustment;

Inflow temperature;

Return flow temperature;

Room temperature;

Blind position (if available).

Input variables for the complete building:

Current time;

Solar radiation on a horizontal plane [W/m^2];

External temperature, north;

External temperature, south (at least during development and test phases);

Season (winter, summer, mid-season): can be derived from the outside air temperature [$^{\circ}\text{C}$];

Heating or cooling equipment power [W]; used for the blind control (optimisation of blind control relative to thermal behaviour of the blind).

Output Variables

Sign of power (heating or cooling);

Power input;

Updated power profile.

⁹ i.e. 6, or, 12, or Hours.

3.2.1.3 ROOM TEMPERATURE PREDICTOR

A neural network using Radial Basis Functions (RBF) has been used for the prediction of the room temperature for the required time horizon of 6 hours. The input variables are:

- External temperature;
- External temperature predicted (6 hours);
- Solar radiation on vertical plane;
- Solar radiation on vertical plane predicted;
- Internal temperature;
- Heating power (heat profile of the last 24 hours);
- Blind position;
- Blind position predicted (6 hours);
- Ventilation rate;
- Ventilation rate predicted (6 hours).

The output is the predicted internal temperature for the time horizon. Training is done continuously. After the first 3 days of initial training, the prediction is very accurate for a given heating power.

3.2.1.4 CLIMATE PREDICTOR

3.2.1.4.1 Model selection

The climate prediction block should provide two data to the room prediction block:

- The vector of external temperatures over a fixed time horizon;
- The vector of solar radiation on the horizontal plane.

Such data could be provided by the available public meteo service if it is locally available through for instance telephone lines. However, in this case the information supplied is often averaged over several hours and is not directly usable for a 6 hours ahead prediction.

On the other hand, a temperature sensor and a solar radiation sensor can easily be made available on site. Moreover, the solar radiation information will be required for lighting control and most thermal control systems now include an external temperature sensor. Having this information available can thus be stated as a prerequisite for the meteo predictor.

The approach used was developed and proven in the NEUROBAT project. Artificial neural networks have been applied for the prediction of the horizontal global solar radiation and for that of external temperature. A simple feed-forward network structure is chosen with one hidden layer and all the neurons completely inter-connected. The Levenberg-Marquart training algorithm is applied due to its convergence faculty and as activation function of the neurons the tangent hyperbolic is chosen due to its non-linearity, continuity and derivability. The training data of the ANN has not been pre-processed, e.g. the raw data has been applied to determine the ANN parameters. The algorithm was written and tested with MATLAB (version 4 and version 5.3 for the final version).

The solar ANN has 4 normalised inputs:

- The relative solar radiation at current time k : $G_{rel}(k)$;
- The relative solar radiation one hour ago: $G_{rel}(k-1)$;

- The relative solar radiation 24 hours before the time of prediction: $G_{rel}(k+horizon-24)$;
- The computed value of maximum solar radiation at the time of prediction: $G_{max}(k+horizon)$.

and 1 normalised output:

- The relative solar radiation at the time of prediction: $G_{rel}(k+horizon)$

The temperature ANN has 4 normalised inputs:

- The current external temperature: $Temp(k)$
- The average external temperature over the last 24 hours: $average_Temp_24$;
- The average solar radiation over the last 24 hours: $average_Ghor_24$;
- The computed value of maximum solar radiation at the time of prediction: $G_{max}(k+horizon)$.

and 1 normalised output:

- The temperature difference compared to current at the time of prediction: $Temp(k)-Temp(k+horizon)$

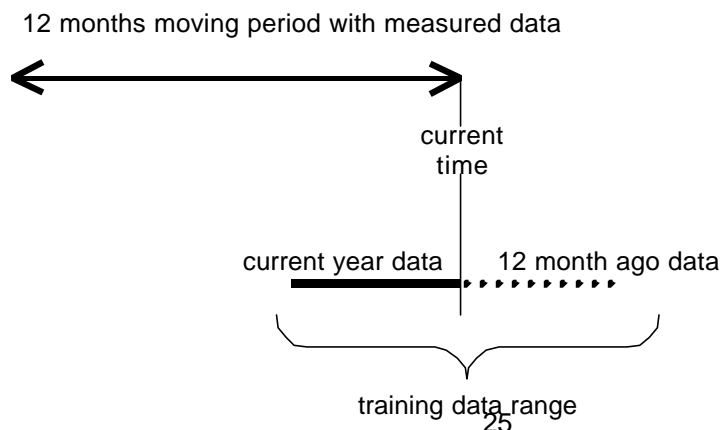
Further testing and development of the model was carried-out with meteo-data from Lausanne, and Catania. It was found that the 6 hours ahead predicted values are rather accurate, with about $\pm 1^\circ C$ error for the Lausanne climate and $\pm 2.5^\circ C$ for Catania. Similar results have been obtained for all seasons and this model can thus be used with confidence. For the prediction of solar radiation the results were relatively good if one considers that there can be wide variations of solar radiation due to cloudy weather. The mean error was very small, which demonstrated the accuracy of the model. Standard deviations were on the order of 70-150 W/m^2 which is a significant fraction of the solar radiation (15-20 %). This is a measure of the "unpredictability" of the solar radiation. Improvements have however been made and they are described in following section.

3.2.1.4.2 Simulink implementation

The climate predictor was used so far in a batch mode, with the idea to train it one year of data. The model could be used as such, without adaptation for the next year.

Another approach is to have an adjustable training period based on previous year data (from any number of days) and to retrain the ANN model at regular intervals (say 1 to several weeks). Since the climate predictor block can be implemented at central level (for the whole building) and on a PC, this should be feasible on the point of view of CPU resources.

This is the scenario chosen, and the training scheme is shown below:



Initialisation

Two files are used for initialisation purpose.

Init Data:

- Loads and transforms data from a one year meteo data file to the 'globDB' matrix [time(hour), Temp, Ghor, Gmax, Grel];
- Defines the geographic data 'scst' and the location normalisation factors 'ech';

Gen Sim Predictors

- Defines the new ANN predictors, train once, and generates Simulink models with the required number of neurons.

The first file needs to be run only once at start of the simulation or if the meteo and geographic data have changed.

The second file is only required for a new ANN structure definition (i.e. more neurons or hidden layers).

Execution

The execution part is done directly in Simulink. When loading the simulink models of the predictors, the "Init_Sim.m" file is executed to load the database matrices and the ANNs parameters. During Execution, Simulink calls the functions "WriteGlobal.m" and "TrainAndUpdata.m".

The same structure has been used as previous for testing this model and several training schemes have been tested:

Training period ->	- 30 to + 30 days	- 14 to + 14 days	0 to 90 days
Time between training	21 days, 5 days	14 days	90 days

The tests have been made one year of synthetic meteo data corresponding to the Lausanne climate and generated with the Meteonorm program.

In all cases, the temperature prediction is good and very similar to what was obtained previously. The 30 days training period was found adequate and used in the experimental tests and the simulation.

However, the solar prediction gives unsatisfactory results and further improvements had to be made which are described in the next section.

3.2.1.4.3 Improvements of solar predictor

After identification and correction of a simulink problem with the use of ANN, this also gave the opportunity for additional testing and simulation with new data, in particular Helsinki data and to look for further improvements.

Obviously, with the inherent variability of the solar radiation from day to day, hour to hour, there is a limit to the time horizon of prediction and to its accuracy. With the knowledge available, a 6 hours ahead prediction seems to be a limit. This means for instance that at 6 in the morning, while it is still night and no information on the solar radiation has been collected since the last sunset, we should be able to forecast the value at 12h00 noon.

The problem of the solar predictor was found in the training block: TrainAndUpdate (solPredictors,tempPredictors,u, ech) and was corrected. New validation tests were performed with Lausanne data.

3.2.1.4.3.1 Validation tests

As previous, the tests have been made one year of synthetic meteo data corresponding to the Lausanne climate and generated with the Meteonorm program. Results are given below and are consistent with the expected errors. Minimum errors are obtained for the April- August period, where the sun radiation is highest and varies the least. All the results refer to the radiation values on the vertical plane whereas previously we used the horizontal plane.

Two runs have been made with different starting months (January and May), showing that the number of previous training periods does not change the results, i.e. the training scheme is well conditioned and converges after one period, see Figure 6 and Figure 7. Another run has been made using a new set of starting weights (they are initialised at random). Figure 8 shows that similar results are obtained. However, it must be stressed that, in some instances, the errors may be much larger on some of the outputs (e.g. for the 3 hours ahead prediction).

Further runs have been made to check upon the influence of the training period and training data range. Figure 9 below gives results obtained with a training data range of -10 to +10 days and retraining every 10 days. This shows that there is no real improvement in increasing the frequency of training.

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. Period	Average error					
0	5.12	15.36	11.94	3.26	2.05	-4.37
1	8.75	8.37	6.57	7.77	11.04	11.36
2	12.61	11.04	10.21	9.27	12.20	11.68
3	5.78	5.68	2.68	1.51	6.10	8.51
4	1.40	0.41	-1.57	-2.95	-3.34	0.62
5	-1.23	-2.60	-4.26	-5.15	-4.18	-3.63
6	0.46	-0.58	0.13	0.37	3.09	0.80
7	0.97	1.66	0.51	0.26	3.17	0.98
8	4.44	7.66	7.30	12.63	17.77	12.78
9	3.53	7.21	13.89	7.63	17.23	11.41
	Standard deviation					
0	73.87	100.54	109.39	121.26	133.28	134.39
1	79.04	96.96	103.54	113.87	114.94	116.74
2	71.55	85.22	96.96	108.03	118.37	116.88
3	46.55	56.88	66.42	72.05	80.93	83.14
4	39.91	43.88	50.07	55.17	58.93	62.53
5	30.90	34.70	40.47	45.38	46.99	49.61
6	26.81	31.58	36.04	39.68	46.51	44.09
7	37.23	42.58	48.82	56.40	65.32	69.81
8	46.69	57.23	66.39	82.55	94.40	99.81
9	73.22	87.88	101.10	113.34	117.96	120.51

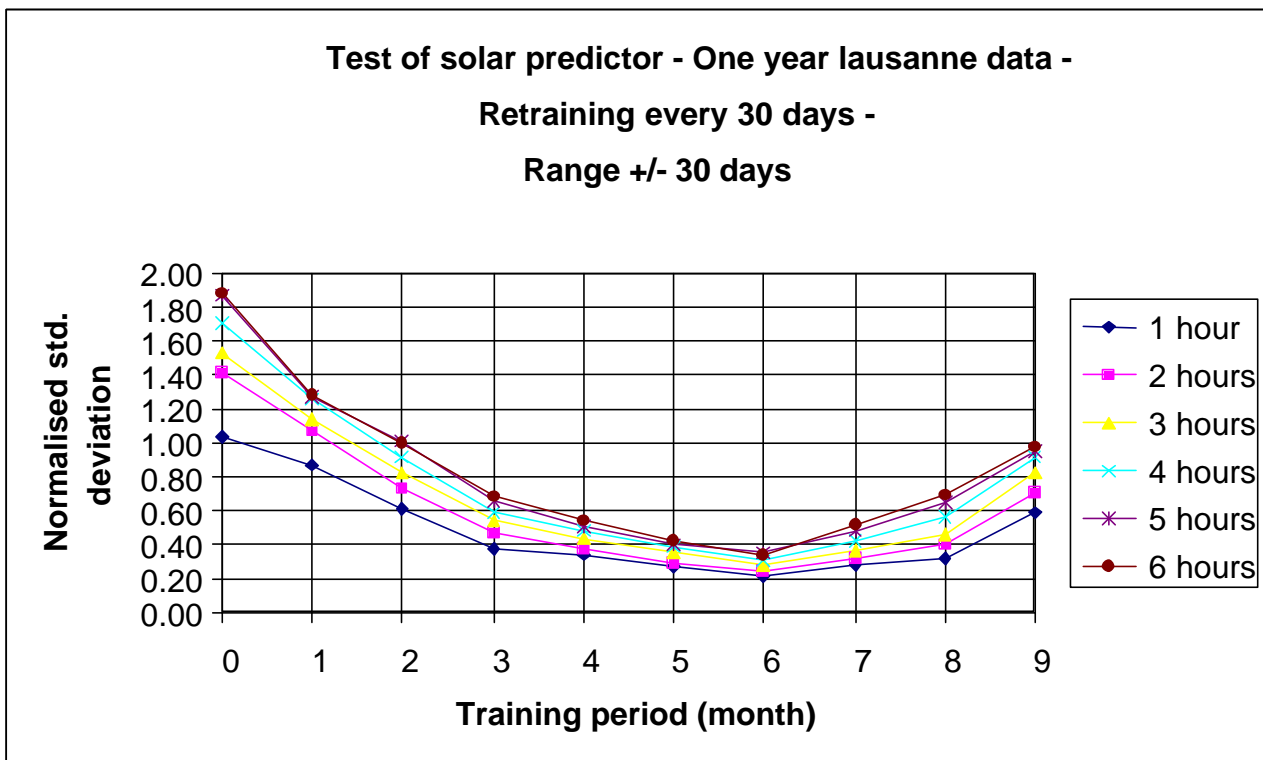


Figure 6: Performance of solar predictor with Lausanne climate

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Month	Average error					
6	-1.53	-2.66	-3.60	-3.45	-1.78	-3.91
7	0.90	-0.05	0.93	0.99	5.24	1.33
8	0.69	0.89	0.82	4.42	3.82	1.39
9	1.47	7.32	7.96	14.73	11.76	12.35
10	5.27	6.65	8.07	9.26	11.90	14.63
11	7.83	14.20	12.89	7.78	12.20	12.96
12	12.70	16.00	19.60	20.47	21.94	19.53
	Standard deviation					
6	31.31	34.70	39.51	44.50	51.13	48.32
7	26.42	31.34	35.66	37.17	49.11	44.29
8	35.13	40.00	45.88	58.36	64.14	66.87
9	45.41	58.89	68.81	91.15	95.07	100.50
10	68.28	85.21	97.19	112.68	120.14	120.06
11	82.39	106.65	117.72	131.71	128.73	137.79
12	88.51	100.80	112.37	123.28	124.99	124.53

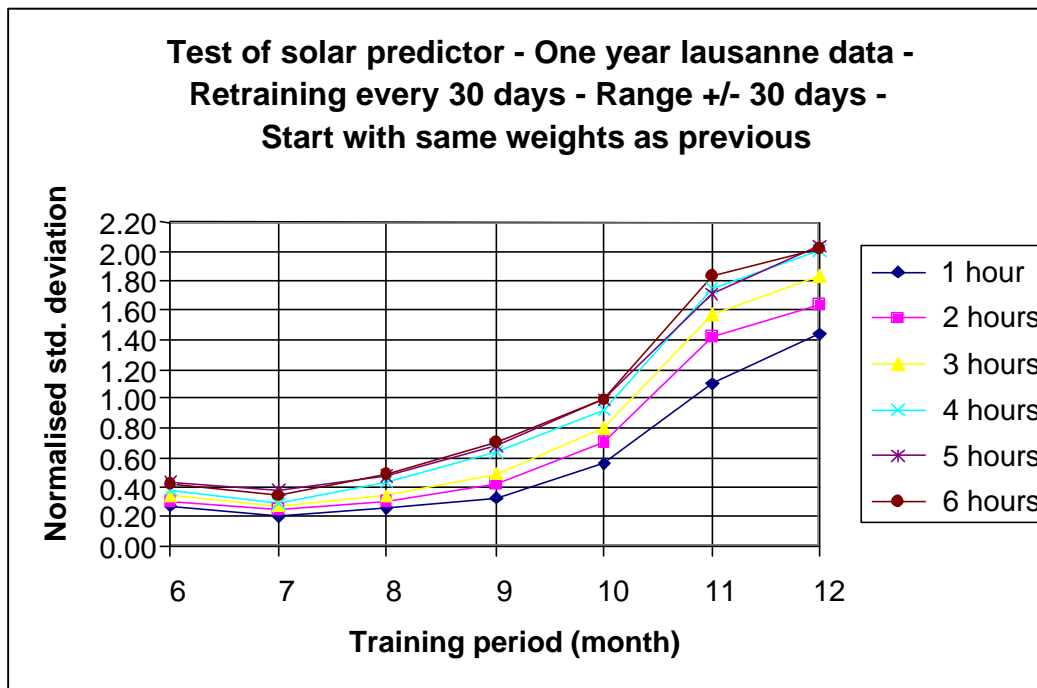


Figure 7: Performance of solar predictor with Lausanne climate, months 6-12

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. Period	Average error					
5.00	28.06	27.30	24.98	23.22	23.24	23.82
6.00	0.39	1.73	4.09	2.09	4.80	2.29
7.00	2.22	2.87	3.66	3.31	0.84	3.70
8.00	5.71	7.91	7.67	5.78	10.29	11.75
9.00	5.70	5.67	5.24	8.15	12.79	14.20
10.00	9.95	15.89	17.30	15.63	10.32	12.44
11.00	11.07	19.79	18.82	20.42	22.60	22.20
	Standard deviation					
5.00	114.49	111.84	111.32	109.39	107.97	107.04
6.00	23.56	29.62	33.89	39.66	42.72	43.56
7.00	31.82	43.29	48.41	52.67	58.01	65.13
8.00	44.53	60.76	69.63	75.67	89.48	98.79
9.00	67.81	89.59	105.16	108.20	119.95	120.02
10.00	86.63	106.91	120.38	125.50	129.86	131.01
11.00	81.27	106.70	118.33	123.11	124.21	127.17

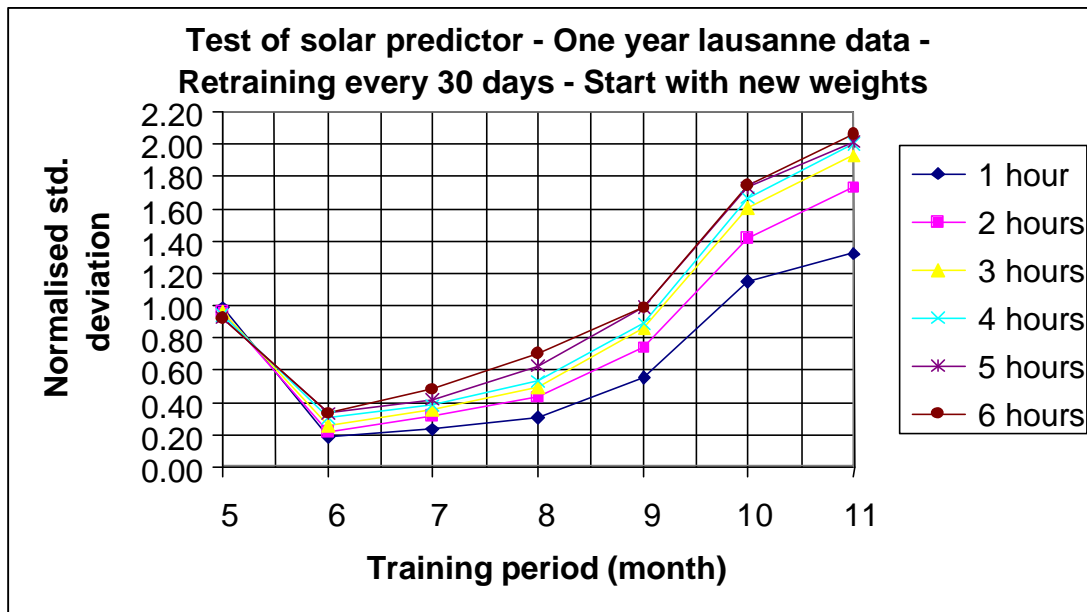


Figure 8: Performance of solar predictor with Lausanne climate, months 6-12 (Starting with new training at the end of month 5).

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. Period	Average error					
5.00	15.80	15.13	12.70	12.13	20.02	11.20
6.00	-0.30	-0.28	-1.11	-0.79	4.83	-0.10
7.00	2.13	2.51	3.49	1.32	4.37	0.18
8.00	4.77	6.57	9.95	7.71	15.66	13.02
9.00	9.47	6.76	13.28	16.76	9.35	13.11
10.00	9.38	9.54	13.85	16.39	18.79	17.59
11.00	9.35	13.13	15.35	21.18	20.51	25.54
	Standard deviation					
5.00	73.09	75.21	77.54	76.29	80.72	75.05
6.00	23.82	30.37	34.08	37.29	46.64	42.64
7.00	34.45	38.48	50.09	50.40	66.75	61.26
8.00	44.44	58.33	71.27	78.16	107.22	96.99
9.00	70.17	81.29	98.03	108.96	126.60	117.14
10.00	79.04	102.57	117.62	126.06	132.03	131.04
11.00	79.53	103.81	117.14	119.39	131.04	121.24

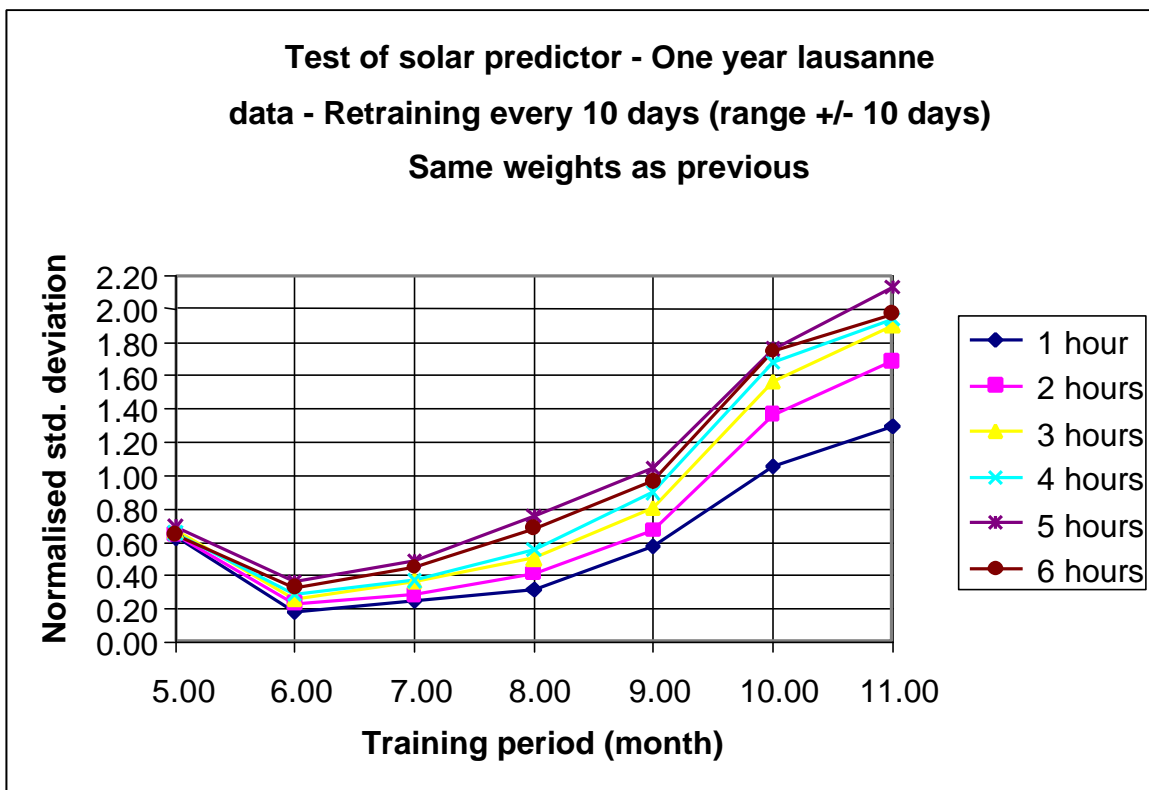


Figure 9: Performance of solar predictor with Lausanne climate, months 6-12 , with same initial weights as previous - Retraining every 10 days. (The standard deviation is monthly averaged).

Validation using non-stochastic data as input

In order to confirm the convergence of the algorithm, and its accuracy, an hypothetical solar radiation profile was built based on the maxima values using the expression:

$$G_{hor} = \text{abs}(\sin(ts_0/3600/12 \cdot \pi)) \cdot G_{\text{max}}$$

Where ts_0 is the current time in seconds and G_{max} the calculated maximum value of solar radiation on the horizontal plane. Results obtained are given below, (Figure 10 and Figure 11) showing very good accuracy of the prediction, despite the step changes in the profile.

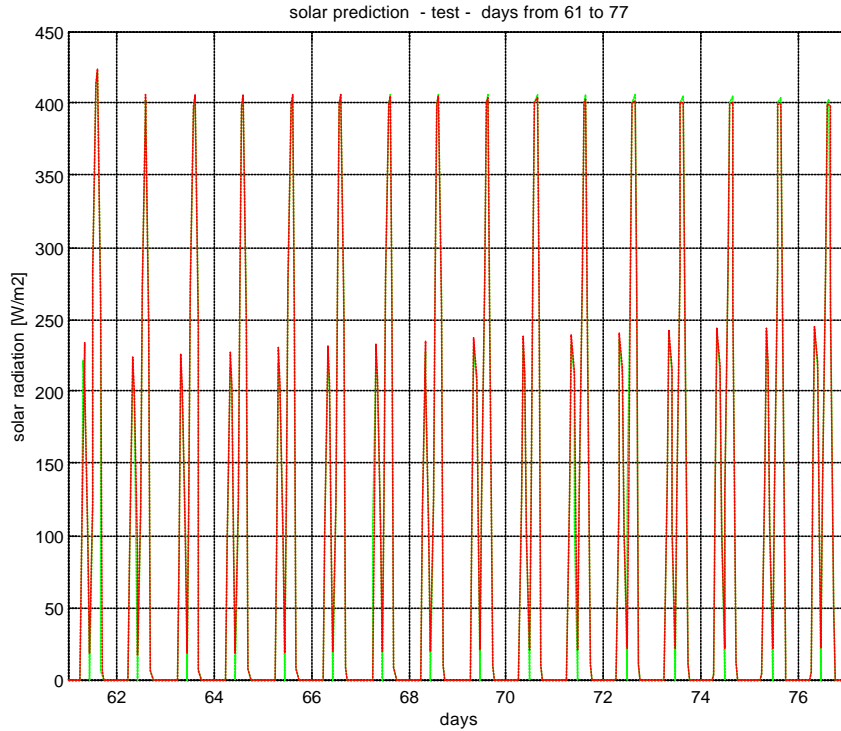


Figure 10: Sample of horizontal radiation profile used

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. period	Average error					
0	-100.275	-94.959	-97.879	-103.044	-91.554	-78.418
1	-0.826	-0.688	0.107	1.229	-0.597	-0.305
2	-0.214	-0.092	0.062	-0.099	-0.067	0.351
3	-0.408	-0.089	0.060	-0.015	-0.224	0.047
4	-0.101	-0.182	0.001	-0.009	-0.091	-0.001
	Standard deviation					
0	236.036	233.260	221.392	210.194	191.193	201.380
1	8.473	6.429	7.268	9.576	8.308	5.764
2	5.955	2.705	2.443	2.091	1.516	2.092
3	2.888	0.646	0.592	0.347	1.342	0.332
4	2.692	0.497	0.074	0.201	0.981	0.039

Figure 11: Results of months January to May

3.2.1.4.3.2 Further improvements

3.2.1.4.3.2.1 Scaling factors and Gmax

An important requirement of the algorithm is that the input values of solar radiation Ghor should be smaller than the maxima computed values Gmax. In fact this was not always the case, even when the data have been generated with meteonorm. A correction was thus introduced to avoid that this occurs.

Another difficulty of the algorithm is to set the right value of the normalisation factor for Ghor, normally set to 1000 W/m². Normally, this value should be close to the maxima measured during the training period. The following formula was used:

$$ech(4) = 1.05 * \max(G_{max})$$

Results obtained with Lausanne data are given below.

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. period	Average error					
0	-62.84	-63.22	-61.68	-60.10	-57.15	-54.22
1	3.27	6.28	3.72	6.63	8.07	7.71
2	5.12	9.60	9.71	12.79	10.35	10.71
3	0.30	4.21	2.52	2.30	2.91	6.95
4	-0.13	1.17	0.33	-1.93	-2.63	-4.13
5	-1.53	-1.64	-3.28	-4.88	-5.18	-6.13
6	0.42	1.42	0.01	0.92	2.93	1.17
7	0.36	1.60	-1.29	-0.82	-2.11	-2.03
8	0.77	4.39	3.36	3.61	-0.32	5.62
9	-0.59	-0.41	1.01	6.58	3.86	6.15
10	2.71	6.18	6.41	8.84	2.87	5.90
11	2.91	8.48	9.88	13.98	12.01	16.05
	Standard deviation					
0	210.39	205.76	197.04	190.70	187.97	185.00
1	63.02	85.60	94.06	99.02	102.14	106.49
2	57.20	81.19	90.05	98.99	106.59	112.39
3	39.62	55.66	65.60	73.29	80.55	84.79
4	33.66	44.67	50.93	55.61	63.40	61.23
5	27.20	35.28	39.84	44.38	50.72	51.36
6	24.60	31.90	35.20	38.55	47.53	43.78
7	29.32	41.51	46.81	49.80	61.33	64.15
8	36.04	56.03	63.42	74.79	87.85	95.78
9	52.26	76.84	90.09	96.28	101.28	110.69
10	60.77	87.51	96.89	112.01	97.29	111.42
11	54.48	89.31	93.49	97.02	99.16	104.45

Figure 12: Results obtained with correction

Results are sensibly better than previous, which is mainly due to the correction of the input data. This is because the neural network uses the relative solar radiation (G_{hor}/G_{max}) which is limited to one. Other runs have confirmed that the adjustment of the scaling factor is not needed.

3.2.1.4.3.2.2 Tests with Helsinki data

The 1997 data from Helsinki were used to check the influence of the location. In particular, the presence of longer nights in winter may introduce a further discrepancy on the predictions. First, it was necessary to correct the overall data as previous to ensure that maxima values of solar radiation are below G_{max} . The initial values of $G_{hor}-G_{max}$ are plotted below to show the level of corrections applied. It is on the order of 200 W/m^2 on the maxima values during the summer season. This was indeed the level of standard deviation errors which were obtained without this correction.

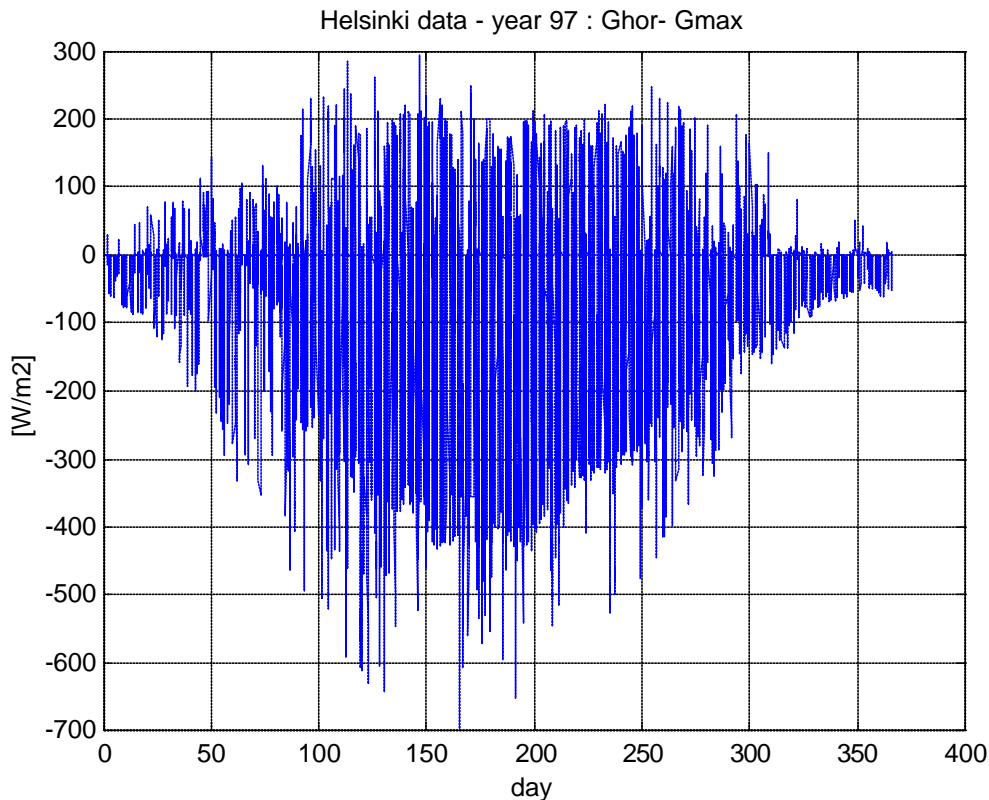


Figure 13: level of correction applied to Helsinki data for 1997 ($G_{hor}-G_{max}$)

Results obtained are given in Figure 14. The accuracy is very similar to previous and the absolute error is generally lower (due to the lower solar radiation) except in the summer months where it is greater. Relative errors are greater during the winter season, which can be attributed to the longer nights.

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Month	Average error					
1	-18.45	-18.09	-16.51	-14.62	-14.00	-13.94
2	1.92	9.14	17.92	18.15	20.24	18.89
3	-0.19	4.45	14.32	22.19	20.82	21.64
4	0.30	-1.17	5.04	8.87	5.06	-1.24
5	-0.94	-1.49	2.32	8.76	3.55	1.56
6	9.87	2.59	5.86	3.13	6.63	6.06
7	-2.61	0.14	0.59	-0.57	5.39	-1.22
8	5.29	5.95	11.09	0.13	8.59	6.03
9	0.65	2.25	2.66	5.69	5.86	4.17
10	5.80	9.80	8.81	7.74	5.40	5.03
11	0.41	0.69	4.27	2.81	3.42	4.47
12	-0.15	-0.81	-0.35	0.01	-0.57	0.57
	Standard deviation					
1	86.53	85.56	80.49	75.70	71.72	71.09
2	45.61	72.01	98.62	110.67	108.84	114.30
3	80.66	103.90	125.67	141.91	149.54	150.71
4	64.66	89.94	117.65	127.10	123.06	121.24
5	57.44	70.66	87.21	98.63	98.91	94.14
6	50.31	61.00	80.90	94.69	88.73	84.65
7	57.09	66.03	73.80	79.46	81.95	79.90
8	49.18	65.91	82.78	99.25	85.78	80.13
9	73.07	97.37	115.54	121.84	119.17	117.18
10	73.79	92.08	111.84	115.60	119.45	114.25
11	34.73	49.35	57.75	59.44	61.55	56.80
12	12.91	15.31	15.87	15.98	16.40	15.87

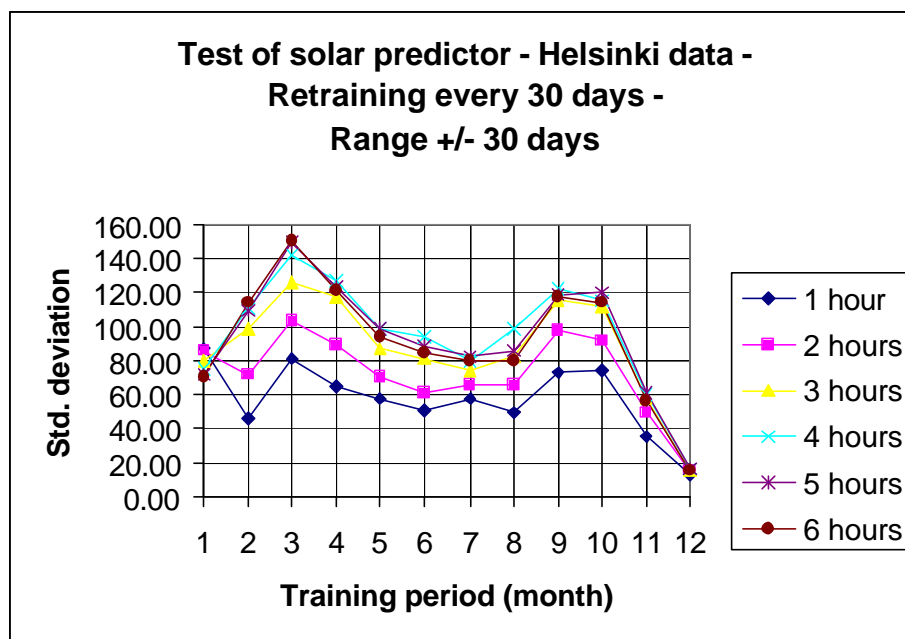


Figure 14: Performance of the solar predictor with corrected inputs for Helsinki and adjusted normalisation factor

3.2.1.4.3.2.3 Change of neural network structure

The neural network comprises normally 4 neurons and one hidden layer. Tests have been made and reported by Conphoebus on the temperature predictor, showing that one additional hidden layer improves slightly the results. Therefore, additional tests have been made with 5 input neurons and 1 hidden layer for the solar predictor. Results are given below showing that, for the solar predictor, there is no real improvement with this new structure.

Model: Original
Train Method: Levenberg-Marquardt
Neuron Layers: 4:1
Training Functions: tansig:tansig
Training: 40 epochs

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. period	Average error					
0	6.75	7.20	12.13	9.48	8.07	7.56
1	1.25	2.85	15.55	8.53	8.37	12.28
2	5.76	8.07	13.61	12.42	12.28	14.01
3	-0.65	4.54	4.44	4.16	3.10	1.47
4	-0.89	1.92	2.24	-1.18	-3.04	-1.85
5	-2.69	-1.25	-0.52	-4.14	-6.00	-5.39
6	-0.36	1.40	3.15	1.07	0.63	4.17
7	-0.48	0.52	2.26	-1.74	-2.68	-0.18
8	1.45	0.25	6.78	2.59	1.36	3.98
9	0.71	-0.63	1.92	2.43	3.22	10.13
10	3.13	2.62	7.46	2.08	6.27	5.11
	Standard deviation					
0	61.76	93.08	104.50	113.24	115.91	117.99
1	65.53	93.18	101.45	105.94	106.31	111.90
2	59.61	86.05	94.29	97.34	103.23	105.16
3	42.05	57.56	67.79	73.77	78.52	91.07
4	33.86	46.08	53.83	56.06	59.03	68.24
5	29.08	35.24	42.45	45.96	47.67	59.53
6	24.29	31.76	38.06	40.95	44.35	49.40
7	30.01	39.45	53.15	56.48	61.16	73.58
8	37.18	52.22	68.11	77.36	92.96	102.52
9	58.05	71.22	95.37	97.21	106.26	109.55
10	63.61	85.71	99.95	102.14	106.08	113.78

Model: **Modified**
Train Method: Marquardt-Levenberg
Neuron Layers: 5:3:1
Training Functions: tansig:tansig:tansig
Total training: 40 epochs

	1 hour	2 hours	3 hours	4 hours	5 hours	6 hours
Tr. period	Average error					
0	13.73	20.36	18.06	15.77	13.21	10.90
1	4.03	8.44	12.31	12.12	12.18	17.30
2	9.21	8.44	10.17	12.79	14.23	16.31
3	1.22	0.62	1.18	1.28	2.25	3.99
4	0.77	0.33	-2.04	-3.73	-2.24	-1.28
5	-1.88	-2.40	-5.03	-4.07	-4.39	-3.42
6	1.10	0.35	-0.40	0.91	1.89	2.47
7	1.21	1.41	1.51	1.40	1.27	0.10
8	5.19	4.97	8.86	8.32	8.53	10.06
9	6.51	7.43	10.70	10.12	10.28	14.04
10	10.34	9.32	17.01	15.46	14.04	16.68
11	11.18	12.70	22.02	21.53	20.57	18.99
	Standard deviation					
0	74.66	104.47	115.59	126.25	128.80	128.91
1	74.39	90.97	105.88	109.76	110.79	117.88
2	66.12	79.86	92.29	102.94	110.51	113.09
3	41.68	58.00	65.14	70.78	75.38	89.95
4	33.68	44.29	50.33	56.54	57.22	61.75
5	28.51	35.19	38.70	41.26	45.73	48.03
6	24.05	30.03	36.00	38.46	40.28	44.67
7	31.00	38.75	49.75	52.69	59.63	65.10
8	43.53	57.22	71.01	76.85	83.38	100.22
9	65.89	78.62	96.49	101.26	110.30	117.14
10	80.38	94.78	117.39	123.94	130.18	123.75
11	75.50	91.94	110.83	117.67	118.49	121.17

Other attempts have been made with a 5:4:1 and a 5:2:1 neuronal structure but results were not better (worse with 5:4:1).

3.2.1.4.3.3 Conclusions

The chosen neural net structure is adequate for solar and temperature predictions for a 6 hours horizon. It is important to ensure that the measured values of Ghor are lower than the maximum computed values. The solar predictor performs equally well in various regions, but with somewhat higher relative errors in regions which are closer to the North pole such as in Helsinki.

3.2.1.5 THERMAL CONTROLLER

3.2.1.5.1 Simulation platform for development purpose

A simulation platform was designed with Matlab 5 and Simulink and is shown schematically below.

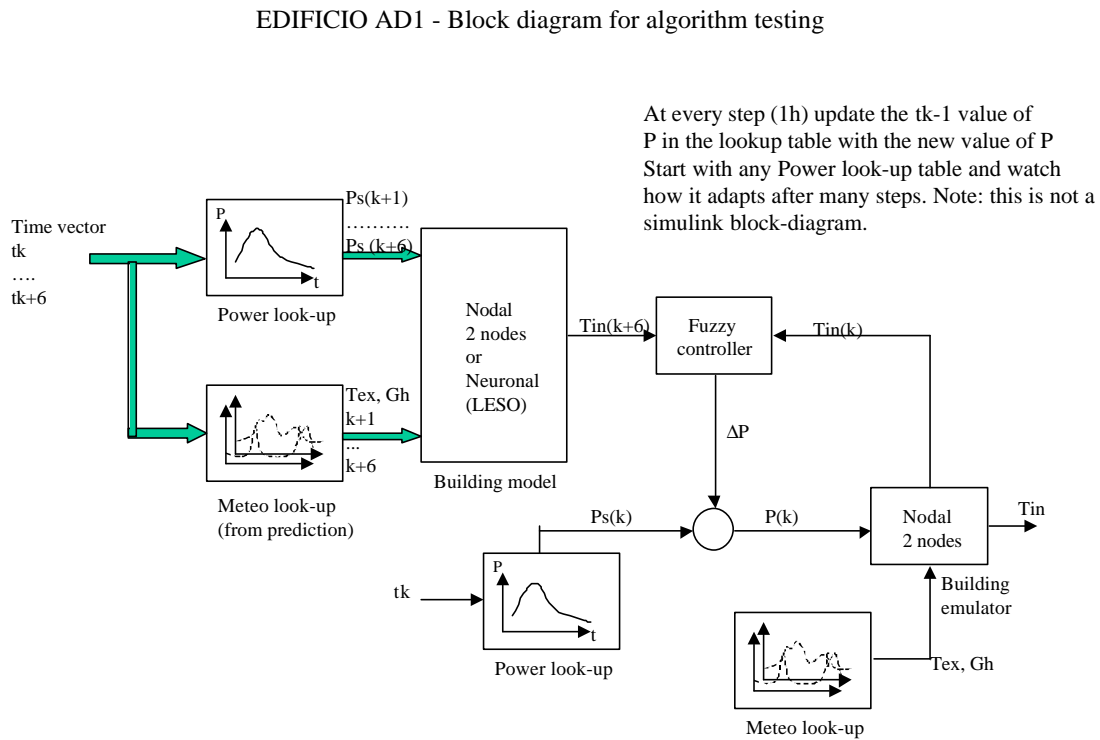


Figure 15: Simulation platform (Matlab and Simulink)

3.2.1.5.1.1 Meteo data (meteo look-up table)

Synthetic climatic data was generated using the Meteororm program. The Lausanne climate for February was chosen as reference case. In the case of predictive control, the predicted data, one to six hours ahead, are obtained by a simple time shift in the weather table. In this way, the "predicted" values are perfect and do not disturb the comparisons of various cases.

3.2.1.5.1.2 Physical building model (building emulator)

A two-nodes, continuous state building model from LESO was used for the tests. The differential equations are as follows where node 1 represents the air and furniture and node 2 the massive parts of the room (walls).

$$\dot{X} = A \cdot X + B \cdot U + 0.5 \cdot \tau_{aw} \cdot a \cdot A_w \cdot C \cdot u_4 * u_5$$

$$Y = X$$

with :

$$A = \begin{pmatrix} (-g_3 - g_1)/C_1 & g_3/C_1 \\ g_3/C_2 & (-g_3 - g_2)/C_2 \end{pmatrix}$$

$$B = \begin{pmatrix} g_1/C_1 & 1/C_1 & 1/C_1 \\ g_2/C_2 & 0 & 0 \end{pmatrix}$$

$$C = \begin{pmatrix} 1/C_1 \\ 1/C_2 \end{pmatrix}$$

$$U = \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix}$$

X represents the temperature vector $\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$ and U is the external excitation vector :

- u1 : external temperature (°C)
- u2 : internal heat gains from the user presence, electrical appliances etc. (W)
- u3 : heating/cooling power (W)
- u4 : the opening of the blinds (0 closed, 1 opened)
- u5 : the solar radiation on the vertical plane (W/m²)

The values of the fixed parameters are :

$C_1 = 1.5e5/3600$ and $1.5e6/3600$ thermal capacity of node1 per time unit (J/°K.s)

$C_2 = 6.8e6/3600$ thermal capacity of node 2 per time unit (J/°K.s)

$g_1 = 19$ and 50 thermal resistance of node1 (vs. Text) (W/K)

$g_2 = 2$ thermal resistance between node1 and node 2 (W/K)

$g_3 = 440$ thermal resistance of node2 (W/K)

$A_w = 3.77$ window area (m²)

$\tau_{aw} = 0.7$ window transmission factor

The factor 0.5 in the third term of the equation is assuming that half of the incident radiation on the window is reflected.

The initial power profile is set constant and equal to 150 Watts

3.2.1.5.1.3 Room predictor

The room predictor used for the tests is a perfect representation of the room model in digital form. For this, the continuous state equations are integrated over the time steps of 1 to 6 hours.

3.2.1.5.2 Fuzzy sets

The first (and simplest) version of the fuzzy algorithm has two inputs, the current and future comfort levels (comf and fcomf) and one output, the DP value to be applied to the current power value (from the profile). Several rule sets have been used and it was found that nine rules were sufficient to regulate correctly the system. These rules are given in the table below:

Fcomf	comf	cold	norm	warm
Cold		DP = +L	DP = +M	DP = +S
Norm		DP = +S	DP = zero	DP = -S
Warm		DP = -L	DP = -M	DP = -S

In this set, the current comfort level has a larger priority than the future one. Another rule set has been tried which gives the same priority to comf and fcomf, and with only 5 output membership functions (-M, -S, zero, +M, +S).

The comfort level is defined as follows:

- $comf = (T_{in}(k) - T_{set}(k))/T_{set}$ for the current value
- $fcomf = (T_{pred}(k+6) - T_{set}(k+6))/T_{set}(k+6)$ for the future value (6 hours ahead prediction).

The maximum and minimum values are set to +0.5 and -0.5 respectively. Which means that, for instance during heating season with $T_{set}=20^{\circ}C$, the maximum increment of DP is applied when the internal temperature falls to $10^{\circ}C$ (current and predicted values). For the simulations the maximum increment of DP was varied from 50 to 1500 Watts. In practice, this value should be a fraction to the maximum power of the heating or cooling device (say 1/10).

During the initial simulation task, the various parameters of the membership function have been varied to find out which ones have a significant influence on the result and should be adapted via the third loop optimisation. The resulting fuzzy set, "sim1000.fis", has been used in the latter versions.

In the "feedback for experiments" task, it was found that the above approach was only suitable when the set-point temperature is constant. A more sophisticated approach was tested at LESO where the set-point temperature is varied over the the day, and were two additional input variables are used by the fuzzy controller:

- the fuzzy presence profile;
- the fuzzy predicted presence profile.

3.2.1.5.3 Updating scheme for the power input

The so-called "power profile" approach was first compared with a simpler method. Using a non-predictive fuzzy algorithm. There only one input fuzzy variable (comf) and the fuzzy output DP value (in fact its hourly average) is integrated (starting with 150 W). Several methods of updating the power value were tried and compared with this reference case:

- Using only the future comfort level as fuzzy input variable (calculated with a constant power);
- Updating the power profile on the current time only (with some variants);
- Updating the power profile on a time span of ± 6 hours around the current time.

Only the third case provided significantly better results than the reference and is reported below. The weight given to DP is nearly parabolic with time as given in the following table.

t-6	t-5	t-4	t-3	t-2	t-1	t	t+1	t+2	t+3	t+4	t+5	t+6
10%	20%	40%	60%	80%	90%	100%	90%	80%	60%	40%	20%	10%

3.2.1.5.4 Simulation test results

Two types of room models were used, one with the initial LESO parameters and a second one where the thermal resistance of node 2 (air and furniture) was increased to 50 W/K.

3.2.1.5.4.1 Case 1: initial room model

Results obtained with the reference case (integ4.mdl) are shown in Figure 16. The top left figure shows the climatic condition (external temperature and solar radiation) which have been used throughout the simulations. The results are quite satisfactory in terms of comfort level with a maximum daily discomfort of about 7% and a peak temperature error of 2.7 °C which occurs when there is a sudden fall of the external temperature. The discomfort here is defined as follows:

a) Instantaneous thermal discomfort level

$$TDL = \frac{T_{in} - T_{set}}{T_{set}} \cdot Pr$$

Where T_{in} is the internal room temperature

T_{set} is the set point temperature

Pr is the presence indication : 0 if user not present, 1 if present.

The histogram of TDL fits with a gaussian curve.

b) Discomfort comparison on a daily basis

$$TDD = \frac{1}{n} \sum_{1-n} TDL^2$$

TDD is the standard deviation of TDL over a day (one value per day of simulation)

n is the number of samples (normally 96 with a 15 minutes sample time)

In practice the sum is replaced by a forward Euler discrete integration in simulink, with a time unit of 1 day.

c) Total (integrated) discomfort comparison on a given period

$$TDP = \int_1^N |TDL| \cdot dt$$

N is the number of days in the period.

In practice, a forward Euler discrete integration is used

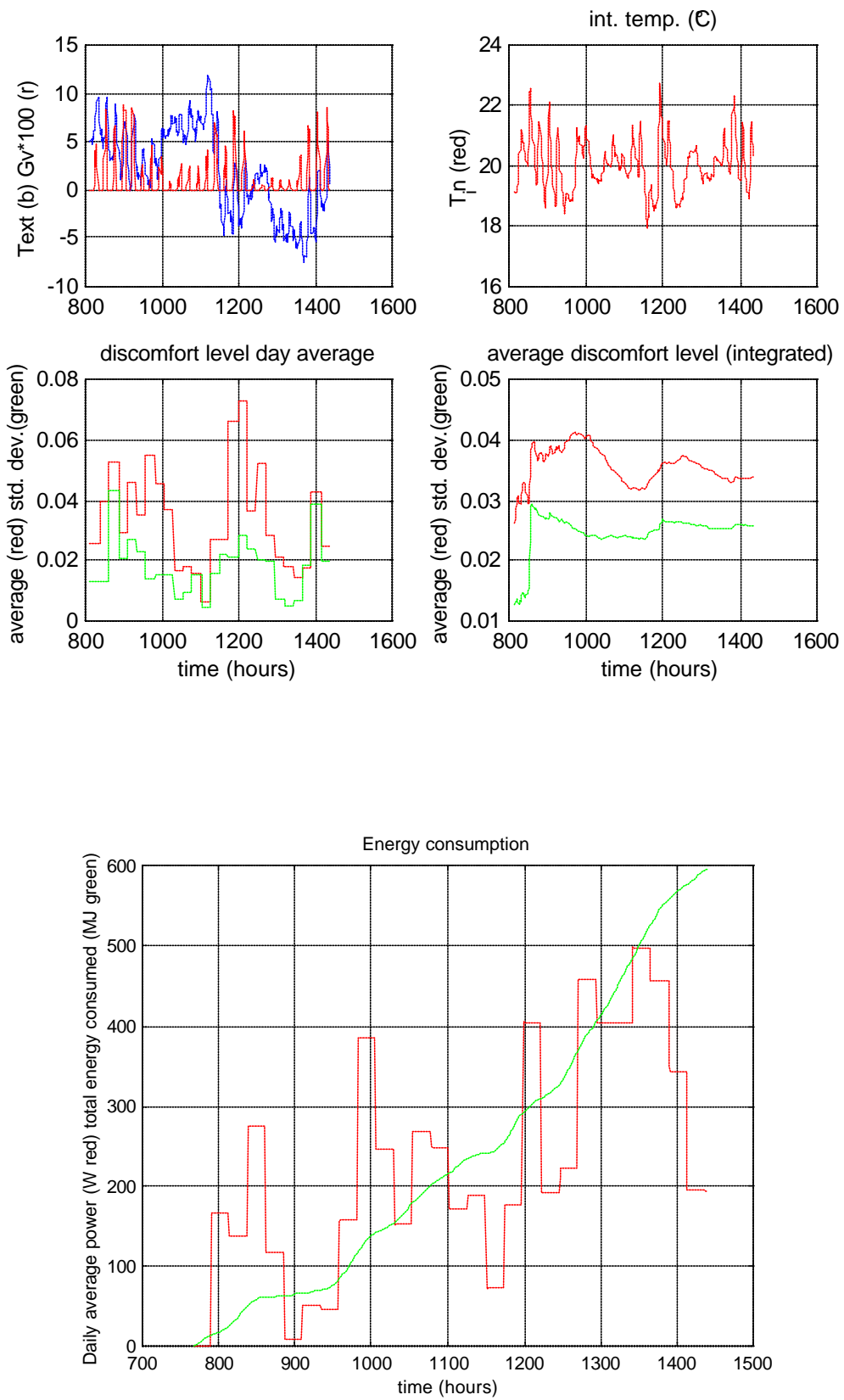


Figure 16: Reference case simulation results (initial room parameters)

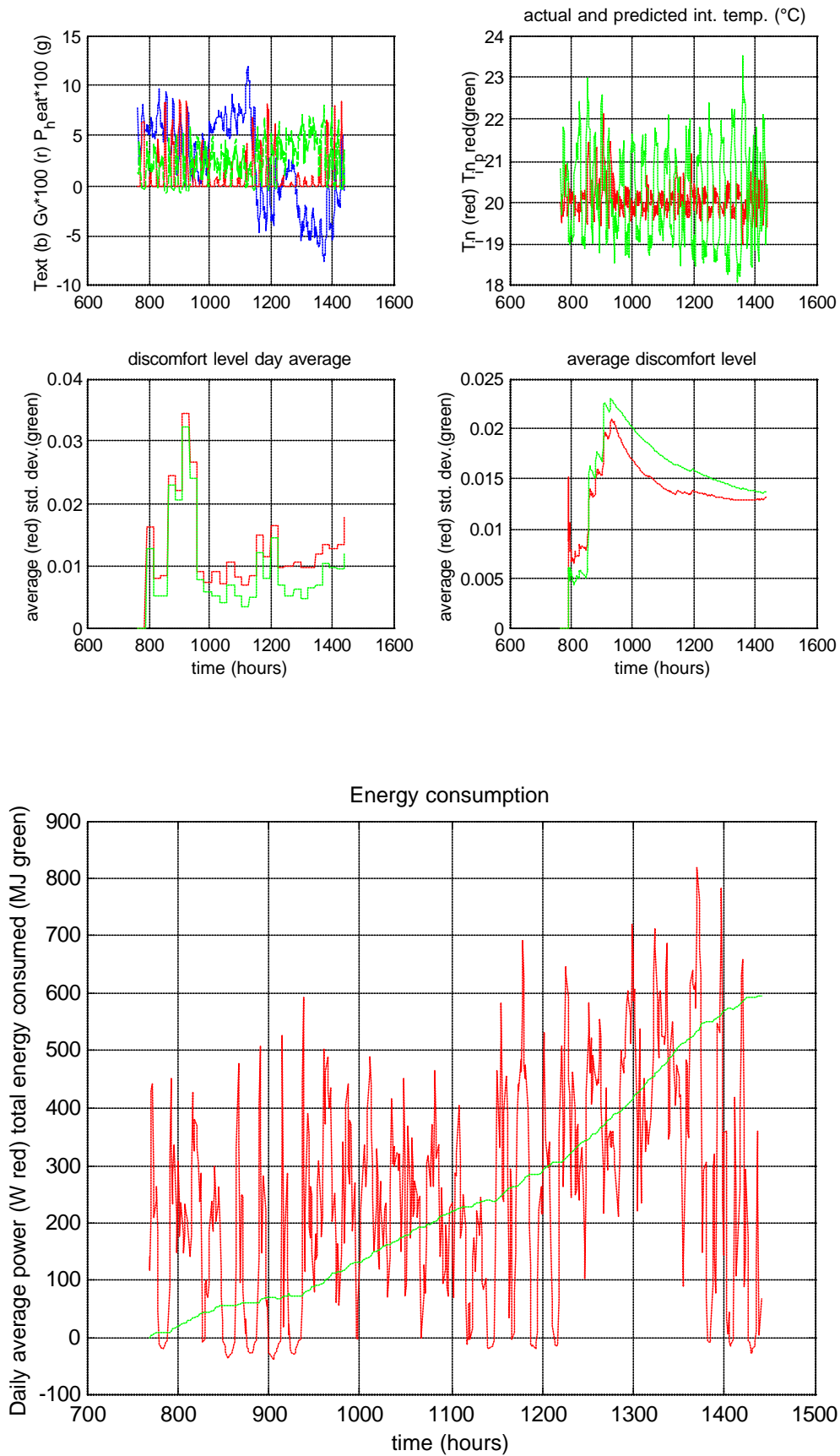


Figure 17: Predictive case simulation results (initial room parameters)

The results for the predictive case are much better in terms of comfort, with a maximum daily discomfort of 3.5% and a peak temperature error of 2.15 °C. The fall of external temperature is anticipated very well with a discomfort of 1.5% compared to the previous value of 7%. This demonstrates that the power profile adaptation works fairly well. However, the total energy consumption, obtained by the integration of the power remains the same at 595 MJ. This is due to the type of physical room model used (pseudo-linear) and the use of a constant set-point temperature. The comparison of both cases is summarised in the following table.

	Max. daily discomfort	Peak daily discomfort	Energy consumption
Non-predictive	0.0727	2.69	595
Predictive	0.0346	2.15	595

3.2.1.5.4.2 Case 2 - Modified room model (C1= 1.5e6, h1= 50)

In this case, the simulation was started with the power profile from previous 48h run to provide a better comparison. As shown in the table below, the comparison of both cases again demonstrate the superiority of the predictive fuzzy algorithm with even a greater gap between both:

	Max. daily discomfort	Peak daily discomfort	Energy consumption
Non-predictive	0.1675	2.49	1844
Predictive	0.0187	0.84	1923

The energy consumption of the predictive case is only slightly higher than the reference. In fact, this is due to the quite low internal temperatures (18°C) which occur with the reference case (energy saving at the expense of user discomfort).

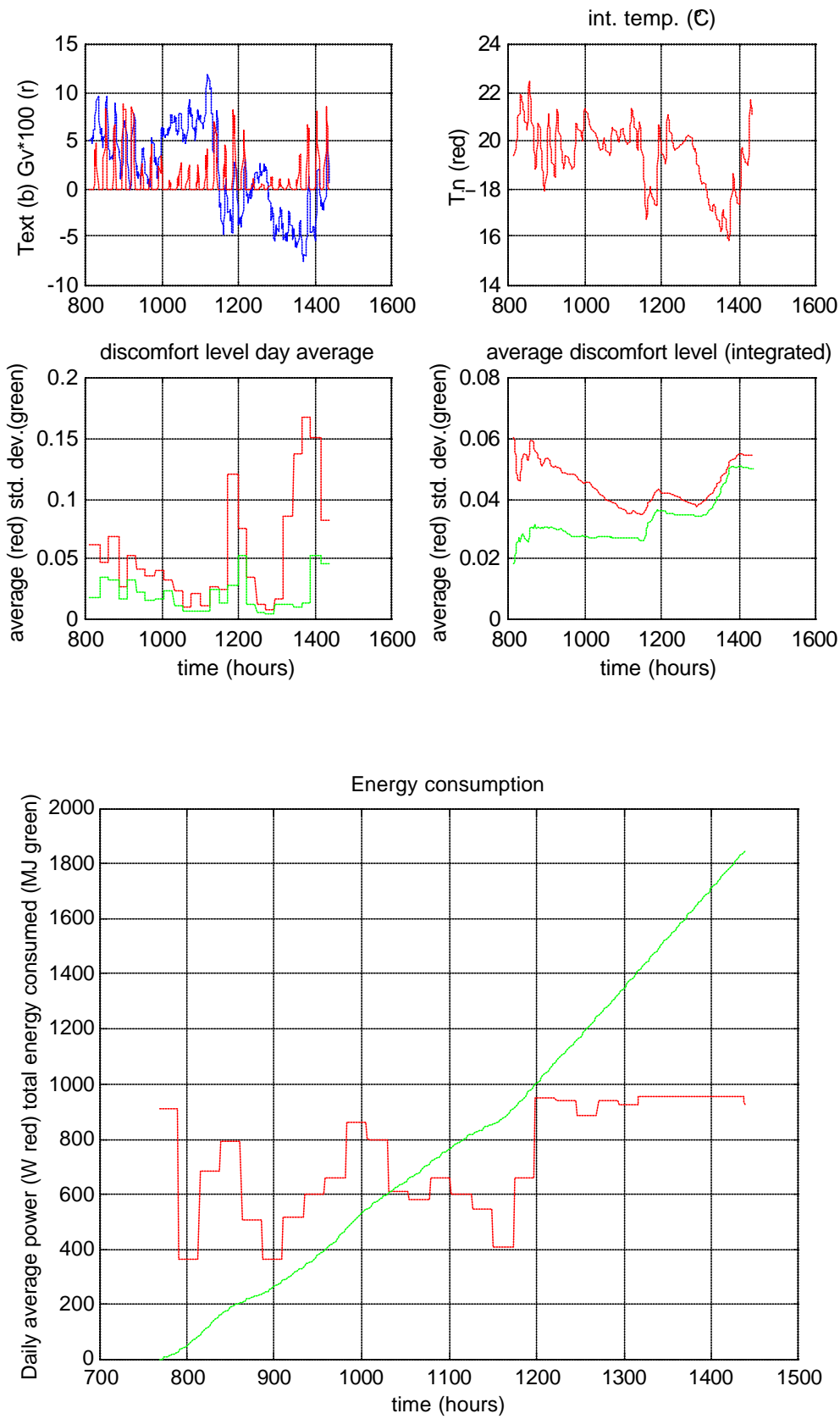


Figure 18: Reference case simulation results (modified room parameters)

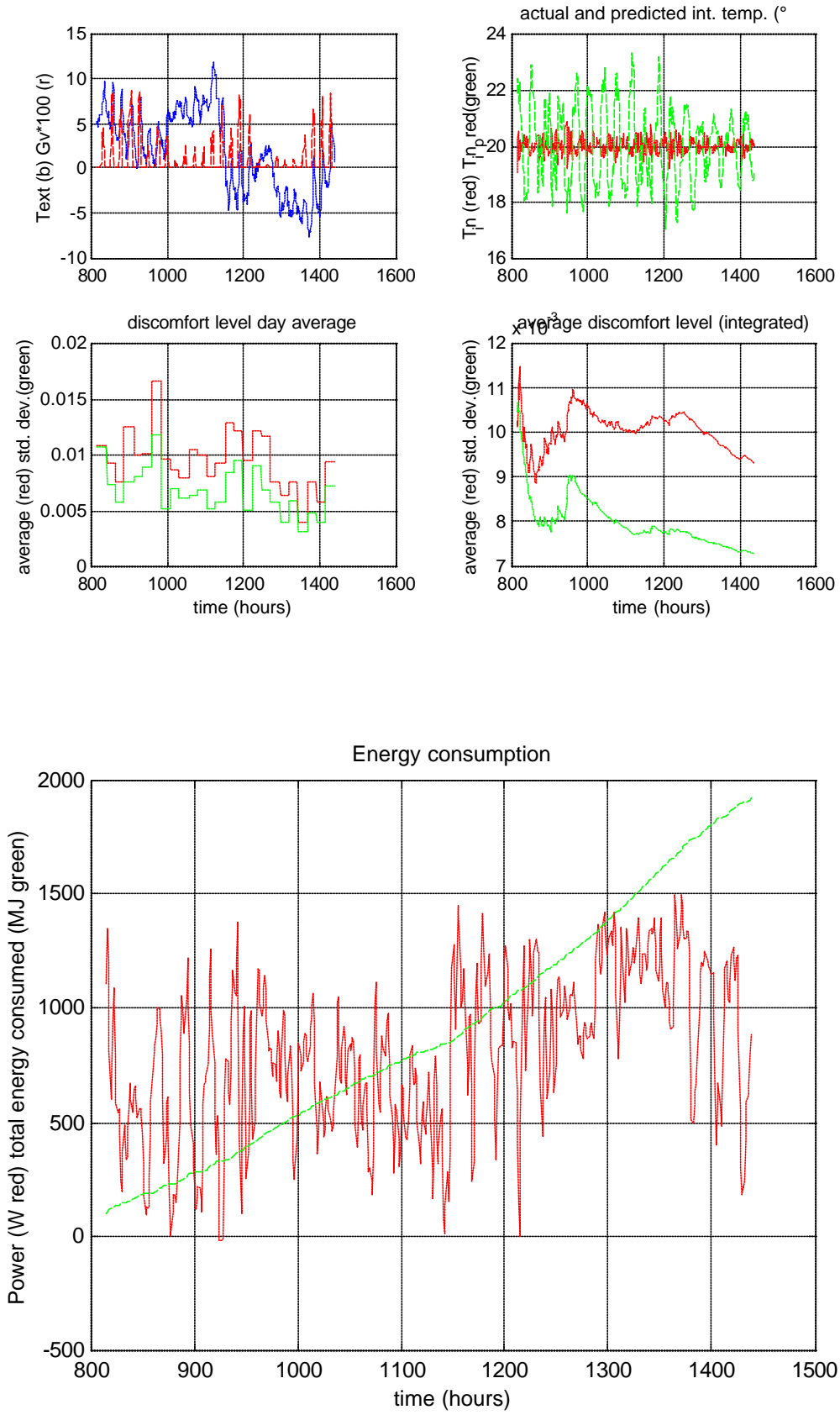


Figure 19: Predictive case simulation results (modified room parameters)

3.2.1.6 CONCLUSIONS

The proposed predictive-fuzzy approach with two input variables (comf and fcomf) is a very effective method to regulate the thermal comfort of a building whilst being compatible with the overall EDIFICIO control scheme. It is however limited to a fixed set-point temperature and was not yet tested on a variety of conditions such as:

- Climate;
- Climate prediction (from the Meteo predictor block);
- External disturbances: user inputs, blind opening, internal gains from user presence;

Nevertheless the performance obtained was quite satisfactory and could be taken as a reference case for further work during the Simulation task where all these aspects are taken into account (see chapter on the Simulation task).

The final version of the algorithm resulting from the simulation task includes in particular (results are given in the simulation task report):

- A set-point temperature for user-presence and user long absence;
- Different set-point temperatures for heating and cooling seasons;
- A four variables fuzzy rule set;
- An automatic switch from one season to another (heating, no-heating/no-cooling, cooling);
- Three different power profiles depending on the day of week: Mondays, Tuesdays-Fridays, Saturdays-Sundays.

Further improvements of the algorithm itself would still be possible, in particular for the selection of an optimised power-profile from previous similar conditions. This approach has not been tried because the results obtained were already more than satisfactory and it is thought that the large discrepancy in the predicted solar gains would offset any further potential improvements.

3.2.2 TASK AD2: VENTILATION CONTROL

The most important motivation for ventilation is to improve the indoor air quality. Another motivation is to influence the temperature or future temperature by ventilation. Night time ventilation, for instance, is used to cool buildings during warm periods to avoid too high indoor temperatures and/or to decrease the cooling requirements.

Different types of ventilation can be indicated as 'base ventilation', 'thermal ventilation' and 'night time thermal ventilation'.

'Base ventilation' is used to maintain sufficient levels of the indoor air quality. For offices, the amount is typically 5.5 to 9 liter per second per person. 'Thermal ventilation' is used to control the thermal situation by ventilation. For this purpose, the ventilation rates should be 10 times larger than 'base ventilation'. 'Night time thermal ventilation' consist of cooling the building at night in warmer periods to decrease overheating or decrease cooling requirements during the day. To be effective the night ventilation rate should be at least 4 times larger compared to 'base ventilation'. Practice shows that ventilation systems or openings designed for 'base ventilation' purposes are often too small for efficient thermal ventilation.

3.2.2.1 ADAPTIVE VENTILATION CONTROL

At present, usually IAQ is controlled by maintaining a certain amount of ventilation per assumed person present. This causes a situation where too much ventilation is provided in nowadays more and more common non present situation and too little ventilation in situations when there are more persons present than assumed. It is very clear that controlling ventilation based on real requirements, energy savings can be realised while improving the indoor air quality.

Based on different projects, for both the on-off control based on occupancy and the control based on CO₂ levels, energy saving potentials are considered to be substantial (estimation: depending on the actual situation 20-60%) and also the potential savings of electricity for electrical ventilators are considered to be substantial.

The problem however is that the IAQ is difficult to quantify because the relation between the actual indoor air including all contaminants and the IAQ is not clear. Another problem is that it is difficult to measure the air contaminants. There are sensors available which measure specific combinations of contaminants but those are too expensive to use in every room and they measure a specific combination. In principle CO₂ and VOC (volatile organic compounds) sensors are feasible. The problem is that VOC sensors are too expensive to be applied in every single room.

3.2.2.2 SMART IAQ VENTILATION CONTROL BASED ON CO₂ SENSOR AND USER PREFERENCES

To overcome this problem of the non availability of suitable VOC sensors, a smart control is developed based on measured CO₂ levels and processed users presence.

In principle two pollution types can be distinguished:

- Human related pollution (by humans produced CO₂, smoke, moisture, smell etc);
- Building related pollution (furniture, carpets related smells etc).

The idea is to adapt the ventilation requirements separately for human related pollution detectable by the measured CO₂ level and building related pollution.

Building related pollution acceptable levels can be adapted using the interaction of the occupants in the morning situation after arrival when the human related pollution's can be assumed low because the CO₂ levels are still low. A simple model can be used to compute a building related pollution index using a dynamic model with a constant source and ventilation levels. Based on this index a level or bandwidth can be fitted which shows to be sufficient for the present occupants.

Saving all simulated index levels of the first period of occupation together with the interaction of the occupants (yes/no). Using this data index levels of more and less acceptability can be derived in probability of interaction. Based on this information ventilation can be controlled. Experiments should show the consistency and the optimal levels for control. It is for instance possible that controlling on 0% probability of user response is not feasible or not optimal because occupants open windows for other reasons than fresh air.

The human related pollution levels to be maintained can be adapted towards the user interactions. To be sure that the data used for future control levels is specifically related to human related pollution, the computed building related pollution should be below specific acceptable levels. Furthermore the occupants should be present for a longer period indicated by the measured CO₂ level development or presence detectors.

Situations within these boundaries can be provide information on acceptable levels of human related pollution indicated by the CO₂ level and the user actions within these situations.

The probability on user interventions as function of the measured CO₂ levels can be determined using data of the past longer period in a similar way as for the building related pollution (following figure for example)

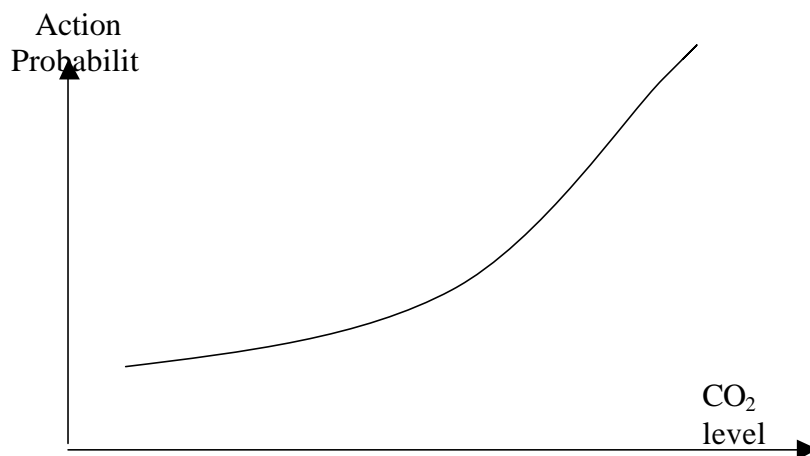


Figure 20: Probability of user interaction as function of CO₂ level (human related pollution)

To come to the intervention probability function first the CO₂ levels should be discretized in 100 ppm steps. All interventions should be stored in the correct ppm vector position together with time steps without intervention. The function can be provided by computing for all CO₂ intervals, the number of intervention divided by total time steps of presence with CO₂ levels within the specified CO₂ intervals. The probability function then provides the number of interventions per time step for all CO₂ level intervals. The same approach can be used to control the human related pollution.

This method can clearly not be tested and validated by simulation

Because the monitoring phase was rather limited in time and different control strategies required testing and optimisation, there was no sufficient time to test and validate this adaptation method.

3.2.2.3 PRACTICAL ISSUES RELATED TO SMART CONTROL PER ROOM

Ventilation is a building related topic for obvious reasons. Usually there is a central exhaust in office buildings which can be based on natural ventilation due to thermal effects (also if ventilation openings in the façade are utilised). The air should possibly leave through this central exhaust. If the ventilation openings on the wind side of a building are opened too much it mostly is impossible to ventilate the rooms on the other side without having cross ventilation (ventilation from the wind side offices to the offices or rooms on the other side - not wind side).

This cross ventilation is not desirable for reasons of IAQ and also for controllability in general and individual ventilation control specifically (the controller 'assumes' air coming from outside).

To enable individual control per room, especially for natural ventilation, special attention should be paid to pressure distributions within the building. One practical approach to enable individual control is to determine constraints for individual room controllers depending on wind speed and direction and specific building properties related building ventilation.

The potential danger of cross ventilation depends highly on the specific building Architecture/layout and installation (e.g. a building with a central open space with exhaust in the top section will provide in principle a good central exhaust with less danger for cross ventilation). Some Architects are already aware of these aspects in their designs.

3.2.2.4 VENTILATION MODELS

The CO₂ concentration has a dynamic response. If a room is occupied (see figure), CO₂ is generated by the persons in the room. By ventilating with outside air, the indoor CO₂ concentration can be controlled towards the limit of the CO₂ concentration of the outside air.

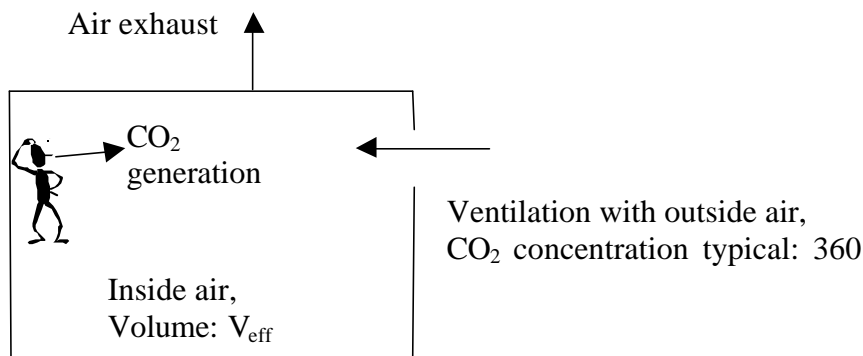


Figure 21: Ventilation with outside air and the human generated CO₂

Usually ventilation improves the indoor air quality. Nevertheless in many nowadays urban situations the outdoor air quality can be very low and worse than inside as for instance in heavy traffic areas. In some situations ventilation must be avoided for certain periods.

In general it is good to assume that the outdoor air quality is constant during the day (Bearg, 1993). The CO₂ concentration of the outside air is taken 360 ppm.

The human CO₂ generation rate depends obviously on the occupant density and the activity level. In office buildings this generation rate can be assumed constant because of the limited occupant activity level fluctuations. For one person doing light work 6.33×10^{-6} m³/s is assumed (Bearg, 1993).

Assuming the indoor CO₂ evenly distributed over the room and the effective room volume as the gross room volume minus the volume of furniture etc. (Bearg, 1993), the dynamic CO₂ concentration can be computed using the following formula:

$$CO_2(t) = \frac{1}{V_{eff}} \int (occupancy(t) \cdot CO_2gen.rate + airflow\ rate(t) \cdot (CO_{2out} - CO_2(t))) dt$$

Where:

$CO_2(t)$ [ppm]	=	the indoor CO ₂ concentration,
V_{eff} [m ³]	=	is the effective volume of the room,
$CO_2genrate$ [cm ³ /s]	=	the CO ₂ generation rate of a person and
CO_{2out} [ppm]	=	the outdoor CO ₂ concentration.

The model is non-linear because of the product of the indoor CO₂ concentration (building state) with the *airflow rate* (control input).

The model for VOC (volatile organic compounds) is assumed to be similar to the CO₂ concentration model. The VOC generation however is not only depending on the room occupation but also on the content (furniture, carpets etc.) within the room.

In the VOC model also a constant generation rate is used. In reality, the VOC generation depends on temperature and on the content and specific furniture (including carpets etc.) within the room. The model for VOC does not provide a physical level of the VOC but a factor that represents the VOC level. This because VOC levels are very difficult to measure.

3.2.2.5 SENSOR SURVEY

A new CO₂ sensor is recently developed at TNO. This sensor will be produced by a Dutch company (confidential) with a possible production prize of approx. 10-50 Euro depending on amounts with similar specs as existing ones of 500 - 800 Euro.

Relative high quality sensors are required for offices to measure the relative low CO₂ levels apparent in offices.

The market prizes should be expected higher in the beginning for marketing reasons.

The important conclusion however is that application of CO₂ sensors per room become feasible!

The position of the CO₂ sensor is critical for accurate measurements. It should not be located in the neighbourhood of the airflow of incoming air (door – window). Studies show that this is not always easy to establish especially if the sensor can not be mounted to the wall because of high cabling costs and aesthetic reasons. Often controllers are applied with a bandwidth to be sure. (For instance set to 600 ppm in stead of 800 ppm to be sure).

VOC (volatile organic compounds) sensors with required accuracy are expensive (>>1000 Euro) and it is not to be expected that more affordable ones will be developed within a several years because of the complex nature of the equipment. There are however sensors on the market which measure smoke from cigarettes/cigars which are reasonably prized. To determine the air movement there are cheap sensors based on double heat wires. They are already applied in ventilation openings developed at TNO together with Dutch companies including control electronics to realise constant independent of wind speed / direction.

3.2.3 TASK AD3: LIGHTING CONTROL

3.2.3.1 BACKGROUND

The lighting control concept deals with the management of two categories of devices: shading devices (blinds, shutters, etc) and artificial lighting (luminaires). Like for the heating (Task AD1), and the ventilation (Task AD2), the control structure has been built in agreement with the overall 3-levels concept. The levels 1 and 2 are specific to lighting controller, but the level 3 shares some functionalities with the other controllers.

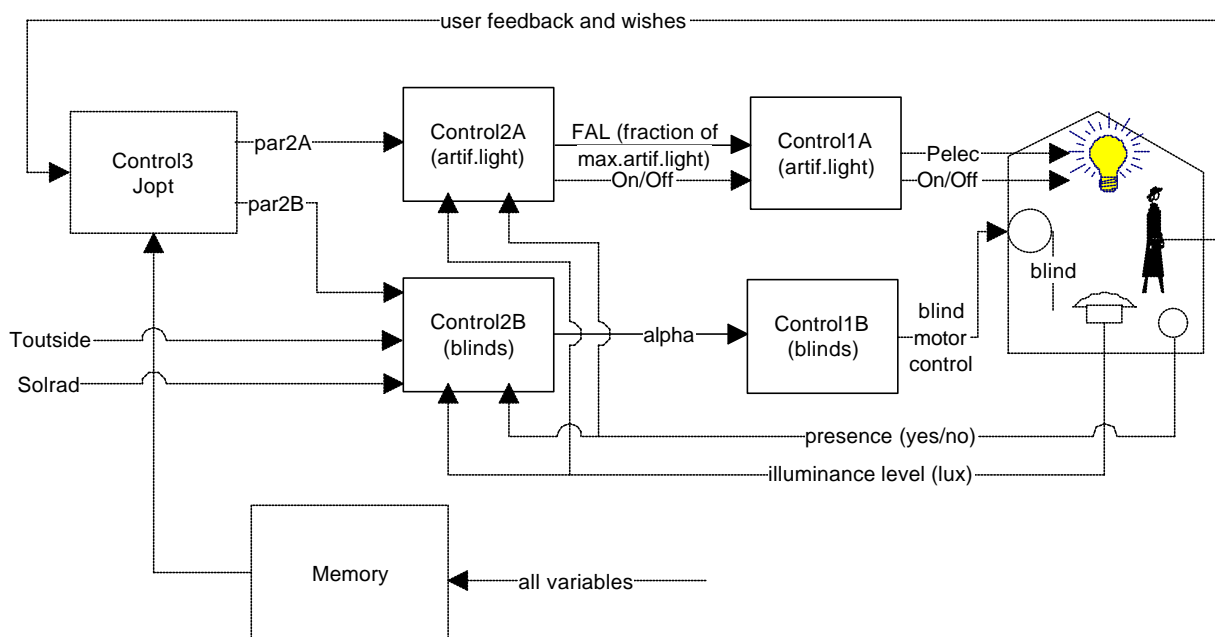


Figure 22: Lighting control concepts

Level 1 control loop is realised by the blocks *Control1A* and *Control1B*. These controllers are tailored to the particular equipment available for each building. For the experimental testing, the level 1 shading device controllers are strongly different for the three locations where experiments will be carried on: Conphoebus has venetian blinds, which require control of both the opening fraction and the slat's tilt angle; LESO has textile blinds, with two blinds per office room (one lower blind for the normal window, and one upper blind for the anidolic daylighting system), which need to be handled in a different way; VTT has no blind at all. Every partner participating to the experimental tests and having to control blinds has elaborated an algorithm for the particular installed blind devices; these algorithms have been translated into micro-controller code for inclusion in the LonWorks control board located in each office room. Among all the partners, the algorithms cover most of the practical situations, thus the interest having experimental tests in rather different building types is a fascinating perspective.

Level 2 control loop is realised by the blocks *Control2A* and *Control2B*, and it includes the fuzzy logic rule bases elaborating the optimal command for the current situation, taking into account the information given by the sensors and the predicted future behaviour of the whole system. Predictors for the future room temperature and room occupancy, using artificial neural network, are continuously adapting to the changing conditions. Two different situations have been considered: (a) room not occupied, (b) occupied room. The occupation status is provided by a sensor, and a small time delay is considered to avoid that the room is considered empty when the user only leaves for short time periods.

Level 3 control loop allows a continuous adaptation of the control parameters for the lower loop controllers, taking into account both an overall "*cost function*" (which represents the penalty for energy used and thermal, visual and air quality discomfort level), and reactions of the user.

This section of the report will essentially address the controllers at level 2. Level 1 controllers are treated with the hardware implementation, and the principle of level 3 controllers will be briefly described in the section devoted to adaptation.

3.2.3.2 PRE-PROCESSING

The controller algorithm needs some variable which are not directly available through the sensors, but which have to be generated by a pre-processing block given in the figure below.

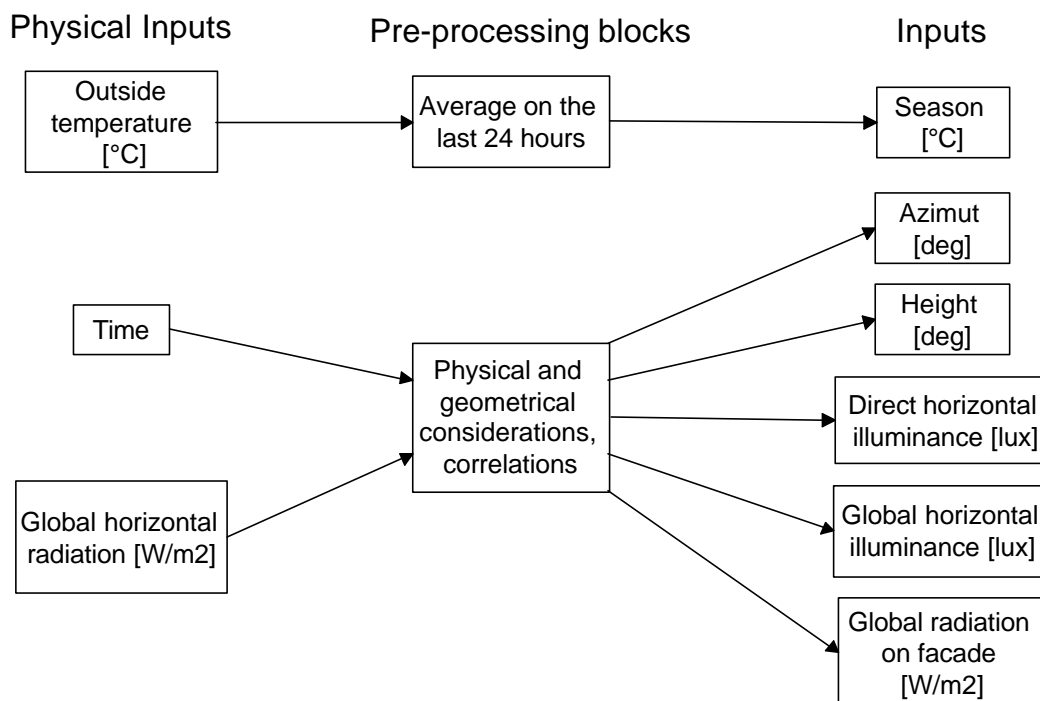


Figure 23: Pre-processing block diagram

The following blocks are provided:

A. Average outside temperature over the last 24 hours

This block provides the average outside temperature during the last 24 hours, including the current outside temperature. It is used essentially to derive the current season as a fuzzy variable.

B. Physical and geometrical considerations

This block provides all the needed illuminances for the lighting controller and the sun angles relative to the facade. Its inputs are the time and the global horizontal radiation [W/m^2]. Furthermore, four parameters are needed for the block calculations: the longitude, the latitude, the time zone and the facade orientation.

After the determination of the solar angles, the needed illuminance and radiation are calculated. The Liu and Jordan correlation is used to reconstruct the direct and diffuse component from the global radiation (Q_h) on a horizontal surface (reference: *The interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar radiation*, B. Liu & R. Jordan, Solar Energy 4, n° 3, 1960). Once the two components of the radiation are available on a horizontal surface, they can be calculated on a vertical surface of any orientation, using the simplifying assumption of isotropic diffuse component.

Finally, the radiation values are converted into illuminance values, using the relationship below (reference: *Daylighting simulation in the DOE-2 Building Energy Analysis Program*, F. Winkelmann & S. Selkowitz, LBL Report, USA, 1984):

$$E_{\text{dir}} [\text{lux}] = 93 \cdot Q_{\text{dir}} [\text{W}/\text{m}^2]$$
$$E_{\text{diff}} [\text{lux}] = 111 \cdot Q_{\text{diff}} [\text{W}/\text{m}^2]$$

3.2.3.3 BLIND AND ARTIFICIAL LIGHTING CONTROLLER, USER PRESENT

The complete scheme of this controller is given in the following figure.

Two adjustable models are used in the controller: a daylighting model and an artificial lighting model. These models are explained first in the next two sections.

The algorithm used for blind control when the user is present is divided into three parts:

- the first part of the algorithm determines a maximum aperture of the blind (alpha max), which is possible without producing glare to the user;
- the second part of the algorithm gives the final aperture of the blind providing a correct daylighting level in the room and compatible with the maximum blind aperture;
- finally, the last part of the algorithm prevents too small and frequent movements of the blind.

The artificial lighting is simply providing the complement to the setpoint value, when the daylighting is not large enough to reach a sufficient inside illuminance level (section 3.5).

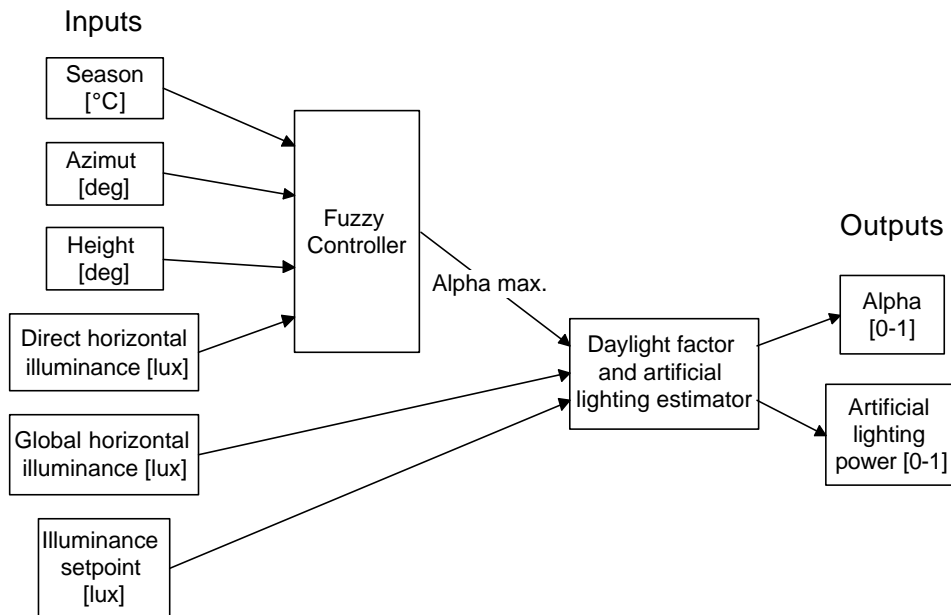


Figure 24: User present controller

3.2.3.3.1 Daylighting model

A simple pseudo-daylighting model has been used in the controller. It is given by the following relationship (see technical report EDIFICIO/LESO/AD3/R14/3.12.1998):

$$E_{\text{inside}} = (a \cdot \alpha + b) \cdot E_{\text{outside}} \quad (\text{I})$$

with E_{inside} = inside illuminance (on a horizontal surface, due only to daylighting) [lux]
 E_{outside} = outside illuminance on the facade [lux]

The two coefficients a and b are regularly updated from available measurements.

3.2.3.3.2 Artificial lighting model

The variables to consider are P_{al} (the relative electrical power applied to the artificial lighting system [0-1]), and $E_{\text{al}}(P_{\text{al}})$ (the illuminance provided by the artificial lighting system [lux]).

At the commissioning (and each night), two points are measured in order to determine the relation between the electrical power applied and the illuminance level corresponding to this power:

$$P_{\text{al}}=1 \text{ (maximum power applied)} \Leftrightarrow E_{\text{al}}(1)$$

$$P_{\text{al}}=0.4 \quad \Leftrightarrow E_{\text{al}}(0.4)$$

Let's define (to simplify the notation)

$$c = E_{\text{al}}(1)$$

$$d = E_{\text{al}}(0.4)$$

The value of 0.4 is chosen because it is sufficiently low to have a good estimation of the slope ($0.4 \ll 1$) and it is high enough for a dimming controller (the dimming controllers are generally not able to provide lighting with a power less than 20% – 30% (P_{\min}) of the maximum electrical power).

So, the relation between the electrical power and the illuminance is given by:

$$E_{al}(P_{al}) = d + (P_{al} - 0.4) \cdot \frac{[c - d]}{0.6} \quad (II)$$

The parameters c and d are determined experimentally and periodically readjusted (see technical report EDIFICIO/LESOAD3/1.12.98). The minimal power (P_{\min} , fraction of the maximum electrical power) needed by the dimming control system to provide artificial lighting should be measured or given at the commissioning.

3.2.3.3.3 Maximum blind position

The basic idea is to take into account not only the incidence angle of the solar radiation on the facade but the exact position of the sun relatively to the facade (see figure, the nine different positions of the sun). So, both the azimuth and the height of the sun are used in the algorithm. This allows having different behaviours for different kind of penetration of sun. If the sun illuminates the wall in front of the user or illuminates the user directly, the algorithm may give different blind position although the incidence angle is the same in the two cases. In particular, it gives the opportunity to adapt the system (through the user wishes) following the user position in the room.

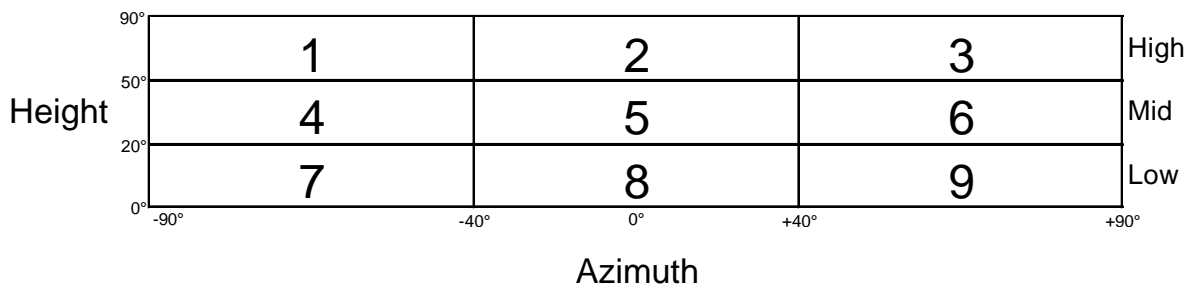


Figure 25: Sun position relatively to the facade

Inputs:

- Direct horizontal illuminance (E_{hdir})
- The season ($Season$), from the average of external temperature during the last 24 hours
- The height of the sun ($Height$)
- The azimuth (relative to the facade orientation) of the sun ($Azimuth$)

Output:

- Maximum blind position ($AlphaMax$)

Rules:

There are 25 rules in the system. At the beginning (before the user adaptation) the rules concerning the same height of sun but with a different azimuth (rules flagged with a * in the listing below)

gives the same value of *AlphaMax* (see figure, the position of the sun 4, 5 and 6 gives the same result, for example). The idea is that the user adaptation will differentiate the rules with the same height of sun but with a different azimuth.

If *Ehdir* is high and *Season* is winter and "position of the sun is 1,2 or 3" then *AlphaMax* is 1 *

If *Ehdir* is high and *Season* is winter and "position of the sun is 4,5 or 6" then *AlphaMax* is 0.7 *

If *Ehdir* is high and *Season* is winter and "position of the sun is 7,8 or 9" then *AlphaMax* is 0.4 *

If *Ehdir* is high and *Season* is summer and "position of the sun is 1,2 or 3" then *AlphaMax* is 0.5 *

If *Ehdir* is high and *Season* is summer and "position of the sun is 4,5 or 6" then *AlphaMax* is 0.3 *

If *Ehdir* is high and *Season* is summer and "position of the sun is 7,8 or 9" then *AlphaMax* is 0.1 *

If *Ehdir* is high and *Azimuth* is $> +90^\circ$ then *AlphaMax* is 1

If *Ehdir* is high and *Azimuth* is $< -90^\circ$ then *AlphaMax* is 1

If *Ehdir* is low and *Height* is high then *AlphaMax* is 1

If *Ehdir* is low and *Height* is mid then *AlphaMax* is 1

If *Ehdir* is low and *Height* is low then *AlphaMax* is 1

If *Season* is summer and *Height* is negative then *AlphaMax* is 1

If *Season* is winter and *Height* is negative then *AlphaMax* is 0.1

3.2.3.3.4 Blind position according to the inside illuminance measurement

The inside illuminance is provided by the daylighting model, and not directly by the inside lighting sensor. Therefore, a closed loop controller, with its unstability potential, is avoided. Moreover, bad measurements of the inside lighting (due for instance to an obstructed sensor) can be filtered out.

The corresponding block calculates the final blind position α (between 0 and α_{max}) and the artificial lighting power, from the inputs global illuminance on the facade and inside illuminance setpoint.

From the daylighting model given by the relationship (I), we want to adjust α such that $E_{inside} = E_{setpoint}$, so with (I) one has:

$$E_{setpoint} = (a \cdot \alpha_{cal} + b) \cdot E_{outside}$$

Solving for α_{cal} , one obtains:

$$a_{cal} = \frac{E_{setpoint}}{E_{outside} \cdot a} - \frac{b}{a}$$

It has to be noted that α_{cal} is not directly a physical value. It may be negative or higher than 1 but in the controller non-physical values are rejected. The parameters a and b are determined experimentally and continuously adjusted (see technical report EDIFICIO/LESO/AD3/R15/3.12.1998)

3.2.3.3.5 Artificial lighting controller

We want that the artificial lighting completes the inside illuminance to the setpoint, therefore:

$$E_{al} (P_{al}) = E_{setpoint} - E_{inside}$$

Solving relationship (II) for P_{al} :

$$P_{al} = 0.6 \cdot \frac{E_{al} - d + \frac{0.4}{0.6} \cdot [c - d]}{c - d} \quad (III)$$

It has to be noted that P_{al} is not a physical value. It may be negative or higher than 1 but in the controller non-physical values are rejected.

Continuous dimming control

If $\frac{E_{inside}}{E_{setpoint}} < E_{low}$ the artificial lighting system is switched on and the electrical power is calculated with the relationship (III):

$$P_{al} = 0.6 \cdot \frac{E_{setpoint} - (a \cdot a + b)E_{outside} - d + \frac{0.4}{0.6} \cdot [c - d]}{c - d}$$

If $P_{al} < 0$ then $P_{al} = 0$

If $0 < P_{al} < P_{min}$ then $P_{al} = P_{min}$

If $P_{al} > 1$ then $P_{al} = 1$

If $\frac{E_{inside}}{E_{setpoint}} > E_{high}$ the artificial lighting system is switched off.

Typical values for $(E_{low}; E_{high})$ can be (0.6; 0.8) according to the features of the dimming and blind controllers.

On/Off control

If $\frac{E_{inside}}{E_{setpoint}} < E_{low}$ the artificial lighting system is switched on.

If $\frac{E_{inside}}{E_{setpoint}} > E_{high}$ the artificial lighting system is switched off.

Typical values for $(E_{low}; E_{high})$ can be (0.5; 0.8) according to the features of the blind artificial lighting controllers.

3.2.3.3.6 Variants

The algorithm described in the previous sections is the base version, valid for a simple roll-down blind. Some of the partners have more complex configurations, which have requested the development of ad-hoc variants.

The two variants which have been considered are the following:

- A venetian blind controller, which needs to control not only the blind position (variable Alpha) but also the slats orientation (variable Beta). The details of the algorithm can be found in the technical report EDIFICIO/LESO/AD3/R23/12.5.99. The controller needs to consider the limit angle for the solar height, over which there is a risk of glare for the users. An additional fuzzy rule base is used.
- A system with two blinds (typically, one normal window and one upper anidolic system with its own blind), where both blinds are controlled independently.

3.2.3.4 BLIND AND ARTIFICIAL LIGHTING CONTROL, USER NOT PRESENT

The complete diagram of this controller is shown in the figure below.

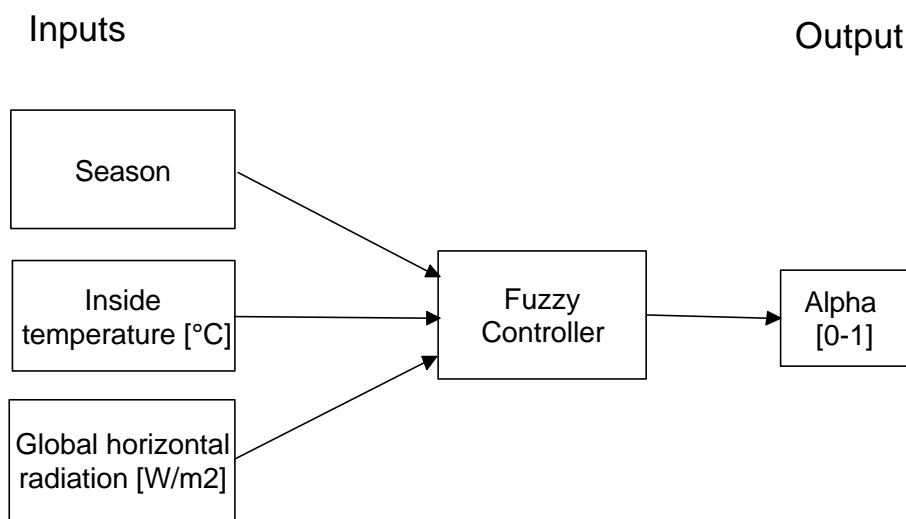


Figure 26: User not present controller

When the user has not been present for a certain amount of time (typically for 15 minutes at least) the controller switches from the visual optimisation to the energy optimisation algorithm. Different actions are carried out:

- The artificial light is switched off;
- The slats (in the venetian blind case) are closed (position $\beta = 90^\circ$), so the control takes place only through the alpha value;
- If there are several blinds, the alpha of each blind follows the same command. It means that all the blinds have the same value of alpha.

The basic idea is to use the window + blind system as a control of the incoming heat, which has to be reduced to minimum in summer and increased to maximum in winter. It has been shown that considering only the season in the fuzzy logic rule is quite satisfactory (see technical report EDIFICIO/LESO/AD3/R9/5.10.98).

The rule base, given below, is rather simple and includes only 8 rules.

Inputs:

Outside average temperature on the last 24 hours (*Season*)

Horizontal global solar radiation (*Ghglob*)

Difference between actual room temperature and setpoint temperature (*Tdiff*)

Output:

Blind position (*Alpha*)

Rules:

If *Season* is winter and *Ghglob* is night and *Tdiff* is normal then *Alpha* is 0

If *Season* is winter and *Ghglob* is day and *Tdiff* is normal then *Alpha* is 1

If *Season* is summer and *Ghglob* is night and *Tdiff* is normal then *Alpha* is 1

If *Season* is summer and *Ghglob* is day and *Tdiff* is normal then *Alpha* is 0

If *Ghglob* is night and *Tdiff* is too cold then *Alpha* is 0

If *Ghglob* is night and *Tdiff* is too hot then *Alpha* is 1

If *Ghglob* is day and *Tdiff* is too cold then *Alpha* is 1

If *Ghglob* is day and *Tdiff* is too hot then *Alpha* is 0

3.2.3.5 OVERVIEW OF THE ADAPTATION

There are three kinds of adaptation in the level 3 :

1. Long-term Adaptation through the cost function (using Genetic Algorithms)
2. Long-term Adaptation to the user wishes
3. Adaptation of the parameters of the different blocks used in the controller (as the daylight factor model, the room prediction, the presence prediction, and so on...)

Each kind of adaptation is quickly explained below.

3.2.3.5.1 Cost function adaptation

In order to use Genetic Algorithms (GA) for the long term adaptation, the difficulty is the need of a *global* cost function. We have only separated cost functions for the energy and the comfort. How find the right weight for each one ? A way to avoid this problem is the use of a *multi-objective GA*. It works as follow.

Instead of taking the best individuals of a single objective (weighting of different cost function) the population is ranked according to each objective individually (each cost function). An overall rank is then generated by taking the *average* of the newly ranked populations. This overall rank is used to produce the next generation. The benefit of this method is the fact that the effort (calculation time) put on each objective is the same...we do not give any weight to each objective.

3.2.3.5.2 Adaptation to user's wishes

Here only the long-term adaptation to the user wishes is described, the immediate change (as increasing the lights, the temperature) should be treated in the controller level (for example, concerning the blinds a command DOWN given by the user should override the automatic system, and concerning the heating/cooling system a change of the temperature setpoint is probably enough).

The idea for the long-term adaptation is to use a wish-space of n-dimensions, with n equal to the number of variables that are measured and affect the user (temperature, sun position, level of illuminance, season, ...). Each time the user interact with the system, we put in the wish-space at the right place (corresponding to the conditions when the user interact) the wish the user has expressed, for example : blinds up of 0.3 or temperature setpoint decreases of 1 degree. After a certain amount of time the wish-space is filled with the user wishes. If several different wishes are given for the same condition (same place in the wish-space) a weighting of the different wishes is done with priority to the newest.

How to initialise this wish-space ? At the beginning the user hasn't yet interacted with the system, therefore the controller is considered as perfect in a comfort point of view, so the wish-space is filled with zero everywhere. (In the genome, the variations of the controller parameters relative to the current controller are coded rather than the parameters themselves, hence a zero value when no variation is provided.)

It should be noted in fact that there are four wish-spaces, one for each controller (heating-cooling, ventilation, blinds and artificial light).

The adaptation is done with GA, it is integrated in the long-term adaptation. The cost function is generated from the difference between the wish-space and a similar space with values produced by the individual considered (an individual = a controller !). A big difference corresponds to a bad controller (user wishes are not well taken into account), and a small difference to a good controller (user wishes are well taken into account). So, this cost function is the comfort cost function.

Note : It's important that the initial population contains several times the current controller (chromosome completely 0) in order not to loose the information that it is containing (hundreds of GA optimisations could have been done to produce it !).

3.2.3.5.3 Block parameters adaptation

Standard methods of adaptation are applied to the different blocks used in the controller:

Name of the block	Frequency of adaptation	Method
Daylight factor model	Daily	new measurement of parameters
Artificial light model	Weekly	new measurement of parameters
Presence prediction	Weekly	(not implemented)
Room temperature prediction	Daily	Back-propagation learning

For both daylighting and artificial lighting models, the adaptation is simply done by doing new measurements of the parameters. For the room temperature prediction model, an artificial neural network (ANN) is used, with an on-line adaptation; when new conditions are met, the ANN learns the corresponding thermal room behaviour.

3.2.4 TASK AD4: SOFTWARE INTEGRATION

3.2.4.1 INTRODUCTION

Starting from the previous tasks, namely AD1, AD2 and AD3, to build up the whole control system (BEMS) task AD4 has been planned.

This works comprised the preparation of the different subtasks on the one hand, and the assembly of the entire system on the other hand. The difficulties were tuning phases of the particular sub-models, the development of additional modules which were necessary for comprehensive simulation studies and the time consuming tests, verifying the accurateness of the simulation package.

The sub-models which had to be integrated in the entire systems were the thermal model, the ventilation model and the lighting model. To become more familiar with the entire control system in the next chapter the system is shown from different points of view.

3.2.4.2 CONTROL SYSTEM IN DIFFERENT DESCRIPTION

The whole system can be seen from different points of view. Figure 27 show the same system in these different view points.

The system under investigation is an independent room in an office building. Such an office room can be modeled as a thermal capacity at a certain temperature with thermal inputs in terms of HVAC (including both ventilation and thermal control). An appropriate controller will produce thermal control using heating/cooling devices and there is also a controller for the ventilation device. An additional “control variable” is the visual comfort, or the light situation which depends on both artificial and natural lighting with their respective devices. This means that two variables have to be controlled, the room temperature and, rather ambiguously, the light situation using three control devices (see following figure):

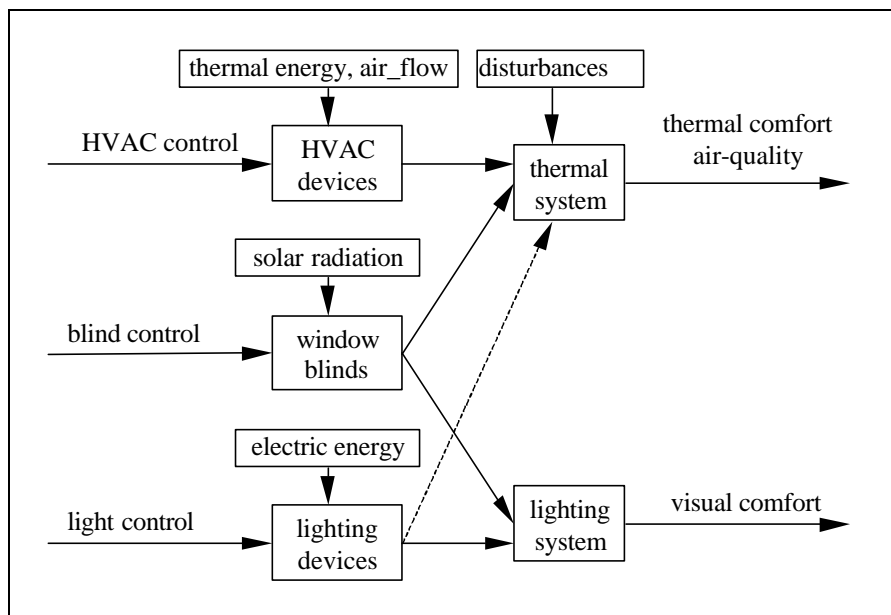


Figure 27: Simplified system model of the system to be controlled (cross-coupling due to the blinds)

- heating/cooling device. The heating/cooling power is input to the HVAC subsystem. This control device has a pure thermal impact and is exclusively used by the HVAC control system;
- ventilation device. The volume-flow of fresh air has to be provided by this device;
- lighting devices. The lighting devices have a weak influence on the thermal situation, but dominant influence on the light situation and are exclusively used by the lighting system;
- window blinds. They are no true control devices because shades modulate an external, independent variable, the thermal and light power of solar radiation. These control devices are shared by the HVAC and the lighting control system, depending on various outside conditions.

Generally speaking, there are three energy sources, which have to be controlled by an integrated and intelligent concept in order to achieve optimal visual and thermal comfort at the same time.

The main question then is, how to utilise the available control devices, especially the blinds, in order to gain both thermal and visual comfort at optimised, i.e. minimised energy expense. The boundary conditions are given by the disturbance inputs, the quasi-stochastic solar radiation and the arbitrary human behaviour. Quasi-stochastic in this context means that solar radiation is arbitrary and periodic at the same time.

From a control point of view, the system on hand is a multiple-input-multiple-output-system (MIMO-system) with partial cross-coupling, where the coupling depends on the amount of solar radiation.

Control inputs are the heating/cooling power, the air-flow, the lighting power, and the blind position which modulates a semi-stochastic signal, the solar radiation. If this input is equal to zero, the MIMO-system falls apart into a thermal single-input-single-output system (SISO-system), and a visual multiple-input-single-output system (MISO-system), comprising lighting devices and shades for control. Outputs of the entire system are the controlled variables thermal and visual comfort. The first one can be represented by the room temperature. The second output cannot be put in terms of numbers, but in user acceptance which is expressed in user actions. Figure 28 shows the total system including the different modules, which are used to determine all needed data.

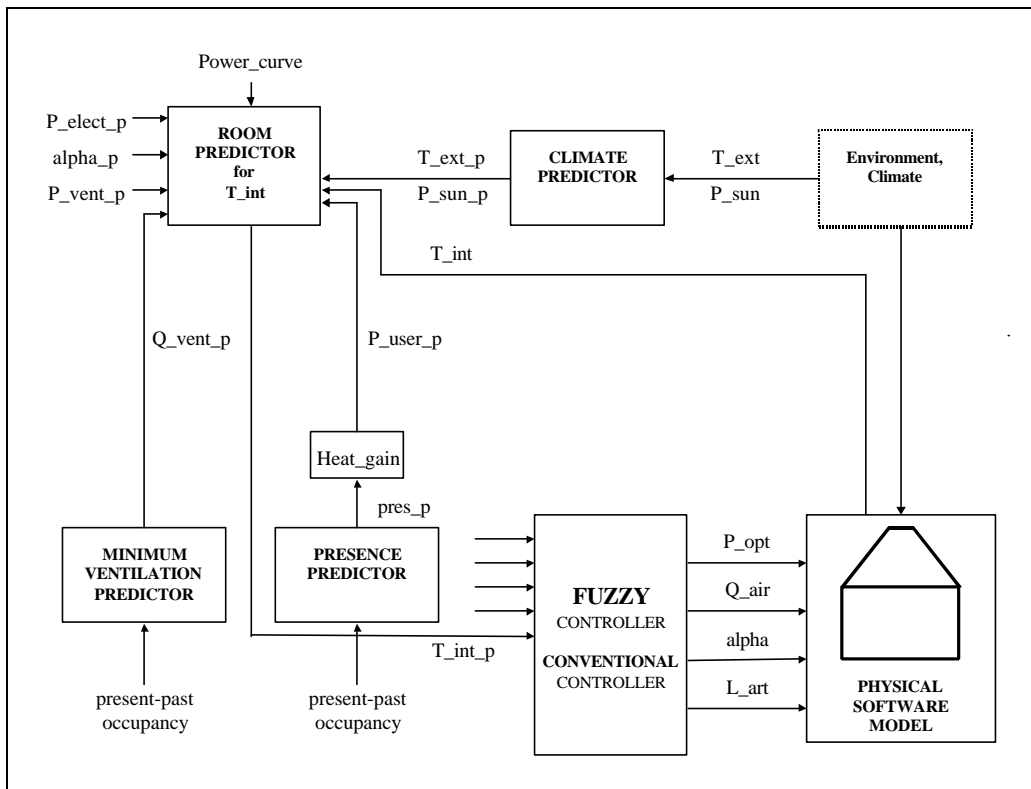


Figure 28: System including the different predictors, Fuzzy-controller and physical sw model

The different blocks are: the climate predictor, the room predictor, the minimum ventilation predictor and the presence predictor. Their outputs, the predicted values are needed as inputs to the Fuzzy controller, which determines the set points P_{opt} , Q_{air} , α and L_{art} for the 1st loop controllers. As it can be seen from the figure all predictors except the room predictor are so called disturbance-predictors (not in the feedback loop), whereas one input to the room predictor is fed back from the physical software model (office room).

In Figure 29 the system from the control point of view is depicted. The flows to and from the different sub-systems are displayed in this figure. Also the 3 different loops can be seen in the diagram. The inner loop which controls the different variables according to the set points (black), the 2nd loop in which the parameters for the Fuzzy-controller are determined (red) and the outer loop in which the membership-function-parameters of the Fuzzy-controller are optimized (blue). There is also an interface (green), with which the user can interact and change set points or other parameter.

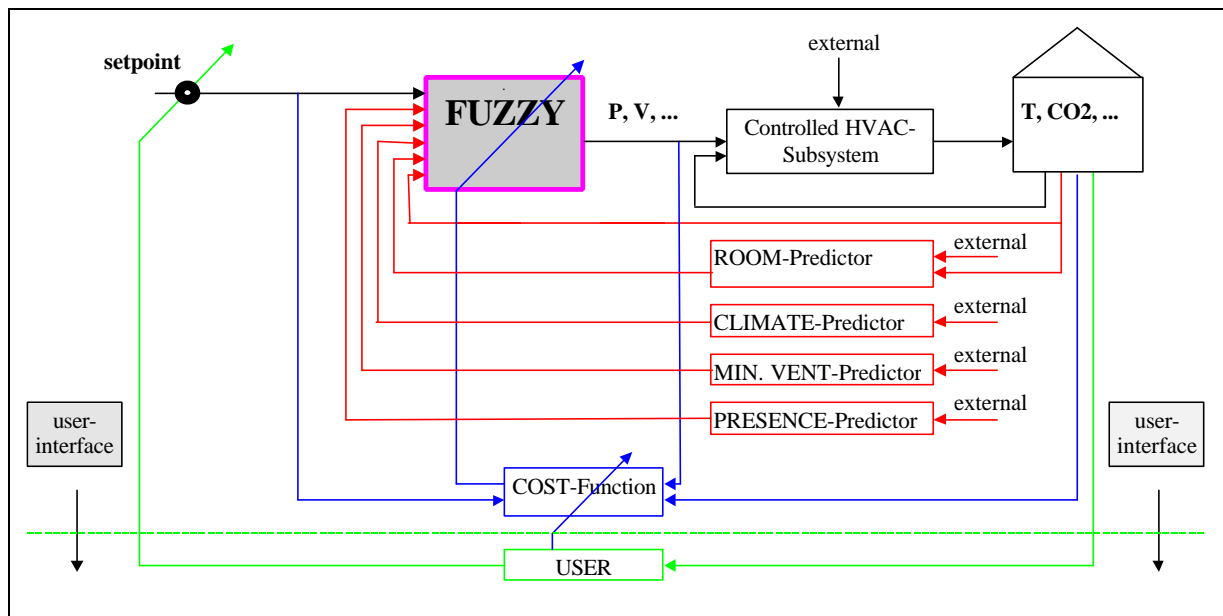


Figure 29: System seen from the control point of view (transfer functions)

The forth way to see the whole system is to see it from the ‘Signal flow’ point of view. There, all signal flows from and to the different modules are shown.. Figure 30 shows the inter-actions and connections between the different blocks can be clearly seen. Various colours show the indoor sensors, outdoor sensors, predicted values, data from the user interface and the power.

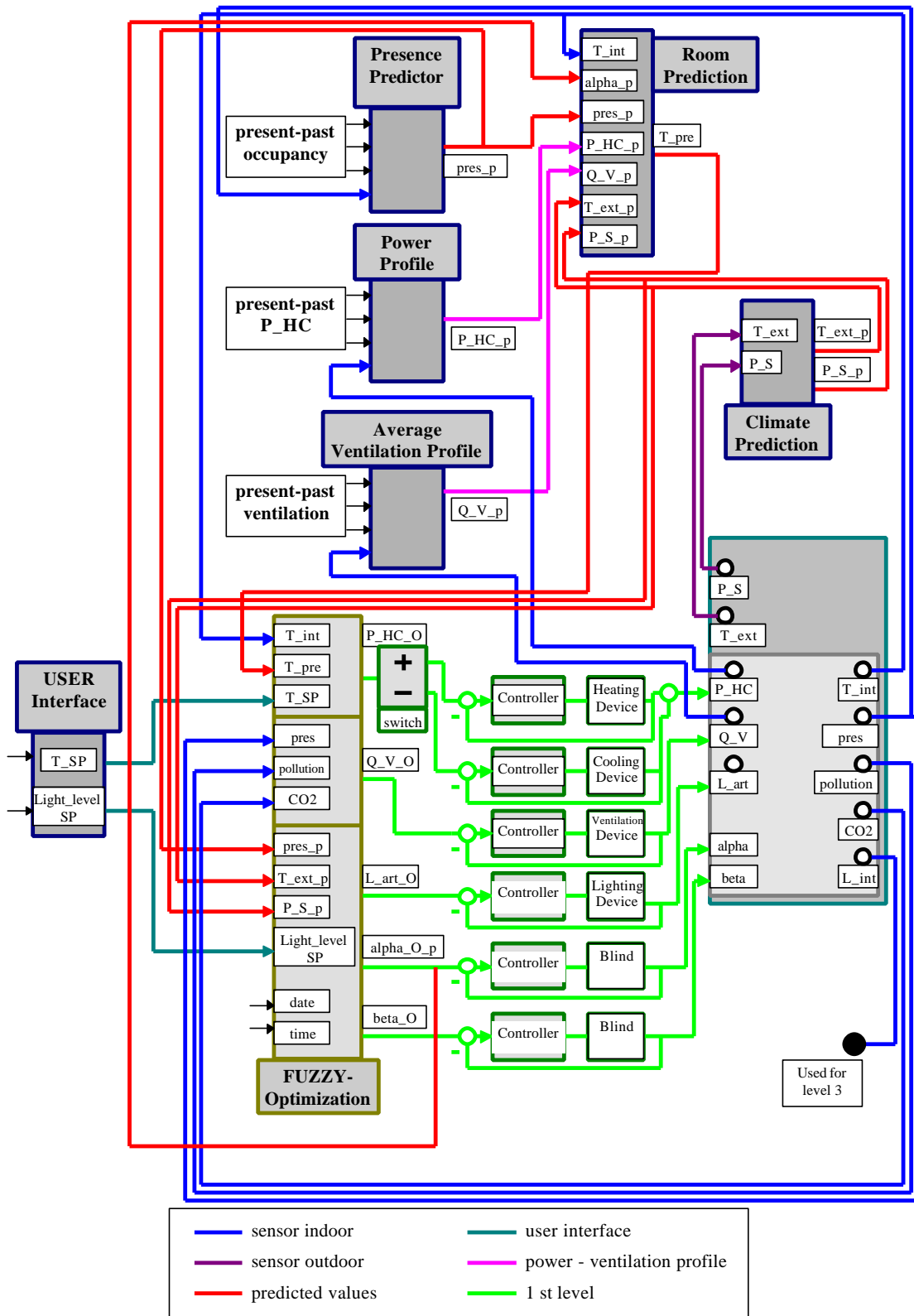


Figure 30: Signal flow diagram

3.2.4.3 SOFTWARE PACKAGE

The Simulink model which has been developed from the the three sub models for thermal control, ventilation and lighting will now be described.

The sub models were developed by the partners who were responsible for the certain subtasks.

Several supplementary models, switches, scopes and displays were added to make a simulation and a following check and judgement easy. The unit for the simulation time was chosen in ‘days’. The fixed step time is 15 minutes or to define it in days: 1/96 (of a day).

To be able to run the Simulink model the initialisation file has to be run first. There, the meteo data file, there are meteorological data from Sicily (Italy), Lausanne (Switzerland) and Espoo (Finland) available, has to be defined. This is used to simulate the environment of the system.

Additionally, the Fuzzy matrices, different tunig parameters, like set point temperature, presence-absence times, ... are defined and finally a function which simulates the presence and absence is loaded.

In the next chapter the different major sub models are described.

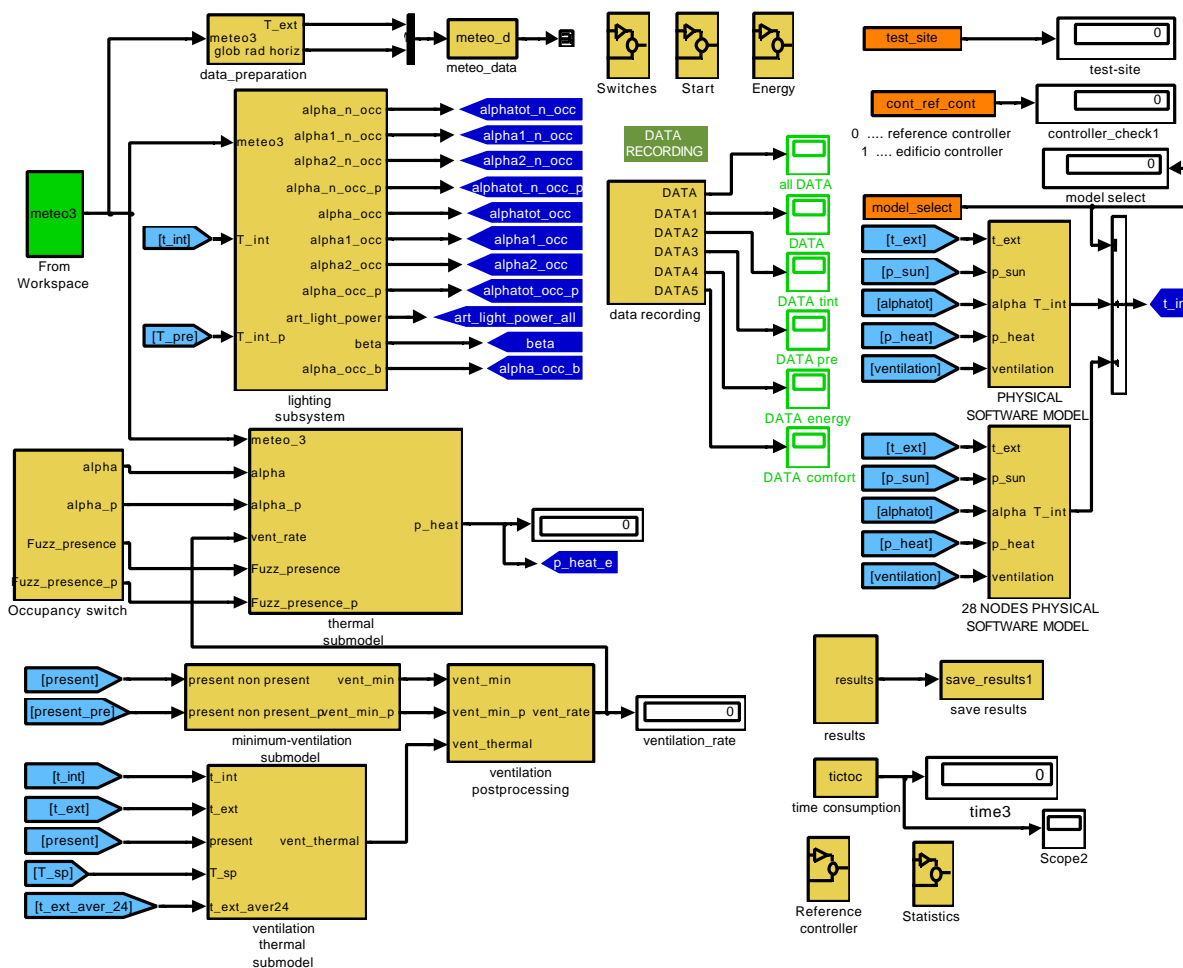


Figure 31: Main model

3.2.4.3.1 Main modules

The main model consists of four modules which are developed from AD1, AD2 and AD3. The ventilation is split into the minimum ventilation block and the thermal ventilation block. Additionally, there are further blocks containing the different switches which have to be set to define the system, the physical software model which simulates the room and a block in which certain parameters are reset when restarting the model. In the block data collection all measured data are collected and can be monitored on different scopes.

3.2.4.3.1.1 Lighting submodel

The lighting sub model again consists of three sub-sub models. In these three models the alpha and beta values depending on whether the room is occupied or not are determined. For the predicted values the same model with different inputs is added (only for the alpha determination) .

Lighting submodel alpha - no-occupancy

This model determines the blind position for the case that nobody is in the room. The target is to optimize the system only from the power consumption point of view. The inputs to the model are the average of the external temperature $T_{ext_aver_24}$, the sun power P_{sun} , the internal temperature T_{int} and the external temperature T_{ext} . Using the average temperature it can be determined whether the available sun radiation should be used or not (during winter it should, during summer it should not) and whether the blinds should be closed during night or not. Taking the predicted values of all inputs, the predicted alpha position can be determined as well.

Lighting submodel alpha - occupancy

This model determines the alpha position if somebody is in the room. First, the maximal alpha position is calculated. This value depends on the season, the direct illuminance and on the sun position. Having calculated this value, the final value is determined by taking into consideration the internal illuminance, the illuminance set point, the global horizontal illuminance and the current alpha.

Lighting submodel alpha-beta occupancy

This model not only determines the alpha value if somebody is in the room but also the beta value. The inputs of the Fuzzy controller are the same as for the alpha occupancy controller. For calculating the beta value the azimuth, the sun height, the direct horizontal radiation, the inside illuminance set point and the previous outputs are also taken into account.

3.2.4.3.1.2 Thermal submodel

In the thermal model showed in Figure 32 the heating power is determined using a power curve and an additional power input calculated by a Fuzzy controller. The inputs to the Fuzzy controller are the set point temperature, the actual internal temperature and the predicted internal temperature. For the determination of the predicted temperature two different models are available, on the one hand a linear model and on the other hand a non linear Radial-Basis-Function network model. There is also a block integrated which determines the so called 'comfort'. The difference between the set point temperature and the actual temperature is taken into account. The result gives information about the reliability of the control system.

3.2.4.3.1.5 Room temperature prediction model

This is a sub model of the thermal model. For the prediction of the internal temperature two different models are available. The one is a linear model and the other on is non linear Radial-Basis-Function Network model. Using the switch 'prediction' one of these two models can be chosen. The inputs to the models are the internal temperature 'T_int', the external temperature 'T_ext', the sun radiation 'P_sun' and the 'alpha' value. There is an additional input for the RBFN model, namely the ventilation rate 'vent_rate'.

3.2.4.3.2 Additional modules

Data collection

In the block data_collection all variables can be listed individually or collected and normalised with certain other parameters on a scope. Additionally the more important parameters are stored to in a mat-file and can be used after the simulation for any analysis.

"Start_define" block

In this block certain parameters are reinitialised when restarting the system. This is necessary due to some blocks implemented in the entire system.

Switch block

In the switchbox all tuning parameters which have to be defined in the initialisation file are listed. There it can easily verified whether the right parameters, e.g. set point temperatures, ... , were set. The definition of the tuning parameters has to be done in the initialisation file and can not be done in the switch block..

3.2.4.4 CONCLUSION

This simulation package consisting of several modules is a comprehensive tool to make extensive simulation studies. These simulation studies are necessary for the optimisation of the algorithms which are then used for the experiments. Before the algorithms are applied at the experiments they are already working well, due to this tool.

The integration of all the different sub modules also allows to analyse any cross coupling between the different models and then the development of optimal controllers for the system. All possible scenarios, different meteo data, different room characteristics, etc., can be tested and finally analysed.

3.2.5 TASK AD5: SOFTWARE TOOLS

3.2.5.1 INTRODUCTION

The software tools for the EDIFICIO project are:

- The “Lon Manager DDE Server” produced by Echelon Corporation. It has been distributed by Senamion Automazione to those project’s partners which was involved in the experimental task (ET3). Essentially Lon Manager DDE server was used to manage the Lonworks network (installation, configuration, setting up etc.);
- The “EDIFICIO System Monitor ” (ESM) has been developed within task AD5 by StMicroelectronics in the aim to help partner’s involved in experimental test to fetch, manage and store data relevant to the experiments.

Other software tools, out of AD5 task, are:

- The EDIFICIO Control System, built in MATLAB/SIMULINK;
- The Datalog DDE Server used nearby EPFL-LESO (Lausanne CH).

3.2.5.2 SOFTWARE TOOL ARCHITECTURE

The whole architecture is showed in the following figure.

ESM is connected using the Windows Dynamic Data Exchange (DDE) protocol to the Lon Manager DDE Server, the Datalog DDE Server (where it is used), and Matlab.

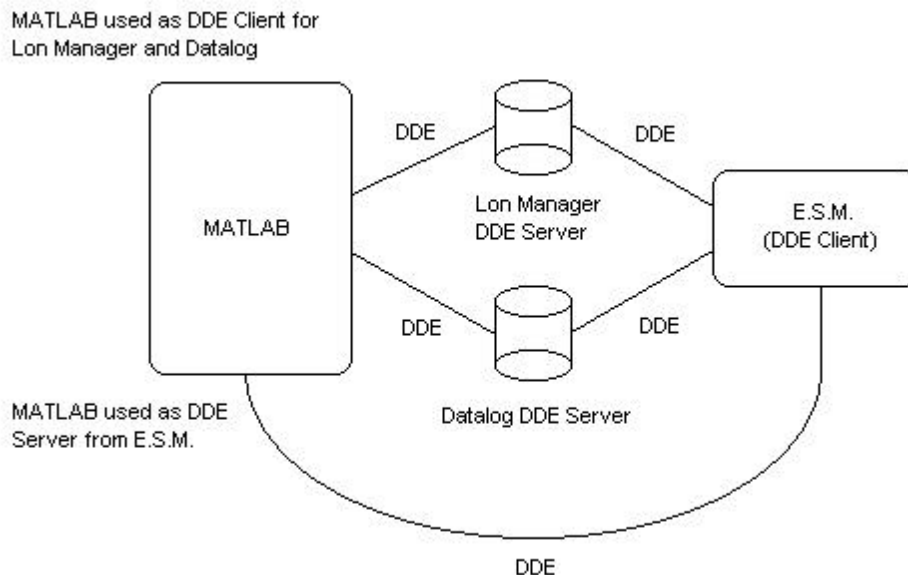


Figure 33: Software tools architecture

The Matlab program (EDIFICIO Control System) is connected as DDE Server with ESM, and as DDE Client to the LonManager DDE Server and to the Datalog (whenever present).

3.2.5.3 OVERVIEW ON THE LONMANAGER DDE SERVER

The LonManager DDE Server is supervisor software, which manages the LonWorks network. It allows to manage all the information related to each network variable. Further, it gives to any DDE compatible Microsoft Windows application, the ability to monitor and control LonWorks control network, via Dynamic Data Exchange technology.

When a Lon network is installed the LonMaker program is provided as well. It's must be used to configure all nodes on the network during the installation of the sensors / actuator.

Other features are specified in the LonManager DDE Server manual.

LONWORKS TERMINOLOGY

LonWorks: A set of tools and components for implementing control networks;

LonTalk: The protocol used on LonWorks networks. It defines a standard way for device to exchange information;

Neuron Chip: A family of VLSI components that implement the LonTalk protocol. A Neuron Chip can manage I/O devices and execute user-written application code. They are used to create a network interface to a host processor;

Application node: Individual sensors and actuator nodes that make up a network. An application node contains a Neuron Chip that usually executes a user-written application program. These programs are developed with a LonBuilder Developer's Workbench and then exported to the application node;

Network variable: High-level objects that application nodes use to communicate with one another. Types, functions and number of network variables in each node are determined by the application code within the node. Network variables make it easy to develop networked control applications by eliminating the low level operations such as building and sending outgoing messages, and receiving and responding to incoming messages;

Explicit message: Low level messages that application nodes use to communicate with one another. Each message contains a *message code* that identifies the type of message. Nodes use the code to determine the action to take when the message is received. When using explicit messages, the node is responsible for building, sending and responding to messages.

3.2.5.4 EDIFICIO SYSTEM MONITOR

The EDIFICIO System Monitor (ESM) is a Windows '95, '98, NT application.

The objectives of ESM are the monitoring of the EDIFICIO control system and the saving on disk of the values of EDIFICIO network.

ESM has been designed in a DDE Client / Server architecture and it is a DDE Client application.

ESM perform its tasks using the Windows Dynamic Data Exchange technology.

The objectives, performed by relative functions, of ESM are:

- To monitor on line the network values in the EDIFICIO System.
- To save on disk these network values at regular intervals, chosen by the user.
- To request and receive the network values from the Servers of the System.
- To poke the network values to the Servers of the System.
- To execute some single commands and some commands controlled by a timer into the Servers.

EDIFICIO System Monitor is internal constituted by main four modules that are integrated and communicate each one. In the following a brief description of each module.

1. DATA INITIALISATION MODULE (DIM)

To supply to the program a high flexibility, the DIM allows choosing:

- The file where to save the set of the selected network variable names. This is called "status file".
- The "status sampling period".

- The file where to save the network variables values correspondent to the selected network variable names. This is called "measurements file".
- The "network variable sampling period".
- Up to three DDE Servers.
- The network variable names with their I/O features.
- The MATLAB variable names.
- The Single Commands and the Timer Commands to execute into the Servers.

2. DATA ACQUISITION MODULE (DAM)

This module allows the user to acquire the information packets present in the EDIFICIO network. It puts them in a RAM memory buffer allocated by ESM. The DAM performs the operations of Requesting Data and Poking Data, on selected variables, according with their I/O features.

The DAM is based on a data structure "ChRec" which contains all the network variables information useful for the system. This is a vector of records, where each record has the following fields:

```
typedef struct {
    HSZ hszItemName;      // Handle of the Item Name;
    HDDEDATA hData;      // Handle of the Data;
    short int Occupied;  // Occupation flag;
    int Number;          // Position in the channel vector;
    char Name[32];       // Node Name & Variable Name;
    char Type[8];        // Input or Output feature;
    char Value[1024];    // Variable Value.
} ChRec;
```

3. DATA MONITORING MODULE (DMM)

The DMM automatically monitors data coming from sensors and acquired by DAM every time they change. Generally this period is different than the network variables "sample and save period" (minimum one minute), used by the DSM.

The DMM visualizes these values in a dialog box, which contains all the active and selected variable for the monitoring. Also the DMM is based on a data structure "ChRec" which contains all the network variables information useful for the system.

4. DATA STORAGE MODULE (DSM)

The DSM registers on disk the values of the selected network variables, when the fixed network variables sample period has passed, in the chosen "measures file".

The DSM registers on disk the names of the selected network variables, when the fixed network variables sample period has passed, in the chosen "status file".

3.3 TASK ET: EXPERIMENTAL PHASE

An experimental phase has been performed in order to test the functionality of BEMS network. In particular the test have been done by means of simulation runs, scaled down experiments and full size experiments in real buildings. This task has been divided into four different subtask, namely:

- ET1: HW & SW integration;
- ET2: Test by simulations;
- ET3: Scaled down experiment;
- ET4: Test in real size occupied building.

The following paragraphs will describe each task rather in details.

3.3.1 TASK ET1: HW & SW INTEGRATION

3.3.1.1 INTRODUCTION

In the following paragraphs hardware and software development of the IRC (Intelligent Room Control) is described. Such device is the main component developed within the EDIFICIO project. Since there's the need to cover also themes concerning tests in real size occupied buildings this matter will be taken into account as well. IRC is a brand new LonWorks device¹⁰. LonWorks technology has been selected within the major network services available today by the market.

The LonWorks system is a leading, open, networked automation and control solution for the building, industrial, transportation, and home markets. Thousands of application developers and millions of devices have been installed world wide, this was just the reason that leads EDIFICIO team to develop IRC based on LonWorks technology.

In a LonWorks network, Intelligent control devices, called nodes, communicate with each other using a common protocol. Each node in the network contains embedded intelligence that implements the protocol and performs control functions. In addition, each node includes a physical interface that couples the node micro controller with the communications medium.

A typical node in a LonWorks control network performs a simple task. Devices such as proximity sensors, switches, motion detectors, relays, motor drives, and instruments, may all be nodes on the network. The overall network performs a complex control application, such as running a manufacturing line or automating a building.

3.3.1.2 H/W SPECIFICATION IRC

The IRC-Board has been designed as a fully-integrated room controller board. Board IO specifications have been defined according to the needs of the Experimental Test Sites (CONPHOEBUS, LESO, VTT) rather than to the needs related to real commercial use.

¹⁰ LonWorks is a product of Echelon Corporation

3.3.1.2.1 Mechanical Description

The IRC has been constructed as a Compact H/W Unit, with a single PCB of 2xEuropa-Dimensions (200 x 160mm).

The enclosure (see Figure 34) has been chosen to be mounted on a wall directly in the Test Room. A transparent cover gives the user the possibility to observe status LEDs which provide information about the IRC functioning.

Connection Cables come into the IRC from the downside part and are directly connected to the Board through Board connectors (see figure).



Figure 34: Prototype for IRC Enclosure

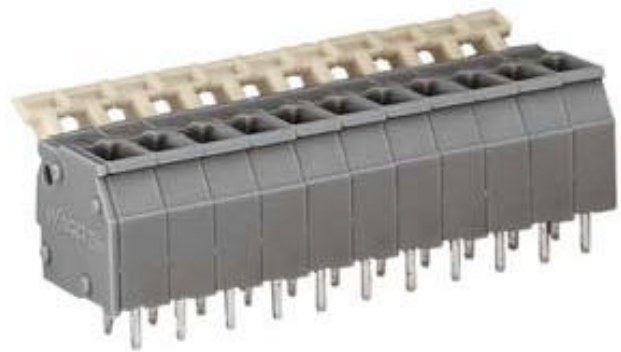


Figure 35: Cables connections

3.3.1.2.2 PCB and H/W Schematic Description

The PCB is executed in a mixed SMD and traditional technique with multi-layer technology (4 layers).

Power supply is 230 VAC, with an internal Transformer generating 24V for powering both the electronic and also to be used as external power supply by other devices, such as the LonWorks User-Interface Devices.

The 5VDC electronic power is generated with a DC/DC-Converter, in order to isolate the electronic circuitry and to minimise circuit power dissipations.

Linear power regulators are used to generate +10 VDC and +12 VDC for internal (AD/DA-Converters) and external use.

The IRC CPU is a Neuron Chip running at 10 MHz, which controls all Input/Output units and communication over a LonWorks network. The Neuron Chip also controls the ST WARP 2.0 Fuzzy co-processor.

An External 32KB Flash memory is used as Program memory for both the Neuron Chip Firmware and the User Application S/W. A further 24KB RAM is used as Data memory, due to the (possibly) large amount of data to be handled by the IRC (in the future).

Configuration Data can both be stored in the Neuron Chip internal EEPROM or in the external Flash.

The WARP co-processor is memory-mapped in the external address space of the Neuron Chip.

The I/O devices are mainly accessed by SPI interface directly from the Neuron I/O pins (IO8..IO10). For LonWorks communication an FTT-10 Transceiver has been used, supporting communication at 78Bbit/s (fixed data rate).

The Neuron Chip firmware allows new User Application S/W to be downloaded over the network, thus simplifying S/W upgrades.

3.3.1.2.3 Sensors Interfaces

Table 6 below shows sensors interfaces.

SENSOR INTERFACES						
IO-Identifier	IO-Characteristics	IO-Connector		Use CON	Use LESO	Use VTT
		Connector-ID	Signal			
S1	Pt100, 4 wire resistance	X1-1	P0 (.mA)	Internal Temperature	Internal Temperature	External Temperature
		X1-2	GND			
		X1-3	Pt1			
		X1-4	Pt2			
S2	Pt100, 4 wire resistance	X2-1	P0 (.mA)	External Temperature	Free for future use	
		X2-2	GND			
		X2-3	Pt1			
		X2-4	Pt2			
S3	Uncommitted Contact	X3-1	IN	IR detector	IR detector	
		X3-2	Pout (10V)			
S4	0-10V input/ 4-20 mA	X4-1	V10+	Internal Luxmeter	Blind position #1	
		X4-2	V10-			
S5	0-10V input/ 4-20 mA	X5-1	V10+	Blind position	Blind position #2	
		X5-2	V10-			
S6	0-10V input/ 4-20 mA	X6-1	V10+	Solar radiation	Luxmeter #1	
		X6-2	V10-			
S7	0-10V input/ 4-20 mA	X7-1	V10+	Wind speed	Luxmeter #2	
		X7-2	V10-			
S8	0-10V input/ 4-20 mA	X8-1	V10+	Wid direction	Luxmeter #3	
		X8-2	V10-			
S9	0-10V input/ 4-20 mA	X9-1	V10+	Free for future use	Free for future use	
		X9-2	V10-			
S10		Reserved				

Table 6: IRC sensors interfaces

3.3.1.2.4 Actuators Interfaces

Table 7 below shows actuators interfaces.

ACTUATOR INTERFACES						
IO-Identifier	IO-Characteristics	IO-Connector		Use CON	Use LESO	Use VTT
		Connector-ID	Signal			
A1	0-10V output	X101-1	V10+	Light dimmer	Light dimmer	
		X101-2	V10-			
A2	0-10V output	X102-1	V10+	3-way valve	Free	
		X102-2	V10-			
A3	0-10V output	X103-1	V10+	By-pass modulation	Free	
		X103-2	V10-			
A4	0-10V output	X104-1	V10+	Free	Free	
		X104-2	V10-			
A5	Relay 230V/15A	X105-1	CON1	Free cooling	Blind #1 Up	open of the first damper
		X105-2	CON2			
		X300-1	Out			
		X300-10	GND			
A6	Relay 230V/15A	X106-1	CON1	Light switch	Blind #1 Down	close of the first damper
		X106-2	CON2			
		X300-2	Out			
		X300-10	GND			
A7	Relay 230V/15A	X107-1	CON1	Blind Up	Blind #2 Up	open of the second damper
		X107-2	CON2			
		X300-3	Out			
		X300-10	GND			
A8	Relay 230V/15A	X108-1	CON1	Blind Down	Blind #2 Down	close of the second damper
		X108-2	CON2			
		X300-4	Out			
		X300-10	GND			
A9	Relay 230V/15A	X109-1	CON1	Fan Min speed	Light switch	on/off control of the heat/ cool
		X109-2	CON2			
		X300-5	Out			
		X300-10	GND			
A10	Relay 230V/15A	X110-1	CON1	Fan Mid speed	Heating switch	Light switch
		X110-2	CON2			
		X300-6	Out			
		X300-10	GND			
A11	Relay 230V/15A	X111-1	CON1	Fan max speed		
		X111-2	CON2			
		X300-7	Out			
		X300-10	GND			
A12	Relay 230V/15A	X112-1	CON1	By-pass		
		X112-2	CON2			
		X300-8	Out			
		X300-10	GND			

Table 7: IRC actuators interfaces

3.3.1.2.5 Power Outputs

Power output is reported in the following Table 8.

POWER OUT						
IO-Identifier	IO-Characteristics	IO-Connector		Use CON	Use LESO	Use VTT
		Connector-ID	Signal			
P1	12 VDC/100 mA	X201-1	12V+		Power for ext. solid state relays circuitry	
		X201-2	12V-			
P2	10 VDC/100 mA	X202-1	10V+	Sensor Power		
		X202-2	10V-			
P3	Reserved					
P4	24 VDC			Power supply for User-Interface Devices		

Table 8: IRC power output

3.3.1.2.6 Notes to IO-Interfaces

- Inputs and analog outputs are not galvanically isolated;
- Max output current for analog outputs is 5 mA (typ);
- Normal resolution for analog inputs/outputs is 8 bit over a Range 0-10V/0-20 mA. Resolution scales linear with signal range;
- Actuator command signals (5V or 10V/12V preferred) for Relays are wired to the IO-connector and can be used for external actuators if needed (LESO: replacement of Relays with external solid-state relays).

3.3.1.3 IRC SOFTWARE SPECIFICATIONS

3.3.1.3.1 Data Formats

In order to communicate with LonWorks devices data formats are defined for the IRC. It isn't necessary to define a communication protocol, since this is already defined and fully implemented by the Neuron Chip Processor (LonTalk Protocol). Two different Presentation Layers exist inside the LonTalk Protocol to format data exchanged over a LonWorks network:

- NETWORK VARIABLE (NV). NVs have a fix data length and have firmware support inside the Neuron Chip to be logically bound to other NVs of the same type on other LonWorks devices. Where possible "SNVT" have been used (Standard Network Variable Types). These types are defined and maintained by the LonMark Organization, whose purpose is to promote interoperability among LonWorks devices from different manufacturers (e.g. User Interface Modules). SNVTs belong to the Application Layer of the communication protocol;
- EXPLICIT MESSAGE (EM). EMs can have a variable data length and are best suited for flexible, proprietary applications, where using the same logical interface (Message tag) application data with flexible formatting can be exchanged between LonWorks devices (e.g. the Host-PC).

The following list summarises all SNVTs used by the IRC to communicate with other LonWorks devices.

SNVT	Neuron C Typedef	Range	Units/ Granularity	Purpose
SNVT_switch	Typedef struct { Unsigned short value; Unsigned short state; } SNVT_switch;	value [0..200] state 0=OFF 1=ON	Value 0.5%	Multifunctional for digital/analog sensors and actuators
SNVT_lux	Unsigned long	[0..65535]	1 lux	Illuminance level
SNVT_angle_deg	Signed long	[-359.98 .. +360]	0.002 degrees	Angle in degrees
SNVT_time_sec	Unsigned long	[0..65535]	1 sec	Time [seconds]
SNVT_str_int	Typedef struct { Unsigned short char_set; Unsigned long wide_char[15]; } SNVT_str_int;	char_set [0..255] wide_char [0..65535]		Multifunctional integer set
SNVT_pwr_fact	Signed long	[-1.0..+1.0]	0.00005	Power factor
SNVT_occupancy	typedef enum occup_t { /* 0 */ OC_OCCUPIED, /* 1 */ OC_UNOCCUPIED, /* 2 */ OC_BYPASS, /* 3 */ OC_STANDBY, /* -1 */ OC_NUL = -1, } occup_t;	[-1..+3]		Occupancy state
SNVT_temp_p	Signed long	[-273.17.. 327.66]	0.01 °C	Temperature
SNVT_temp_setpt	Typedef struct { Signed long occupied_cool; Signed long standby_cool; Signed long unoccupied_cool; Signed long occupied_heat; Signed long standby_heat; Signed long unoccupied_heat; } SNVT_temp_setpt;	[-273.17 .. 327.66]	0.01 °C	Temp. Setpoint
SNVT_hvac_mode	typedef enum hvac_t { /* 0 */ HVAC_AUTO, /* 1 */ HVAC_HEAT, /* 2 */ HVAC_MRNG_WRMUP, /* 3 */ HVAC_COOL, /* 4 */ HVAC_NIGHT_PURGE, /* 5 */ HVAC_PRE_COOL, /* 6 */ HVAC_OFF, /* 7 */ HVAC_TEST, /* 8 */ HVAC_EMERG_HEAT, /* 9 */ HVAC_FAN_ONLY, /* -1 */ HVAC_NUL = -1, } hvac_t;		N/A	HVAC Operating Modus
SNVT_time_stamp	Typedef struct { Unsigned long year; unsigned short month; unsigned short day; unsigned short hour; unsigned short minute; unsigned short second; } SNVT_time_stamp;		N/A	Date and Time
SNVT_obj_status	Typedef struct {... } SNVT_obj_status;		N/A	Functional Object Status

Table 9: IRC SNVT's summary

The following Tables summarise the NVs of the IRC for every functional area of use.

It must be noted that:

- A NV already has a direction (input or output) describing if the associated data is sent (output) or received (input) over the network;
- A Neuron Chip based LonWorks device can have a maximum of 62 NVs.

BLIND CONTROL

NV-name	NV-type	NV-direction	Data description
NviBldUp[2]	SNVT_switch	Inputs	Control the Up-Motion of two blinds
NviBldDn[2]	SNVT_switch	Inputs	Control the Down-Motion of two blinds
NviBldFine[2]	SNVT_switch	Inputs	Fine tuning of Slats position
NvoBldAlpha[2]	SNVT_switch	Outputs	Show the Blind positions
NvoBldBeta[2]	SNVT_switch	Outputs	Show the slat orientations
NviBldSetAlpha	SNVT_switch	Input	Setpoint Blind absolute position (can be overridden)
NviBldSetBeta	SNVT_angle_deg	Input	Setpoint Slat orientation (can be overridden)
NviBldAutoDisable	SNVT_switch	Input	Disable/Enable automatic blind regulation
NvoBldAutoFb	SNVT_switch	Output	Feedback of Disable/Enable automatic blind regulation status
NvoBldOverride	SNVT_time_sec	Output	Shows the timeout value for override validity of user-interface interventions
NciBldConfSet	SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Table
EmiBldAlarm	Msg.code = 0x20 Msg.len = 1 Msg.data[0] = <enEmiBldAlarm> Typedef enum { /* 0 */ AL_STOP_BLOCK, /* 1 */ AL_UP_BLOCK, /* 2 */ AL_DN_BLOCK, /* 3 */ AL_NO_ALARM } enEmiBldAlarm;	Input	Commands to set Blinds in specific positions and enable/disable control and user-interface interventions
EmiBldResync	Msg.code = 0x21 Msg.len = 1 Msg.data[0] = <enEmiBldResync> Typedef enum { /* 0 */ RESYNC_START } enEmiBldResync;	Input	Command to resync blind position
TOTAL NVs	16		

Table 10: IRC NV's summary for every functional area of use (blinds,HVAC..)

ARTIFICIAL LIGHTING CONTROL

NV-name		NV-type	NV-direction	Data description
NviLigOnUp[2]		SNVT_switch	Inputs	Turn on lights and increase dimmer levels
NviLigOffDn[2]		SNVT_switch	Inputs	Decrease dimmer levels and turn off lights
NviLigSetLLevel		SNVT_lux	Input	Setpoint Illuminance Level
NvoLigSts[2]		SNVT_switch	Outputs	Show Lighting states and dimmer levels
NvoLigOverride		SNVT_time_sec	Output	Shows the timeout value for override validity of user-interface interventions
NciLigConfSet		SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Table
TOTAL NVs	9			

Table 11: IRC NV's summary for functional area of use (Artificial lighting)

ROOM OCCUPANCY CONTROL

NV-name		NV-type	NV-direction	Data description
NviOccAutSw		SNVT_switch	Input	Signal from a remote presence sensor
NviOccAutOcc		SNVT_occupancy	Input	Signal from a remote presence detector sensor (type alternat. to SNVT_switch)
NviOccCmdOn		SNVT_switch	Input	Pulse command to activate/disable forcing of presence to "ON"
NviOccCmdOff		SNVT_switch	Input	Pulse command to activate/disable forcing of presence to "OFF"
NvoOccSts		SNVT_occupancy	Output	Shows the occupancy status of the room
NvoOccCmdOn		SNVT_switch	Output	Shows the forcing status for presence "ON" (for user-interface feedback)
NvoOccCmdOff		SNVT_switch	Output	Shows the forcing status for presence "OFF" (for user-interface feedback)
NvoOccOver		SNVT_time_sec	Output	Shows the timeout value for override validity of user-interface interventions
NciOccConfSet		SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Table
TOTAL NVs	9			

Table 12: IRC NV's summary for functional area of use (Room occupancy control)

TEMP DEVICES CONTROL

NV-name		NV-type	NV-direction	Data description
NviTempSensInt[2]		SNVT_temp_p	Input	Actual measured internal Temperatures
NviTempSensExt		SNVT_temp_p	Input	Actual external Temperature
NviTempSet		SNVT_temp_setpt	Input	Temp Setpoints
NviTempOffset		SNVT_temp_p	Input	Temp Setpoint User-Correction
NvoTempInt		SNVT_temp_p	Output	Actual mean-value internal Temperature
NvoTempExt		SNVT_temp_p	Output	Actual external Temperature
NvoTempSet		SNVT_temp_p	Output	Actual working Temp Setpoint
NciTempConfSet		SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Table
TOTAL NVs	9			

Table 13: IRC NV's summary for functional area of use (Temperature devices control)

HVAC LEVEL 1 CONTROL

NV-name		NV-type	NV-direction	Data description
NviHvacSetHCPow		SNVT_pwr_fact	Input	Setpoint Heating/Cooling power factor
NviHvacSetVPow		SNVT_pwr_fact	Input	Setpoint Ventilation power factor
NviHvacMode		SNVT_hvac_mode	Input	Operating mode of the HVAC Level 1 Control
NvoHvacHeatDev		SNVT_switch	Output	State of the heating device
NvoHvacCoolDev		SNVT_switch	Output	State of the cooling device
NvoHvacVentDev		SNVT_switch	Output	State of the ventilation device
NviHvacHeatOver		SNVT_switch	Input	Overrides Level 2 and controls Heating device
NviHvacCoolOver		SNVT_switch	Input	Overrides Level 2 and controls Cooling device
NviHvacVentOver		SNVT_switch	Input	Overrides Level 2 and controls Ventilation device
NvoHvacSts		SNVT_obj_status	Output	Status of the HVAC Level 1 Control
NciHvacConfSet		SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Table
TOTAL NVs	11			

Table 14: IRC NV's summary for functional area of use (HVAC level 1 control)

INTEGRATION CONTROL

NV-name		NV-type	NV-direction	Data description
NviGenDateTime		SNVT_time_stamp	Input	Date and Time
NvoGenSts		SNVT_obj_status	Output	Status of the IRC
NciGenConfSet[2]		SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Table
TOTAL NVs	4			

Table 15: IRC integration control

FUZZY CONTROL

EM-Code and -Name	EM-Format	EM-Direction	Data description
EmiFuzExtNormIn	Msg.code = 0x22 Msg.len = 16 Msg.data[0..15] = < strEmiFuzExtNormIn > typedef struct { struct { unsigned char ucIndex; unsigned char ucData; } strChan[8]; } strEmiFuzExtNormIn;	Input	Normalized Input Values [0..255] to the Fuzzy Control (max 8). All Inputs are present in the same message.
EmiFuzExtAmMfIn	Msg.code = 0x24 Msg.len = 3 Msg.data[0..2] = < strEmiFuzExtAmMfIn > typedef struct { unsigned char ucInIndex; unsigned char ucMfIndex; unsigned char ucMfData; } strEmiFuzExtAmMfIn;	Input	MFs for AM UcInIndex selects 1 of 8 Inputs [1..8] UcMfindex selects 1 of 8 MFs [1..8] UcMfData contains the MF
EmiFuzExtPcmMfIn	Msg.code = 0x26 Msg.len = 2 Msg.data[0..1] = < strEmiFuzExtPcmMfIn > typedef struct { unsigned char ucMfIndex; unsigned char ucMfData; } strEmiFuzExtPcmMfIn;	Input	MFs for PCM UcMfindex selects 1 of 256 Rules [0..255] UcMfData contains the MF
EmoFuzExtNormOut	typedef struct { unsigned char ucCode; struct { unsigned char ucIndex; unsigned char ucData; } strChan[4]; } strEmiFuzExtNormOut;	Output	Normalized Output Values [0..255] from the Fuzzy Control (max 4)
NvoFuzSts	SNVT_obj_status	Output	Status of the Fuzzy Control
NciFuzConfSet[2]	SNVT_str_int	Input	Application-specific, proprietary Configuration Parameter Tables
TOTAL NVs	3		

Table 16: IRC fuzzy control

3.3.1.3.2 Blind Level 1 Control Description

3.3.1.3.2.1 Functional description

The IRC Blind Control has to perform Level 1 control using closed loop or open loop, depending on the presence of a blind position sensor. Blind position setpoints are given by a fuzzy control, located either on IRC or on a Host-PC. The Level 1 Blind Control also contains several other tasks, e.g related to user interfaces. Following list all Level 1 tasks (in descending priority order):

1. internal hw-sw status (e.g. over-current control);
2. alarm Conditions (e.g meteorological conditions);
3. resync Command;
4. user Wishes (manual control);
5. automatic Control (Level 1).

Moreover user-selected blind positions and slats orientations remain active for a given time after setting. This time is fixed and configured by the Parameter CNF_BLD_TO_OVERRIDE_x. Automatic Control can also be completely disabled, if it causes too many user disturbances. The user can disabled it with his keyboard. Also, to prevent too many disturbing blind movements, a time filter has been used to limit the number of movements. Blind motion control is achieved both with the configured Parameters and with internal hidden S/W parameters, which prevent the Blind components of being damaged in case of bad configuration.

3.3.1.3.2.2 Scope of NV's and EM's

NV-name	Binding/Poll	When Value Update	Function Description
NviBldUp[2]	Bound to User interface push-buttons	When a push-button is pressed/released on User interface	Every array member controls the up-/down-motion of one separated blind
NviBldDn[2]			Every ON-pulse on this NV generated a pulse of pre-defined duration on the Blind control relay(s)
NviBldFine[2]			
NvoBldAlpha[2]	Polled by Host-PC	After motion stops	External regulations and Visualisation
NvoBldBeta[2]			
NviBldSetAlpha	Bound to Host-PC / Internal Update by Fuzzy Control	Values periodically checked by S/W to perform regulation	Level 1 open/close loop control is performed
NviBldSetBeta			
NviBldAutoDisable	Bound to User interface push-button	When a push-button is pressed/released on User interface	The blinds are set accordingly to NviBldSetAlpha and NviBldSetBeta or exclusively by user interventions
NvoBldAutoFb	Bound to User interface LED	When Automatic status changes	Signalization of the disabled (ON) or enabled (OFF) status of automatic blind control
NvoBldOverride	Polled by Host-PC	At regular intervals until User interface override timer expires	Polled. Shows the timeout value for override validity of user-interface interventions. Timeout value to be configured with NciBldConfSet.
NciBldConfSet	Updated by Host-PC	At commissioning time only (Max 10'000 write cycles !)	Application-specific, proprietary Configuration Parameter Table
EmiBldAlarm	Updated by Host-PC	E.g. during Blind maintenance or due to meteo conditions	The blind are set in the given position and blocked. The value AL_NO_ALARM enables blind control
EmiBldResync	Updated by Host-PC	E.g. once a day	The blinds are resynchronized

Table 17: IRC scope of NV's and EM's

3.3.1.3.2.3 Configuration parameter

NciBldConfSet

NV-Field	S/W Param-Name	Range	Meaning
Char_set			Unused
LOW Wide_char[0]	CNF_BLD_TO_MAN_AUT_1	0..255	100 msec ticks for changing from start-stop to start-aut blind movement of Blind 1
HIGH Wide_char[0]	CNF_BLD_TO_MAN_AUT_2	0..255	100 msec ticks for changing from start-stop to start-aut blind movement of Blind 2
LOW Wide_char[1]	CNF_BLD_TO_TOT_SLAT_1	5..255	20 msec ticks for slat total movement of Blind 1
HIGH Wide_char[1]	CNF_BLD_TO_TOT_SLAT_2	5..255	20 msec ticks for slat total movement of Blind 2
Wide_char[2]	CNF_BLD_TO_OVERRIDE_1	Full	1 sec ticks for user-interface override timeout of Blind 1
Wide_char[3]	CNF_BLD_TO_OVERRIDE_2	Full	1 sec ticks for user-interface override timeout of Blind 2
Wide_char[4]	CNF_BLD_TO_AUT_FILTER	Full	1 sec ticks for filter blind movements due to automatic control
LOW Wide_char[5]	CNF_BLD_TO_END_STOP_1	Full	1 sec ticks for motion-stop timeout of Blind 1 if no feedback sensor
HIGH Wide_char[5]	CNF_BLD_TO_END_STOP_2	Full	1 sec ticks for motion-stop timeout of Blind 2 if no feedback sensor
LOW Wide_char[6]	CNF_BLD_TO_FINE_REG_1	0..10	20 msec ticks for one fine regulating pulse on Blind 1
HIGH Wide_char[6]	CNF_BLD_TO_FINE_REG_2	0..10	20 msec ticks for one fine regulating pulse on Blind 2
LOW Wide_char[7]	CNF_BLD_BO_FB_SENS_1	0,1	0 = no position feedback sensor on Blind 1 1 = position feedback sensor present on Blind 1
HIGH Wide_char[7]	CNF_BLD_BO_FB_SENS_2	0,1	0 = no position feedback sensor on Blind 2 1 = position feedback sensor present on Blind 2
LOW Wide_char[8]	CNF_BLD_BO_SLATS_1	0,1	0 = no slat orientation on Blind 1 1 = slat orientation present on Blind 1
HIGH Wide_char[8]	CNF_BLD_BO_SLATS_2	0,1	0 = no slat orientation on Blind 2 1 = slat orientation present on Blind 2
LOW Wide_char[9]	CNF_BLD_SLAT_POS_UP_1	0..100	Slat 1 position during up motion, expressed in % (0 = horizontal, 100 = vertical). If no slat pos. Sensor only
HIGH Wide_char[9]	CNF_BLD_SLAT_POS_UP_2	0..100	Slat 2 position during up motion, expressed in % (0 = horizontal, 100 = vertical). If no slat pos. Sensor only
LOW Wide_char[10]	CNF_BLD_SLAT_POS_DN_1	0..100	Slat 1 position during down motion, expressed in % (0 = horizontal, 100 = vertical). If no slat pos. Sensor only
HIGH Wide_char[10]	CNF_BLD_SLAT_POS_DN_2	0..100	Slat 2 position during down motion, expressed in % (0 = horizontal, 100 = vertical). If no slat pos. Sensor only
Wide_char[...]			Unused

Table 18: IRC configuration parameters

Default Values for NciBldConfSet

S/W Param-Name	Default Value	Physical Value
CNF_BLD_TO_MAN_AUT_1	30	3 secs
CNF_BLD_TO_TOT_SLAT_1	25	500 msec
CNF_BLD_TO_FINE_REG_1	2	40 msec
CNF_BLD_TO_OVERRIDE_1	1200	20 minutes
CNF_BLD_TO_END_STOP_1	60	1 minute
CNF_BLD_BO_FB_SENS_1	1	position feedback sensor present on Blind 1
CNF_BLD_BO_SLATS_1	0	no slat orientation on Blind 1
CNF_BLD_SLAT_POS_UP_1	0	horizontal
CNF_BLD_SLAT_POS_DN_1	100	vertical
CNF_BLD_TO_MAN_AUT_2	30	3 secs
CNF_BLD_TO_TOT_SLAT_2	25	500 msec
CNF_BLD_TO_FINE_REG_2	2	40 msec
CNF_BLD_TO_OVERRIDE_2	1200	20 minutes
CNF_BLD_TO_END_STOP_2	60	1 minute
CNF_BLD_BO_FB_SENS_2	1	position feedback sensor present on Blind 2
CNF_BLD_BO_SLATS_2	0	no slat orientation on Blind 2
CNF_BLD_SLAT_POS_UP_2	0	horizontal
CNF_BLD_SLAT_POS_DN_2	100	vertical
CNF_BLD_TO_AUT_FILTER	600	10 minutes

Table 19: IRC configuration default values for “NciBldConfSET”

S/W Const Parameters

S/W Param-Name	Value	Meaning
SW_BLD_TO_INV	6	20 msec ticks (total 120 msec) timeout for blind motor motion reversion
SW_BLD_TO_MAX_MOV	120	1 sec ticks, timeout for absolute max motion duration

Table 20: IRC configuration default values for sw. Const parameters

3.3.1.3.3 Artificial Lighting Level 1 Control

3.3.1.3.3.1 Functional Description

The Level 1 Lighting Control performed by IRC consists of following tasks (in descending priority order):

1. User-Interface commands;
2. Automatic Control following Level 2 Fuzzy Setpoints.

The necessary controls handling with occupancy and natural light level are performed in Level 2. No Level 1 controls are performed for these issues. As User-interfaces two push-buttons are used to control every light. One push-button can turn the light on and increase the dimmer level, depending on the time length of the push-button pressing action. The second button turns light off and decreases the dimmer level. When lights are turned on, it's possible to configure the dimmer level which has to be set. It can be the old level (memory function), the Level 2 setpoint level or a pre-

defined one. Once the dimmer level has been changed by the User, a timeout is activated for the validity of the User Override action. After expiration of the timeout, the dimmer is set at the Level 2 Setpoint following a configurable time-function.

3.3.1.3.3.2 Scope of NV's and EM's

NV-name	Binding/Poll	When Value Update	Function Description
NviLigOnUp[2]	Bound to User interface push-buttons	When a push-button is pressed/released on User interface	Depending on the duration of the ON-OFF pulse, lights are turned on and/or dimmer levels are increased
NviLigOffDn[2]	Bound to User interface push-buttons	When a push-button is pressed/released on User interface	Depending on the duration of the ON-OFF pulse, lights are turned off and/or dimmer levels are decreased
NviLigSetLLevel	Bound to Host-PC / Internal Update by Fuzzy Control	Values periodically checked by S/W to perform regulation	Level 1 open/close loop control is performed
NvoLigSts[2]	Polled by Host-PC	At regular intervals while changing	Polled. Show Lighting states and dimmer levels
NvoLigOverride	Polled by Host-PC	At regular intervals until User interface override timer expires	Polled. Shows the timeout value for overriding validity of user-interface interventions
NciLigConfSet	Updated by Host-PC	At commissioning time only (Max 10'000 write cycles !)	Application-specific, proprietary Configuration Parameter Table

Table 21: IRC scope of NV's and EM's

3.3.1.3.3.3 Configuration parameters

Default Values for NciLigConfSet

S/W Param-Name	Default Value	Physical Value
CNF_LIG_SENS_1	5	Ca. 200 mV
CNF_LIG_SENS_2	5	Ca. 200 mV
CNF_LIG_TO_STEP_1	3	60 msec
CNF_LIG_TO_STEP_2	3	60 msec
CNF_LIG_LEV_ON_1	255	Level 2 setpoint
CNF_LIG_LEV_ON_2	255	Level 2 setpoint
CNF_LIG_TO_USER_OVER_1	900	15 minutes
CNF_LIG_TO_USER_OVER_2	900	15 minutes
CNF_LIG_TO_ONOFF_DIM_1	3	300 msec
CNF_LIG_TO_ONOFF_DIM_2	3	300 msec
CNF_LIG_TO_REST_LEV2_1	1800	30 minutes
CNF_LIG_TO_REST_LEV2_2	1800	30 minutes

Table 22: IRC default values "NciLigConfSet"

NciLigConfSet

NV-Field	S/W Param-Name	Range	Meaning
Char_set			Unused
LOW Wide_char[0]	CNF_LIG_SENS_1	1..63	Granularity of dimmer level increase/decrease [bits] . Light 1
HIGH Wide_char[0]	CNF_LIG_SENS_2	1..63	Granularity of dimmer level increase/decrease [bits] . Light 2
LOW Wide_char[1]	CNF_LIG_TO_STEP_1	1..25	20 msec ticks for increasing/decreasing the dimmer level of 1 pre-defined step. Light 1
HIGH Wide_char[1]	CNF_LIG_TO_STEP_2	1..25	20 msec ticks for increasing/decreasing the dimmer level of 1 pre-defined step. Light 2
LOW Wide_char[2]	CNF_LIG_TO_ONOFF_DIM_1	1..30	100 msec ticks for dimmer start or turn light off. Light 1
HIGH Wide_char[2]	CNF_LIG_TO_ONOFF_DIM_2	1..30	100 msec ticks for dimmer start or turn light off. Light 2
Wide_char[3]	CNF_LIG_TO_REST_LEV2_1	0..65535	1 sec ticks for restoring the Level 2 Setpoint after expiring of User Override timeout. Full-scale value (scaling is applied). Light 1.
Wide_char[4]	CNF_LIG_TO_REST_LEV2_2	0..65535	1 sec ticks for restoring the Level 2 Setpoint after expiring of User Override timeout. Full-scale value (scaling is applied). Light 2.
LOW Wide_char[5]	CNF_LIG_LEV_ON_1	0..255	Dimmer level after turning light ON. [bits] 0 = old level. 255 = Level 2 Setpoint. Light 1
HIGH Wide_char[5]	CNF_LIG_LEV_ON_2	0..255	Dimmer level after turning light ON. [bits] 0 = old level. 255 = Level 2 Setpoint. Light 2
Wide_char[6]	CNF_LIG_TO_USER_OVER_1	Full	1 sec ticks for user-interface override timeout. Light 1
Wide_char[6]	CNF_LIG_TO_USER_OVER_2	Full	1 sec ticks for user-interface override timeout. Light 2
Wide_char[...]			Unused

Table 23: IRC configuration parameters “NciLigConfSet”

3.3.1.3.4 Room occupancy control (level 1 pre processing)

3.3.1.3.4.1 Functional Description

The Room Occupancy Control generates a “logical room occupancy status” synthesising the signal from the room occupancy sensor and the User-interfaces actions. This control is rather thought to be used as “help-function” during the experimental tests, in order to force Level 2 and Level 3 algorithms to work in a certain occupancy status.

3.3.1.3.4.2 Scope of NVs and EMs

NV-name	Binding/Poll	When Value Update	Function Description
NviOccAutSw	Not used in Experimental testing	Internal S/W status “occupancy” set accordingly, if not forced	Signal from a remote presence detector sensor
NviOccAutOcc			Signal from a remote presence detector sensor (type alternative to SNVT_switch)
NviOccCmdOn	Bound to User Interface push-buttons	Internal S/W status “occupancy” forced	Pulse command to activate/disable forcing of presence to “ON”
NviOccCmdOff			Pulse command to activate/disable forcing of presence to “OFF”
NvoOccSts	Bound to User Interface LED and polled by Host-PC	When internal S/W status “occupancy” changes	Shows the logical occupancy status of the room
NvoOccCmdOn	Bound to User Interface LED	When forcing status of occupancy changes	Shows the forcing status for presence “ON” (for user-interface feedback)
NvoOccCmdOff			Shows the forcing status for presence “OFF” (for user-interface feedback)
NvoOccOver	Polled by Host-P	At regular intervals until User interface override timer expires	Shows the timeout value for override validity of user-interface interventions
NciOccConfSet	Updated by Host-PC	At commissioning time only (Max 10'000 write cycles !)	Application-specific, proprietary Configuration Parameter Table

Table 24: IRC Scope of NVs and Ems

3.3.1.3.4.3 Configuration Parameters

NciOccConfSet

NV-Field	S/W Param-Name	Range	Meaning
Char_set			Unused
Wide_char[0]	CNF_OCC_TO_USER_OVER	Full	1 sec ticks for user-interface override timeout. 0 = no forcing allowed 65535 = forever
Wide_char[...]			Unused

Table 25: IRC configuration parameters “NciOccConfSet”

Default Values for NciOccConfSet

S/W Param-Name	Default Value	Physical Value
CNF_OCC_TO_USER_OVER	65535	User can force occupancy status with no expiring timeout

Table 26: IRC default values for “NciOccConfSet”

3.3.1.3.5 Temperature Devices Control (Level 1 pre-processing)

3.3.1.3.5.1 Functional Description

This Control manages all Devices (Sensors and User-Interfaces) which generates Temperature values or Temperature-related control commands. These devices are:

- Temperature Sensors (internal and external Temperature);
- Setpoint devices (Level 2 Controls);
- User Interfaces to correct Temperature Setpoints.

The control pre-processes incoming values from these devices and generates a sw. internal operating Temperature Setpoint, which is then used to perform Level 1 HVAC Control.

3.3.1.3.5.2 Scope of NVs and EMs

NV-name	Binding/Poll	When Value Update	Function Description
NviTempSensInt[2]	Not used in Experimental Tests	A mean value is computed and sent to Level 2	These two Inputs allow two different internal temp. Sensors to be used. The mean value gives the S/W-internal Temperature
NviTempSensExt	Bound to Host-PC/not bound (depends on Test Site)	The value is sent to Level 2	The external Temperature is forwarded to Level 2 Control (internal or external to IRC)
NviTempSet	Bound to Host-PC / Internal default value	Values periodically checked by S/W to perform pre-processing of operating Temp. Setpoint	Pre-processing only
NviTempOffset	Bound to User Interface	Pre-processing of operating Temp. Setpoint	Pre-processing only
NvoTempInt	Polled by Host-PC	When changes. Internal polling by Level 2 Fuzzy Control if present	Polled. Actual mean-value internal Temperature
NvoTempExt	Polled by Host-PC (depends on Test Site)		Forwarding only
NvoTempSet	Bound to Host PC / Internal Bound to Fuzzy Control	When one of Setpoint Input changes (NviTempSet and/or NviTempOffset)	The Actual working Temp Setpoint used by Level 2 Fuzzy Control
NciTempConfSet	Updated by Host-PC	At commissioning time only (Max 10'000 write cycles !)	Application-specific, proprietary Configuration Parameter Table

Table 27: IRC scope of Nv's and EM's

3.3.1.3.5.3 Configuration Parameters

No Parameters are foreseen for this Control. No Default Values for "NciTempConfSet".

NciTempConfSet

NV-Field	S/W Param-Name	Range	Meaning
Char_set			Unused
Wide_char[...]			Unused

Table 28: IRC configuration parameters "NciTempConfSet"

3.3.1.3.6 HVAC level 1 control

3.3.1.3.6.1 Functional Description

The HVAC Level 1 must control different types of HVAC actuators using different algorithms. In the actual version, the Control handles with the actuator types present in the Experimental Test Sites. An extension and general rules for the algorithms are suitable at a later phase. For heating the control support 3 different scenarios, since every Test Site uses different actuators:

1. Fan-Coil (CONPHOEBUS);
2. Time-Modulating Valve (LESO);
3. Heating Coil + Damper (VTT).

For Cooling, fan-coil only is supported (CONPHOEBUS). The other test sites don't have a cooling plant. Ventilation is present at CONPHOEBUS and VTT with almost the same solution (Damper Actuator), but VTT can further use the damper actuator coupled with the Heating Coil for ventilation purposes. Since a problem could happen where combined Heating/Cooling plants with seasonal switching are used (CON), the NV "NviHvacMode" can give information to the IRC about the operating mode of the primary combined plant through the Host-PC (not a configuration parameter). Also, to enhance testing possibilities for the algorithms, a direct control of the HVAC actuators can be used instead of the Poer Factors generated by the Level 2 Control. Comparing the different results can help in optimising the Level 2 algorithms.

3.3.1.3.6.2 Scope of NVs and EMs

NV-name	Binding/Poll	When Value Update	Function Description
NviHvacSetHCPow	Bound to Host PC / Internal Bound to Fuzzy Control	Periodical check by Level 1 Control	Heating/Cooling power factor. Neg.Values mean "Cooling", Pos. Values mean "Heating"
NviHvacSetVPow			Ventilation power factor. This factor will proportionally affect the damper actuator positions. Positive Values only.
NviHvacMode	Bound to Host PC	Periodical check by Level 1 Ventilation Control	Depending on the mode (HEAT/COOL/AUTO) the proportional valve controls are set
NvoHvacHeatDev	Polled by Host-PC	Periodical update	Polled. State of the heating device [%]
NvoHvacCoolDev			Polled. State of the cooling device [%]
NvoHvacVentDev			Polled. State of the ventilation device [%]
NviHvacHeatOver	Bound to Host-PC	Set correspondig device accordingly	Direct HVAC Control. To be used to override the Power Factors generated by Level 2. For testing purposes.
NviHvacCoolOver			
NviHvacVentOver			
NvoHvacSts	Polled by Host-PC	Periodical update	The complete Status of the HVAC Level 1 Control is given for Visualization of Alarming functions
NciHvacConfSet	Updated by Host-PC	At commissionig time only (Max 10'000 write cycles !)	Application-specific, proprietary Configuration Parameter Table

Table 29: IRC scope of NV's and EM's

3.3.1.3.6.3 Configuration Parameters

NciTempConfSet

NV-Field	S/W Param-Name	Range	Meaning
Char_set			Unused
LOW Wide_char[0]	CNF_FAN_MIN_MID	0..100	% Thermal Power Factor value for fan switching from min to mid
HIGH Wide_char[0]	CNF_FAN_MID_MAX	0..100	% Thermal Power Factor value for fan switching from mid to max
LOW Wide_char[1]	CNF_HEAT_DAMPER	0..100	% minimum Thermal Power Factor value requested for damper actuator enabling (VTT)
HIGH Wide_char[1]	CNF_VENT_DAMPER	0..100	% minimum Ventilation Power Factor value requested for 2. damper actuator enabling (VTT). If Heating is using the same damper, a mean value is used
Wide_char[2]	CNF_HEAT_TO_STEP	1..65535	1 sec ticks for Power Factor History
LOW Wide_char[3]	CNF_HEAT_TYPE	[0..3]	0 = no heating plant present 1 = fan-coil heat (CON) 2 = time-modulation (LESO) 3 = heating coil + damper (VTT)
HIGH Wide_char[3]	CNF_COOL_TYPE	[0..1]	0 = no cooling plant present (LESO,VTT) 1 = fan-coil
LOW Wide_char[4]	CNF_VENT_TYPE	[0..2]	0 = no ventilation present (LESO) 1 = by-pass ventilation (CON) 2 = damper actuators (1 combined with heating)
Wide_char[...]			Unused

Table 30: IRC configuration parameters “NciTempConfSet”

3.3.1.3.7 Fuzzy control (level 2)

Despite implemented in IRC, fuzzy control wasn't implemented in this project at IRC level. Fuzzy rules have been applied and implemented at software level (within Matlab applications). For this reason description of fuzzy functionality is swept out from this report.

3.3.1.3.8 IRC integration control

3.3.1.3.8.1 Functional Description

The main purpose of the IRC Integration Control is to map the physical Ios of the board to the functional S/W objects. This is necessary to guarantee the necessary flexibility to the IRC required by different Test Sites, without having to write different S/W applications for everyone of them. This feature will probably be required even in real use conditions.

Other tasks to be performed by the Integration Control are:

- Calendar & Clock Function;
- Monitoring of the operations inside IRC and alarming in case of malfunctioning.

3.3.1.3.8.2 Scope of NV's and EM's

NV-name	Binding/Poll	When Value Update	Function Description
NviGenDateTime	Updated by Host-PC	--	Date and Time. At the moment not used.
NvoGenSts	Bound to Host-PC	When changes	Status of the IRC
NciGenConfSet[2]	Updated by Host-PC	At commissioning time only (Max 10'000 write cycles !)	Application-specific, proprietary Configuration Parameter Table

Table 31: IRC scope of NV's and EM's

3.3.1.3.8.3 Configuration Parameters

“Logical” sensors and actuators used by the Level 1 Controls have following IDs to be used in the Configuration Parameter settings:

Sensor/Actuator Name	Sensor/Actuator ID
SENS_INT_TEMP_1	0X01
SENS_INT_TEMP_2	0X02
SENS_EXT_TEMP	0X03
OCC_SENSOR	0X04
BLIND_POS_1	0X05
BLIND_POS_2	0X06
SOLAR_RAD	0X07
LUX_SENS_1	0X08
LUX_SENS_2	0X09
LUX_SENS_3	0X0A
WIND_SPEED	0X0B
WIND_DIR	0X0C
LIGHT_DIMMER	0X81
LIGHT_RELAY	0X82
FAN_COIL_VALVE	0X83
FAN_COIL_FAN_MIN	0X84
FAN_COIL_FAN_MID	0X85
FAN_COIL_FAN_MAX	0X86
VENT_BY_PASS_MOD	0X87
POWER_10_V	0X88
FREE_COOL	0X89
BLIND_UP_1	0X8A
BLIND_UP_2	0X8B
BLIND_DOWN_1	0X8C
BLIND_DOWN_2	0X8D
HEAT_TIME_MOD	0X8E
HEAT_VENT_DAMPER	0X8F
HEAT_COIL	0X90
VENT_DAMPER	0X91
BY_PASS_REL	0X92

Table 32: IRC logical sensors and actuators names

NciGenConfSet[0]: SENSOR MAPPING

NV-Field	S/W Param-Name	Range	Meaning
Char_set		See Table Above with IDs	Unused
LOW Wide_char[]	CNF_IOMAP_SENS_S1		Function of S1, PT100
HIGH Wide_char[]	CNF_IOMAP_SENS_S2		Function of S2, PT100
LOW Wide_char[]	CNF_IOMAP_SENS_S3		Function of S3, Uncommitted Contact
HIGH Wide_char[]	CNF_IOMAP_SENS_S4		Function of S4, 0-10V/0-20mA
LOW Wide_char[]	CNF_IOMAP_SENS_S5		Function of S5, 0-10V/0-20mA
HIGH Wide_char[]	CNF_IOMAP_SENS_S6		Function of S6, 0-10V/0-20mA
LOW Wide_char[]	CNF_IOMAP_SENS_S7		Function of S7, 0-10V/0-20mA
HIGH Wide_char[]	CNF_IOMAP_SENS_S8		Function of S8, 0-10V/0-20mA
LOW Wide_char[]	CNF_IOMAP_SENS_S9		Function of S9, 0-10V/0-20mA
HIGH Wide_char[]			
Wide_char[...]			Unused

Table 33: IRC sensors mapping “NciGenConfSet[0]”

Default Values for NciGenConfSet[0]

S/W Param-Name	Default Value	Physical Value
CNF_IOMAP_SENS_S1	0X01	SENS_INT_TEMP_1
CNF_IOMAP_SENS_S2	0X03	SENS_EXT_TEMP
CNF_IOMAP_SENS_S3	0X04	OCC_SENSOR
CNF_IOMAP_SENS_S4	0X08	LUX_SENS_1
CNF_IOMAP_SENS_S5	0X05	BLIND_POS_1
CNF_IOMAP_SENS_S6	0X07	SOLAR_RAD
CNF_IOMAP_SENS_S7	0X0B	WIND_SPEED
CNF_IOMAP_SENS_S8	0X0C	WIND_DIR
CNF_IOMAP_SENS_S9	0	Not used

Table 34: IRC default values for “NciGenConfSet[0]”

NciGenConfSet[1]: ACTUATOR MAPPING

NV-Field	S/W Param-Name	Range	Meaning
Char_set			Unused
LOW Wide_char[3]	CNF_IOMAP_ACT_A1	See Table Above with IDs	Function of A1, 0-10V
HIGH Wide_char[3]	CNF_IOMAP_ACT_A2		Function of A2, 0-10V
LOW Wide_char[3]	CNF_IOMAP_ACT_A3		Function of A3, 0-10V
HIGH Wide_char[3]	CNF_IOMAP_ACT_A4		Function of A4, 0-10V
LOW Wide_char[3]	CNF_IOMAP_ACT_A5		Function of A5, Rel. 230V/15A
HIGH Wide_char[3]	CNF_IOMAP_ACT_A6		Function of A6, Rel. 230V/15A
LOW Wide_char[3]	CNF_IOMAP_ACT_A7		Function of A7, Rel. 230V/15A
HIGH Wide_char[3]	CNF_IOMAP_ACT_A8		Function of A8, Rel. 230V/15A
LOW Wide_char[3]	CNF_IOMAP_ACT_A9		Function of A9, Rel. 230V/15A
HIGH Wide_char[3]	CNF_IOMAP_ACT_A10		Function of A10, Rel. 230V/15A
LOW Wide_char[3]	CNF_IOMAP_ACT_A11		Function of A11, Rel. 230V/15A
HIGH Wide_char[3]	CNF_IOMAP_ACT_A12		Function of A12, Rel. 230V/15A
Wide_char[...]			

Table 35: IRC actuator mapping “NciGenConfSet[1]”

Default Values for NciGenConfSet[1]

S/W Param-Name	Default Value	Physical Value
CNF_IOMAP_ACT_A1	0X81	LIGHT_DIMMER
CNF_IOMAP_ACT_A2	0X83	FAN_COIL_VALVE
CNF_IOMAP_ACT_A3	0X87	VENT_BY_PASS_MOD
CNF_IOMAP_ACT_A4	0X88	POWER_10_V
CNF_IOMAP_ACT_A5	0X89	FREE_COOL
CNF_IOMAP_ACT_A6	0X82	LIGHT_RELAY
CNF_IOMAP_ACT_A7	0X8A	BLIND_UP_1
CNF_IOMAP_ACT_A8	0X8C	BLIND_DOWN_1
CNF_IOMAP_ACT_A9	0C83	FAN_COIL_FAN_MIN
CNF_IOMAP_ACT_A10	0X84	FAN_COIL_FAN_MID
CNF_IOMAP_ACT_A11	0X85	FAN_COIL_FAN_MAX
CNF_IOMAP_ACT_A12	0X92	BY_PASS_REL

Table 36: IRC default values for “NciGenConfSet[1]”

3.3.1.4 USER INTERFACE MODULES

Two OEM LonWorks devices are used in every test room as user interface device description:

- LFT-DESK-12: This is a 12-buttons-keyboard, which can be placed on the desk inside the test room. The 12 buttons can be used to turn on/off the light, to regulate the light intensity, to control the blinds and the ventilation. Furthermore we can use buttons to control some software functions inside the IRC (to be defined);
- LFTDOOR-2-LEDS: This device is used to set up the internal temperature set point in a room. With two push buttons the set point can be incremented / decremented in steps of 0.5°C. With some leds of different colours the actual set point is indicated to the user.

3.3.1.4.1 Multifunctional Keyboard LFT-DESK-12

3.3.1.4.1.1 12-Keys Sensor

This object detects push-button state changes. It sends the corresponding NV-output over the network with the correspondent value. Limits:

- Once a push-button is pressed, other push-button pressed will not be detected.
- The push-button releases is only detected upon release of all pressed push-buttons.

3.3.1.4.1.2 12-LEDs/Buzzer Actuator

This object has a NV-Input for the Buzzer and 12 NV-Inputs for the LEDs. Depending on the value of nci03InvLed, the LEDs are turned ON or OFF accordingly to the values of the NV-Inputs or to the opposite of their values (if nci03InvLed is FALSE, then NV-Input ON => LED ON).

3.3.1.4.1.3 Reset Behavior

The 12-Keys Sensor enables the keyboard and it initialises nvo02KeyPressed = 0.

The 12-LEDS/Buzzer Actuator polls the corresponding NV-Inputs and sets the LEDs and Buzzer accordingly.

3.3.1.4.1.4 Input Network Variables

Obj.NVID	Type	Name	Function	Range
@0 1.	SNVT_obj_request	nvi00Request	Not used	
@0 3.	SNVT_time_stamp	nvi00TimeSet		
@0 25.	SNVT_switch	nvi00Reserve1		
@1 1.	SNVT_switch	nvi01EnterReq		
@1 6.	SNVT_switch	nvi01EnterResp		
@1 7.	SNVT_switch	nvi01WaitResp		
@1 8.	SNVT_switch	nvi01BusyResp		
@1 13.	SNVT_switch	nvi01AbsentResp		
@3 1.	SNVT_switch	nvi03Led[12]	LEDs control	
@3 2.	SNVT_switch	nvi03Buzzer	Buzzer control	

Table 37: Input network variables

3.3.1.4.1.5 Output Network Variables

Obj.NVID	Type	Name	When Transmitted	Range
@0 2.	SNVT_obj_status	nvo00Status		
@0 5.	SNVT_count	nvo00FWVersion	S/W Version	Const
@0 26.	SNVT_switch	nvo00Reserve1	Not used	
@1 2.	SNVT_switch	nvo01ELedReq		
@1 3.	SNVT_switch	nvo01WLedReq		
@1 4.	SNVT_switch	nvo01BLedReq		
@1 5.	SNVT_switch	nvo01BuzzReq		
@1 9.	SNVT_switch	nvo01ELedResp		
@1 10.	SNVT_switch	nvo01WLedResp		
@1 11.	SNVT_switch	nvo01BLedResp		
@1 12.	SNVT_switch	nvo01BuzzResp		
@1 14.	SNVT_switch	nvo01AbsLedReq		
@1 15.	SNVT_switch	nvo01AbsLedResp		
@2 1.	SNVT_switch	nvo02Key[12]		Corresponding push-button pressed/released
@2 2.	SNVT_switch	nvo02KeyPressed	One of 12 keys is pressed/ None is pressed	

Table 38: output network variables

3.3.1.4.1.6 Configuration Network Variables

Obj.NVID	Tipo	Nome	Effetto	Range
@0 4.	SNVT_elapsed_time	nci00MaxSendT		
@0 6.	SNVT_lev_disc	nci00EEpromLock	EEPROM lock/unlock: ST_LOW : unlock EEPROM ST_MED : app reboot ST_HIGH : lock EEPROM	
@1 16.	SNVT_elapsed_time	nci01BuzzTime	Buzzer duration	
@3 3.	SNVT_switch	nci03LedInv[12]	LED control inversion	

Table 39: configuration network variables

3.3.1.4.1.7 HW and NV Associations

The Association between physical Ios and NVs are showed in the following table.

nvo02Key[0] nvi03Led[0]	nvo02Key[1] nvi03Led[1]	nvo02Key[2] nvi03Led[2]
nvo02Key[3] nvi03Led[3]	nvo02Key[4] nvi03Led[4]	nvo02Key[5] nvi03Led[5]
nvo02Key[6] nvi03Led[6]	nvo02Key[7] nvi03Led[7]	nvo02Key[8] nvi03Led[8]
nvo02Key[9] nvi03Led[9]	nvo02Key[10] nvi03Led[10]	nvo02Key[11] nvi03Led[11]

Table 40: HW –NV associations

3.3.1.4.2 Setpoint Control Device LFTDOOR-2-LEDS

3.3.1.4.2.1 Functional Description

The device can adjust the Temperature set point by means of two push-buttons or using a NV-input. The step-scaling of every Temp. Set point increment/decrement is configurable. After Reset the Offset value is also reset to 0.

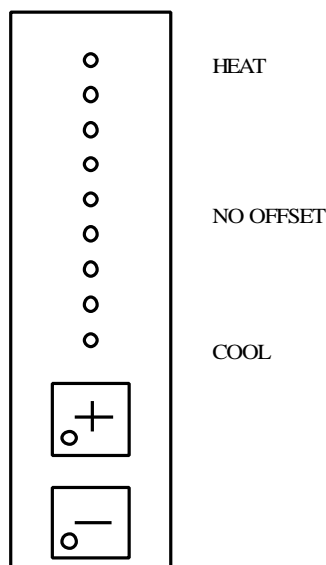


Figure 36: Control device LFTDOOR-2-leds

3.3.1.4.2.2 Input Network Variables

OBJ: NV ID	# OF BYTES	TYPE	NAME	DESCRIPTION
#1:1		SNVT_switch	nvi01Occupied. state	Command occupied/not occupied. (1 = occupied, 0 = not occupied)
#1:3		SNVT_temp_p	nvi01OffsetTemp. state	Temp. Setpoint with Offset
#1:5		SNVT_switch	nvi01Buzzer.state	Buzzer activation
#1:7		SNVT_switch	nvi01Spare1[0]	Offset increasing command
#1:7		SNVT_switch	nvi01Spare1[1]	Offset decreasing command
#1:9		SNVT_count	nvi01Spare2[2]	Réserve.

Table 41: input network variables

3.3.1.4.2.3 Output Network Variables

OBJ: NV ID	# OF BYTES	TYPE	NAME	DESCRIPTION
#1:2		SNVT_temp_p	nvo01OffsetTemp	Feedback Setpoint with offset
#1:4		SNVT_temp_p	nvo01SupOffTemp	Feedback Setpoint with offset (for Supervisor)
#1:6		SNVT_switch	nvo01KeyPlus.state	Push Button Status for increasing offset
#1:8		SNVT_switch	nvo01KeyMinus. state	Push Button Status for decreasing offset
#1:10		SNVT_switch	nvo01Spare1[2]	Not Used
#1:11		SNVT_count	nvo01Spare2[2]	Not Used

Table 42: output network variables

3.3.1.4.2.4 Configuration Network Variables

OBJ: NV ID	# OF BYTES	TYPE	NAME	DESCRIPTION
#1:12	2	SNVT_temp_p 2 bytes	nci01KeyTemp. DeltaKey	Temp. Offset granularity
#1:12	2	SNVT_temp_p 2 bytes	nci01KeyTemp. Occupied	Temp. Offset if occupied
#1:12	1	Unsigned 1 bytes	nci01KeyTemp. ActiveOccup	Offset enable/disable on occupancy (1 = enabled, 0 = disabled)
#1:12	2	SNVT_temp_p 2 bytes	nci01KeyTemp. NotOccupied	Temp. Offset if not occupied
#1:12	1	Unsigned 1 bytes	nci01KeyTemp. ActiveNotOccup	Offset enable/disable on not-occupancy (1 = enabled, 0 = disabled)
#1:12	1	Unsigned 1 bytes	nci01KeyTemp. uCount	Offset changing limit
#1:12	1 * 22	Unsigned 1 bytes	nci01KeyTemp. Spare[22]	Not Used
#1:13	2	SNVT_count 2 bytes	nro01FWVersion	S/W Version Default 101

Table 43: configuration network variables

3.3.2 TASK ET2: TEST BY SIMULATIONS

The objectives of this subtask were:

- To check the correct operation of the integrated software
- To simulate conditions which are not tested during the experiments:
 - Control block variants, e.g. set-back, start-up, set-points
 - Seasons/climates
 - Room and device types, e.g. heating and cooling where there is no cooling
 In order to establish a wider comparison of the performance of the Edificio controller, compared to a standard controller.

A large number of simulations had already been done along with the development of the integrated software (task AD) and the first objective was thus already fulfilled.

3.3.2.1 SIMULATION SET-UP

The integrated model was used for the simulation with some modifications as presented previously. Only the level 2 software was simulated since level 3 was the object of a separate study and with a different approach.

The fixed items were:

- The ventilation rate when ventilation was applied
- The user presence schedule. (As no suitable user presence predictor could be made available for this task).

The variable items were:

- The rooms: LESO, VTT and Conphoebus cases (all oriented towards south)
- The models of the rooms: either a 28 nodes or an identified model using experimental results. The latter could only be produced for the LESO and VTT cases and only valid for the specific experimental period
- The set points for the internal temperature and for the illuminance.
- The controller: Reference or Edificio.

The various fixed and variable parameters are described below in more details.

3.3.2.1.1 Room types

The characteristics of the rooms are given in the table below.

Room	LESO	CONPHOEBUS	VTT - METOP 13	VTT - METOP 12
Controler	Both	both	reference	edificio
Floor (m2)	15.6	11.8	10.78	10.395
Volume (m3)	43.7	38.35	31.54	30.76
windows area (m2)	3.8	6	2.3	2.3
window orientation	South	South	South	South
window/floor ratio	0.244	0.508	0.213	0.221
lights	on/off and dimming	on/off and dimming	on/off	on/off and dimming
Light power (W)	0-240	0-144	130	0-21-131
heating power (W))	1000	4000	250	250
cooling power	--	-2000	--	--
Ventilation min (l/s)	0	15	10	10
Ventilation max (l/s)	0	27	40	40

3.3.2.1.2 Reference case

Climate

The Lausanne climate serves as reference for comparisons. The other base cases are with the Catania and Espoo climates. The year is divided in the respective heating/cooling periods to sum the energy and comfort index (when and where applicable).

User

There is only one user with a fixed presence schedule.

Thermal controller

The base case is a proportional controller with night setback for all rooms.

$P_{heat} = P_{max}$ if $T < 18^{\circ}C$

$P_{heat} = 0$ if $T > 22^{\circ}C$

$P_{cool} = P_{max}$ if $T > 24$

$P_{cool} = 0$ if $T < 20$

Ventilation controller (TNO report 30.9.99)

The ventilation renewal rate is 1.666 during office hours, zero otherwise.

Variant: twice this value

Blind controller (LESO report R26, 28.9.99)

A simple blind strategy with hysteresis is proposed as a base case for the simulation:

- When the user is present in the room, the blind is closed to $\alpha = 0.25$ when the incident solar radiation on the facade becomes higher than 300 W/m^2 ;
- When the user is present in the room, the blind is open ($\alpha = 1$) when the incident solar radiation on the facade becomes lower than 100 W/m^2 ;
- The blind is never moved when there is no (simulated) occupancy, according to the occupancy schedule;
- When the user enters the room (from the occupancy schedule), the blind is moved according to the first two rules, if one of them applies.

Artificial lighting controller (LESO report R26, 28.9.99)

The following strategy was applied:

- When the user is present in the room, the artificial lighting is switched on when the inside luminance (due to daylighting) becomes lower than 200 lux ;
- When the user is present in the room, the artificial lighting is switched off when the inside luminance (due to day lighting) becomes higher than 600 lux ;
- The artificial lighting is switched off when the user leaves the room (at the end of the daily occupancy period);
- Then the user enters the room (from the occupancy schedule), the artificial lighting is switched on according to the first rule (i.e. if it is valid).

The inside luminance is calculated from the daylighting room model, following a simple linear model including the blind effect:

$$E_{in} = E_{out} \cdot (RI_0 \cdot (1 - a) + RI_1 \cdot a)$$

where: E_{in} = inside illuminance on the desk [lux]

- E_{out} = outside illuminance on a horizontal surface [lux]
- RI_0 = illuminance ratio factor when the blind is closed
- RI_1 = illuminance ratio factor when the blind is open
- a = blind position (0 = closed, 1 = open)

The following values are proposed for the illuminance ratio factors in the simulation:

- $RI0 = 0.005$
- $RI1 = 0.05$

The outside illuminance can be approximated simply in function of the global solar radiation:

$E_{out} [lux] = 110 \cdot G_h [W/m^2]$ where G_h is the global solar radiation on a horizontal surface.

3.3.2.1.3 EDIFICIO Controller

Thermal controller

Reference:

Predictive fuzzy with four input parameters (as in test sites)

Smoothed temperature set-point

Power profile continuous adaptation - working/non-working day and Monday profile

Variants:

Change max/min set-points

With/without free cooling

Predictive fuzzy with two input parameters.

Lighting controller

Blind variants

Blind type: venetian blinds, textile roll-down blinds

Controller variants

Setpoint illuminance value (300 and 600 lux)

Artificial lighting control strategy (continuous dimming)

3.3.2.2 SIMULATION CASES

The list of simulation cases is given in the table below.

Case Nr.	Controller	Test site	Room model	Climate file	Thermal Str.	T set points	Blind set-points	Illumin. Set-point
1	Reference without set-back	LESO	28 nodes	Lausanne	Ref.	22/18	0.25(300) 1(100)	200/600
1b	Reference with set-back	LESO	28 nodes	Lausanne	Ref.	22/18	0.25(300) 1(100)	200/600
2	Reference w. set-back	METOP w. ventil.	28 nodes	Espoo	Ref.	22/18	0.25(300) 1(100)	200/600
3	Reference w. set-back	CATANIA w. Ventil & thermal ventil.	28 nodes	Catania	Ref.	22/18 22/24	0.25(300) 1(100)	200/600
4	Edificio	LESO	28 nodes	Lausanne	Therm1006	22/18	0.25(300) 1(100)	600
5	Edificio	METOP	28 nodes	Espoo	Therm1006	22/18	0.25(300) 1(100)	600
6	Edificio	CATANIA w. Ventil & thermal ventil.	28 nodes	Catania	Therm1006	22/18 22/24	0.25(300) 1(100)	600
7	Reference w. set-back	LESO w. cooling & ventil.	28 nodes	Lausanne	Therm1006	22/18 22/24	0.25(300) 1(100)	600
8	Reference w. set-back	LESO w. cooling & ventil.	28 nodes	Lausanne	Ref.	20/16 20/24	0.25(300) 1(100)	200/300
9	Reference w. set-back	LESO experiment	Identified model	Lausanne	Ref.	22/18	0.25(300) 1(100)	200/600
10	Reference w. set-back	METOP experiment	Identified model	Espoo	Ref.	22/18	0.25(300) 1(100)	200/600
11	Edificio	LESO w. cooling & ventil.	28 nodes	Lausanne	Therm1006	22/18 22/24	0.25(300) 1(100)	600
12	Edificio	LESO w. cooling & ventil.	28 nodes	Lausanne	Therm1006	20/16 20/24	0.25(300) 1(100)	600
13	Edificio	LESO experiment	Identified model	Lausanne	Therm1006	22--- 18	0.25(300) 1(100)	600
14	Edificio	METOP experiment	Identified model	Espoo	Therm1006	22/18	0.25(300) 1(100)	600
15	Edificio - perfect climate prediction	LESO w. cooling & ventil.	28 nodes	Lausanne	Therm1006	20/16 20/24	0.25(300) 1(100)	600

Table 44: Main parameters of the various simulation cases

3.3.2.3 DISCOMFORT INDICES

3.3.2.3.1 Thermal discomfort calculation

Two methods were used: a linear definition of discomfort and the one derived from Fanger's formalism as follows. Each method will provide a comparison of the controllers on three different time scales:

- Instantaneous value
- Day basis
- Seasonal

3.3.2.3.1.1 Linear method

$$TDL = \frac{T_{in} - T_{set}}{T_{set}} \cdot Pr$$

Where T_{in} is the internal room temperature

T_{set} is the set point temperature

Pr is the presence indication : 0 if user not present, 1 if present.

a) Instantaneous thermal discomfort level

The histogram of TDL fits with a gaussian curve.

$$TDD = \frac{1}{n} \sum_{1-n} TDL^2$$

TDD is the standard deviation of TDL over a day (one value per day of simulation)

n is the number of samples (normally 96 with a 15 minutes sample time)

b) Discomfort comparison on a daily basis

In practice the sum is replaced by a forward Euler discrete integration in simulink, with a time unit of 1 day.

c) Total (integrated) discomfort comparison on a given period (season)

$$TDP = \int_1^N |TDL| \cdot dt$$

N is the number of days in the period.

In practice, a forward Euler discrete integration is used

3.3.2.3.1.2 Method with Fanger's formalism

a) Instantaneous thermal discomfort level

$$PMV = a \cdot (T_{int} - T_{set}) \cdot Pr$$

with $a \cong 0.2$ and

$$PPD = 100 - 95 \cdot \exp\{-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)\} \quad [\%]$$

b) Discomfort comparison on a daily basis

Thermal discomfort (warm) = fraction of time $PMV > 0.5$

Thermal discomfort (cold) = fraction of time $PMV < -0.5$

Note that this does not allow a fine comparison of good thermal controllers i.e. controllers which always give an error of less than 2.5°C

c) Total (integrated) discomfort comparison on a given period (season)

Same method:

Thermal discomfort (warm) = fraction of time $PMV > 0.5$

Thermal discomfort (cold) = fraction of time $PMV < -0.5$

3.3.2.3.2 Visual discomfort

The visual discomfort may come from three different reasons:

- The illuminance level could be not adequate (too bright or too dark)
- There could be a problem of glare
- The quality of the artificial light is worse than the natural light

Unfortunately, the glare problem cannot be taken into account in a reliable way, because it depends on the user position in the room, and on geometrical characteristics of the room. So, a visual discomfort function has been based only on the two other points:

$$\text{Discomfort function} = C_1 \cdot \frac{(I_{tot}/I_{set} - 1)^2}{I_{tot}/I_{set}} + C_2 \cdot I_{art}/I_{tot}$$

Where C_1 and C_2 are the coefficients chosen to balance the different effects.

With $C_1 = 1$ and $C_2 = 0.5$, the four different following situations, for instance, lead to the same discomfort:

with $I_{set} = 600$ lux,

$I_{art} = 0$ $I_{tot} = 1200$ then discomfort = 0.5

$I_{art} = 0$ $I_{tot} = 300$ then discomfort=0.5
 $I_{art} = 600$ $I_{tot} = 600$ then discomfort=0.5
 $I_{art} = 180$ $I_{tot} = 360$ then discomfort=0.5 (about)

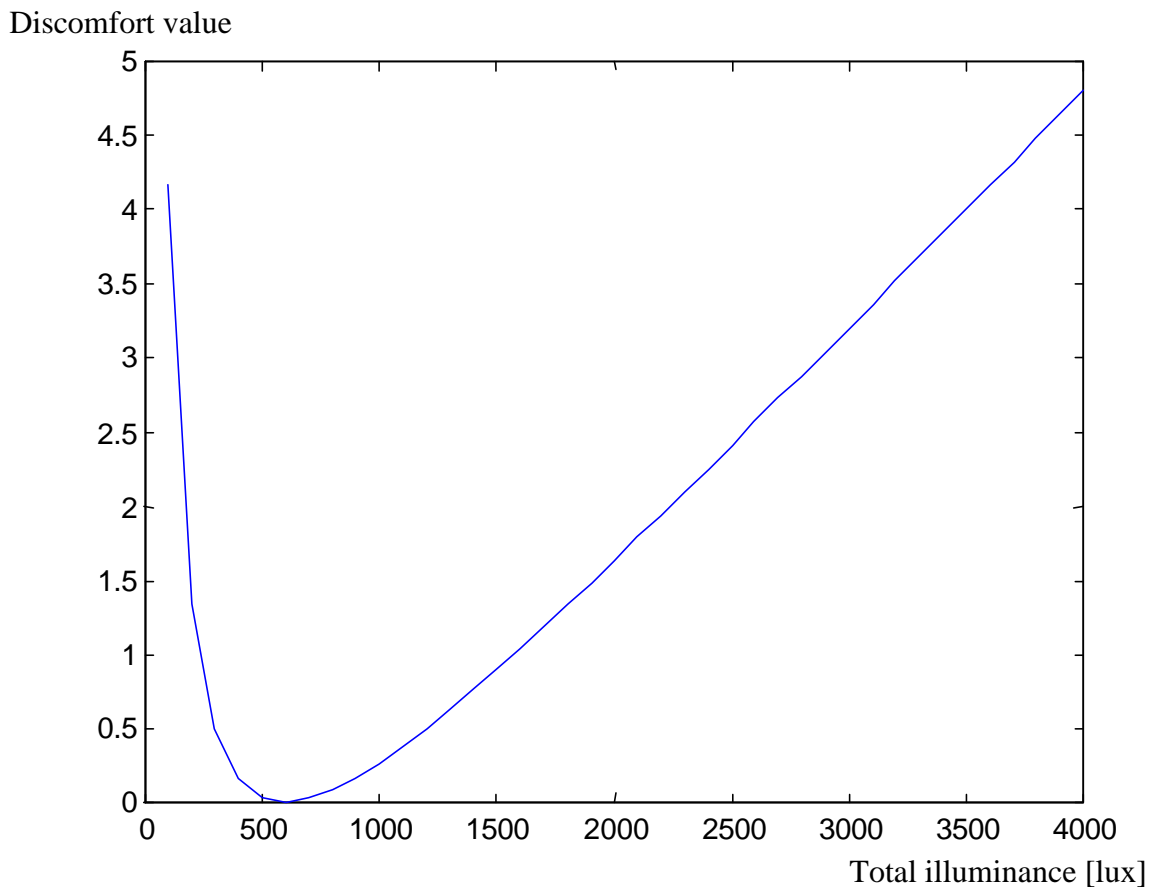


Figure 37: Graphical representation of the discomfort value

(The illuminance setpoint is set to 600 lux and there is no artificial lighting).

3.3.2.4 RESULTS

In the following the most representative case studies analysed by the simulations are reported.

3.3.2.4.1 Leso case - Comparison with reference case without night setback (case 4 vs. case 1)

In the following figure are reported the data on solar radiation used for all Leso cases and the prediction error of the Edificio climate prediction block. The error is consistent to what was already observed in task AD1.

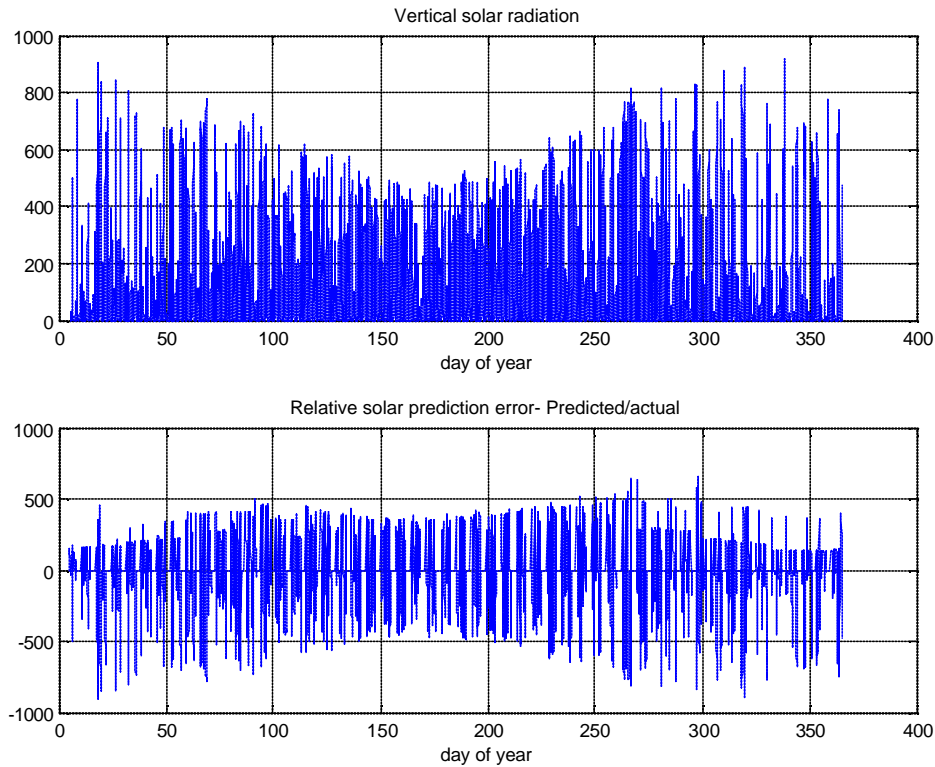


Figure 38: Vertical solar radiation and prediction error

In the following figures it is possible to observe that the Edificio controller tends to switch-off the heating power sooner in the year than the reference case. Up to day 80, the thermal comfort is rather the same on both cases but the Edificio controller provides 32% less energy consumption. This can also be observed, to a lesser extent on days 270-365. However, contrarily to experimental findings, the lighting energy consumptions are very similar in both cases. This may be due to the reference lighting model used, which performs better than a simple manually driven system (lights and blinds).

The thermal discomfort is quite similar during heating periods. The difference in favour of the reference controller is due to a more even heating rate at the expense of a higher energy consumption. The illuminance comfort is slightly better for Edificio during the summer season, due to better blind controls. Note that the overall lighting discomfort is averaged over the elapsed period and this explains the high values at start (not meaningful in terms of results).

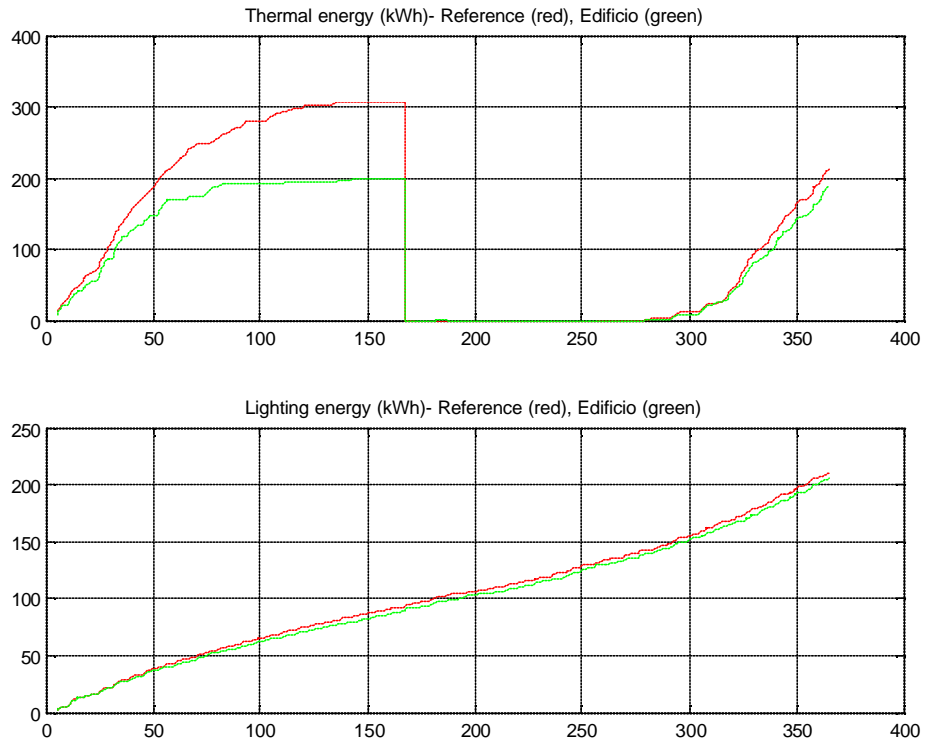


Figure 39: Overall thermal and lighting energy consumption

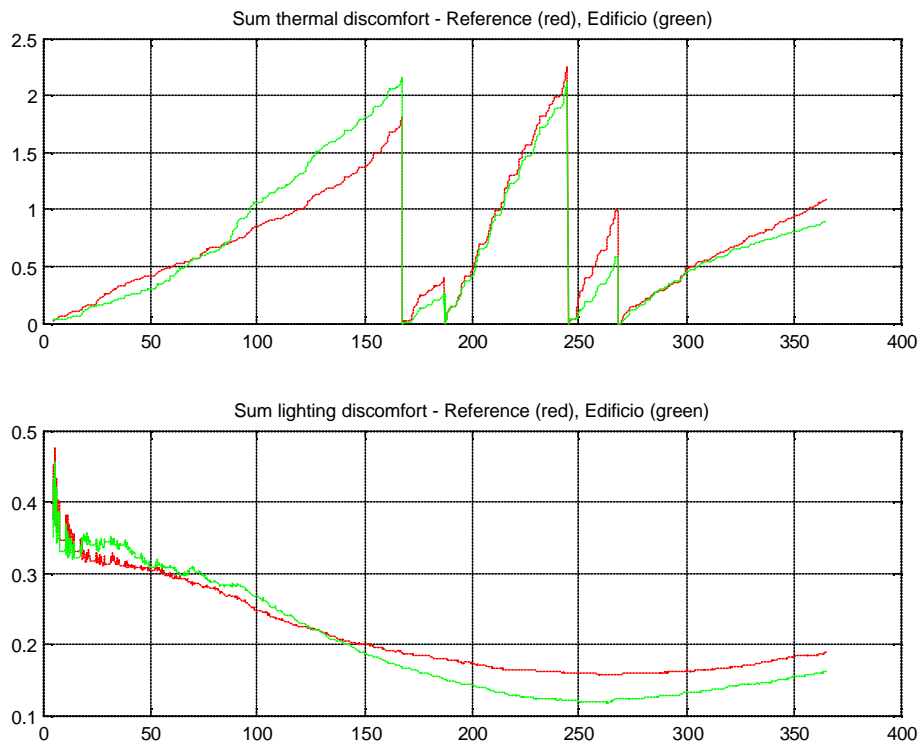


Figure 40: Overall thermal and lighting discomfort

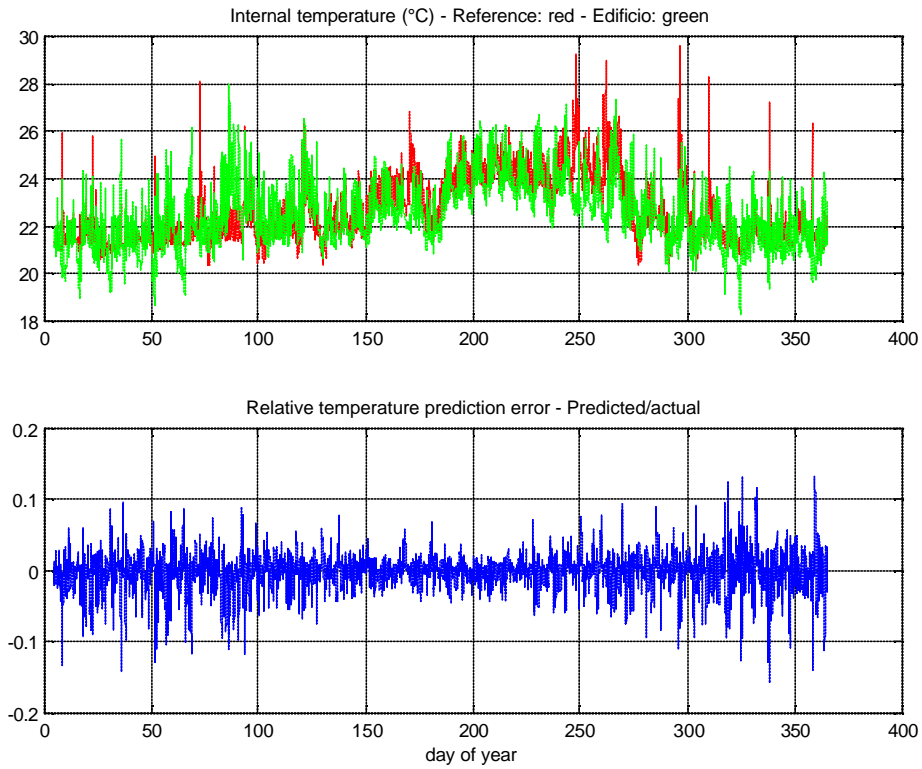


Figure 41: Internal temperature and relative prediction error

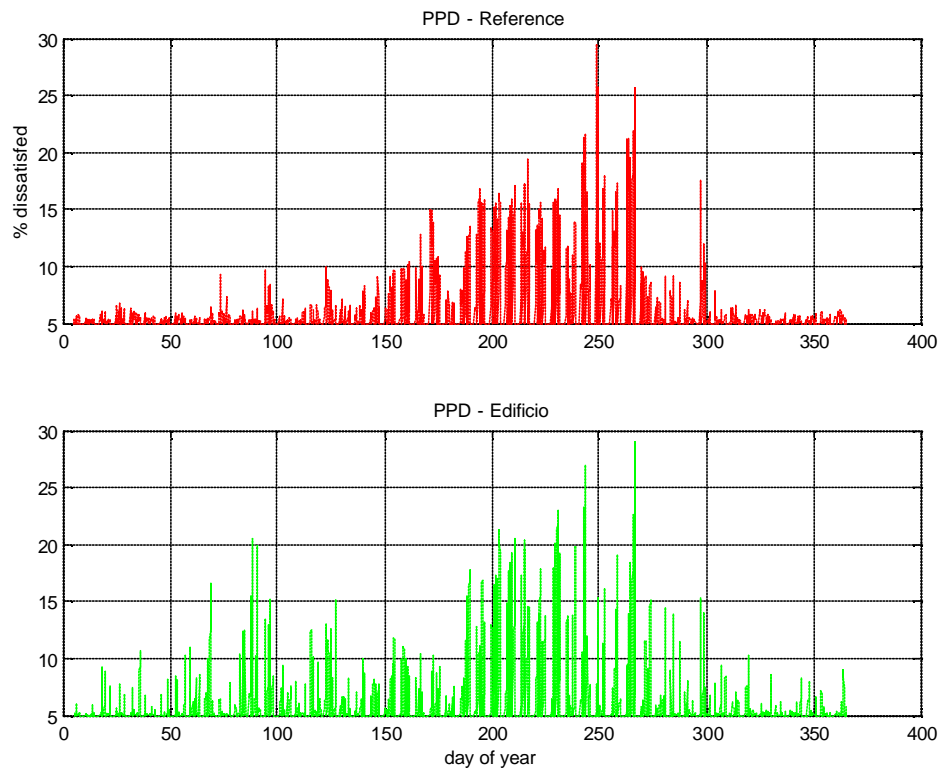


Figure 42: PPD comparison

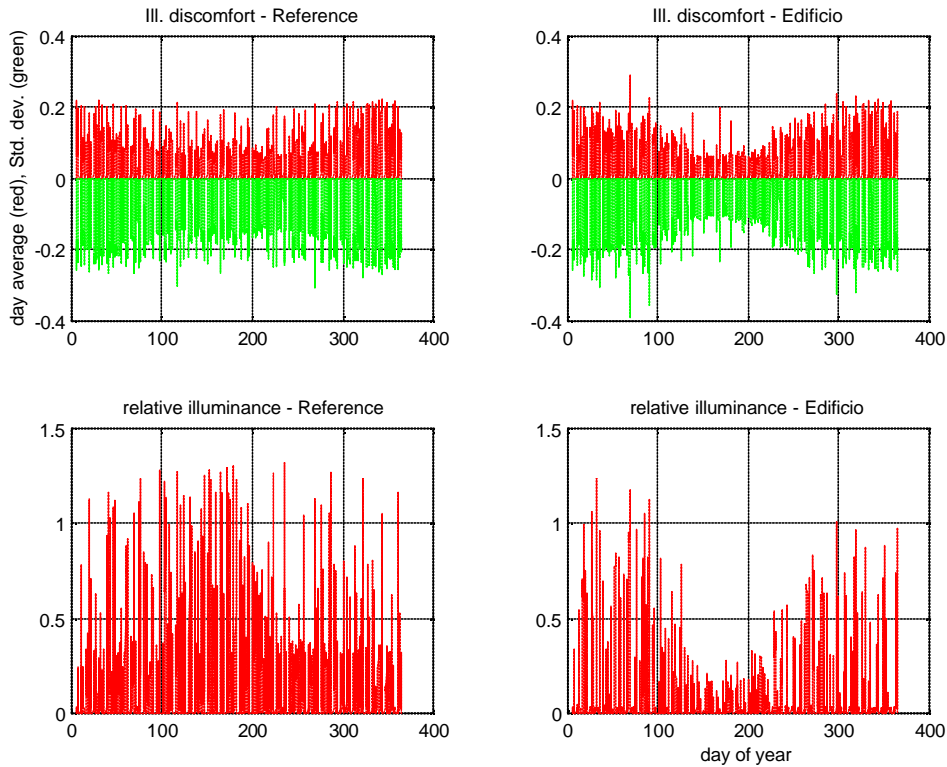


Figure 43: Illuminance discomfort comparison

3.3.2.4.2 Leso reference case with night set-back (case 4 vs. case 1b)

In this case, a set-back is applied to the user schedule to start and to stop heating during the day. In the night period, the set-point temperature is lowered by 4 °C.

Results are given for the 90 first days of the year, showing a 20% smaller energy consumption for the Edificio case. The night set-back represents about 40 kWh less energy consumption for the reference controller (16%). The lighting controller is not affected by the thermal change in this case.

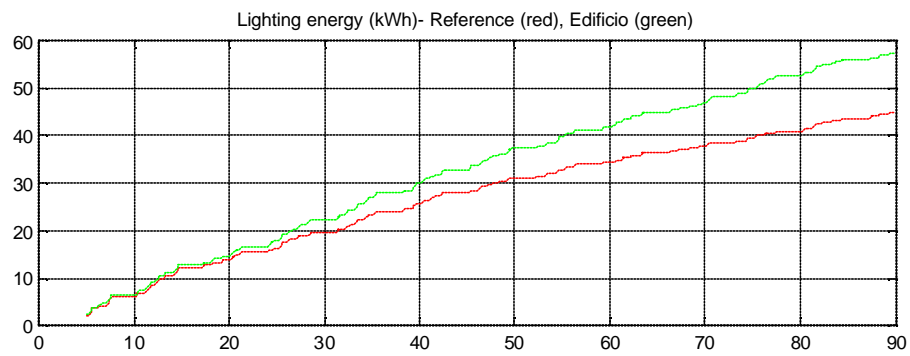
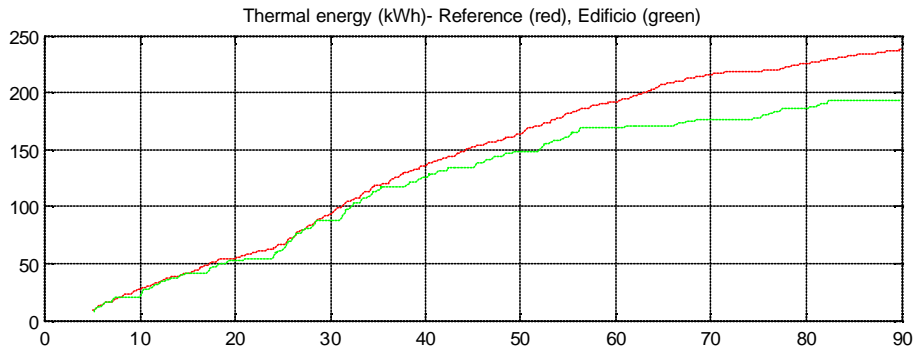


Figure 44: Overall thermal and lighting energy consumption

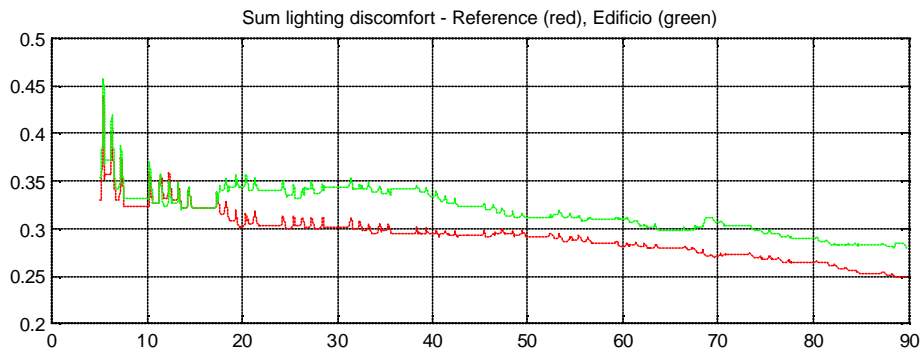
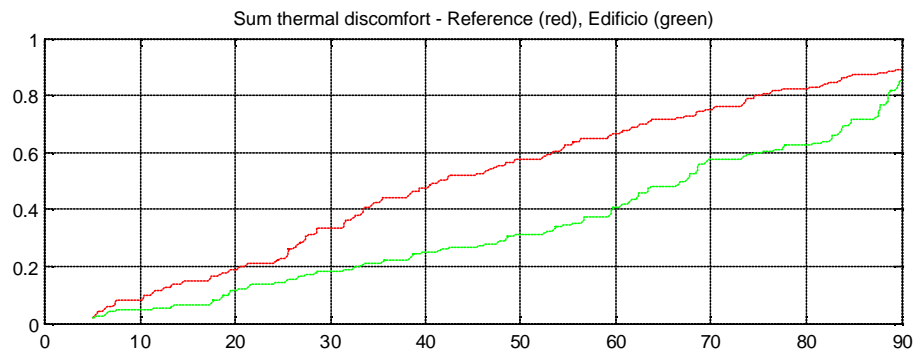


Figure 45: Overall thermal and lighting discomfort

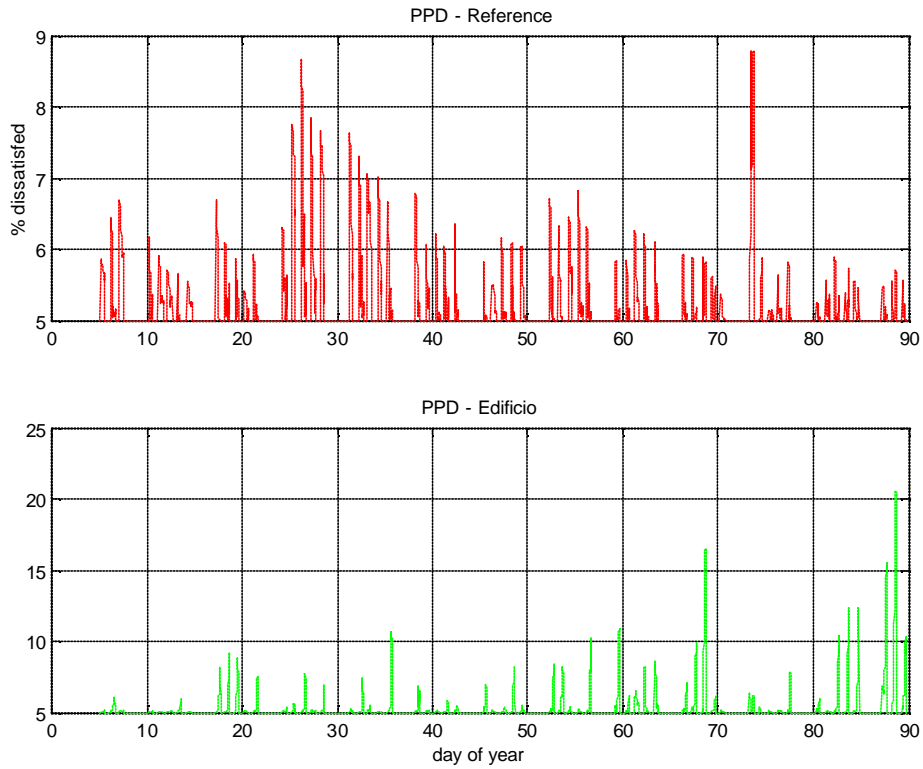


Figure 46:PPD comparison

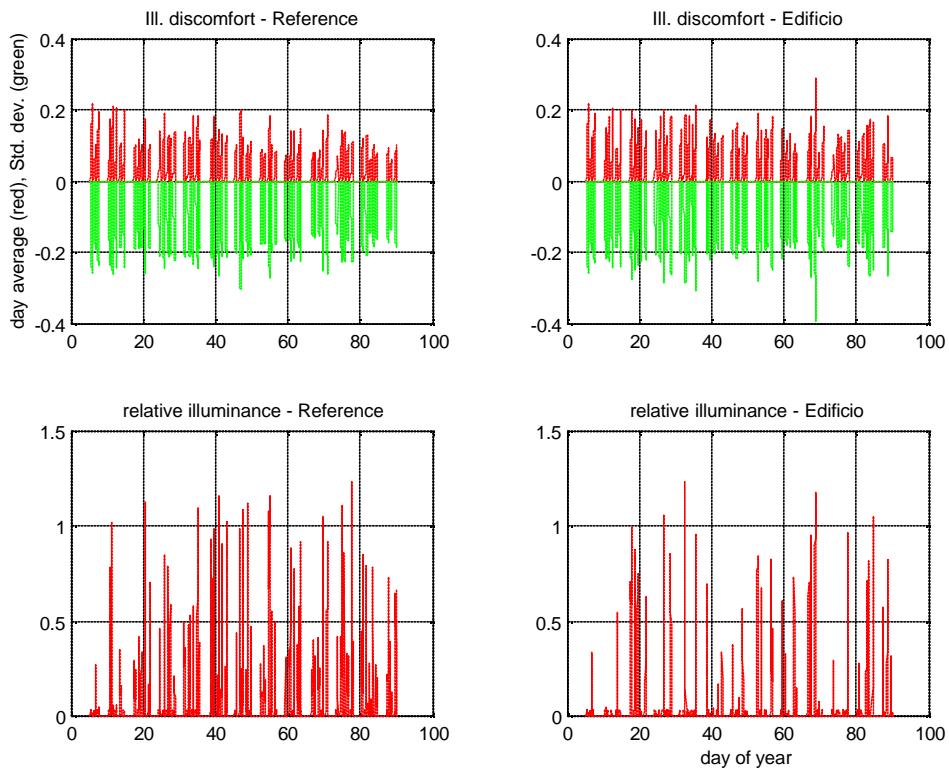


Figure 47: Illuminance discomfort comparison

3.3.2.4.3 Leso Case with lower set-point temperature (case 12 vs case 8)

The effect of a lower set-point temperature is an overall lower thermal energy consumption as seen on the following figure. The cooling season is clearly visible together with the in-between mid-seasons (where both cooling or heating are allowed but not simultaneously). The advantage of the Edificio system for the thermal side is not so clear as before, however there is a clear benefit on the lighting side with nearly half the total consumption compared to the reference. This can only be explained with the coupling between the thermal and the blind controller, where in that case more of the sunlight has been used. This results both on lower energy consumption for lighting and on a better visual comfort.

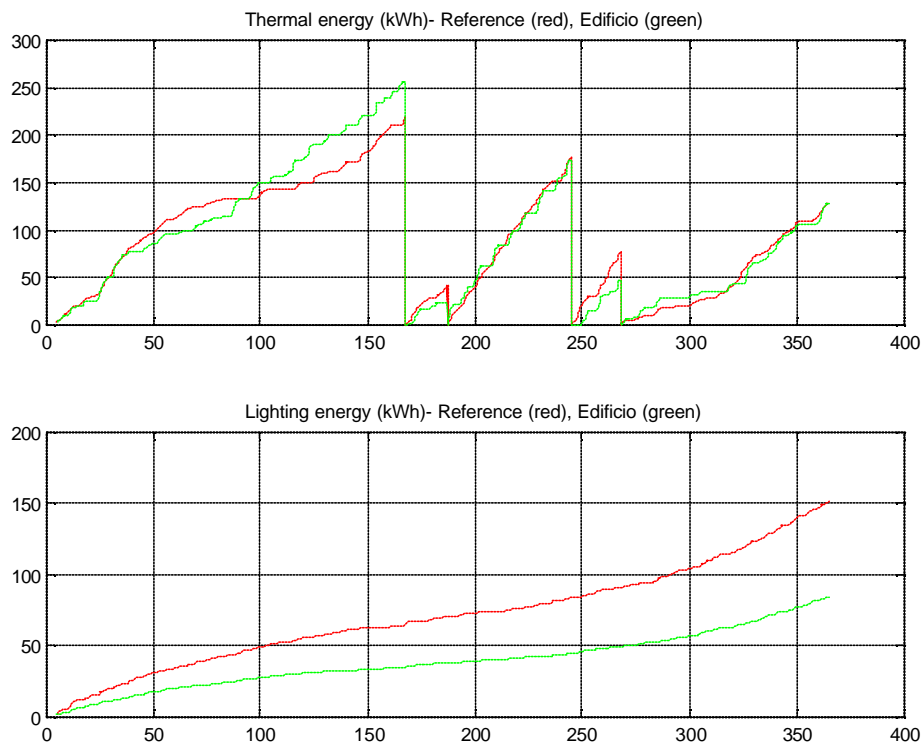


Figure 48: Overall thermal and lighting energy consumption

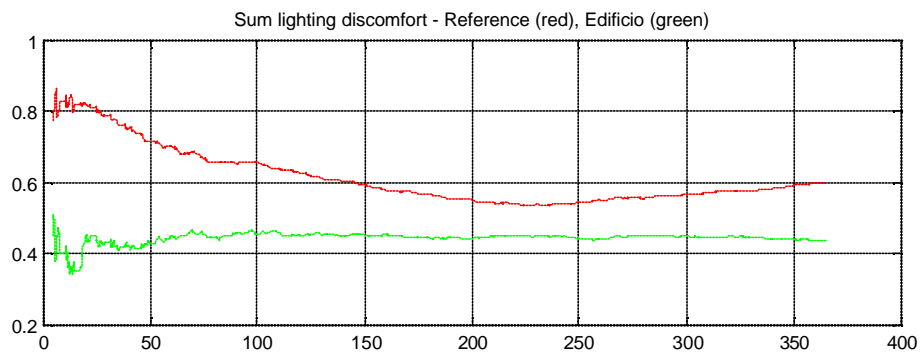
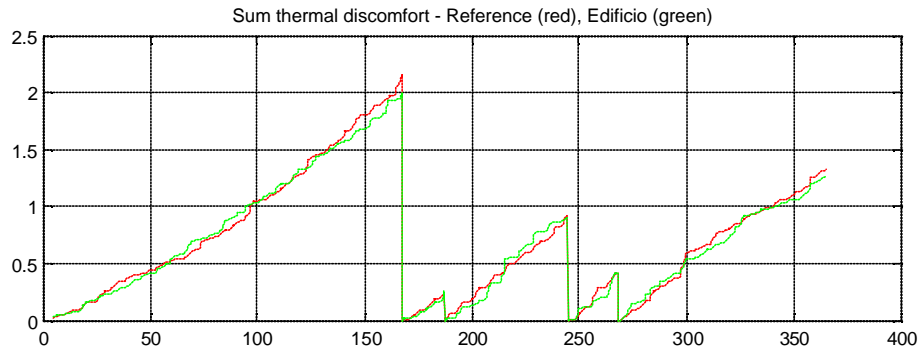


Figure 49: Overall thermal and lighting discomfort

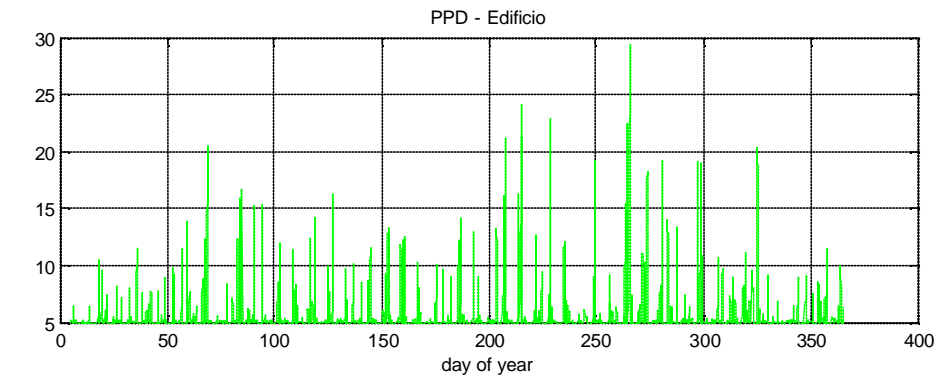
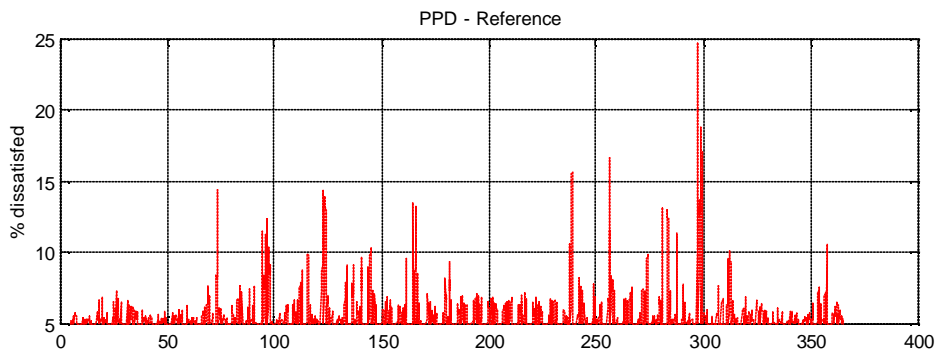


Figure 50: PPD comparison

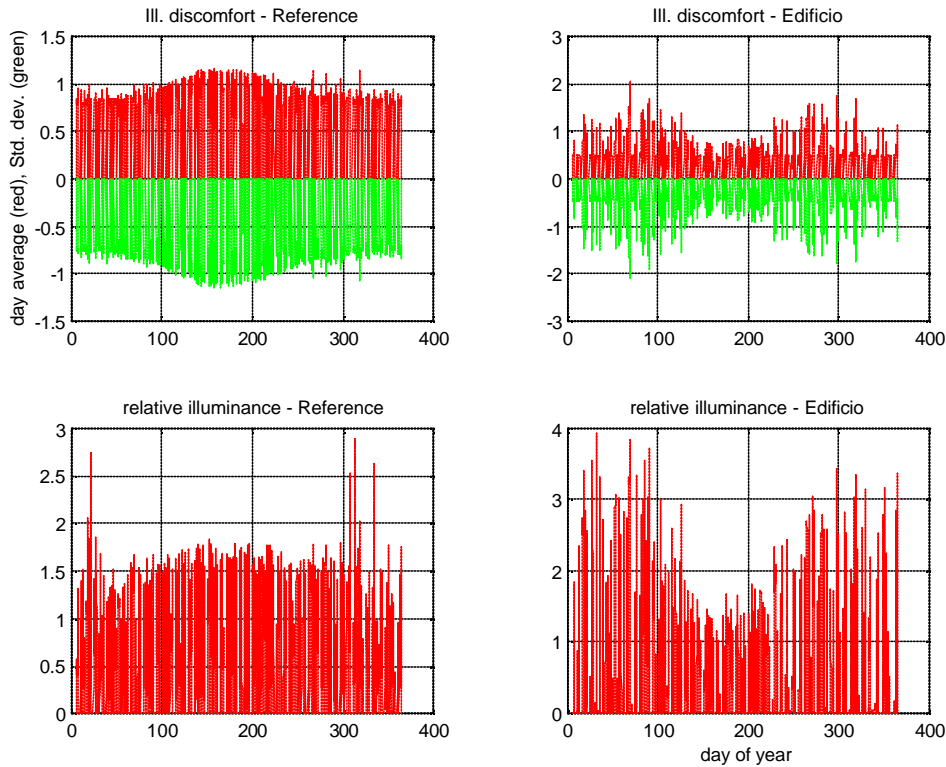


Figure 51: Illuminance discomfort comparison

3.3.2.4.4 Metop (VTT) case (case 5 vs. case 2)

The Figure 53 to Figure 57 show a significantly better Edificio controller performance in terms of thermal comfort. The reference controller does not succeed in reaching the set-point temperature, whereas the Edificio controller follows very well the presence/absence cycles. In terms of PPD comparison this results in about twice the number of dissatisfied users (say 6-8% for the reference controller).

3.3.2.5 CONCLUSIONS

From these results it would be wrong to draw definitive conclusions on the relative benefits of the Edificio controller compared to a standard controller in all possible situations. This is because the model in itself has not been sufficiently validated against experimental data and also because the coupling between the lighting and the thermal controller may not be optimum. Results show that this may be the case and suggest that a level 3 optimisation or other similar approach to optimise the parameters would be required for best benefits.

Other non-linear effects should also be included in the simulation package, in particular those resulting from the user behaviour. This was however beyond the scope of this task.

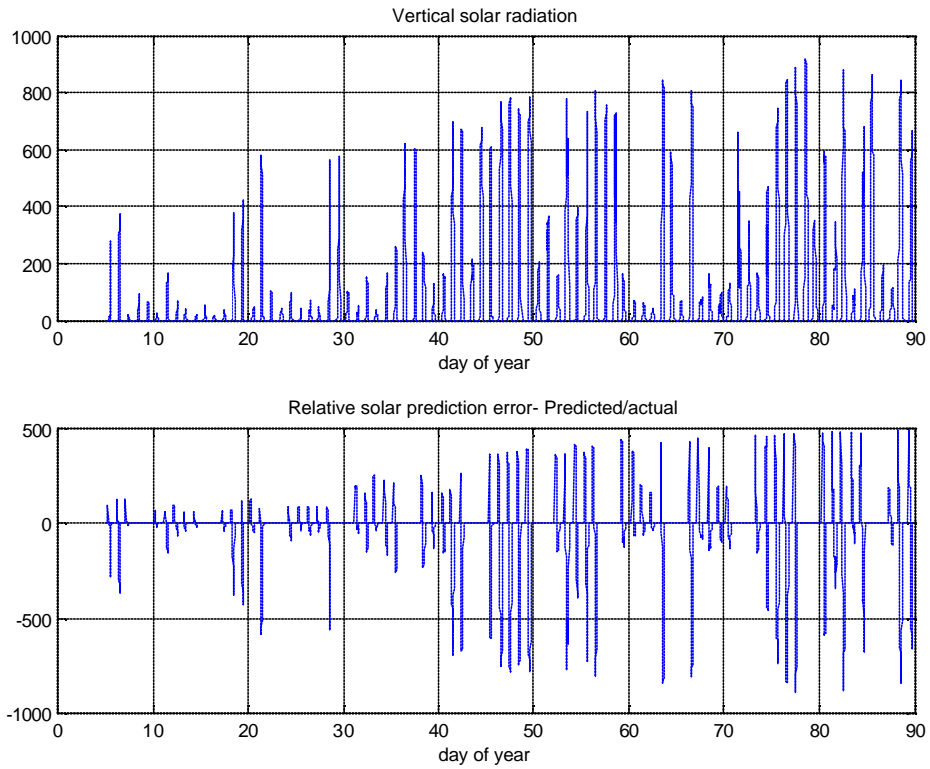


Figure 52: Vertical solar radiation and prediction error

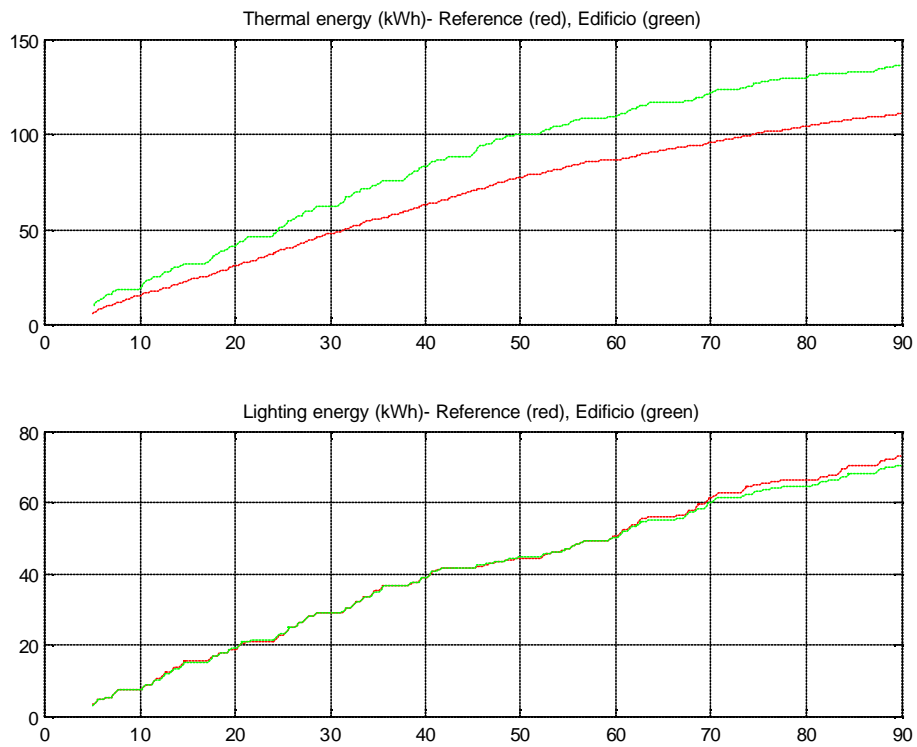


Figure 53: Overall thermal and lighting energy consumption

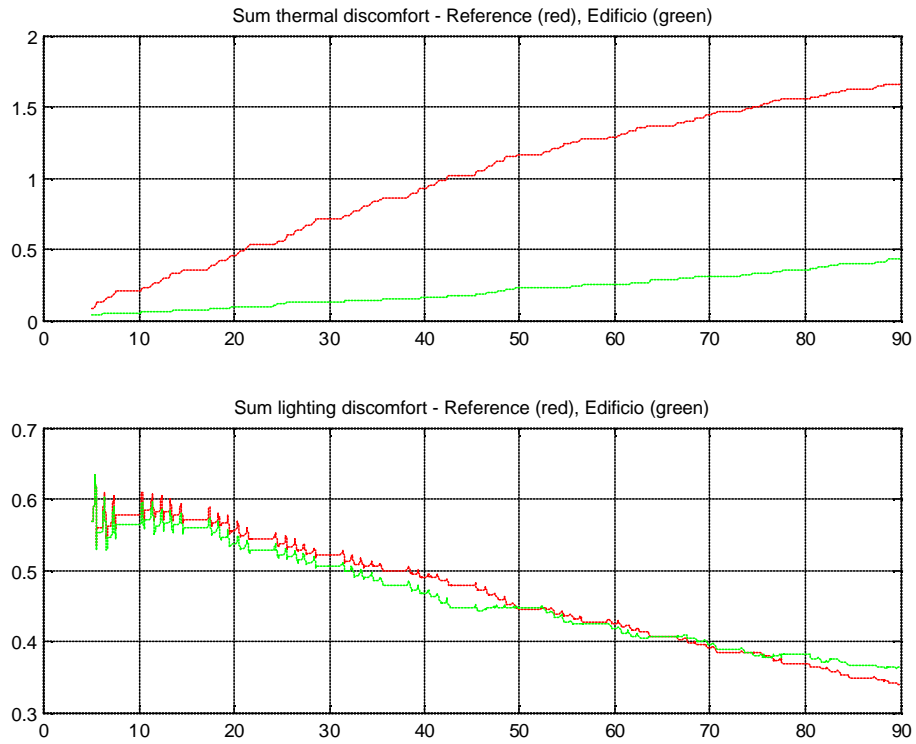


Figure 54: Overall thermal and lighting discomfort

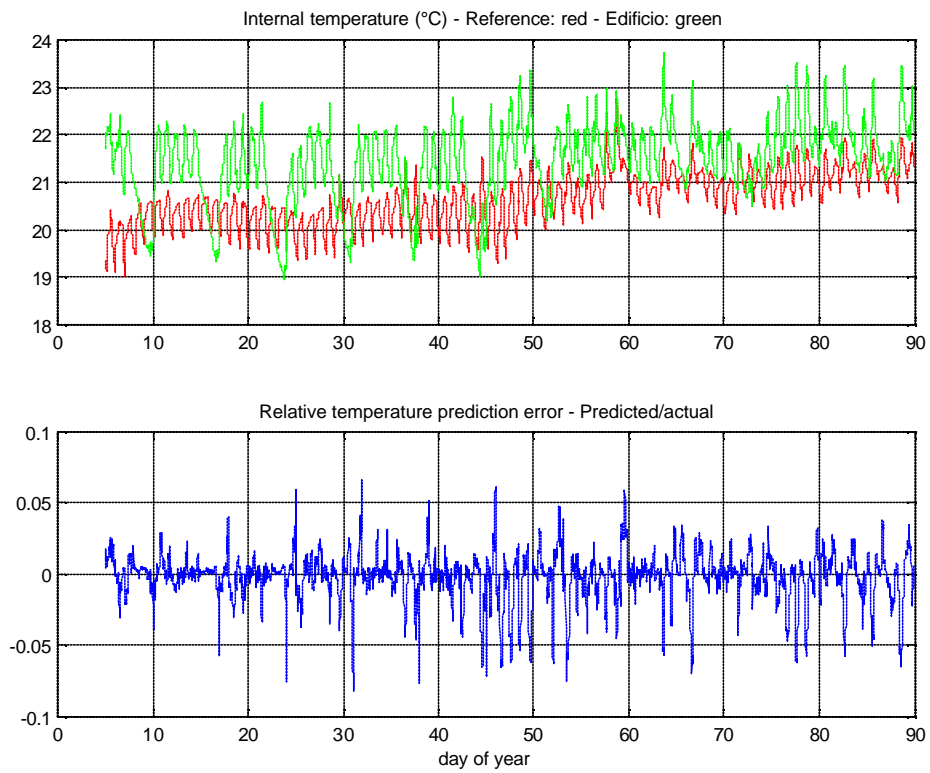


Figure 55: Internal temperature and relative prediction error

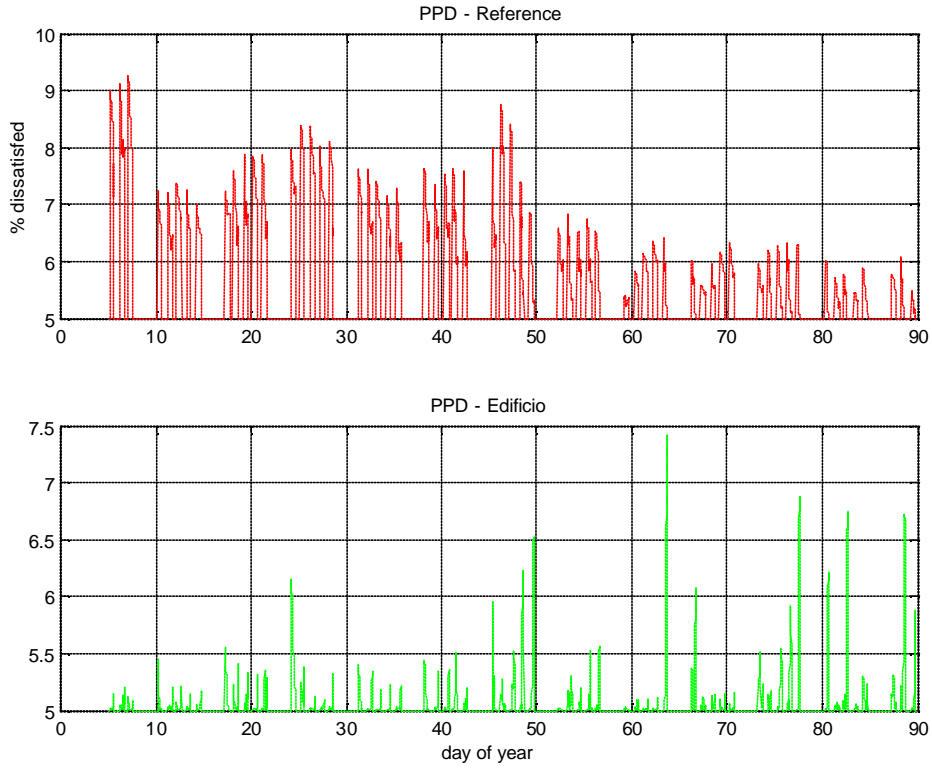


Figure 56: PPD comparison

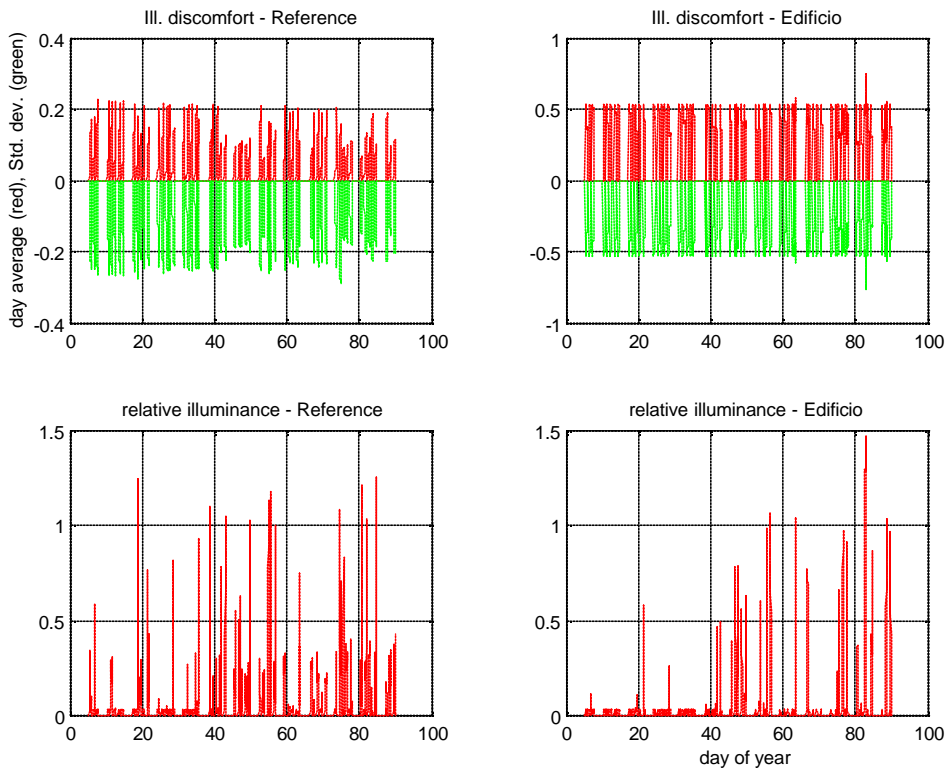


Figure 57: Illuminance discomfort comparison

3.3.3 TASK ET3: SCALED DOWN EXPERIMENT

3.3.3.1 PASSYS TEST SITE

The main purpose of the small scale measurements was to encounter and solve problems of the first versions of the EDIFICIO controller in a well controlled laboratory environment. For this reason the PASSYS test site were selected.

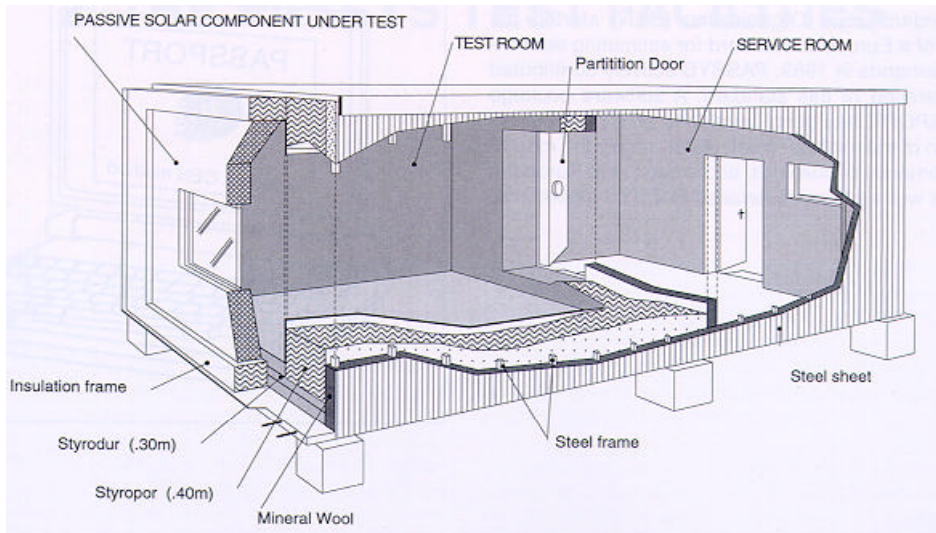


Figure 58: PASSYS test cell with control service room, test room and the mountable façade

3.3.3.1.1 General description

At the TNO test facility for solar energy in Delft, four PASSYS test cells are installed. These test cells were developed within the EU PASSYS I and PASSYS II projects.



Figure 59: Photo of the TNO PASSYS test cells and moveable cold box (on the right)

The service room is located at the north side of the test cell. In the service room, the data acquisition and control equipment is located. The partition door between the service room and test room is highly insulated.

The test room is located at the south side of the test cell and is highly insulated with 400 mm of expanded polystyrene (PS30). The south wall consists of an insulated frame (which was especially designed to minimise edge and corner losses due to thermal bridges) which can be equipped with different test components.

The test site is located at a latitude of 51°58'N and a longitude of 4°22'E at an altitude of -1.8 meters (below sea level !).

The PASSYS test cell is instrumented with a large number of sensors, forming the basic instrumentation. Calibration of these and all other sensors used at TNO Building and Construction Research is an integral part of the TNO ISO 9001 procedures, which states that no uncalibrated equipment may be used. All equipment is calibrated on a regular basis by the manufacturer or in-house. The basic instrumentation is given in the following table and is described extensively in the PASSYS test reports.

Sensor	sensors
Air temp in test room	7
Air temp in service room	2
Surf. temp in test room	21
Surf. temp outer skin test cell	21
Heat flux meter	6
Iglobal vertical	1
Iglobal horizontal	1
Idiffuse vertical	1
Idiffuse horizontal	1
Outdoor temperature ventilated	1
Outdoor temperature shielded	1
Wind direction	1
Wind speed	1
Relative humidity	1
Hot wire anemometer	2
Tracer gas equipment	1
Pressurization test equipment	1

Table 45: Basic instrumentation of the PASSYS test cell.

The solar irradiances are measured with pyranometers (Kipp and Zonen, type CM11) with shadow ring for the measurement of diffuse radiation. The accuracy for solar radiation measurement is 3%.

The ambient air temperature sensor is a ventilated and shielded platinum resistance thermometer (Metatemp). The accuracy is ± 0.2 K in the range of -20 °C to +70 °C.

Wind speed and wind direction are measured according to the meteorological conditions, at 10 meters height above ground level with an anemometer (Thies). The accuracy in the wind speed measurement is ± 1 m/s in the range from 0.6 to 50 m/s. The accuracy in the wind direction measurement is 10 °.

The air temperature in the test room is measured with 7 double shielded PT100 (Metatemp), using 4 wire technique. The accuracy is 0.2 K.

The PASSYS test cell is equipped with an air distribution system in order to minimize air temperature stratification. The stratification is measured to be less than 1 K. The energy input from the air distribution system is measured separately from the energy input of the heater with an accuracy of 1 W.

All data is measured using the MUP-DAS data acquisition system, capable of measuring 100 signals. Measurements are done with a 1 minute sampling interval. 5 samples are averaged (non-weighted) and all data is written to hard disk every 5 minutes. The error contribution of the data acquisition system can be ignored compared to all other error contributions.

3.3.3.1.2 The new façade

To enable measurements and tests related to realistically sized active windows a new façade was designed, realised and implemented. The façade is made out of wood enabling changes to the façade. The opaque part is insulated. The window is double glazed with possibility to use shading in the gap because the inner sheet of glass can be removed

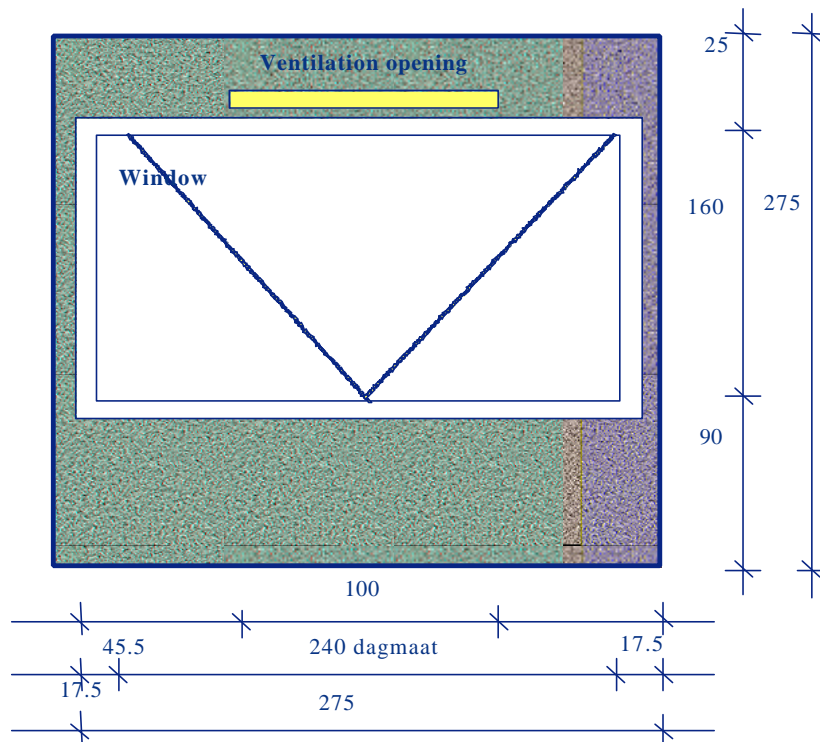


Figure 61: The façade designed and implemented for testing of active windows (measures in cm).

3.3.3.2 THE CONTROL AND MONITORING SYSTEM

3.3.3.2.1 Adjustments of systems in the controlled office

Heating: To control and monitor the heating energy an electrical oil-filled radiator is used which can be directly controlled by computer. Through pulse modulation the actual power can be controller between 0 and 2000 Watt.

Ventilation: A ventilation opening with electrically controlled opening is mounted in the façade. The ventilation opening used is the new Alcoa ventilation opening with motor control. For this system the air flow as function of the pressure difference over the ventilation opening is measured for different opening positions. This information will be used to enable to control the ventilation by calculating the air flow using the measured pressure difference over the façade and the opening position.

In addition to the ventilation opening the window will be openable using linear motor mounted at the right bottom part of the window. This feature can be used mainly for free cooling, additional night time ventilation to cool the building in warmer periods. The realized ventilation will be computed using the pressure difference over the façade. The controlled opening will be in 2 steps. (closed – half open – open).

Solar shading: Indoor / in gap motorized venetian blinds are be mounted to the windows. TNO will installed potentiometers on the rod of the blind to be able to measure the blind angle. This is possible for this system because the wire network supporting and controlling the lamellas are connected and supported to a cylinder which is mounted on the rod.

Because the cylinder has more or less the same width as the lamellas and the wires are fixed to the cylinder, the relation between the angle of the lamellas and the cylinder (and rod) is fixed. Therefore the angle of the rod can be used to determine the angle of the lamellas. (usually the angle of the rod is not representative for the angle of the lamellas because usually the wires are supported directly by the rod. Because the diameter of the rod is much smaller than the width of the lamellas, the wire is not fixed to the rod because the rod has to be rotated several times to rotate the lamellas. Therefore the wires are always slipping over the rod.

Lighting: Units with integrated sensors and control system controlling the Illuminance levels are used. If the control of the lighting system becomes apparent, the sensors will be replaced by controlled voltages with which the output can be controlled. The power consumption of the units will be measured.

The light level measured by the sensor is kept constant when the light is switched on. The constant light level is manual adjustable by rotating the ring around the sensor (narrowing or opening the angle).



Figure 62: Electrical lighting system with integrated sensor and control.

3.3.3.2.2 Overview on the measured variables

The following table provides an overview on the to be installed sensors for both offices.

Elements	PASSYS cell	units
Indoor		
Indoor temperature	2	[oC]
Energy consumption for heating	1	[kWh]
Illuminance both sides shading system	2	[lux]
Lighting levels on the desk	1	[lux]
Visual comfort (by questionnaire)	q	[-]
The angle of the lamellas (included in controller)	1	[degr]
Electricity consumption for lighting	1	[kWh]
Ventilation opening (from actuator)	1	[1..10]
Window angle (from actuator)	1	[degr]
Pressure difference indoor - outdoor	c	[Pa]
Outdoor conditions (from nearby TNO weather station)		
Outdoor temperature	c	[oC]
Relative humidity	c	[%]
Air pressure	c	[Pa]
Solar radiation (global horizontal, global vertical, diffuse)	3c	[W/m2]
Wind speed	c	[m/s]
Wind direction	c	degrees

c = centrally measured and available through the computer network

1 = installed

q = questionnaire

* = back and window side separately controlled

Table 46: Available sensors set.

3.3.3.3 THE CONTROLLER MONITORING SYSTEM

3.3.3.3.1 Integration of the controller for the monitoring task

For maximum flexibility and ease of implementation, adjusting and optimising controllers, an very open architecture is chosen in which the controller can be executed in the environment in which the controllers are under development (Matlab Simulink). This is realised using the real time toolbox supporting real time control and direct control of IO cards. The output of the central weather station is available on the computer network. The computer program 'PC anywhere' is used facilitating full control of the centrally placed monitoring computer from the office desk.

The data from the sensors is collected partly using a IO-board which is controlled directly from Simulink using the timers provided by the real time toolbox to make it real time.

The centrally measured data are collected trough the computer network using a program Mupdas which sends the data on the TNO network and enables collection from any PC on the TNO network. The temperatures are measured with thermocouples requiring special facilities offered by a data logger connected to the control computer by network.

In the following figure the controller in the Matlab Simulink model is shown. In the left boxes (submodels) the first level input functions are located including hardware reading of sensors, file read functions etc. The right submodels contain first level output functions including hardware control of all systems and output of monitoring files. In the central submodel the Controller is located (at present only the heating system is controlled).

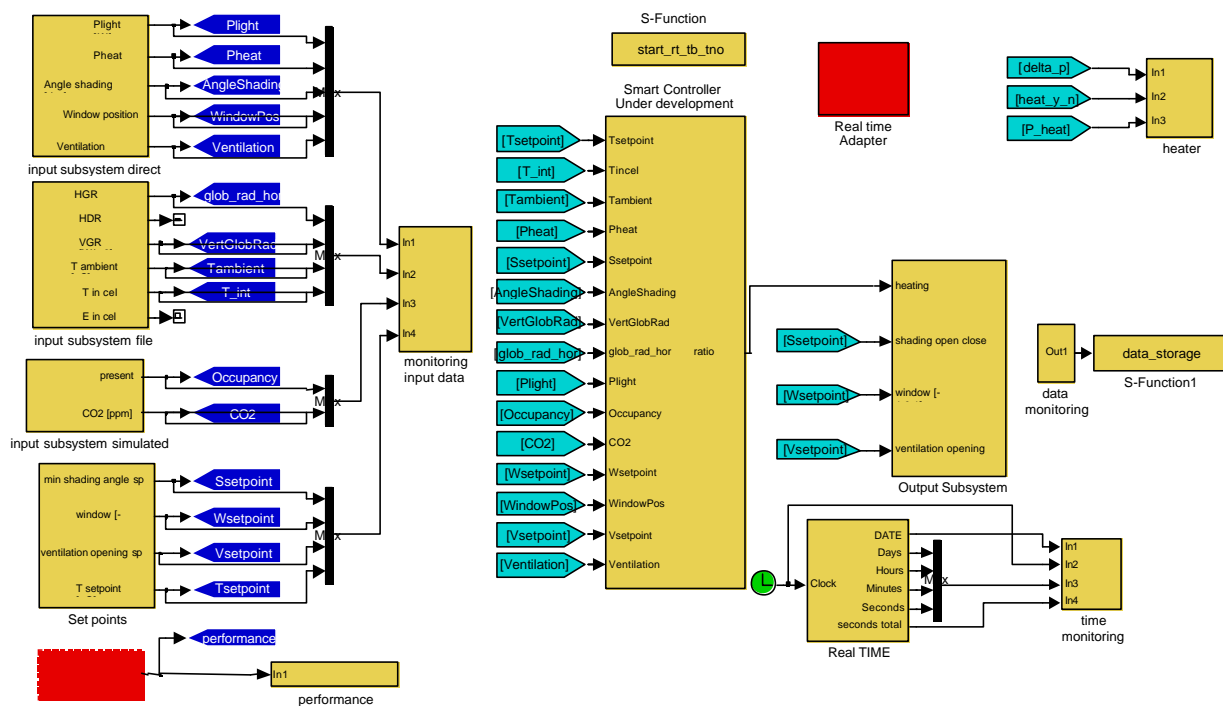


Figure 63: Controller in the Matlab Simulink model.

3.3.4 TASK ET4: TESTS IN REAL SIZE OCCUPIED BUILDINGS

3.3.4.1 DESCRIPTION OF THE METHODOLOGY

3.3.4.1.1 Introduction

The experimental tests of the EDIFICIO controller is aimed at checking several issues:

- the correct operation of the controller (using "common sense" evaluation);
- the energy saving and comfort improvement potential, when compared to a traditional controller;
- the user's satisfaction.

These issues are discussed in the section below, providing some guidance on how to analyse the raw experimental results.

When a comparison is done between the EDIFICIO controller and the conventional controller, the latter should be defined in a reasonable way, typically corresponding to the most usual situation for the location where the tests are carried on. For instance in Switzerland, the heating controller provides a constant setpoint temperature during the occupancy period with a night setback, the blind are only controlled manually (it has been shown that a convenient approximation of the user's behaviour is pulling the blind the lower when there is more solar radiation incident on the window surface), and the artificial lighting is switched on when needed and kept on even the daylighting level becomes high enough, until the user leaves the room.

3.3.4.1.2 Controller operation: check on short periods

A conventional controller, even not smart, is able to provide a rather constant and comfortable indoor climate (air temperature, air quality, lighting level, absence of glare, for instance). The EDIFICIO controller should provide, during the time the user is present, similar conditions. Errors in the control algorithms (algorithm errors, programming errors, wrong choice of setpoint values, etc) may cause the controller to provide indoor conditions less adequate than a conventional controller, or to obviously miss a possibility to save energy or improve the indoor comfort.

In order to check the EDIFICIO controller operation, short typical periods should be considered (between a couple of days and one week), possibly with a change of average conditions for testing the short term adaptation. Relevant variables should be plotted (for instance for the heating controller: the outside and inside temperatures, the heating power, the blind position, the incident solar radiation on the window surface, the occupancy). A careful "common sense" analysis allows then to see whether the controller operates in a correct way. Only one room needs to be considered for such a test.

As a complement of this method, one can include a comparison between the EDIFICIO controller and a conventional controller. The methodology is similar, using "common sense" knowledge, except that a comparison is done between the two variants. In order to be able to do a valid comparison, similar conditions should be used for the two controllers:

- either considering simultaneously two rooms in parallel with a similar occupation pattern (in order to reduce the differences due to outside conditions),
- or (preferably) considering the same user and room (in order to reduce the differences due to user behaviour and room characteristics) on two very similar periods (same outside conditions).

3.3.4.1.3 Energy consumption comparisons with two rooms and periodic exchange

Two rooms are used for that test, one room equipped with the EDIFICIO controller, one room equipped with conventional controller.

In order to reduce the experimental bias due to room characteristics and user behaviour, the rooms (room1 and room2) should be regularly exchanged, for instance every 10 days (cf. research projects DELTA and NEUROBAT), following the scheme below:

- one period with EDIFICIO controller in room1 and conventional controller in room2,
- one period with EDIFICIO controller in room2 and conventional controller in room1,
- one period with EDIFICIO controller in room1 and conventional controller in room2,
- etc...

At the end of the experiment (the total duration should be at least two months), the following data is therefore available, by summing the energy consumptions and the times:

- room1, EDIFICIO controller: total time duration t_1 , total energy consumption $E_{EDI,room1}$
- room1, conventional controller: total time duration t_2 , total energy consumption $E_{conv,room1}$
- room2, EDIFICIO controller: total time duration t_2 , total energy consumption $E_{EDI,room2}$
- room2, conventional controller: total time duration t_1 , total energy consumption $E_{conv,room2}$

The average power for EDIFICIO and conventional controllers are then respectively given by:

$$P_{EDI} = (E_{EDI,room1} + E_{EDI,room2}) / (t_1 + t_2)$$

$$P_{conv} = (E_{conv,room1} + E_{conv,room2}) / (t_1 + t_2)$$

This method can be used for the energy consumption due to heating, cooling, or artificial lighting.

3.3.4.1.4 Energy consumption comparisons with two rooms, without room exchange

When it is not possible to exchange regularly the EDIFICIO and conventional controllers between the two rooms, it is necessary to take into account a corrective factor due to discrepancies of room characteristics and user's behaviour.

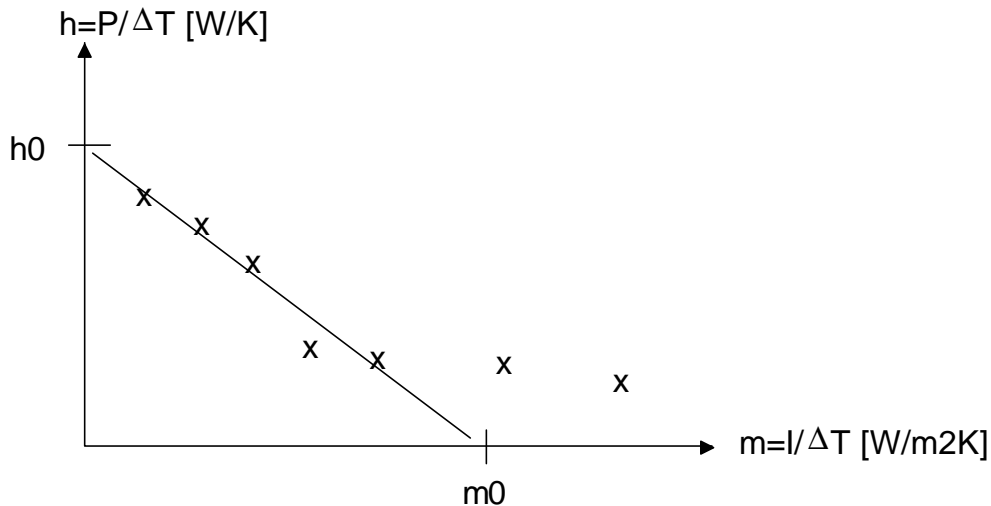
Let's suppose that room1 is equipped with the controller EDIFICIO, and room2 with the conventional controller. At the end of the measurement period, we have two energy consumptions, respectively $E_{EDI,room1}$ and $E_{conv,room2}$. From these values, we have no way to derive directly the energy saving, because room1 and room2 may have some differences both for the physical characteristics and for the user's behaviour.

In order to allow an indirect comparison, the differences between the rooms have to be accounted for. The h/m method gives a convenient way to track these differences for the heating or cooling, and it is explained briefly below. A series of measurements, using the same controller in both rooms, must be available. Each of these measurements should be taken for a short period (for instance one week), the measurements should spread over all the different seasons, and the number of available points should be large enough to cancel the statistical bias.

Two variables are considered:

- $m = I/\Delta T$, where I [W/m²] is the solar radiation incident on the most significant facade (or possibly the solar radiation on an horizontal surface, when all the facades have similar significance on the point of view of solar gains), and ΔT [°C] is the temperature difference between inside and outside;
- $h = P/\Delta T$, where P is the average power used for the heating or cooling during the considered period.

The graphics obtained when plotting h and m for all the periods (one h/m point for each period) looks like the one below:



During the cold season, where the utilization factor of the solar gains is constant, the points should be rather well aligned on a straight line, corresponding to the (linear) equation of the heat balance. On the graphics above, this line has been drawn, using an empirical adjustment. (It is of course also possible to do a least square adjustment, but the outliers should be eliminated first.)

The terms h_0 and m_0 are respectively the heat loss coefficient when there is no solar gains, and the value for m where no heating is needed. In reality, the heating is needed even when $m > m_0$, because during these periods the utilisation factor of free heat gains (solar and internal gains) is getting lower. Nevertheless, these two coefficients allow a reasonable characterisation of a room, at least during the heating season. It should be noted that they depend on the controller's characteristics, and that they need to be measured with the same controller in order to be able to do the comparison. In the following, we will assume that they are measured with the conventional controller.

In our case, we have two rooms, one (room1) with the EDIFICIO controller and thermal characteristics $h_{0,1}$ and $m_{0,1}$ (measured with the conventional controller), the other one (room2) with the conventional controller and thermal characteristics $h_{0,2}$ and $m_{0,2}$ (also measured with the conventional controller). During the EDIFICIO measurements, several short periods are available, with energy consumptions $E_{i,1}$ (for room1, equipped with EDIFICIO controller) and $E_{i,2}$ (for room2, equipped with a conventional controller). The index i refers to the considered period (from 1 to n , with n large enough, for instance 10 or 20 periods).

For the period i , we have the situation below:

EDIFICIO, room1: measured energy consumption $E_{i,1}$, with room1 thermal characteristics;

EDIFICIO, room2: derived energy consumption $E_{i,1} \cdot h_2(m_i)/h_1(m_i)$, with room2 thermal characteristics (this is the energy consumption that the EDIFICIO controller would have when placed in room2).

conventional, room2: measured energy consumption $E_{i,2}$, with room2 thermal characteristics;

In the expression of the derived energy consumption with EDIFICIO controller in room2, h_1 is calculated from the h/m function for room1, using the value of m for the considered period (m_i):

$$h_1(m_i) = h_{0,1} - m_i \cdot h_{0,1} / m_{0,1}$$

Similarly, h_2 is calculated from the h/m function for room2, using the same value of m:

$$h_2(m_i) = h_{0,2} - m_i \cdot h_{0,2} / m_{0,2}$$

In order to get the complete consumption of both controllers with room2 characteristics, one has to sum over all the available periods:

$$E_{EDI} = \sum_{i=1}^n E_{i,1} \cdot h_2(m_i) / h_1(m_i)$$

$$E_{conv} = \sum_{i=1}^n E_{i,2}$$

Then, the energy consumption comparison can be done on the two values E_{EDI} and E_{conv} .

3.3.4.1.5 Comfort comparisons

A simple method is proposed here, only for the thermal comfort. The easiest way is to use the Fanger's formalism, with the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied persons). The PMV and PPD are expressed by rather complex formulas, taking into account the air temperature, the mean radiant temperature, the humidity, the air movement. Some parameters are also needed, such as the clothing or the metabolic activity of the persons. (Reasonable hypotheses should be done, such as a typical office room with clothing adapted to the season.)

The PMV and PPD can be represented as histograms. The thermal comfort is the better when the PMV histogram is the more centered on zero (the optimal comfort), and when the PPD histogram is the more near to zero. (But the PPD is always equal or higher than 5 %: even in an ideal situation, there are always at least 5 % of the people dissatisfied with thermal conditions.) This is a first (simple) evaluation of the comfort conditions.

A numerical evaluation can be provided by the fraction of histogram with PPD larger than 10 % (or PMV larger than 0.5 in absolute value; both evaluations are equal).

3.3.4.1.6 User satisfaction

The user satisfaction can be best evaluated with a questionnaire. At LESO, such a questionnaire has been elaborated and filled regularly by the users of both experimental rooms. Such a questionnaire can be used for the evaluation of:

- thermal comfort (for instance asking the user to evaluate the comfort using the Fanger's PMV scale);
- visual comfort (lighting level, presence of glare);
- air quality comfort (acceptable or not);
- control system operation (problems not understood by the user);
- system well adapted to the user (yes or not);
- how many times the user had to adjust the devices by himself (the evolution of that number during the first months of controller use allows to assess the system adaptation characteristics).

3.3.4.2 FULL-SIZE MEASUREMENTS IN LESO BUILDING

The EDIFICIO controller system (including heating, shading device and artificial lighting controllers) has been tested on the occupied LESO-PB office building, and the following issues have been checked:

- the correct operation of the controller (using common sense evaluation)
- the energy saving and comfort improvement potential, when compared to a conventional controller
- the user's satisfaction

A brief description of the building and the results concerning these issues are shown in the following.

3.3.4.2.1 Description of leso office building

The LESO Building is a small office building (about 20 office rooms), hosting the activities of the Laboratory of Solar Energy and Building Physics, EPFL (Federal Institute of Technology, Lausanne). Its South facade has been used for several years for experimenting various components. Recently, it has been retrofitted with a new facade conforming to the criteria of the sustainable development.

In 1999, the whole facade has been replaced by a new wooden facade, whose principle is given below. The office rooms are all equipped with an anidolic (non-imaging) daylighting device, which is very effective for providing a large coverage of lighting needs by daylighting only, but requires an additional blind and window area. The system is sketched in the figure below.

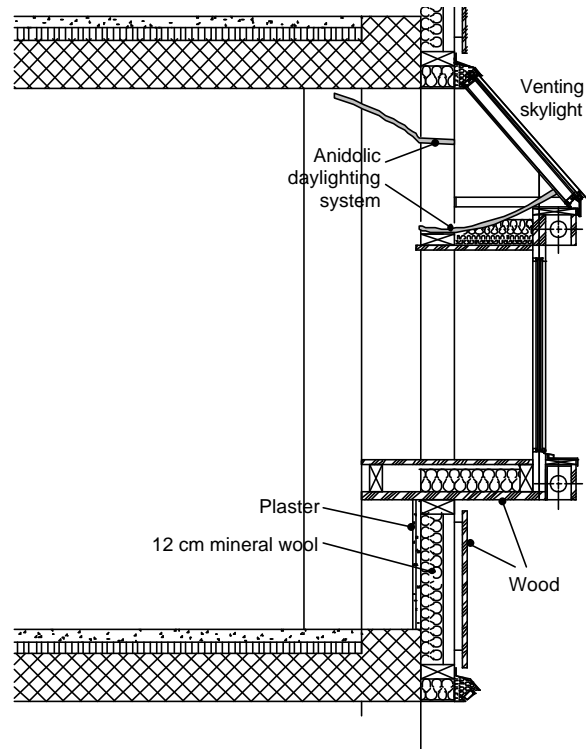


Figure 64: Vertical section through the facade

The figure below give a view of the facade from outside, showing the anidolic and normal windows provided for each office room. Each facade element (for one typical office room) needs two blinds: one for the lower (normal) window, and one for the upper (anidolic) fixed window. Both blinds need to be controlled independently.



Figure 65: View of the south facade of LESO building

The two rooms situated at upper floor, in the middle thermal cell of the building, have been used for the EDIFICIO measurements (rooms 203 and 204). In order to allow comparative tests, both rooms have been equipped with the complete LonWorks sensors and actuators, one room being driven by the EDIFICIO smart control algorithms and the other room by a simple reference algorithm corresponding to the usual control systems.

During the measurements, the rooms have been regularly exchanged (room 203 with the EDIFICIO algorithm and room 204 with the simple reference algorithm, then room 204 with the EDIFICIO algorithm and room 203 with the simple reference algorithm), in order to avoid the experimental bias due to the difference of behaviour between the two users (both rooms are used by only one person each), and also small differences in the thermal characteristics of the rooms. (See also the section on experimental methodology.)

3.3.4.2.2 Experimental set-up

Two rooms have been used for the experiments. One room is equipped with the EDIFICIO system and one room with a conventional controller (no automatic blind control, no automatic artificial lighting control, proportional heating controller with saturation). The control system is hosted by a computer, which controls both rooms. The conversation between the computer, the actuators and the sensors is done via a Lonworks™ bus with the standard protocol "Dynamic Data Exchange" (for details, see LESO paper 21 "Experimental Set-up for LESO Building: Measurements and Software Structure " dated 11.4.1999).

In order to reduce the experimental bias, due to the room characteristics and the user behaviour, the EDIFICIO controller is periodically (typically, every two weeks) replaced by the conventional controller while in the other room the conventional controller is replaced by the EDIFICIO controller. For the results analysis, the time each controller has worked in a room is taken into account (for details, see LESO paper 34 "Measurement Methodology" dated 12.6.2000).

The experiments have been undertaken in two phases.

1. Experimental set-up phase

Period of the experimental test phase at LESO: 04.11.2000 → 27.01.2000.

During this period the EDIFICIO system was running, but since there were still many bugs, the data are not very reliable. Anyway they have been stored, and some of them could be interesting for further studies.

2. "Real" experiments phase

Period of the "real" experiments at LESO: 27.01.2000 → 25.07.2000.

During this period the EDIFICIO system was working quite good, and only very minor bugs have been fixed. That means there are available data for nearly 6 months of experiments.

3.3.4.2.3 Controller operation: check on short periods

3.3.4.2.3.1 Shading device controller

The following figure shows some qualitative results concerning the blind and artificial lighting operation. Two days of experiments are shown. The first day is a working day (Friday, January 7th 2000) and the second one is a day-off (Saturday, January 8th).

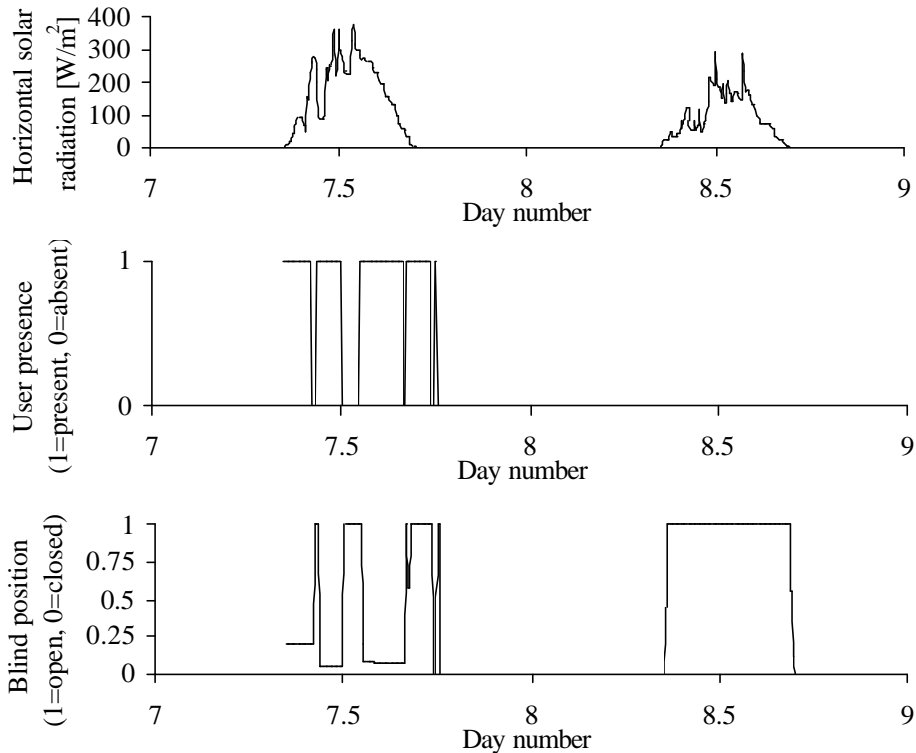


Figure 66: Global solar irradiance, presence and blind position provided by the integrated controller, Day 8.00 corresponds to Saturday, January 8th 2000 at midnight

During the working day (day 7), the user has left the room for a short time each in the morning and in the afternoon, and he had a longer lunch break at noon. The last peak in the presence graph corresponds to the coming of the cleaning staff. The corresponding blind position shows that when the user is present, the blind has a very low position (<0.2) for glare considerations (winter + sunny day = high glare risk) and when the user is absent, the blind is completely open for thermal considerations. In the evening, the user is present while the solar irradiance is low, then the blinds are completely open in order to have a maximum of day lighting.

Since the measuring season was winter and the user was not present the day 8, the blind was open during this day in order to accept the maximum of solar gains and closed during the night in order to have a better thermal insulation of the window.

Concerning the artificial lighting controller, the day 7 (user present) shows that it operates correctly, bringing additional lighting only when it is necessary: early in the morning and late in the evening when the natural lighting was not sufficient and when somebody was in the room.

Moreover, it has to be said that the user has not interacted with the shading device controller during the whole working day (day 7), which means the visual comfort provided by the controller was probably sufficient. Questionnaires that are filled in by the user twice or three times a day have confirmed it. These questionnaires give information about the visual comfort, the thermal comfort and the user opinion about the automatic system.

3.3.4.2.3.2 Heating controller

A new version of the heating controller has been developed and implemented. It uses an energy-saving setpoint applied during nights and weekends. The following figure shows the results concerning the new thermal controller (the previous version was giving very bad results).

It corresponds to eight days in the year 2000 from Thursday, February 10th to Thursday February 17th. The inside temperatures in the two rooms (one with the EDIFICIO controller and one with the conventional controller) are shown in parallel with the heating power profiles of the two controllers. The temperature setpoint was 22°C in both rooms.

The EDIFICIO controller shows a very interesting advantage compared to the conventional controller. It avoids overheating (Day 41 for instance) in the afternoon by taking into account the solar gains.

It should be noted that the steps of the heating power of the conventional controller are due to a discretisation of the inside temperature measurement. Since the heating power is calculated using the inside temperature, a discretisation of this latter leads to a discretisation of the heating power.

Thursday, February 10th 2000 at midnight

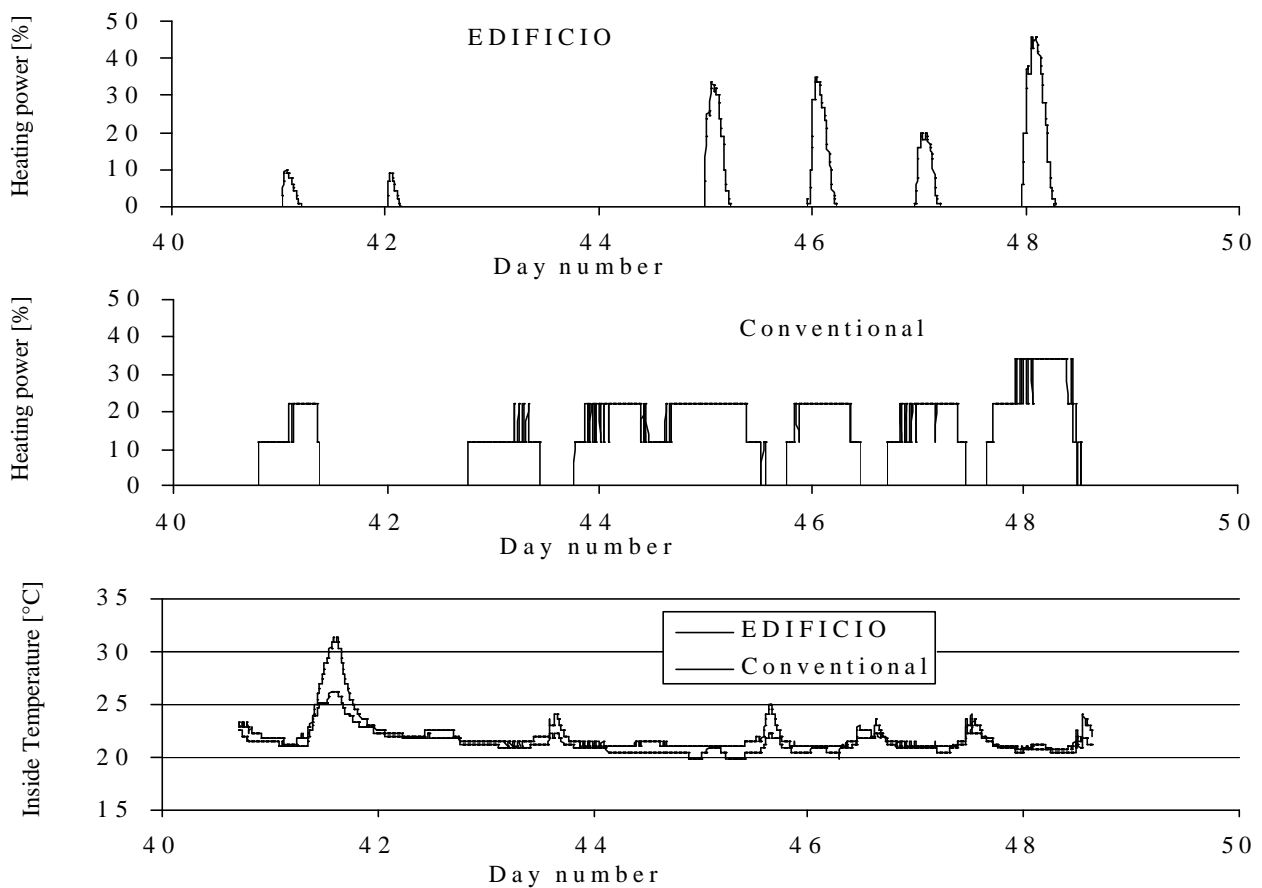


Figure 67: Inside temperatures and corresponding heating power profiles

3.3.4.2.4 Results: Files description

The results data files are separated in two categories: ESMQ and Matlab depending on their origin. ESMQ is the software used for the monitoring of all the available data in the LESO building. This

software is very similar to the ESM software, but it has been developed directly by the LESO in order to solve some problems of the latter during the experimental set-up phase.

The ESMQ results files are CSV files (Comma Separated File), which are readable by many programs. There are also ESMQ files in a LOG format, which contains information about the recording of the variables and the errors.

The Matlab files are MAT files that contains workspace variable for Matlab.

All these results files have been compressed in six ZIP files saved on six floppies:
 LESO_Results_ESMQ_old, LESO_Results_ESMQ_1, LESO_Results_ESMQ_2
 LESO_Results_Matlab_old, LESO_Results_Matlab_1, LESO_Results_Matlab_2

The results data of the experimental set-up phase period coming from Matlab are stored in "LESO_Results_Matlab_old" and the ones coming from ESMQuick are stored in "LESO_Results_ESMQ_old"

The results data of the “real” experiments period are stored in "LESO_Results_ESMQ_1" and "LESO_Results_ESMQ_2" for the data coming from ESMQ and in “LESO_Results_Matlab_1" and "LESO_Results_Matlab_2" for the data coming from Matlab.

Period begin	Period end	Room with EDIFICIO	Data files of ESMQ	Data files of Matlab	LESO Zip files number
27.01.2000	09.02.2000	LE 204	204_0902	recordvar0902	1
09.02.2000	17.02.2000	LE 203	203_1702	recordvar1702	1
18.02.2000	01.03.2000	LE 203	203_2502 203_0103	recordvar0103	1
01.03.2000	13.03.2000	LE 203	-----*	recordvar1303	1
14.03.2000	27.03.2000	LE 203	-----*	recordvar2903	1
27.03.2000	29.03.2000	LE 203	203_2903	recordvar2903	1
29.03.2000	01.05.2000	LE 204	204_0105	recordvar0504' recordvar0105	1
01.05.2000	05.06.2000	LE 203	203_0506	recordvar1805 recordvar2205 recordvar0506	1
05.06.2000	26.06.2000	LE 204	204_0606 204_1406 204_1406' 204_2606	recordvar2606	2
26.06.2000	11.07.2000	LE 203	203_1107	recordvar1107	2
12.07.2000	20.07.2000	LE 204	204_2007	recordvar2007	2
20.07.2000	25.07.2000	LE 203	203_2507	recordvar2507	2

* These data have not been recorded because of hardware problems in the VNR datalogger

Table 47: List of available files of the real experiments phase

3.3.4.2.5 Energy consumption comparisons

The total energy consumption results (heating + artificial lighting + electrical appliances) are presented independently for the three different seasons. It should be noticed that the energy consumption includes the energy used by the IRC and all the sensors and actuators. So, the fact that the EDIFICIO system consumes more electrical energy than the conventional system (more blinds movement, for instance) is taken into account.

System	EDIFICIO in room A (21 days)	EDIFICIO in room B (13 days)	Total energy consumption (and corresponding power) (34 days)
EDIFICIO	154.5 MJ	121.8 MJ	276.3 MJ (= 94W)
Conventional	276.9 MJ	180.0 MJ	456.9 MJ (= 156W)

Table 48: Results of the controller for the period: 27 January 2000 – 1 March 2000

System	EDIFICIO in room A (28 days)	EDIFICIO in room B (33 days)	Total energy consumption (and corresponding power) (61 days)
EDIFICIO	165.0 MJ	139.3 MJ	304.3 MJ (= 58W)
Conventional	172.8 MJ	154.7 MJ	327.5 MJ (= 62W)

Table 49: Results of the controller for the period: 1 March 2000 – 1 May 2000

System	EDIFICIO in room A (45 days)	EDIFICIO in room B (29 days)	Total energy consumption (and corresponding power) (74 days)
EDIFICIO	157.1 MJ	94.3 MJ	251.4 MJ (= 39W)
Conventional	195.7 MJ	109.2 MJ	304.9 MJ (= 48W)

Table 50: Results of the controller for the period: 1 May 2000 – 25 July 2000

System	EDIFICIO in room A (94 days)	EDIFICIO in room B (75 days)	Total energy consumption (and corresponding power) (169 days)
EDIFICIO	476.6 MJ	355.4 MJ	832.0 MJ (= 57W)
Conventional	645.4 MJ	443.9 MJ	1089.3 MJ (= 75W)

Table 51: Results of the controller for the whole period: 27 January 2000 – 25 July 2000

The EDIFICIO controller leads to 40% of energy savings in winter, 18% during summer and 7% during mid-seasons.

Total energy consumption (measured)

Conventional:	1090 MJ
EDIFICIO:	830 MJ

The energy consumption in both rooms is clearly lower with the EDIFICIO system. It has saved 260 MJ during the whole period, equal to 24% of energy consumption in comparison with the conventional controller over the whole experiments period.

The fact the conventional heating controller has no night setback may lead to have over-estimated good results for the EDIFICIO controller. In order to ensure the good results, two simulations have been done to evaluate the energy savings of the night setback for a conventional heating controller. The simulation tool used is the tool developed in the SMARTWINDOW project by Simone Molteni (LESO-PB) because it was easier to configure for these simulations than the EDIFICIO simulation package.

The simulation results show that the implementation of a night setback only reduces the total energy consumption of 5%. It may be explained by the fact that the heating energy represents only 15% of the total energy consumption in the LESO building (these values are coming from the simulation), while the appliances and the artificial lighting represents about 40% each. So, the energy savings concerning the heating system do not influence very much the total energy consumption even if the heating system is very efficient. Moreover, the building is very heavy, making a night set-back not very efficient because the temperature does not get much lower during the night than during the day.

It has been calculated that about 5 MJ (0.5% of the total energy consumption) has been saved thanks to the supplementary insulation (blinds down) during night.

So, in conclusion there is 18.5% (24% – 5% – 0.5%) of energy savings, which remains to be explained. Firstly a better use of solar gains leads to quite large energy savings. The main part of the free solar gain accepted corresponds to energy savings for the heating system. Secondly, thanks to the prediction capability of the EDIFICIO controller, it reduces the heating power during the night and the morning when it knows that solar gains will provide a large amount of solar energy in the afternoon, which avoids overheating and resulting discomfort. Thirdly, the last contribution for the energy saving is the better management of the artificial lighting. For instance, it switches off the lights as soon as the latter is not needed anymore (when the natural lighting is sufficient or when the user is not present for more than 15 minutes).

3.3.4.2.6 Comfort comparison

3.3.4.2.6.1 Thermal comfort

In order to compare the thermal comfort provided by the EDIFICIO controller and the conventional one, PMV calculations have been done on the whole experiments period. Since the temperature sensors used for the control (linked to the IRC board) have been calibrated with big difficulty and without any confidence, it has been chosen to use for both rooms the ventilated temperature measured by the VNR datalogger. These temperatures are more reliable and the PMVs have been calculated from these values.

The variable “cool-discomfort” is the fraction of presence time during which the PMV is between -0.5 and -1.0. The variable “warm-discomfort” is the fraction of presence time during which the PMV is between 0.5 and 1.0. The variable “cold-discomfort” is the fraction of presence time during

which the PMV is less than -1.0 . The variable “hot-discomfort” is the fraction of presence time during which the PMV is more than 1.0.

The results are presented in the following tables.

Room	Total time of presence [hours]	cold-discomfort	cool-discomfort	Comfort	warm-discomfort	hot-discomfort
A (EDIFICIO)	371	0%	0.5%	65.5%	33%	1%
B (Conventional)	208	0%	0%	70%	22%	8%

Table 52: Discomfort time fraction for the experiments period when EDIFICIO was in the room A.

Room	Total time of presence [hours]	cold-discomfort	cool-discomfort	Comfort	warm-discomfort	hot-discomfort
B (EDIFICIO)	317	0%	0.5%	65.5%	30%	4%
A (Conventional)	227	0%	0%	69%	26%	5%

Table 53: Discomfort time fraction for the experiments period when EDIFICIO was in the room B.

Clearly, both systems provide a quite good thermal comfort in the room. During 2/3 of presence time the comfort in the room is good. There is never a cold-discomfort, and very rarely a cool-discomfort with the EDIFICIO system. The latter comes from the fact that sometimes the system does not heat because it predicts overheating in the afternoon and accepts a little bit cool-discomfort in the morning in order to avoid a large overheating in the afternoon. The following figure illustrates this issue.

Moreover, this preventing of overheating explains why the EDIFICIO controller leads less often to hot-discomfort than the conventional controller.

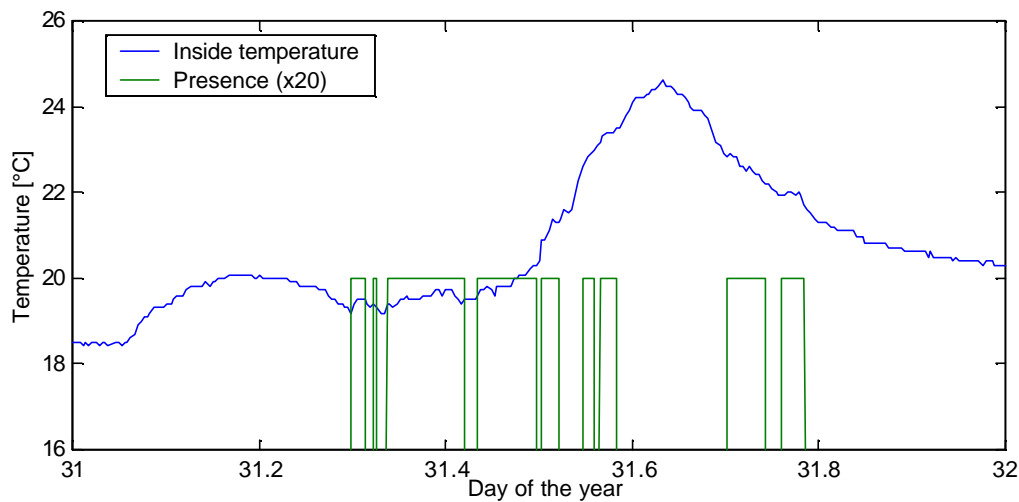


Figure 68: Inside temperature and presence in the EDIFICIO room during day 31st January 2000.

In fact, in the EDIFICIO room, the hot-discomfort is prevented, and only a warm-discomfort appears. The results of the larger warm-discomfort in the EDIFICIO room than in the conventional one are then also explained, because the main hot-discomfort periods are “shifted” in warm-discomfort period.

3.3.4.2.6.2 Visual comfort

We have used the PIECLE method for evaluating the visual comfort. David Francioli (Institute of Occupational Health Sciences in Lausanne, Switzerland) has shown that a sufficient estimation of the visual quality of a work place could be done with the consideration of only vertical and horizontal illuminances at the work place. The idea is to use only two sensors: one that measures horizontal illuminance on desk and one that measures vertical illuminance near the eyes of the user. The method gives an estimation of the visual quality at the work place through the percentage of unsatisfied people. There is a lot of work in the background of this method. In fact one hundred of work places have been study in order to produce it¹¹.

The percentage of dissatisfied people (PPD) has been translated in a quality of the visual comfort, using the following standard conversion.

PPD	Visual Comfort
25% → 37.5%	Good
37.5% → 50%	Fair
50% → 75%	Bad
75% → 100%	Very bad

Note: 25% is the minimum value of PPD (similar to the minimum of 5% of PPD for the thermal comfort)

Table 54: Translation of the PPD in quality of visual comfort

The fraction of time during which the visual conditions were in each category of comfort is given in the following tables.

Room	Total time of presence [hours]	Very bad	Bad	Fair	Good
A (EDIFICIO)	96	0%	4%	17%	79%
B (Conventional)	38	4%	1%	9%	86%

Table 55: Comfort fraction of time distribution (EDIFICIO system in room A)

Room	Total time of presence [hours]	Very bad	Bad	Fair	Good
B (EDIFICIO)	91	0%	2%	24%	74%
A (Conventional)	59	12%	13%	7%	68%

Table 56: Comfort fraction of time distribution (EDIFICIO system in room B)

¹¹ J.J. Meyer, D. Francioli, P. Rey, L. Deschamps, R. Compagnon: *Le nouvel indice d'inconfort visuel*. Economie et Ingénierie, XXIX^{ème} congrès de la SELF, Paris, 1994

Using the PIECLE method, the EDIFICIO controller seems to provide more often an acceptable visual comfort (Good and Fair conditions) than the conventional one. In the first case (EDIFICIO in room A) the fraction of time of acceptable visual comfort is similar (96% for EDIFICIO and 95% for conventional), but in the second case (EDIFICIO in room B), EDIFICIO is definitely better (98% of time of acceptable visual comfort for EDIFICIO and only 75% for the conventional). Moreover, the EDIFICIO system always avoids the very bad visual comfort, which is not the case for the conventional (up to 12% of time of very bad visual comfort).

These good results are simply explained by the fact that in the conventional room there is no automatic control for the blinds, and that the user does not interact regularly with the blinds system. For instance, he immediately closes the blinds since direct sunlight enters the room but he does not raise up again the blinds in the afternoon, which could lead to a lack of daylighting at dusk.

So, the automatic control applied on the blinds seems to fulfil its purpose: the visual comfort is improved, and there is a better management of the solar gains (in both “user present” and “user absent” cases).

3.3.4.2.7 User’s satisfaction

The questionnaires (shown in the LESO paper 30 "First results of full-size experiments at LESO" dated 24.11.1999), which have been regularly filled by the users, have been very useful in the experimental set-up phase in order to find the numerous bugs in the controller systems.

In these questionnaires, the number of user interactions with the system is evaluated, and the results are given in the following table.

Control system	EDIFICIO	Conventional
Average number of interactions per day	3.1	3.2
Standard deviation	1.6	1.8

Table 57: Number of interactions per day of the user with the automatic control system

Although these results are not very reliable (not regularly enough given by the users), one may conclude that the EDIFICIO system does not need more interactions than the conventional system in order to get comfortable conditions.

At the end of the experiments, one of the user is rather satisfied with the EDIFICIO system and would prefer to keep this system instead of coming back to a conventional system, while the other is greatly angry towards the automatic system and is looking forward to get back to the conventional controller.

The questionnaires have shown that the user is quickly angry at the automatic system when it does not take into account his wishes. For example, the user does not like the current blind position and he moves it. The automatic blind control is then held up during a certain amount of time (typically during one hour) in order to avoid moving the blind again to the position disliked by the user. But since the user's wish is not taken into account in the long-term by the system, the automatic control will keep giving an inadequate blind position.

In our very small sample of users (2), only 50% of people are satisfied with the EDIFICIO system. That strongly demonstrates the need of a long-term adaptation to the user wishes in order to increase the percentage of satisfied people who will use the EDIFICIO system.

3.3.4.2.8 Conclusions

The performance of the system has been studied for a long period including winter, mid-season and summer, and the results are good on the three periods. On the whole period of experiments (nearly six months), the EDIFICIO system has saved a very interesting amount of energy (25%) while keeping quite a good thermal comfort level and even improving the visual comfort level. This is explained by the energy efficiency control of blinds and also by the smart heating controller with the energy-saving setpoint applied during nights and weekends.

The users' satisfaction is the critical point. Only one of the two users has been satisfied with the EDIFICIO system. The conclusion is that the system should adapt on a long-term basis to the user's wishes while keeping, from an energy point of view, the most efficient possible control of the blinds.

3.3.4.3 FULL-SIZE MEASUREMENTS IN VTT

3.3.4.3.1 Building description

The building module prototype "METOP" for a low-energy office building was built in 1991 in the test house area of VTT in Espoo, Finland. The low-energy office, whose total costs were quite low, was built using a new Finnish component system building technology. The main objective was to put into practice good indoor air quality, thermal comfort and low energy consumption simultaneously and economically.

The frame construction was made of pillars and beams of concrete. The facing elements and double pre-stressed solid planks of concrete which were used as "plenum" floors and ground slabs were heat insulated with 120 mm thick polyurethane without CFC. The roof was heat insulated with a 350 mm thick layer of loose-fill insulation. The amount of thermal insulation of the office building slightly exceeded the requirements in Finland. The U-value of the external walls is 0.19 W/m²K.

The hollow spaces of the double pre-stressed solid planks and the hollow core slabs were partly used as installation spaces for building services and as air ducts. Structures were used for storage of heating and cooling energy. Quality of the construction was good and the air tightness of the building envelope was 0.8 air change per hour (50 Pa pressure difference). The energy consumption of the METOP-office building was thoroughly monitored in the year 1992 and was found to be 60 % less than the average consumption in Finnish office buildings.

The simple factory pre-adjusted variable air flow decentralised ventilation heating and cooling (VHC) system controls the air filtering, heat recovery and cooling recovery, heating, cooling with outdoor air, forced indirect evaporative cooling, pressures and ventilation of the building. The demand-controlled and silent VHC system serves the functionally independent building module and offers the possibility to choose the level of the room temperature and ventilation separately room by room.

The new window design (twin double-glazed frames with argon gaps, calculated U-value 0.5 W/m²K) reduces the heat losses through the window almost to one fourth of that of a triple-glazed window normally used in Finland. In addition, windows reduce well the need for cooling. Only 12 % of the direct solar radiation energy penetrates directly through the windows, which is 30 % of that of a triple-glazed window. Solar protection provided by glazing does not have any

considerable effect on the amount of visible light coming through the window, or on the appearance of the window.

Two adjacent office rooms on the ground floor of the METOP building were selected to serve as experimental rooms in EDIFICIO project. The two test rooms are quite similar in their geometry, and each has two identical windows, all facing south (see following tables).

3.3.4.3.2 The equipment in the test rooms

Both rooms were equipped with nearly identical set of control hardware arranged and connected to the LON network. Basic difference was an intelligent controller used in Room 12 as compared with the conventional controller used in Room 13. The intelligent controller enabled the control of dimming effect on lighting (on/off in the other room), ventilation control due to CO₂ concentration (no CO₂ control in the other room), and, most of all, intelligent heating control including scheduling due to presence patterns and night/weekend set-back of setpoint temperature (simple proportional temperature control without set-back features in the reference room).

		Room 12 (smart system)	Room 13 (conventional system)
Width	m	2.70	2.80
Length	m	3.85	3.85
Height	m	3.02	3.02
Floor	m ²	10.4	10.8
Volume	m ³	30.76	31.54
Number of windows	-	2	2
External walls	-	South	South, East
Window / floor area	m ² /m ²	0.221	0.213

Table 58: Main dimensions of experimental rooms in METOP building

Glass height	m	1.02
Glass width	m	0.72
Glass area	m ²	0.73
Frame height	m	1.22
Frame width	m	0.94
Total area	m ²	1.15

Table 59: Main dimensions of a window used in METOP

The air conditioning system in the METOP building is designed to fulfil the minimum ventilation requirements defined by the Finnish building codes (even with the minimum air flow rate). The Finnish building code defines a minimum ventilation rate as one air change in two hours. Accordingly, even though both of the dampers might be in off-positions but the central AHU (Air Handling Unit) is in operation, minimum air flow rate still enters the room. The ventilation is controlled step-wise.



Figure 69: View of the experimental METOP-building (N and W facade)

The following figure shows the principle of the HVAC system in each of the two experimental rooms in METOP. The terminal units include two VAV (Variable Air Flow) units in two separate ducts and an electrical heating coil in the first duct. In the first duct, the damper is riddled so even if the damper is closed 10 l/s of air is supplied into the room. Only if the building's central AHU is turned off, no air is supplied to the room. In addition, it is not possible to influence on the control of the central AHU, which includes for example a heat recovery unit.

The electric heating coil is controlled using a pulse with modulation in order to heat the supply air from the first duct in such a way that the actual heating power is the same as the desired heating power. This routine is called every 15 minutes in order to let the room adjust to the new control actions. The heating coil is on for a pre-set period of time and only the off-time is calculated in the controlling software.

Cooling of the room can only be done by increasing the air flow rate. There are not any additional terminal cooling devices in the room.

In both experimental rooms the setpoint temperature and the reference illuminance values are set from manual interface devices operated by the user. The ventilation air flow rate (in both rooms) and the lighting power (in the smart controller room) can also be adjusted manually from the interface device.

The experiments properly took place between mid September and mid December 2000, i.e. the systems were then working in the designed way. This period was extraordinarily warm in Southern Finland. Therefore, in order to get any heating demand in the low-energy office, the setpoint of the indoor temperature needed to be set to a quite high level (often 24 °C).

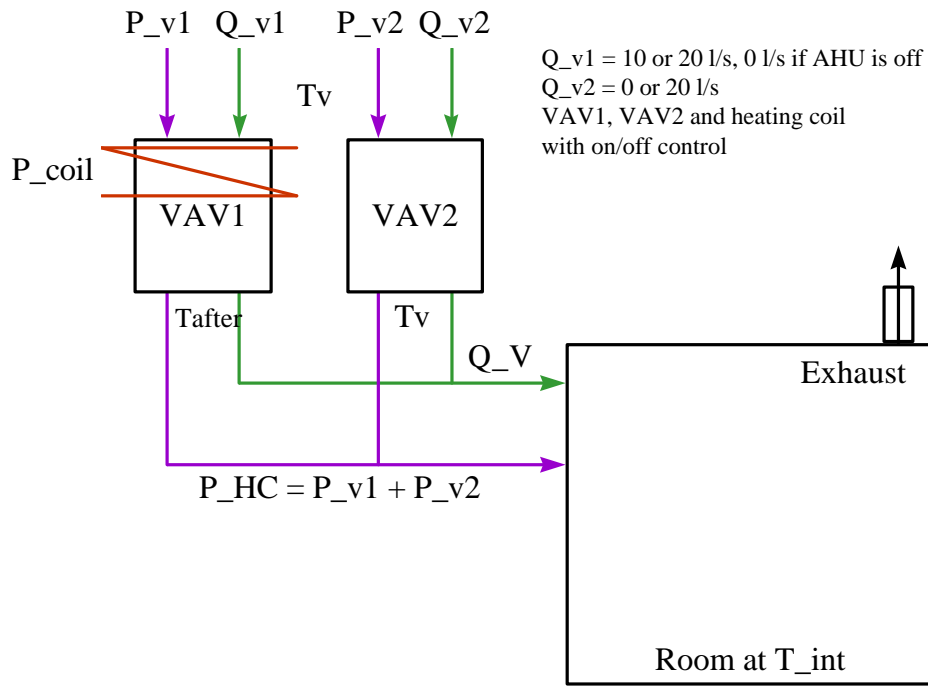


Figure 70: Combined ventilation and heating system arrangement in experimental room in Metop

The two rooms where the tests took place are not identical in their thermal behaviour. The first room with smart controller (room 12) is located in the middle of the building and has only one external wall. The other room with traditional controller is a corner room (room 13) having a similar external wall facing south as in the room 12 but it also has an external wall facing east. Geometrically, both rooms are nearly identical.

Monitoring of energy consumption started on 13 September 2000 at 12:30 and ended on 11 December 2000 at 12:15. Experiments were conducted in 13 periods, each lasting from a few days to two weeks. A summary of measured values is given in the following table.

	Outdoor temperature	Solar radiation	R12 avg air temperature	R12 avg heating power	R12 measured heating	R13 avg air temperature	R13 avg heating power	R13 measured heating
	C	W/m ²	C	W	kWh	C	W	kWh
Average	6.8	39	22.6	57	-	22.3	146	-
Min	2.1	9	21.3	4	-	21.1	29	-
Max	11.6	130	23.5	105	-	23.3	205	-
Set-point	-	-	21...24	-	-	21...24	-	-
Total energy					119			302
Normalised total energy					266			302

Table 60: Monitored values (summary of 13 experiments)

Due to different thermal behaviour of the rooms, their characteristics were determined using the method suggested by one EDIFICIO partner. Individual thermal characteristic of each room is derived using long term measured values of solar radiation, temperature difference and a corresponding heating power. The thermal characteristics were obtained as $h = -1.366m + 7.71$ and $h = -2.03m + 15.5$ for the room 12 and the room 13, correspondingly. There $m = I/\Delta T$ in W/m^2K , where I is the solar radiation incident on the most significant (south) facade in W/m^2 , and ΔT is the temperature difference between inside and outside. The $h = P/\Delta T$ in W/K , where P is the average power used for heating during the considered period. Thermal characteristics of the rooms were derived based on the measured results from 8 out of 13 experimental periods. Goodness of fit was $R^2=0.87$ (Room 12) and $R^2=0.80$ (Room 13).

Using the mentioned method, the monitored energy consumption was normalised to enable comparison. Here normalisation means that measured energy consumption in Room 13 with conventional controller is compared with calculated energy consumption the same room would have had if it had been served by smart controller identical to the one operated in Room 12. This calculation is made using measured energy consumption in Room 12 and thermal characteristics of each room. It was calculated that *the energy consumption with the conventional controller is 14 % higher than with the (smart) EDIFICIO controller*. This conclusion applies only to the monitored period that was relatively long (2127 hours) but unusually little diverse and exceptionally warm.

3.3.4.3.3 Control operation results

Figure 71 shows a typical operation of the smart thermal controller. The controller has learned the operation periods of the office room. Heating is not used during the weekend and during the nights even though the measured room temperature is below its setpoint. Still during the office hours the indoor temperature is maintained close to the setpoint level.

Figure 72 shows a typical example of the ventilation performance. Ventilation is controlled based on the CO_2 level. When the CO_2 level increases the supply air flow rate is increased step-wise.

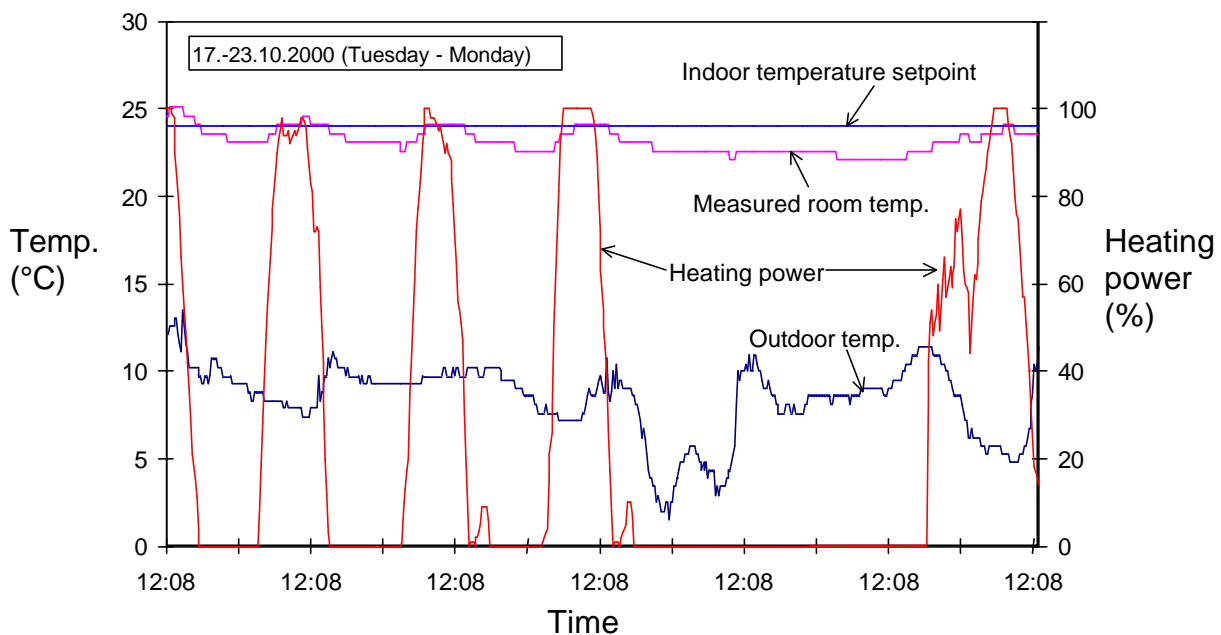


Figure 71. A typical operation of the smart thermal controller.

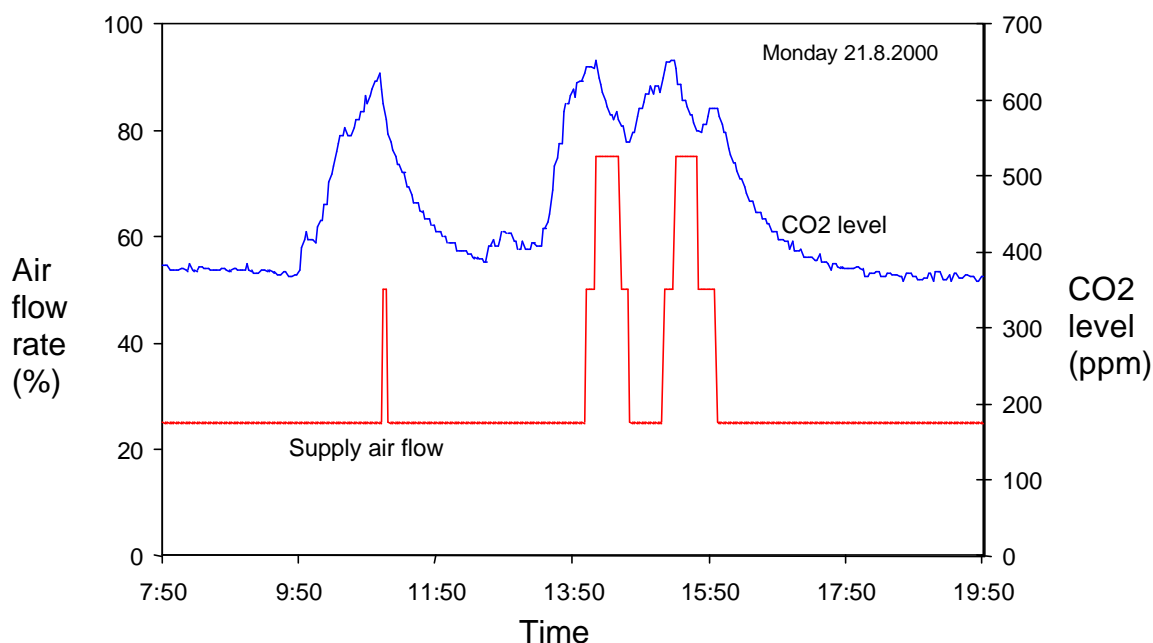


Figure 72. Ventilation control based on the CO2 level. (Air flow rate in percents of its maximum.)

3.3.4.3.4 Comfort results

Thermal comfort was evaluated using widely known Fanger's formalism related to a concept of PMV (Predicted Mean Vote). The PMV index is an estimate of a vote a statistical person would give to describe his perception of thermal comfort on a scale ranging from -3 (very cold) to +3 (very hot) with 0 being the optimal comfort situation. It was assumed in present study that setpoint temperature is a temperature of perfect comfort perception, i.e. then $PMV=0$. Deviations of air temperature from the setpoint value were then considered as an indicator of discomfort. PMV values were calculated in both experimental rooms at each time step (15 minutes) within "office hours" (8:00...16:00) all through the experiment and for all 13 experiments. Histograms were then calculated to show duration values for each degree of discomfort ranging from $PMV < -1.0$ to $PMV > 1.0$ with 0.5 intervals.

Smart controller provided a little better thermal comfort than conventional controller but in general both performed almost perfectly well according to used judging scale. It should be observed that criterion of $PMV = \pm 0.5$ as a limit for comfort is not stringent at all. In terms of air temperature it means a deviation of ± 1.7 K from setpoint value of 24 °C and even more for lower setpoint temperatures (e.g. ± 2.4 K for 21 °C).

	Duration (hours)	Unpleasant Cold $PMV < -1.0$	Unpleasant cool $-1.0 = PMV < -0.5$	Pleasant comfort $-0.5 = PMV < 0.5$	Unpleasant warm $0.5 = PMV < 1.0$	Unpleasant hot $PMV = 1.0$
Room 12 (EDIFICIO)	499.5	0.0 %	0.0 %	99.6 %	0.4 %	0.0 %
Room 13 (conventional)	499.5	0.0 %	1.4 %	98.6 %	0.0 %	0.0 %

Table 61: Distribution of calculated comfort perception summarised for all experiments

3.3.4.3.5 User's satisfaction

The test rooms were occupied only periodically. However, the users were asked to give their comments about the indoor conditions. A summary of the feedback is described in the following text.

In order to get any heating demand, the setpoint of the indoor temperature was kept in 24 °C. Of course, for many this is not a very comfortable level. However, the feedback in general was positive. It was found that perhaps there was a timing problem because some remarks were received about heating being on even at high indoor temperature.

The ventilation control was in general found to be acceptable. The air quality was very good with the developed ventilation control which was a function of the CO₂ concentration. The free cooling worked in principle OK but there was some draught. So, the gradation of air flow rate could be better. The manual control of the ventilation rate by means of a key-board interface was found handy. The lighting control was found to be very convenient for a lazy user because the lights turn on automatically when entering the room. The lighting control was mostly pleasant in use, except for the annoying blinking at certain sun/wind conditions. There was an excellent possibility for manual control of dimming with the key-board interface.

3.3.4.3.6 Conclusions

The performance of the system was monitored for 3 months covering a period of time that normally is autumn and beginning of winter in Finland. However, outdoor temperature varied quite little and remained exceptionally high. This, together with the fact that experimental building, METOP, is a heavy construction low-energy building, resulted in quite modest values of measured heating energy consumption. The values showed that a conventional controller consumed only 14 % more energy than EDIFICIO smart controller. There were very little differences in thermal comfort values in both systems (small advantage of EDIFICIO), since both were close to perfect in METOP. Ventilation control based on the CO₂ level and free cooling belonging to EDIFICIO system performed both very well. Perhaps a gradation of air flow rate for free cooling would have prevented from a few draught complaints. Dimming control of lighting in EDIFICIO, both automatic and manual, received considerable appreciation from users.

3.3.4.4 FULL-SIZE MEASUREMENTS IN CONPHOEBUS BUILDING

3.3.4.4.1 Building description

Conphoebus has a main office building of about 6000 m³. It consists of three stories, connected vertically by means of two stairs blocks. The building is subdivided into four vertical 2-stories modules plus a common ground floor. Each module is thermally insulated and fully monitored. The envelope components are installed as curtain wall, whereas the roof is covered by a gravel layer. The larger facades are oriented towards South and North. Four different bioclimatic solutions are in the South facade, one of that consists of a recessed window with external motorised venetian blinds.



Figure 73. Conphoebus office building

One of the room having this type of shading system has been chosen for the full-size measurements. The room have net dimension of 2.90 x 3.90 m and height equal to 3.50 m. It has only the South facade facing with the external ambient. In this external wall there is a large window having a height of 2.40 m (and starting 50 cm above the floor) and 2.50 m large. The window is recessed of about 50 cm.



Figure 74: External view of the room where monitoring has been done

The upper part of the window (50 cm) is shaded by the carter containing the venetian blinds. The room is placed on the first floor so both floor and ceiling are in contact with heated spaces. Two of the internal walls consist of furniture whereas the last one is a traditional brick wall. Only a man works inside the room and his desk is placed near the center. The following photo shows the room seen from inside.



Figure 75: Internal view of the room chosen for monitoring

3.3.4.4.2 Measurements in Conphoebus

Two IRC were used in Conphoebus for the monitoring of the system. In particular one IRC was used for the room acquisition while the second one was devoted only to meteo data acquisition. Due to the not correct version of the blind controller it was not possible to test an automatic movement of the blind jointly to the other used controllers, whereas only manual movement of the blind was allowed.

As consequence, not all the functionalities of the EDIFICIO system has been tested.

Since blind movement are not automatically controlled by BEMS it was decided to rise manually blind position (slat in fixed position horizontally) in three different configurations:

- 25% opened
- 50% opened
- 75% opened

A first set-up phase has been devoted to solve problems and bugs. After that phase several weeks were devoted to data acquisition.

The measurements give us the possibility to evaluate the correct operation of the controller concerning the following devices:

- Light control (dimmer);
- Presence control;
- Three way valve opening percentage connected to cooling/heating device;
- Fan coil fan speed (3 velocities).

The following figure shows the HVAC control system for a specific working day (18/10/2000) during the monitoring when the venetian blind was positioned 50% raised.

The internal temperature was fixed equal to 20°C. In the graph the user presence, the temperatures (external and internal) and the percentage of cooling power needed for maintaining the set temperature are reported.

As it is possible to see during the afternoon, when internal temperature increases over the set, the cooling plant is turned on. Also after the working period, the HVAC system is turned on until midnight in order to obtain the correct temperature at startup of the day after. This is an effect of the adaptive module of the controller.

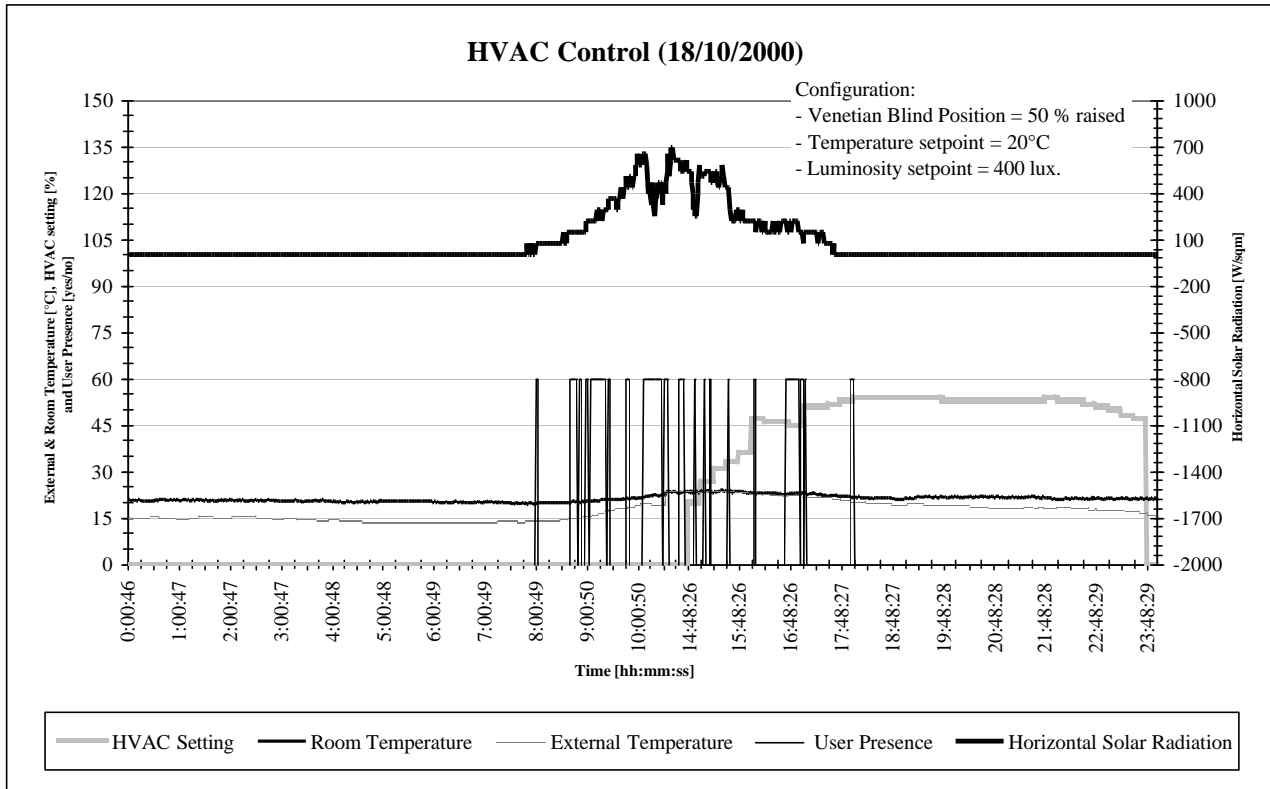


Figure 76: Monitoring of the HVAC control in a working day

In the following figure the artificial lighting control is analysed. During the day solar radiation gives a good internal illuminance for the whole working hours except before 9 a.m. and after 5 p.m. While external radiation is low during these periods, only during room occupation, the artificial lighting control is turned on, giving the required illuminance by means of a dimming control.

The complete set of data taken from the monitoring are stored in zip files available for further analysis.

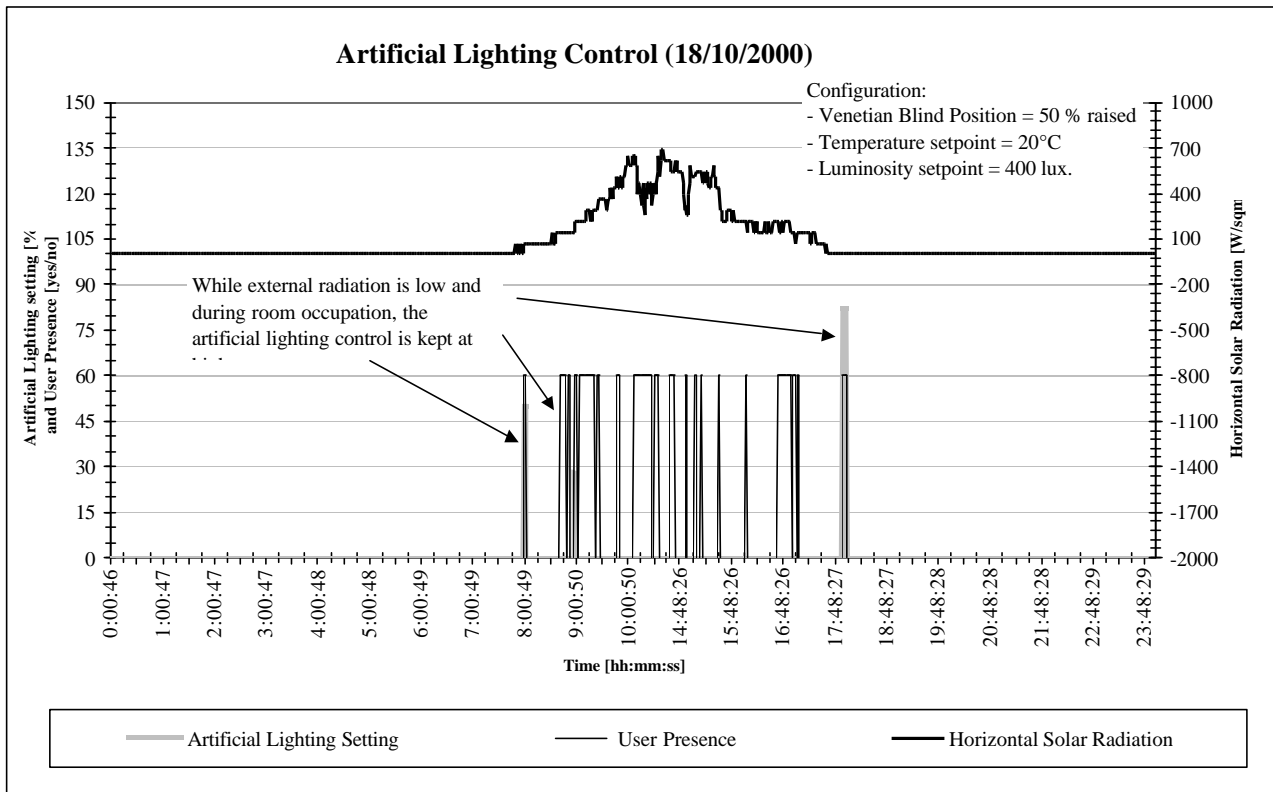


Figure 77: Monitoring of the artificial lighting control in a working day

3.3.4.4.3 Conclusions

The performance of the system was monitored for several weeks between August and November covering a period during which in southern Italy, there is need of cooling. The measurements allow to test the behaviour of the proposed EDIFICIO smart controller concerning the artificial lighting and the HVAC plant. All the modules of the smart controller tested in Conphoebus work well as aspected.

3.4 TASK DI: DISSEMINATION PHASE

The original proposal for dissemination phase was subdivided into two parts: the first one took into account the possibility to contact professionals and specialised firms in Building Management Systems; the second one was based on the idea to develop a pilot project implementing project's brand new concepts.

Each of this sub task, namely DI1 and DI2, have been modified along the project development. Particularly, as described in the Modified Technical Annex document, task DI2 has been cancelled. In fact, project's partners decided to focus attention on real test rooms, instead of a pilot project. Proceeding this way visitors and technicians interested in advanced BEMS concepts have the opportunity to visit real equipped test rooms nearby the three test sites.

Concerning DI1, taking opportunities of Internet technology, it was decided to install on the main internet server of some project's partners a comprehensive documentation on the EDIFICIO project. Except Conphoebus, which at the moment hasn't got an Internet server, all the other partners expressed availability to host project's documentation and results.

It was recognised that the most important part of the project must be considered the software development. Just on algorithms development and applied concepts partners are going to spread out information hosted on their own Internet server. To achieve "visibility" on the web it was also decided to index some keywords concerning this project on the major search engines (preferably specialised search engines).

Availability of information on the project will be "public" on Commission explicit permission. Concerning material to be published on internet, the basic idea is to put in evidence new concepts applied in EDIFICIO project not the sources codes developed by each partners. On the other hand, the Consortium Agreement signed by the project's partners, states rules for all aspect linked to all possible commercial aspects.

The dissemination of information will be achieved also by publications in scientific and technical journals, national and international workshops with building designers, manufactures of components and controls. Some of these dissemination actions have been already done, some others will be done in the future.

Every partner is also responsible to establish contacts in his own country with the companies which could be interested in the results of the project and to establish a link with the national ongoing projects in the same area of this project.

Some project partners are involved in educational activities and will be able to teach the building practitioners (engineers, architects, building administrator) about these new techniques.

4. COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED

During the project's mid term assessment meeting held in Lausanne on the 20th of September 1999, some problems arose about level 2 software's implementation into Warp co-processor. SNAU (partner G) introduced some budget problems concerning mainly the remaining man work to spend essentially in partner's support (task ET4). On its own, TUW.IMP (partner H) stressed strongly budget problems as well. They had (and still they have) to face larger man months effort than the planned one. During this session, a discussion born on the opportunity to abandon Warp implementation, emphasising, contemporary, the necessity to work more fruitful on ET4 task which was expected to require, till the project's end, a great software tuning-up effort. To recover economic resources within the already assessed project's budget, the Co-ordinator (Conphoebus partner) proposed some modifications to the project technical program aimed to save both the technical contents of the project and its innovative aspects. Within this frame the Co-ordinator proposed the following modification.

OLD WORK PROGRAMME	NEW WORK PROGRAMME
<p style="text-align: center;">TASK ET1: hardware/software integration</p> <p>Planned work</p> <ul style="list-style-type: none"> • Implementation of the control system into the Fuzzy Logic microprocessor The new smart control system will be implemented into the fully dedicated high speed Fuzzy Logic microprocessor, produced by industrial partner D. • Integration of the Fuzzy Logic microprocessor into the BEMS network. The fully dedicated high speed Fuzzy Logic microprocessor, incorporating the new adaptive control system, will be integrated into the BEMS network proposed by the industrial partner G, with an ad-hoc communication protocol and hardware interface. 	<p style="text-align: center;">TASK ET1: reduced</p> <p>Notes</p> <p>To cancel Fuzzy logic implementation into high speed processor doesn't mean that partner G halts its activities. Indeed, so far, and almost up to the end of the project, it is asked to assist project's partners involved in phase ET4 in IRC maintenance and software upgrade (level 1) whenever it's necessary.</p> <p>Different is the position of partner D which didn't never start development in Fuzzy logic processor implementation. On the other hand they distributed to all project partners a proprietary software developing tool for fuzzy implementation.</p>
<p style="text-align: center;">TASK DI2: elaboration of a pilot project</p> <p>Planned work</p> <p>To make realistic the use of the new adaptive control algorithms, the design of a demonstration pilot BEMS network in a real building, implementing the new smart control system, will be performed. This task is more directed towards the real end-users. The pilot project will show how the new techniques can be incorporated into a real building, and the convenience of their adoption.</p>	<p style="text-align: center;">TASK DI2: cancelled</p> <p>Notes</p> <p>It was noted that experimental sites in which the "Edificio systems" are actually in-service should be enough self-explicative to show how BEMS works and no other demonstration project are needed.</p> <p>Partners involved in such task are Co-ordinator and G.</p>

Table 62: Old and new project tasks comparison

Due to some tasks re-organisation, a new table concerning cost breakdown have been made by the project co-ordinator. Such table, approved by all project's partners have been delivered to the European Commission for final approval.

5. CONCLUSION

The EDIFICIO project activities were focused mainly on energy saving management in office buildings. It's clear that same conclusions on effectiveness of all achieved results can be applied to other buildings types such as commercial and even private residences. In fact the concepts developed during these last three years of project's activities concern energy saving in general, and, apart some technical adjustments (from the software point of view), same methodology can be applied satisfyingly to other fields.

EDIFICIO studies demonstrated that predictive algorithms' application can successfully improve standard controls in buildings. More, not only energy saving has been achieved but users comfort improved as well.

Despite great effort from all project's partners, the original idea to implement within this project a brand new industrial product, namely IRC device, have been partially reached. In fact, IRC device, which is at the moment a LonWorks device, isn't really fully implemented at industrial level, but it's rather a prototype.

It's out of doubt that its manufacture at industrial level requires specific skill in such task, specially when cost reduction is mandatory.

Concerning software development and its implementation at industrial level, EDIFICIO project offers a lot of variety of solutions for those subjects (firms, practitioners, etc.) interested in new software technique. In fact application of Fuzzy Logic, Genetic Algorithms, Neural Networks all together assembled in a unique compound software package give the opportunity to test such new techniques in energy saving management.

Finally the new concept introduced by the project is that nowadays it's possible to build a BEMS based on "Distributed Intelligence". The distributed intelligence is represented by each LonWorks devices, in this case the IRC, which superintends to all users' actions when one is at work in an office room. IRC let the users wishes to be accomplished without "forget" that energy saving must be maximised. On the other hand, when the user isn't present in the room, control of the whole thermal and lighting system passes entirely to the IRC which acts in such a way that energy saving is the first priority. It has been demonstrate that users acceptance of "Intelligent" device superintending users actions on room devices (operations on shading devices, blinds, lights, fan ventilation, etc.) was well accepted by the users themselves without particularly difficulties.

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