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EXPERIMENTAL RESULTS OF A SELF-ADAPTIVE INTEGRATED CONTROL SYSTEM IN BUILDINGS: A PILOT STUDY

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Abstract—An innovative integrated system for building energy and comfort management has been implemented on two occupied offices of the LESO-PB building. The measurements concern both energy consumption and comfort assessment. The results show that the system saves 19% of total energy consumption in comparison with a conventional heating controller with night setback. The thermal comfort level has been kept at a high level and the visual comfort has even been improved by the integrated control system. These good results are mainly explained by the integration concept of the overall controller and the energy efficient control of the blinds, which allow an optimal use of the passive solar gains. The user's satisfaction has been studied; it highlights the need of a long-term adaptation of the controllers to the user's wishes and preferences for a better acceptance of automatic control systems.

1. INTRODUCTION

An integrated self-adaptive controller has been developed in the framework of the European EDIFICIO project. This self-adaptive system for building energy and comfort management includes heating, shading device and artificial lighting controllers; its detailed description may be found in a previous author's paper (Guillemin and Morel, 2001). Several models are used in the control system to improve the efficiency of the different controllers. These models concern the physical room characteristics, the local weather forecast and the inside illuminance related both to the outside solar radiation and the artificial lighting electrical power. They are all regularly adapted to the measurements. Therefore, the automatic control system continuously adapts itself to the changing environment and room characteristics. It has been tested on the occupied LESO-PB office building during nearly 6 months, and the following issues have been checked:

- the energy saving and comfort improvement potential, when compared to a conventional controller
- the user's satisfaction

This paper shows the results concerning these issues.

2. CONTROLLER

The inputs needed for the controller are the setpoints expressed by the user (concerning the temperature and lighting aspects) and the 'weather and room' data which are the current time, the indoor and outdoor temperatures, the solar radiation, the presence or absence in the room, etc. The controller is divided into several different modules that are depicted in Fig. 1.

An artificial neural network (ANN) using radial basis function (RBF) allows the prediction of the room temperature. Using this RBF model of the room and a fuzzy logic rule base, the heating controller module is able to reduce at best the heating power consumption while keeping the right temperature setpoint when the user is present in the room. That means anticipating user presence, solar gains and so on. The weather predictor also helps the heating controller in this task. It consists in a simple feed-forward ANN with one hidden layer (containing four neurons).

The fuzzy lighting controller in addition with the lighting models provides a value for the blind position that avoids glare and that leads to an adequate illuminance level in the room. Moreover, the lighting models module detects lack of daylighting and provides the artificial lighting

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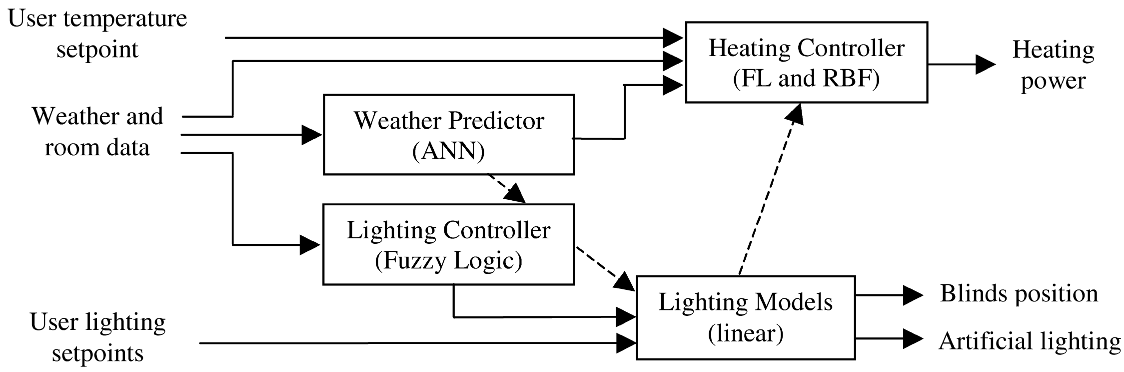

Fig. 1. Diagram of the integrated controller. Dashed lines concern predicted values.

power that gives a sufficient illuminance level on the working plan. It also calculates the horizontal indoor illuminance from the vertical outdoor illuminance on the façade. The weather predictor, the lighting models and the RBF model of the room are continuously adapted to the latest measurements. All these models and controllers are described in detail in the previous author's paper (Guillemin and Morel, 2001).

3. EXPERIMENTAL SET-UP

Two office rooms of the LESO-PB building, both occupied by one person, 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 software components organized in a 'client–server' mode, using the LonManager DDE server for the Lonworks communication and the Matlab environment for the algorithm calculations (see Fig. 2). A data logger (called VNR), independent of the Lonworks bus, is used to collect data concerning both weather and room conditions. The Monitoring Module allows grouping together the data coming from Matlab, Lonworks and VNR, and then displaying or storing them.

The dimensions of the two rooms are $4.75 \times 3.6 \times 2.8$ m. The windows are on the south wall, and the net glazing area for a room is 4.1 m^2. They are rather large openings, but thanks to the low U-value (1.4 W/m^2K) of these windows, the rooms are quite well thermally insulated. Electrical convective heating devices are used in both rooms.

In order to reduce the experimental bias, due to

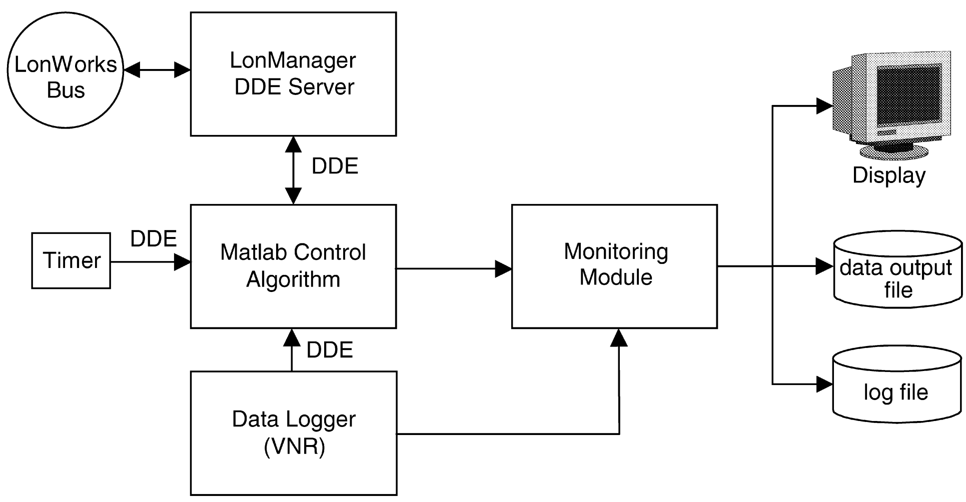

Fig. 2. Architecture diagram of the complete system.

the room characteristics and the user behaviour, the EDIFICIO controller is periodically (typically, every 2 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 been operating in a room is taken into account. At the end of the experiments the following data are therefore available, by summing the energy consumptions and the times:

- room 1, EDIFICIO controller: total time duration t_1, total energy consumption $E_{\mathrm{EDI,\ room1}}$
- room 1, conventional controller: total time duration t_2, total energy consumption $E_{\mathrm{conv,\ room1}}$
- room 2, EDIFICIO controller: total time duration t_2, total energy consumption $E_{\mathrm{EDI,\ room2}}$
- room 2, conventional controller: total time duration t_1, total energy consumption $E_{\mathrm{conv,\ room2}}$

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

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

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

Users interact with the system through a simple keyboard for raising or lowering the blinds, dimming the artificial lighting and changing the temperature setpoint. This keyboard is used in both rooms, so that users are not confused when the automatic and conventional systems are exchanged between the two rooms. Moreover, since the users are building energy specialists, they adapt themselves immediately to the new controller applied in their room. The occupancy profile observed in these rooms is similar to usual office hours (from 8 to 17) with a lunch break of 1 h at noon. In addition to the weekend, once or twice a week the users are absent during a whole day.

4. ENERGY CONSUMPTIONS COMPARISON

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 also includes the energy used by the electronic devices and all the sensors and actuators. So, the fact that the EDIFICIO system consumes more electrical energy than the conventional system, due to additional blind movements or electronic devices consumption, is taken into account.

The EDIFICIO controller leads to 40% of energy savings in winter (27.01.00–1.03.00) compared to the conventional controller, 7% of energy savings in mid-season (1.03.00–1.05.00) and 18% of energy savings in summer (1.05.00–25.07.00). Fig. 3 shows that the energy savings potential is logically the highest in winter. It corresponds to the period with the largest heating and artificial lighting demands.

Over the whole experimental period, the EDIFICIO controller saves 260 MJ or 24% of the total energy consumption compared to the conventional controller. Nevertheless, this raw value has to be corrected to take into account some experimental biases. The fact the conventional heating controller has no night setback may lead to over-estimated good results for the EDIFICIO controller. In order to ensure accurate results, two simulations have been done to evaluate the energy

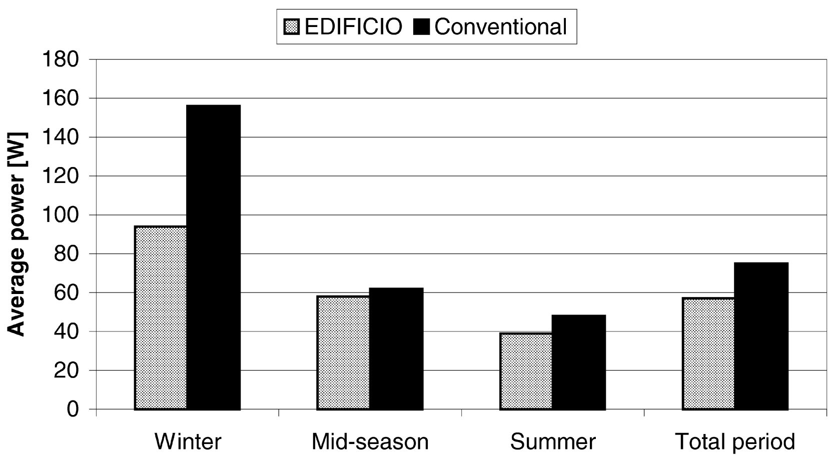

Fig. 3. Average power: comparison between the EDIFICIO and the conventional systems.

savings due to the night setback in a conventional heating controller. The simulation tool used here is the one developed in the European SMART-WINDOW project by Molteni and Morel (2001). The description of the simulations is given in Appendix A.

The results of these simulations show that the implementation of a night setback in the conventional controller only reduces the total energy consumption by 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 represent 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 thermal mass of the building being large, a night setback in the heating system may only lead to limited decreasing of the heating energy consumption.

In conclusion, comparing the EDIFICIO controller with a conventional heating controller with a night setback, 19% (24%–5%) of energy saving could be measured. That may be considered as a very good value for a well-insulated building with a large thermal mass. These energy savings may be broken up in different factors described below.

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.

The remaining 18.5% (19–0.5%) of energy savings cannot be strictly divided in exact percentages. Nevertheless, the different factors may be mentioned. Firstly, a better use of solar gains leads to quite large energy savings, especially when the user is absent. For instance in winter, the automatic system accepts a maximum of solar gains while the user could have left the blinds half closed and then could have lost the half part of solar gains. The main part of the free solar gains correspond 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 are not needed anymore, that is not the case with the conventional controller: the user switches on the artificial lighting on his morning arrival and forgets to switch it off when the natural lighting becomes sufficient. The artificial lighting remains uselessly switched on.

5. COMFORT COMPARISON

5.1. Thermal comfort

In order to compare the thermal comfort provided by the EDIFICIO controller and the conventional one, PMV (Predicted Mean Vote, see ISO 7730, 1984) calculations have been done on the whole experimental period and have been translated in a thermal discomfort value (see Table 1). This translation is based on the ISO 7730 standards for the comfortable range ($-0.5<$ PMV<0.5), and on author's considerations for the other ranges (chosen to be well suited to the results analysis).

The results, presented in Table 2, clearly show that 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 of cool-discomfort in the morning in order to avoid a large overheating in the afternoon. Fig. 4 illustrates this issue.

Moreover, this reduction of overheating explains why the EDIFICIO controller leads less often to hot-discomfort than the conventional controller. The larger warm-discomfort time in the EDIFICIO room than in the conventional one is then also explained, because hot-discomfort periods are 'shifted' in warm-discomfort periods.

5.2. Visual comfort

We have used the PIECLE method for evaluating the visual comfort. 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

Table 1. Translation of the PMV in a thermal discomfort evaluation

Predicted mean vote value	Thermal discomfort associated
PMV <-1.0	Cold
$-1.0<$ PMV <-0.5	Cool
$-0.5<$ PMV <0.5	Comfortable
$0.5<$ PMV <1.0	Warm
$1.0<$ PMV	Hot

Table 2. Discomfort time fraction for the experimental period comparison

Controller	Total time of presence [h]	Cold [%]	Cool	Comfortable	Warm	Hot
EDIFICIO	689	0	0.5	66.5	31	2
Conventional	435	0	0	69	24	7

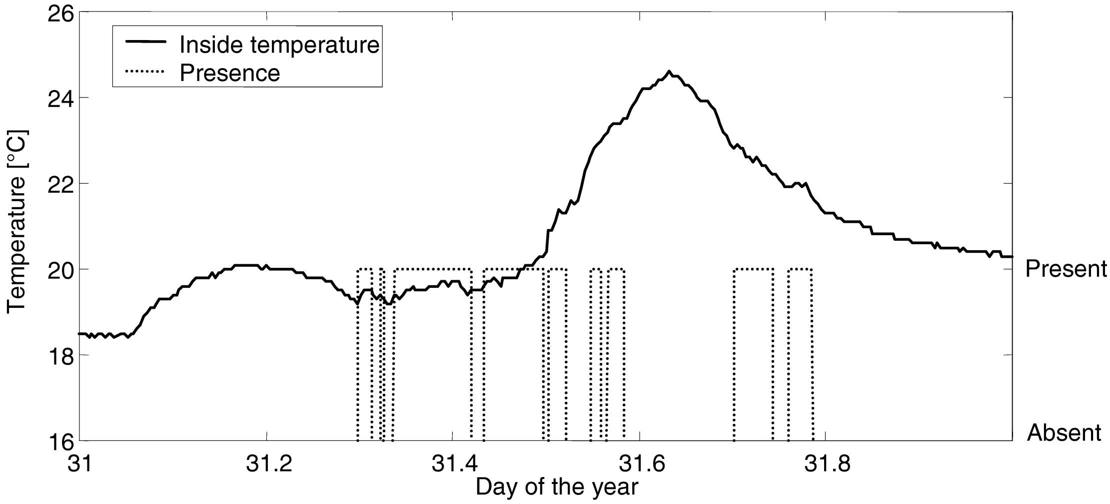

Fig. 4. Inside temperature and presence in the room with the EDIFICIO controller during day 31st January 2000. In the beginning of the day (day 31.3 corresponds to the 31st January 2000 at about 8 a.m.), the automatic system provides a slightly too low inside temperature but this reduces the overheating in the afternoon.

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; more than one hundred work places have been studied in order to produce it (Francioli *et al.*, 1999).

The predicted percentage of dissatisfied people (PPD) has been translated in a quality of the visual comfort, using a conversion provided by the PIECLE's authors (see Table 3).

The fraction of time during which the visual conditions were in each category of comfort is given in Table 4. The visual comfort is evaluated only during the effective presence time from the measured illuminance values. Note that the visual comfort experiments have been run only during 6 weeks in the summer period.

Using the PIECLE method, the EDIFICIO controller appears to provide more often an acceptable visual comfort (good and fair conditions) than the conventional one. Table 4 shows that the EDIFICIO controller is definitely better (97% of time of acceptable visual comfort for EDIFICIO and only 85% for the conventional). Moreover, the EDIFICIO system always avoids very bad visual comfort, which is not the case for the conventional (8% 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 blind system.

Table 3. Translation of the PPD in quality of visual comfort

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 4. Comfort fraction of time distribution

Controller	Total time of presence [h]	Very bad	Bad	Fair	Good
EDIFICIO	187	0%	3%	20.5%	76.5%
Conventional	97	8%	7%	8%	77%

For instance, he immediately closes the blinds when 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.

6. USER'S SATISFACTION

The user's dissatisfaction may be roughly assessed by counting the number of interactions of the user with the system during one day. It comes from the fact that the user is interacting with the blind, artificial lighting or heating systems when they do not provide adequate conditions in the room. A small number of interactions then characterises an efficient controller from a comfort point of view. The number of time the user has interacted with the system has been measured during the whole experimental period and the results are given in Table 5.

The EDIFICIO system does not lead to less user interactions than the conventional system. Even if the goal of the automatic system is to increase the comfort in the room, by automatically setting the blinds, artificial lighting and heating, the user had to interact as often as without automatic control. It proves that comfortable (measured) indoor conditions are not sufficient for the users.

Questionnaires, which have been daily filled by the users, show that the users become quickly angry towards the automatic system since it does not take into account his wishes. For instance, the user does not like the current blind position and he moves it. The automatic blind control is then held during a certain amount of time (typically during 1 h) in order to avoid moving the blind again to the position disliked by the user. But after this delay the automatic control is switched on again and it is very probable that the blind goes back to the position disliked by the user. As long as the user's wishes are not taken into account on a long-term basis by the system, the automatic control will keep giving an inadequate blind position. This has been pointed out very strongly by one of the two users who is clearly dissatisfied with the system. The other is quite satisfied with it and he has asked to keep the automatic control in his office at the end of the experiments. That demonstrates the need of a long-term adaptation to the user wishes in order to increase the percentage of satisfaction in people who will use an automatic control system in buildings.

Table 5. Number of interactions with the control system per day of one user

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

7. CONCLUSIONS

The performance of the EDIFICIO 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 6 months), the automatic system has saved a very interesting amount of energy (a net value of 19% of the total energy consumption when compared to a conventional heating controller with night setback) while keeping quite a good thermal comfort level and even improving the visual comfort level. This is explained by the energy efficient control of blinds and by the smart integration concept of the overall controller. The automatic control applied on the blinds seems to fulfil fully its purpose: the visual comfort is improved, and there is a better management of the solar gains.

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 automatic system should not only provide conditions that are called 'comfortable' from a physical values point of view (illuminance and temperature setpoints) but should also take into account, on a long-term basis, the particular preferences of the user. Authors are currently developing a new controller (using genetic algorithms) that will learn the user preferences and adapt itself to them, while keeping an efficient behaviour from an energy point of view.

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APPENDIX A. SUPPLEMENTARY SIMULATIONS FOR ENERGY CONSUMPTION ANALYSIS

The natural ventilation rate has been set to $0.12\,h^{-1}$ in the simulations. This value comes from measurement done in the test rooms with the windows and doors closed. The internal gain due to the appliances is set to 50 W all the time. The

Table A.1. Comparison of the total energy consumption with and without night setback in the heating controller

Simulated heating system	Total energy consumption on the whole period
Conventional with night setback	1224 MJ
Conventional without night setback	1290 MJ

presence schedule is fixed to 8.00–17.00 with a lunch break between 12.00 and 13.00.

The heating controller is a proportional heating controller with saturation (maximum deviation of 4°C). If the inside temperature setpoint is set to 22°C, the heating controller will give the maximum power at 18°C and will be turned off at 22°C. In the first simulation (without night setback) the heating controller is always heating as described above. In the second simulation (with night setback) the heating controller is heating from 6.00 to 18.00 with the given setpoint (22°C) and the rest of the time with the night setback setpoint of 18°C. The lighting controllers are simplified models of user behaviour and are rigorously identical in both simulations.

The simulations have been done exactly on the same period that the experiments have been undertaken, that means from the 27 January to the 25 July. The energy consumption results (including heating, artificial lighting and electrical appliances) are given in Table A.1.

The results show that the implementation of a night setback reduces the total energy consumption of 5% for a conventional controller.

Several reasons may be mentioned to explain the discrepancy between the simulated (1290 MJ) and measured (1080 MJ) total energy consumptions for the conventional controller:

- The temperature setpoints are different (fixed in the simulation case and changed by the user in the experimental case).
- The uses of blinds are different (simplified models in simulations versus user wishes during experiments).
- The occupancy schedules and internal gains are different.

REFERENCES

Francioli D., Meyer J. J. and Kerkhoven H. (1999) Méthode PIECLE pour l'évaluation du confort visuel dans un local. In *Proceedings of CISBAT'99*, Lausanne, Switzerland, pp. 271–276.

Guillemin A. and Morel N. (2001) An innovative lighting controller integrated in a self-adaptive building control system. *Energy and Buildings* **33**(5), 477–487.

ISO 7730 (1984) Moderate Environment Determination of the PMV and PPD Indexes and Specification of the Conditions for Thermal Comfort.

Molteni S. and Morel N. (2001) SMARTWINDOW: a window component with an integrated controller for blinds and ventilation. In *Proceedings of CISBAT 2001*, Lausanne, Switzerland, pp. 297–302.