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Energy and Buildings 38 (2006) 1084–1092
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Design and installation of an advanced EIB™ fuzzy indoor comfort controller using Matlab™

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Received 13 November 2005; received in revised form 19 December 2005; accepted 29 December 2005

Abstract

The aim of this paper is to present the design and installation of a fuzzy logic controller of indoor thermal and visual comfort as well as indoor air quality, using the EIB (European Installation Bus) system through interconnection with Matlab. An experimental chamber is implemented for testing and optimization of the system. The chamber which controls the indoor environment, consists of interconnected nodes (sensors and actuators) in an EIB fieldbus network infrastructure connected with a PC, through RS-232 port. Control is achieved by a fuzzy controller, which is programmed in Matlab. The interconnection between EIB and Matlab is realized via the EIB OPC server and an OPC Client for Matlab. In this way artificial intelligence control, EIB-based platforms and Matlab are interconnected in order to explore the possibilities of using advanced control techniques in energy efficient practices in real buildings.

Keywords: Energy management; Indoor environment; Fuzzy controller; Energy efficiency; Fieldbus systems; EIB; OPC client

1. Introduction and state of the art

Buildings Energy and Indoor Environment Management Systems (BEMS) contribute significantly to the reduction of energy consumption and to improvement of indoor environment [1]. Although the implementation of BEMS used to be cost effective only in new buildings due to extended wiring required for the communication demands, recent developments in the building automation and control sector by the introduction of various transmission media, helped considerably the feasibility of energy management in existing buildings. Moreover the requirement for a global interoperability in heterogeneous building automation environment consisting of different fieldbuses and data networks is recently a field of continuous research that is still far from being satisfied. Generally, interoperability is achieved when heterogeneous operating entities can communicate transparently and work together for a common scope [2]. One major scope of BEMS is to satisfy the thermal and visual comfort, the air quality demands as well as reduce the energy consumption. Factors that influence the users' comfort are the indoor thermal comfort, the indoor visual comfort and the indoor air quality.

European Installation Bus (EIB) technology is a building automation fieldbus that focuses on the energy management of electric installations, the demand side management, the environmental control and safety. An EIB system can be installed in all building types (i.e. offices, schools, hospitals, industries, public and private buildings, etc) and monitors and controls various environmental procedures and functionalities, such as heating, cooling, ventilation, air conditioning, lighting, shading, window opening, alarms, etc.

The various components are programmed via EIB Tool Software (ETS), a specialized EIB software tool. This software is a common software platform that programs the components of one or many manufacturers, for use by the EIB protocol. Although ETS is a necessary platform for the interconnection of the various devices, its programming capabilities and alternative solutions are limited since only basic I/O functions can be configured for each device [3,4].

The conventional control strategies for indoor comfort are ON–OFF and conventional PID methods [5]. The ON–OFF control in buildings has shown that the controlled variable

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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2005.12.007

swings continuously. Moreover the ON–OFF control in thermal comfort means control of indoor temperature only, without taking into account other critical thermal comfort variables.

Classical PID as well as ON–OFF control have been proved to be energy 'inefficient' [5,6]. The controlled variable creates overshootings and oscillations once the reference signal is reached. Overshootings and oscillations are the main cause for energy waste.

In recent years, a great number of sophisticated controllers have been developed for the control of indoor comfort, i.e. thermal comfort, visual comfort and indoor air quality [5,7–10]. These specialized controllers are based on artificial intelligence techniques (fuzzy logic, neural networks, genetic algorithms, etc.). There is, however, a need for programming, commissioning and testing such controllers in real time and conditions and to combine the capabilities of these controllers with advanced automation systems such as EIB, in order to obtain the maximum of both technologies.

In the present paper a BEMS is described, which considers the users' preferences as a dynamic part of the system and it is implemented in a test chamber using the EIB protocol. It also shows that is possible to interconnect Matlab and EIB platforms in order to test various sophisticated controllers in real environments and real time.

2. Test chamber

The test chamber is constructed in order to test and/or compare various sophisticated controllers supporting BEMS for the adjustment of the indoor environmental characteristics before their final installation in real buildings.

The variables that influence indoor comfort are: thermal comfort, visual comfort and indoor air quality.

Thermal comfort depends upon indoor temperature, relative humidity, air movement and indoor surface temperatures. Additionally thermal comfort depends upon subjective parameters such as clothing, metabolism and activity level. The first four parameters are measured, while subjective parameters are estimated on the basis of the building type and activities [11–13].

Visual comfort depends upon indoor illuminance levels (monitored) [15].

Finally, indoor air quality depends on the CO_2 concentration inside a building (monitored) [14,16].

The various components (tabulated in Table 1) i.e. sensors, actuators and interfaces are interconnected using specific devices for the EIB protocol and the EIS standard (EIB Interworking Standard). The intelligent controllers are developed in Matlab in order to be easily programmed, tuned and updated. The interconnection between MATLAB and EIBUS is performed via the OLE for Process Control (OPC) Standard. The structure of the system is depicted in Fig. 1.

2.1. Description of the test chamber

The test chamber's dimensions are 1 m × 1 m × 2 m and its six sides are easily assembled and disassembled in order to be easily transferred (Figs. 2 and 3).

Table 1
Test chamber's components

	Component	Type	Characteristics	Comments
1	Power supply + choke	EIBUS Siemens	220 V to ±24 V	Provides the necessary voltage for the EIB devices and the communication media
2	Communication interface	EIBUS Siemens N-148	RS-232	PC–EIB connection interface
3	EIB Universal I/O units	EIBUS I/O unit N-670 (5WG1 525-2AB01)	Two analog inputs/outputs, 2 relays (each)	Additional 24 V supply for powering the units
4	EIB–2 Binary output interface	ABB Shutter Actuator two-fold, MDRC LR/S 2.2.1	Two binary outputs	One binary output used for heater/cooler
5	Light controller	EIBUS Siemens UP-525 (5WG1 525-2AB01)	Dimming	Two-rocker switch and dimmer interface
6	Light sensor	Analog sensor	Range 0–2000 lux; Output 0–10 V; 24 V dc	Measurement of indoor lighting levels
7	Indoor temperature sensor and fire alarm combo	Siemens EIBUS 5WG1- 256-1AB01	EIB coded	Direct connection to EIB line
8	Outdoor temperature sensor	Analog sensor	Range −10–+40 C; Output 0–10 V; Power supply 24 V dc	Interconnection via the Siemens I/O unit interface
9	Relative humidity sensor	Analog sensor	Range 0–100%; Output 0–10 V; Power supply 24 V dc	Interconnection via the Siemens I/O unit interface
10	Air flow/hotwire anemometer	Analog sensor	Range 0–16 m/s; Output 0–10 V; Power supply 24 V ac	Interconnection via the Siemens I/O unit interface
11	CO_2 sensor	Analog sensor	Range 0–2000 ppm; Output: 0–10 V; Power supply 24 V ac	Interconnection via the Siemens I/O unit interface
12	Window motor	Actuator	220 V ac power supply	Interconnection via the Siemens I/O unit interface
13	Shading motor	Actuator	220 V ac power supply	Interconnection via the Siemens I/O unit interface
14	Venetian blinds motor	Actuator	24 V dc symmetrical power supply	Interconnection via the Siemens I/O unit interface
15	Tungsten filament lamp	Actuator	220 V ac power supply	Interconnection via UP-525
16	Air conditioning	Actuator	220 V ac power supply	Interconnection via ABB LR/S 2.2.1

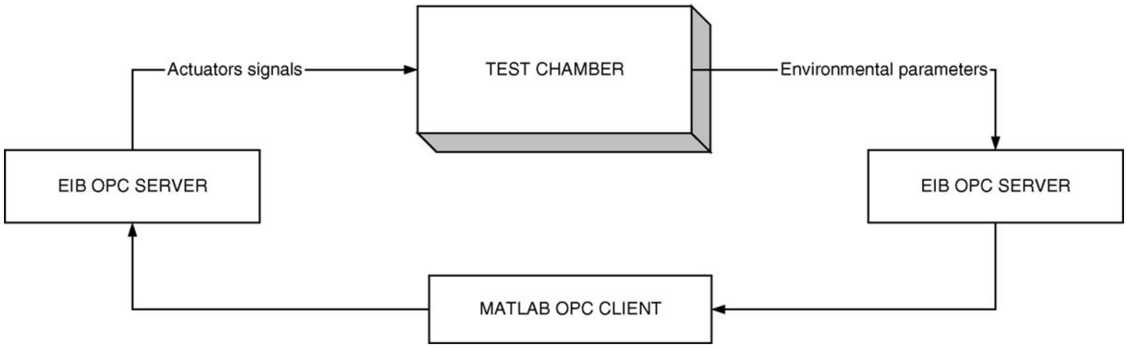

Fig. 1. The structure of the test chamber system.

The entrance of the test chamber is an aluminum door having a fixed, single glazed window. This is shaded with manually operated roller blinds in order to increase/decrease the light penetration. The indoor air quality conditions are controlled via an openable, double glazed window operated by a ac motor. This window is also equipped with internal venetian blinds, which are not used for illuminance control, but are set to a fixed position on initialisation. Indoor illuminance is controlled via external, motor-operated blinds (see) and also via a tungsten filament lamp controlled by a dimmer. Heating and cooling is provided at this stage by a split air conditioning unit located on the top of the test chamber.

A schematic of the overall installation is depicted in Fig. 4. All components are tabulated in Table 1.

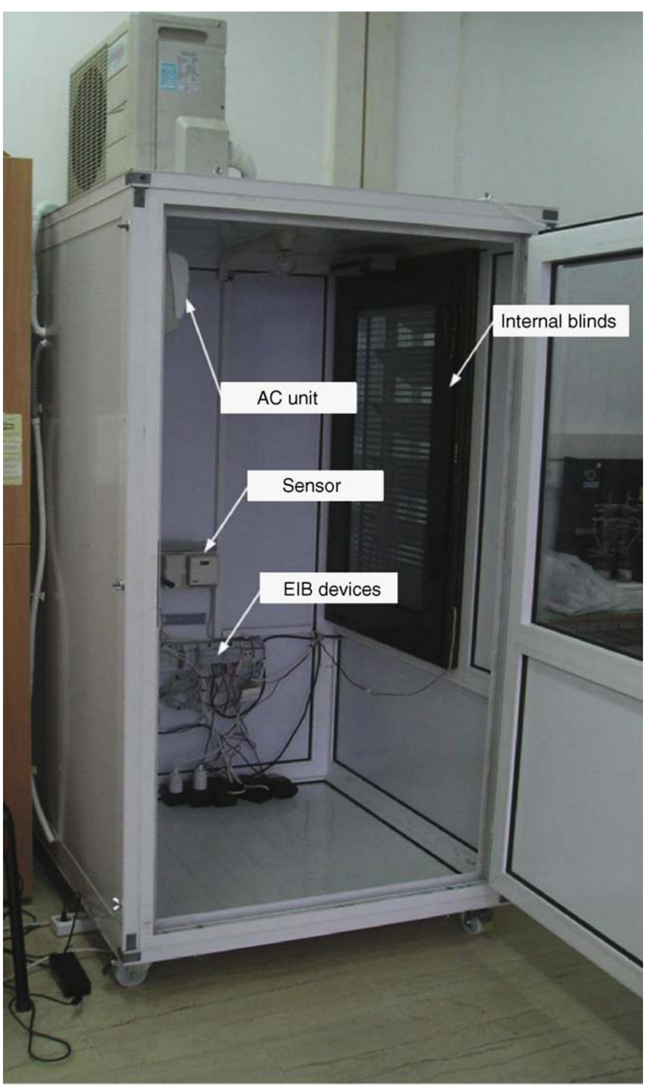

Fig. 2. The internal layout of the test chamber.

2.2. EIBUS–MATLAB interface

The overall system is implemented in the MATLAB environment. In this way its state can be monitored on a PC and various control scenarios can be directly examined. The configuration is realized using the OPC standard, which is based on OLE, COM (Computer Object Model) and DCOM

Fig. 3. The external layout test chamber.

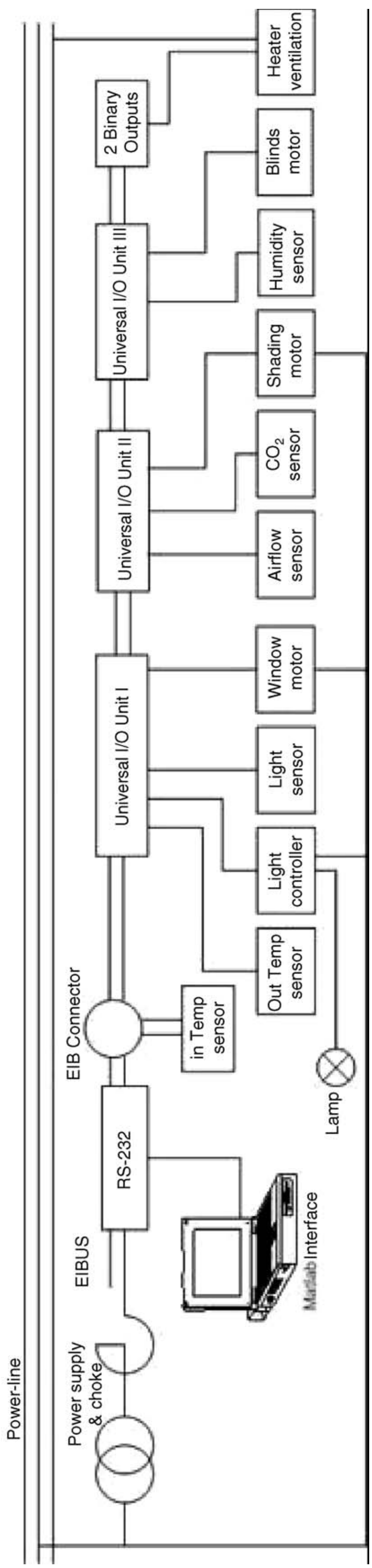

Fig. 4. The interconnections of the test chamber.

(Distributed Component Object Model) Microsoft technologies. Basically, OPC is a software concept, which implements a unified interface between different installation bus technologies like EIB on one hand and automation and visualization software on the other.

The interconnection of EIBUS with MATLAB is realized by the effective connection and cooperation of the following software tools:

1. The EIB Tool Software (ETS).
2. The EIB OPC server.
3. A MATLAB OPC client (it is used the one manufactured by IPCOS of Belgium). It is to be noted however that current versions of MATLAB (7 and greater) implement natively the OPC standard.
4. The MATLAB environment (specifically the fuzzy toolbox).

The ETS software is a package available to planners and electrical installers for the planning, software design and commissioning of EIB systems and provides the following facilities:

- Graphical User Interface.
- Database access.
- Access to EIB components via RS-232.
- Importing/exporting products and projects.
- Software interface for future modules.

The design of a new project and/or installation using ETS software includes the following steps:

- Set-up of ETS (EIB Tool Software).
- Set-up of the necessary EIB product databases available by manufacturers.
- Set-up the structure of the project, i.e. the building structure and bus topology.
- Insertion of the EIB products (devices and their corresponding applications) into the building structure.
- Definition of the physical addresses by assigning the configured EIB components to the bus topology.
- Set the parameters of the EIB components according to the installation's requirements.
- Creation of group addresses.
- Linking of communication objects of the EIB components with the group addresses.
- Assigning of the configured EIB components to the installed functional areas.
- Monitoring and testing the EIB components' operation.

The EIB OPC-Server is an intelligent device driver that is able to communicate with EIB devices. Additionally the EIB OPC-Server is equipped with a Server-Explorer, which is a user interface that allows manipulation of the driver's settings. As soon as the configuration is completed, the driver's settings may be applied by any software with OPC abilities such as MATLAB. Any software that is using the OPC-Server's configuration, is named OPC-Client.

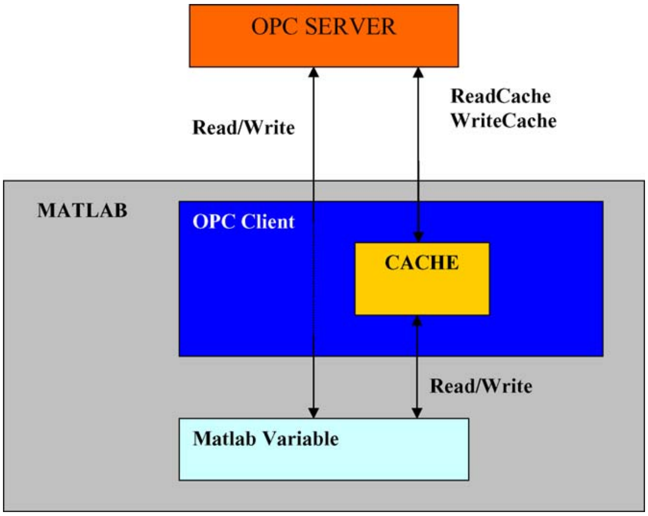

Fig. 5. The OPC MATLAB client.

The OPC-Client software has ability to display the configuration of the OPC-Server and allows the selection of the desired communication objects, i.e. the EIB group addresses, that are to be operated. The EIB OPC-Server is started automatically, whenever the client needs access to the bus objects, and stopped afterwards. Once the EIB-Server has been configured, the OPC-Client takes over the operation of the OPC-Server. During this execution mode the OPC-Server works invisible in the background, similar to a normal PC device driver. The EIB OPC-Server communicates via RS-232 serial interfaces with the EIB.

The OPC-Client for MATLAB is a set of MATLAB functions that communicate with the OPC-Server through the MATLAB environment. Data transferring is accomplished via Direct transfer with the read- and write-commands as depicted in Fig. 5.

The EIB sensors' values are read periodically through the BUS. The MATLAB environment is synchronized with the overall procedure for real time operation and control. This procedure allows the use of MATLAB functions and toolboxes (fuzzy logic, neural networks, etc.) in real time operation. Since MATLAB functions are single threases, they cannot be asynchronically polled by the OPC-Server. In order to overcome this difficulty, MATLAB operations are suspended and they are triggered either after specific time period or by the OPC-client. Therefore, MATLAB is externally activated as a simulation machine and is returned in suspension state after the procedure's completion. The sample time for real time operation can be as low as 0.1 s.

3. The controller

Two fuzzy controllers are developed for the test chamber's evaluation and calibration using Matlab's Fuzzy Toolbox.

The first one, termed the thermal-indoor air quality (TIAQ) controller, controls the thermal characteristics and the indoor air quality of the building.

It accepts the following inputs:

- Predicted Mean Vote (PMV index) defined by Fanger [11,12]. The PMV Index is calculated through a complex mathematical function of human activity, clothing and environmental parameters. In the present study, it is derived using the following measured parameters of the test chamber:
  - Indoor temperature;
  - Mean radiant temperature;
  - Indoor relative humidity;
  - Indoor air velocity.

  The PMV is a widely accepted mathematical expression of thermal comfort. This index is a real number and comfort is obtained if it lies within the specific limits of the comfort range. Since 1984, the index has been the basis of the international standard ISO-7730 [17].
- The outdoor temperature in order to have an indication of the seasonal variations and to define whether heating or cooling is needed.
- The CO_2 concentration and the rate of change of the CO_2 concentration for the estimation of the indoor air quality.

And produces the following outputs:

- The heating or cooling requirements of the test chamber.
- The window opening of the test chamber.

The second one, termed the visual comfort (VC) controller, modulates the indoor visual comfort using the following inputs:

- The indoor illuminance levels measured in lux.
- The level of the electric lighting and shading in order to avoid oscillations in the lighting levels.

And produces the following outputs:

- The artificial lighting level.
- The shading position.

Indicative fuzzy rules for the TIAQ controller are listed in List 1 and rules of the VC controller are listed in List 2. The

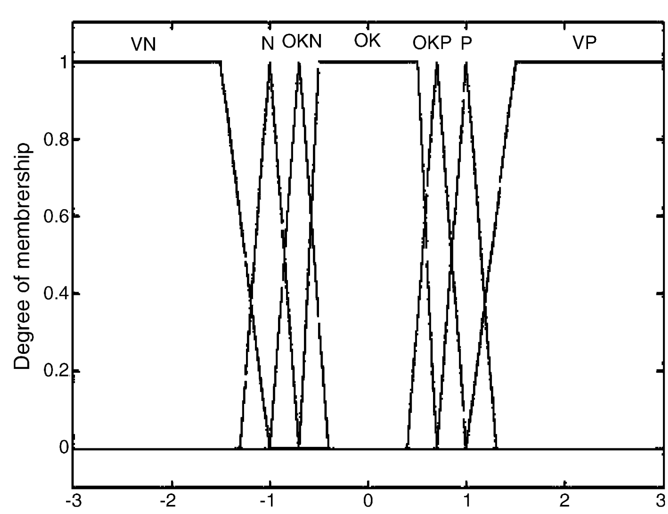

Fig. 6. PMV index membership functions (input).

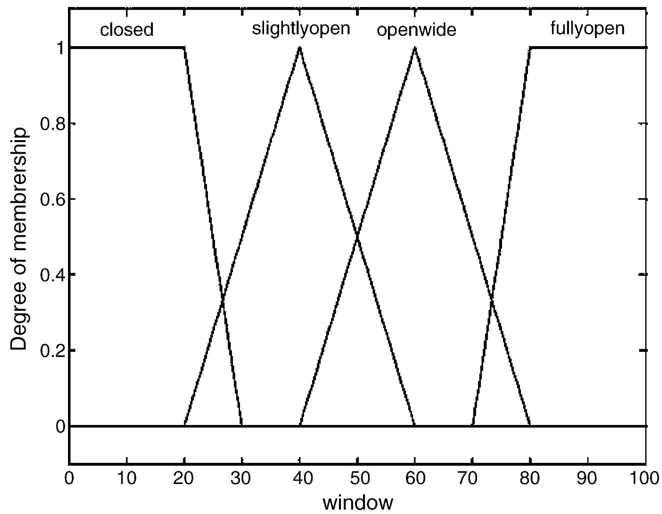

Fig. 7. Window opening membership functions (output).

rules are formulated to give priority to passive techniques, i.e. natural ventilation, daylighting in order to contribute to the reduction of the energy consumption [18]. Indicative membership functions are depicted in Figs. 6 and 7.

Indicative fuzzy rules of the climate controller

1. IF *(PMV is VeryNegative) and (tamb[a] is Low)* THEN *(heating is VeryBig)(cooling is **OFF**)(window is **closed**)(1)*
2. IF *(PMV is Negative) and (tamb is Low)* THEN *(heating is PositiveBig)(cooling is **OFF**)(window is **closed**)(1)*
3. IF *(PMV is OK_Negative) and (tamb is Low)* THEN *(heating is PostiveMedium)(cooling is **OFF**)(window is **closed**)(1)*
4. IF *(PMV is **OK**) and (tamb is Low)* THEN *(heating is **OFF**) (cooling is **OFF**)(window is **closed**)(1)*
5. IF *(PMV is **OK_Positive**) and (tamb is Low)* THEN *(heating is **OFF**) (cooling is **OFF**)(window is **closed**)(1)*
6. IF *(PMV is Positive) and (tamb is Low)* THEN *(heating is **OFF**) (cooling is **OFF**)(window is **slightlyopen**)(1)*
7. IF *(PMV is VeryPositive) and (tamb is Low)* THEN *(heating is **OFF**) (cooling is **OFF**)(window is **slightlyopen**)(1)*
8. IF *(PMV is VeryNegative) and (tamb is LowMedium)* THEN *(heating is PositiveBig)(cooling is **OFF**)(window is **closed**)(1)*
9. IF *(PMV is Negative) and (tamb is LowMedium)* THEN *(heating is PositiveMedium)(cooling is **OFF**)(window is **closed**)(1)*
10. IF *(PMV is OK_Negative) and (tamb is LowMedium)* THEN *(heating is PositiveSmall)(cooling is **OFF**)(window is **closed**)(1)*

[a] Ambient temperature.

Indicative fuzzy rules of the light controller

1. IF *(ill[a] is small) and (shade is **fullshade**) and (light is **off**)* THEN *(shading is **halfshaded**)(al[b] is **off**)(1)*
2. IF *(ill is **small**) and (shade is **1/2shade**) and (light is **off**)* THEN *(shading is **unshaded**)(al is **off**)(1)*
3. IF *(ill is **small**) and (shade is **unshade**) and (light is **off**)* THEN *(shading is **unshaded**)(al is **halfon**)(1)*
4. IF *(ill is **small**) and (shade is **unshade**) and (light is **halfon**)* THEN *(shading is **unshaded**)(al is **on**)(1)*
5. IF *(ill is **small**) and (shade is **unshade**) and (light is **on**)* THEN *(shading is **unshaded**)(al is **on**)(1)*
6. IF *(ill is **ok**) and (shade is **unshade**) and (light is **off**)* THEN *(shading is **unshaded**)(al is **off**)(1)*
7. IF *(ill is **ok**) and (shade is **unshade**) and (light is **on**)* THEN *(shading is **unshaded**)(al is **on**)(1)*
8. IF *(ill is **ok**) and (shade is **1/2shade**) and (light is **off**)* THEN *(shading is **halfshaded**)(al is **off**)(1)*
9. IF *(ill is l) and (shade is **unshade**) and (light is **off**)* THEN *(shading is **halfshaded**)(al is **off**)(1)*
10. IF *(ill is l) and (shade is **unshade**) and (light is **halfon**)* THEN *(shading is **unshaded**)(al is **off**)(1)*

[a] Indoor illuminance.

[b] Artificial lighting.

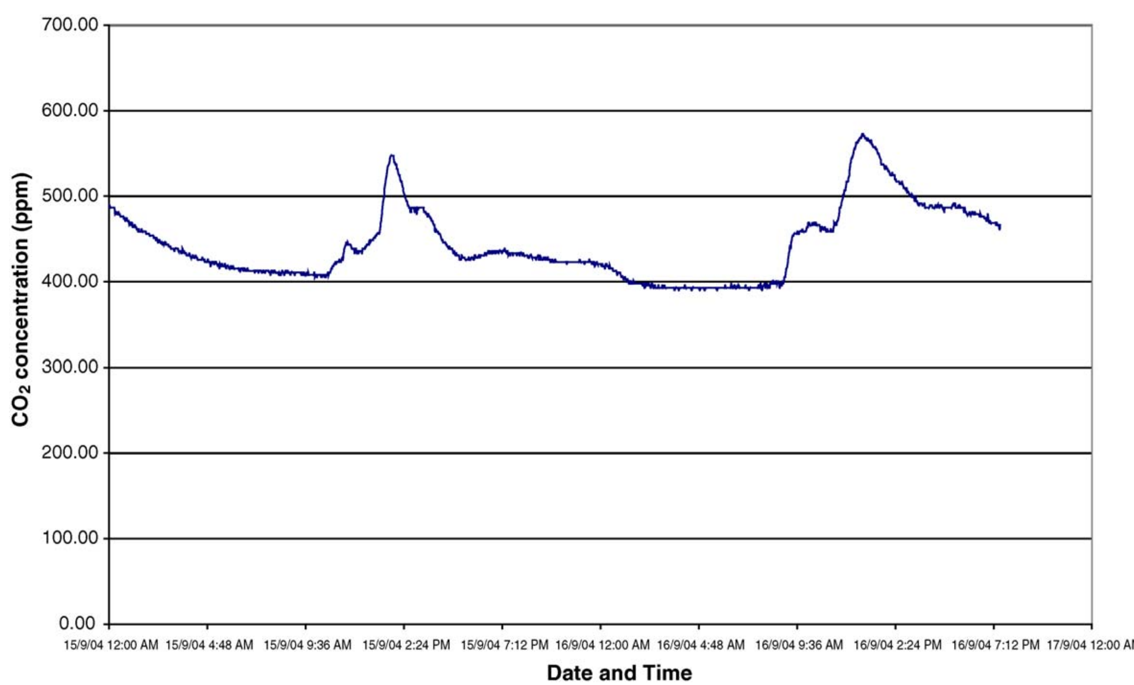

Fig. 8. The CO_2 concentration (ppm) measured in the test chamber.

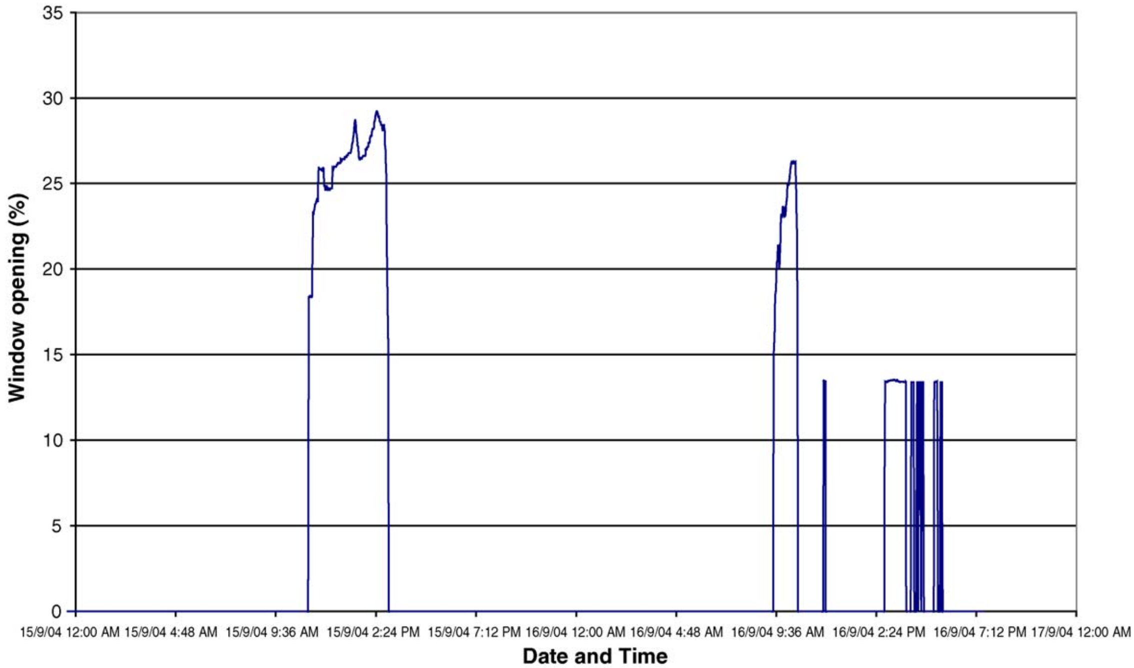

Fig. 9. Window opening (%).

4. Results and discussion

The functionality of the controller in the EIB system and the behavior of the resulting system are validated by a series of tests. In this section the experimental results using the test chamber are presented and discussed. The measuring period is from September 15, 2004 until September 17, 2004 with sampling period of 2 s, that is 1440 samples are taken. The test chamber was situated in the Laboratory of Industrial Control, Technical University of Crete, Greece.

Figs. 8 and 9 show the indoor air quality behaviour by the measured CO_2 concentration inside the test chamber. As can be seen, whenever there is an increase in CO_2 concentration, the window controller reacts immediately causing a drop in the concentration. Generally all the observed increases of the CO_2 concentration occur during the high

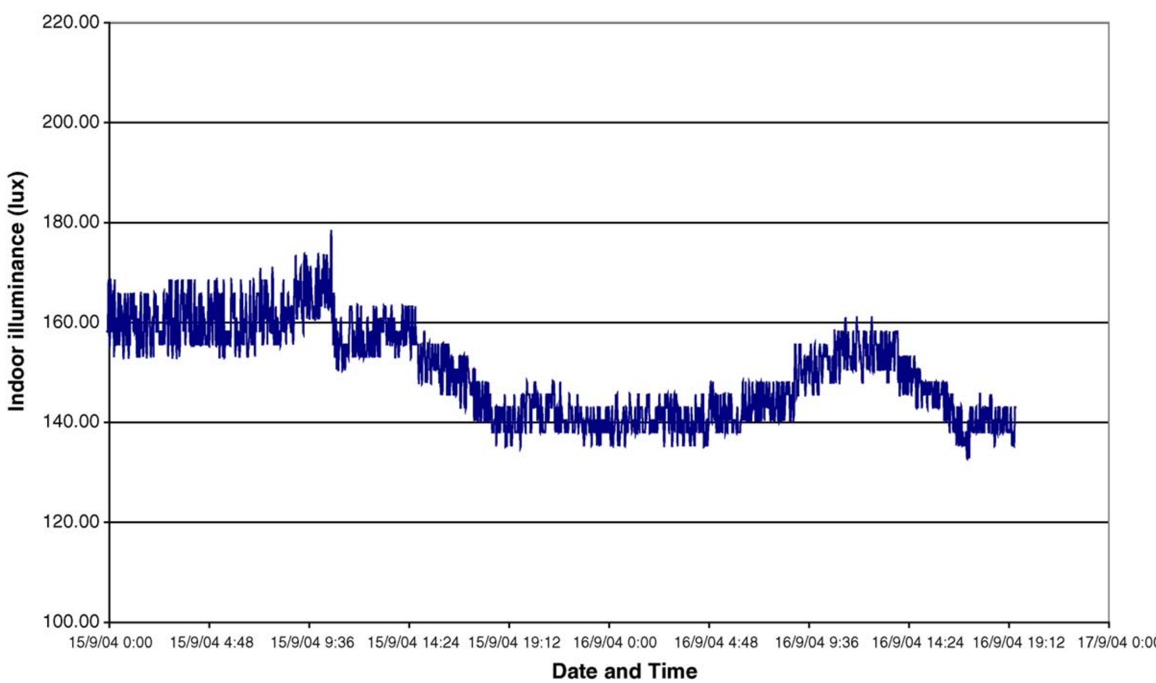

Fig. 10. The indoor illuminance (lux).

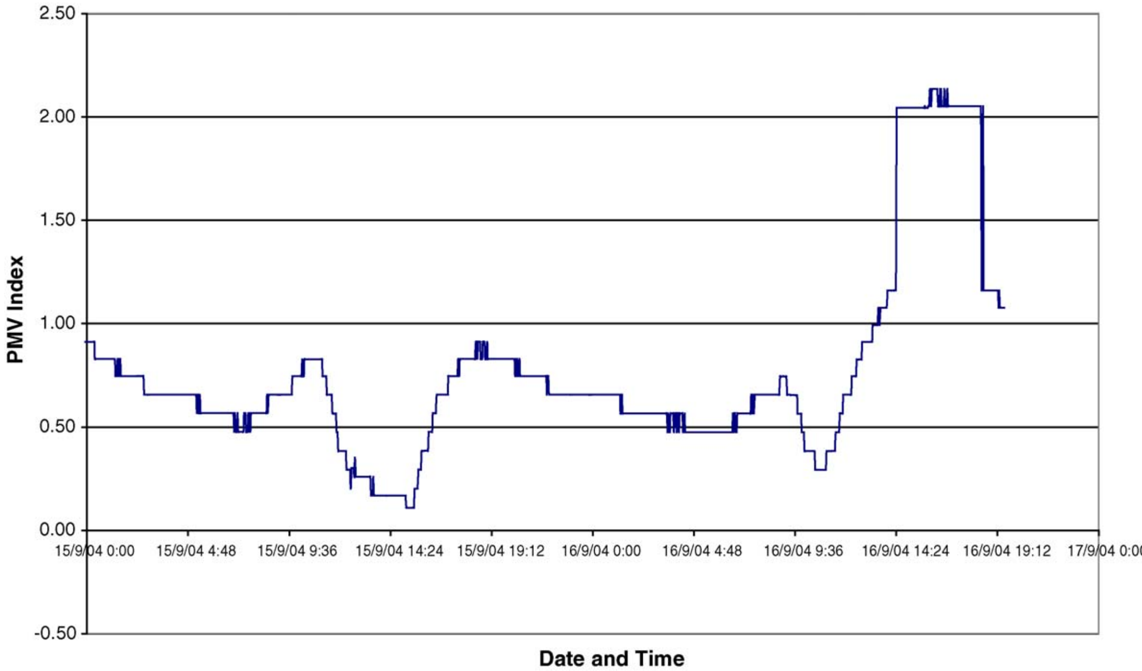

Fig. 11. PMV values in chamber environment.

occupancy hours of the lab i.e. 11:00–16:00 h. Finally it can be observed that the chamber's indoor air quality is kept between 600–800 ppm, which indicates that the indoor air quality is sufficient.

Before focusing at the indoor visual comfort, depicted in Fig. 10, it should be mentioned that the chamber is placed indoors for safety reasons. Therefore, the daylight penetration to the test chamber is limited as it is part of the indoor illuminance of the laboratory that hosts the test chamber. Due to this fact the highest proportion of the test chamber's indoor illuminance is contributed from electrical lighting and the shading is zero most of the time. During daytime a small rise is observed due to natural lighting.

According to Fig. 11, the PMV index fluctuates around 1, which corresponds to ''slightly warm'' according to Fanger's definitions [11,12]. The indoor temperature is above 26 °C but it is affordable for the summer season of the Southern Europe (Fig. 12).

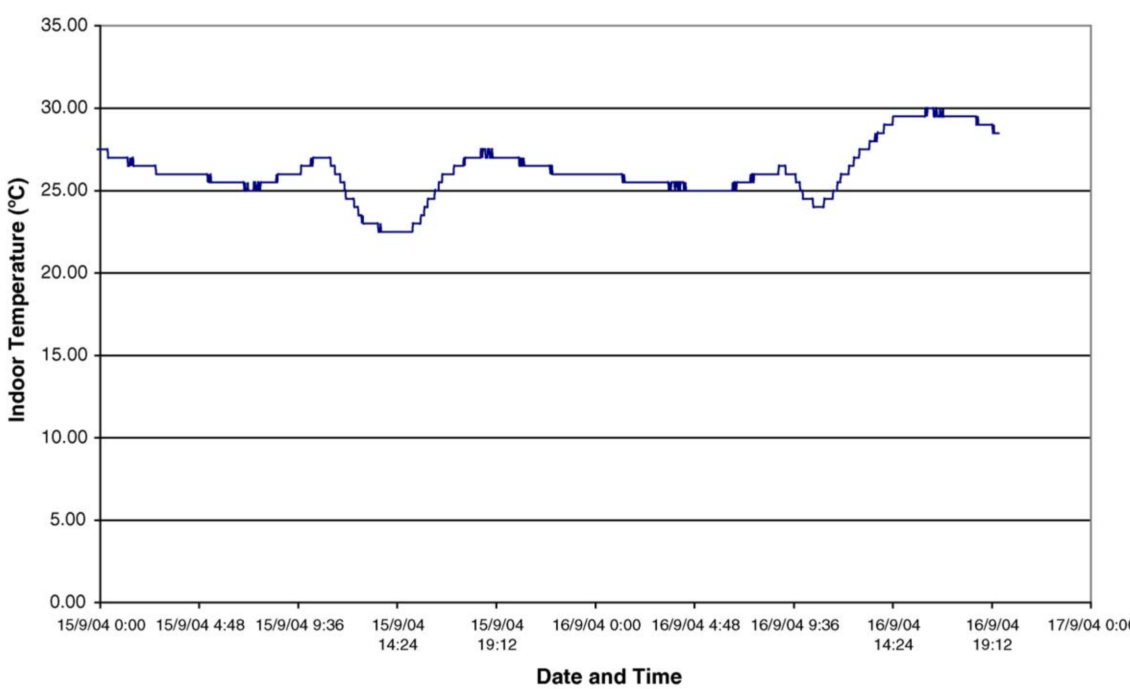

Fig. 12. The indoor temperature (°C).

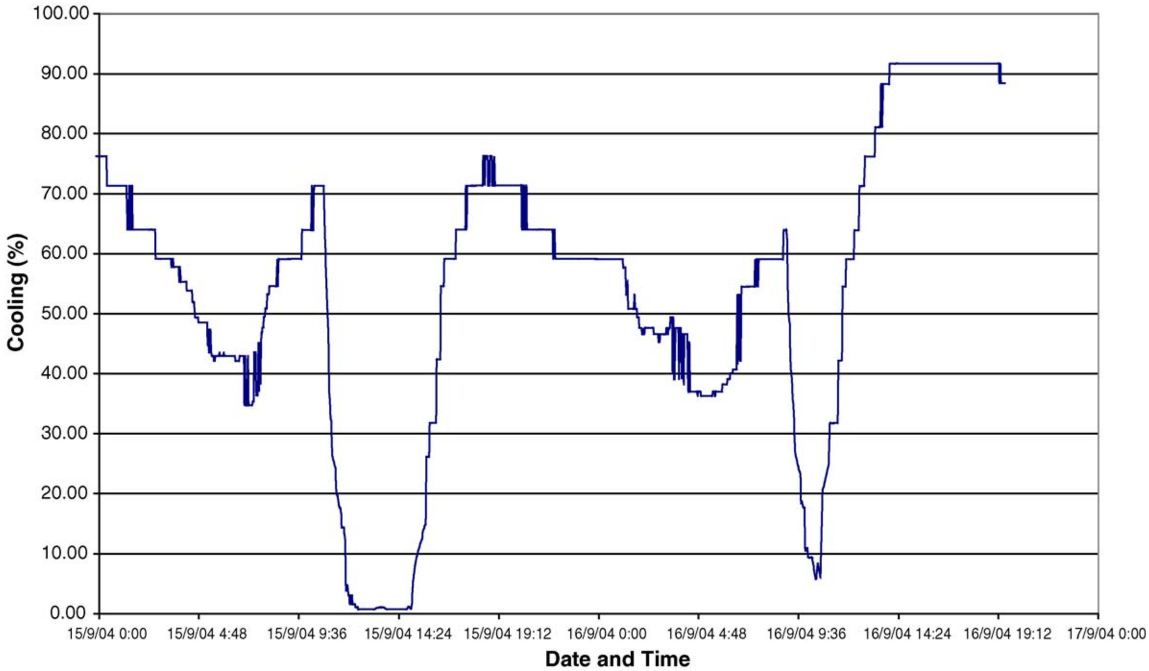

Fig. 13. The output cooling (%).

The ac system (Fig. 13) responds and follows closely the PMV index rises and drops. The fact that although the cooling is almost 94% in the afternoon of September 16, 2004 and the PMV rises to 2, meaning that a significant discomfort is occurred, shows that the adopted cooling system cannot support the internal thermal conditions of the test chamber in extreme meteorological conditions.

5. Conclusions

The developed test chamber integrates Matlab environment with EIB installation via an OPC server-client configuration. Additionally the test chamber incorporates all the necessary devices for measuring and evaluating indoor comfort. The integration with Matlab makes the test chamber a plug and play testing equipment for the validation of artificial intelligence in real time. This is a valuable tool in order to define and test the control strategy that should be followed for each building. Finally, the use of the test chamber saves significant commissioning time, which is an important step in building automation installations.

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