Solar gains regulation via holistically defined control system of the internal environment

Mitja Košir[1*], Aleš Krainer[1] and Živa Kristl[1]

[1] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Chair for Buildings and Constructional Complexes, Jamova 2, 1000 Ljubljana, Slovenia

[*] mitja.kosir@fgg.uni-lj.si

Abstract

Indoor living and working environments can greatly benefit from the application of automatically controlled internal environment and can achieve lower energy consumption as well as higher user efficiency. Through properly designed and regulated building envelope higher utilization of available solar gains as well as better daylighting and natural ventilation in the internal environment can be attained. Any design of such automated system should therefore acknowledge the need for the integral and holistic treatment of working and living environment with regard to its thermal, visual and air quality conditions. The presented system of integral control of internal environment (ICsIE) is based on the above stated presumptions and regulates thermal, visual and air quality conditions of an occupied office in the building of the Faculty for Civil and Geodetic Engineering University of Ljubljana (UL) in Ljubljana. The ICsIE is comprised of a sensor array monitoring both internal and external conditions. The data transmitted from the sensors are processed by the programmable logical controller (PLC) and are presented on an interface application running on a standard PC. The control system is based on the combination of conventional PI and advanced fuzzy logic controllers. In the paper special attention is paid to the ICsIE's thermal control.

1. Introduction

Quality of indoor environment in continuously occupied buildings is directly related to the occupants' productivity and health as well as to the overall energy consumption of buildings. One of the key issues in reducing the energy consumption of buildings is proper utilization of available solar radiation that penetrates into the building through transparent part of its envelope. Influence of solar radiation can be roughly split into two inseparable parts: one being its thermal influence (i.e. solar gains) while the other influences the visual aspects (i.e. daylighting). Due to this duality a holistic approach, which is at the core of bioclimatic architecture is necessary in the design of building envelopes and their components. Efficiency in the context of bioclimatic design does not only mean lower energy consumption, but especially better internal conditions for the users [1, 2]. In general, bioclimatic approach could be described as a cross-section of user demands and wishes with the climatic and geomorphologic characteristics of micro, mezzo and macro location of the building. Functioning and interaction between the two elements is achieved with the appropriate usage of available technology. The idea of balancing users' demands with the given climatic conditions of the chosen site is not new, as it can be seen in the selection of the first human shelters in the Palaeolithic and later in artificial human settlements all the way from Neolithic trough the antiquity to the present day.

Properly designed building's external envelope that acts as an interface between internal and external environment can greatly improve the functioning of the building as a system and reduce the consumption of conventional energy sources needed to sustain the internal environment. Nonetheless, even if the building envelope is well designed, sufficient level of control has to be provided for the proper functioning of its parts (e.g. automated shading) in order to provide comfortable internal conditions (e.g. providing daylighting as well as shading). The level of applied control is most crucial in the functioning of transparent parts of a building's envelope, as this is the most active part in the exchange of energy (e.g. solar gains), matter (e.g. ventilation) and information (e.g. visual connection to the outside) [3]. Proper coordination between the three must be a priority when the formation of internal living and working environment is concerned, as inadequate functioning can lead to unreasonable user reactions and dissatisfaction with the system. In the context of regulation building envelope represents a dynamic interface between two environments that can actively control internal environmental conditions with regard to the external climatic conditions. This is attainable with appropriate functioning of flexible shading elements that can provide selective penetration of solar radiation into internal environment. The paper presents the integral control system of internal environment (ICsIE) [3] that regulates thermal and visual environments as well as ventilation of an occupied office in the building of the Faculty for Civil and Geodetic Engineering. Special emphasis will be given to the regulation of the thermal environment.

2. Internal environment of buildings and its regulation

Creation of artificial environments represents a fundamental base of our civilisation and a direct link between artificial and natural environment. If appropriate level of control and energy input is provided a meta-stable state of satisfactory internal conditions can be maintained and with this also the proper functioning of human society. Because internal environment represents a functional section of user demands and external influences of a given location, appropriately formulated building envelope is crucial in providing desirable internal conditions. Internal environment as a greater whole can be subdivided into five distinctive sub-environments according to the human sensory reception system. The five sub-environments and their key influential factors are:

- VISUAL environment [4, 5] (human reception: vision) - daylighting, artificial lighting, level and uniformity of illumination, contrast levels, glare control, flickering, visual contact with the outside,
- THERMAL environment [5, 6] (human reception: thermoception) - air temperature, surface temperatures, radiation, air movement speed, metabolism level, clothing, relative humidity,
- OLFACTORY environment [6] (human reception: olfaction) - level of pollutants, presence of mould, odours, level of air exchange, relative humidity,
- SONIC environment [5] (human reception: audition) - reverberation time, resident noise, presence of noise sources, level of sound insulation,
- ERGONOMIC environment [7] (human reception: equilibrioception and somatic senses) - dimensions and proportions of building elements, dimensions and proportions of furnishing, surface structure, surface materials.

The influential factors for the appropriate sub-environments exhibit a high level of interconnectivity and can therefore not be treated individually. Nonetheless, the number of factors considered in the regulation of the internal environment can be reduced. Firstly the sub-environments can be divided according to their level of dynamics, meaning that some are relatively static in their behaviour, while other exhibit extremely dynamic behaviour. In this respect we can classify sonic and ergonomic sub-environments as distinctly static, as they mostly do not change until a change in the external (e.g. a new highway is constructed) or internal (e.g. different use of space) environment occurs. In comparison to these the visual, thermal olfactory sub-environments are constantly changing with regard to the external conditions as well as to the user preferences and user behaviour. Additionally to the exclusion of static sub-environments from the considerations in an automated regulation system of internal environment also only a few control variables are necessary to sufficiently cover the aspects of adequate level of control. For instance, regulation of CO_2 levels in most environments occupied by people suffices for the regulation of air quality. According to the above presumptions the formulation of an integral control of internal environment (ICsIE) [3] can focus on the regulation of the visual, thermal and olfactory sub-environments of the working and living environment.

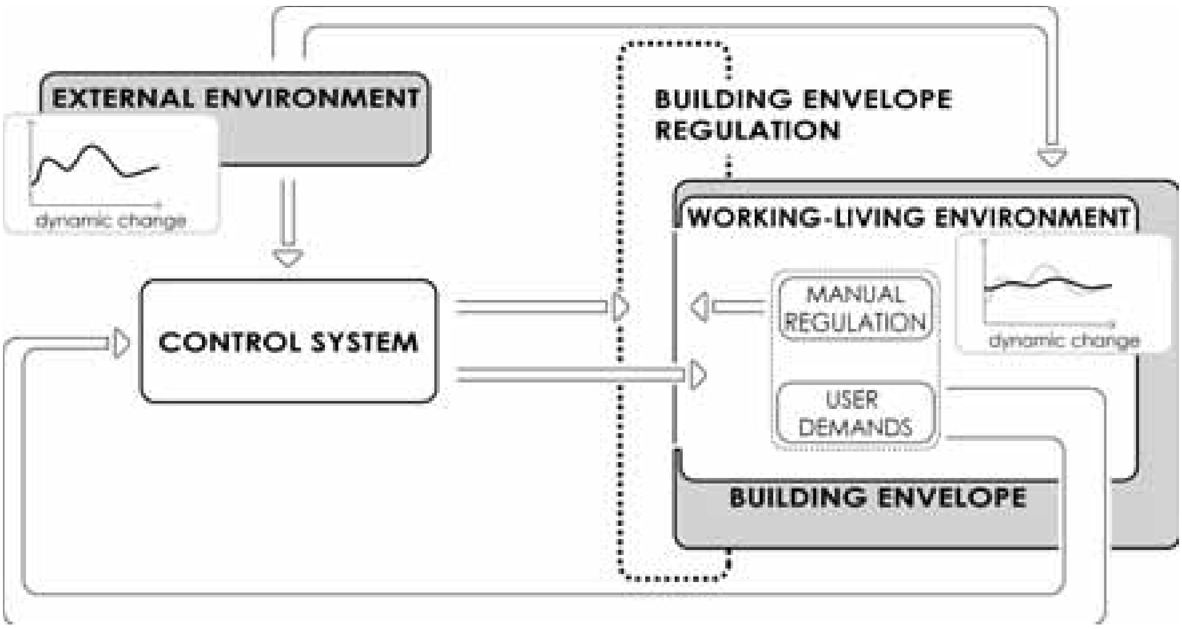

Fig. 1. Conceptual scheme of the regulation system of the internal environment – basic concept behind the formulation of the ICsIE.

Due to the dynamics of the external weather conditions and the state of building technology we can rightly say that the majority of influences on the internal environment will pass trough the transparent parts of the building envelope. At the same time internal demands with regard to illumination, internal temperatures and air quality influence the building envelope from the inside and are sometimes in strong contradiction to the external conditions. The contradiction of interactions and influences demands a highly flexible and responsive system which can be attained with correctly designed and regulated building envelope (Fig. 1.).

Most common regulation types employed to buildings are manual or conventional ON-OFF type. Both have been proven inadequate in attaining a sufficient dynamical response to the influences defining the internal environment [8]. Sufficient level of automation in the build environment can be reached with the use of conventional PID controllers that are very common in the control of industrial processes.

Although such control systems are efficient, it can be extremely complicated to design and tune them correctly in the case of highly complex systems. A possible alternative to conventional PID controllers are fuzzy logic controllers [9]. The presented ICsIE utilizes both as it is designed as a hybrid system with PID and fuzzy logic controllers. The use of fuzzy logic controllers enables designers to apply expert knowledge about the process in the form of IF-THEN statements that relate input variables directly to the output value of the regulator and by doing so make the whole decision process more transparent and intuitive to the designers and users.

3. ICsIE and the regulation of the thermal sub-environment

The ICsIE is installed in an occupied office of the building of Faculty of Civil and Geodetic Engineering in Ljubljana. The office has a floor area of 38.80 m^2 with a corresponding volume of 163.40 m^3. The Office has one external wall with a western oriented window of a total of 11.40 m^2 of glazing. The level of occupancy is relatively small, as there are only two work places in it amounting to 0.05 persons/m^2. The western oriented glazing is segmented into six individual windows, each with an externally fixed motorized venetian blind to control daylighting and solar gains. The ventilation of the office is achieved by natural ventilation trough the operation of a motorized window. The heating and cooling of the thermal environment is achieved by six ceiling-mounted low-temperature radiative elements, each 125 cm by 125 cm. In conditions when the available daylight is insufficient for the visual tasks performed in the office, additional illumination is provided by six fluorescent lamps suspended from the ceiling.

On the level of structure the ICsIE can be divided into three distinctive parts: the sensor array, the process level and the supervision and data acquisition level. The sensor array can further be divided according to the position of the sensors into external and internal sensors. The external sensors monitor the following variables: direct solar radiation, reflected solar radiation, external illumination, temperature and relative humidity of air, detection of precipitation, direction and speed of wind. Internal sensors monitor illumination on two workplaces, temperature and air humidity, concentration of CO_2 and consumption of energy for cooling and heating. The supervision of the system operation as well as data acquisition, storage and analysis is performed via a computer application running on a standard PC. The PC application enables the communication of system operator with the process level of the ICsIE. At the process level the system is based around a programmable logic controller (Mitsubishi A2SHCPU(S1)) that performs all of the appropriate actions in correlation to the set-point values and current external and internal environmental conditions. Control system is designed as a cascade hybrid system with primary fuzzy logic controllers and secondary PI controllers. Fuzzy logic controllers can be switched off and the ICsIE becomes a conventional PI controller based system. Dual functioning of the control system was conceived for the purpose of comparison between the two different modes.

With respect to the functioning of the ICsIE the system regulates the aspects of thermal, visual and olfactory sub-environments of the office. This is translated into regulation of work plane illuminance, cooling, heating, shading, and cooling with ventilation and physiological ventilation according to CO_2 concentration. The regulation system can be roughly split into illumination, thermal and ventilation control loops, although these tree loops are interconnected (e.g. daylight and solar gains control is achieved by the same actuators – positioning of the blinds) and as such must be treated as a whole at least on the conceptual level. In the following section a detailed explanation of the functioning of the thermal control will be given, as this is the focus of the presented paper. Additional information on the structure of the illumination and ventilation control of the ICsIE can be found in the work by Košir et al. [3, 10].

3.1. Thermal control – solar gains utilization

Regulation of thermal comfort in the internal environment was probably the first aspect of human comfort actively controlled by the occupants by providing insulation to their bodies and habitats or/and introducing additional thermal energy. Regardless of the type of climate, the principal influence on thermal sub-environment in the external as well as internal environment is the solar radiation with the sun as a primary energy source. Therefore, thermal conditions in buildings are a combination of direct influence of solar radiation (i.e. direct solar gains), exchange of thermal flows with the exterior and of user interventions. Because solar gains are regulated by the ICsIE in the same way as daylighting (e.g. through positioning of external blinds), the system prioritizes between the two according to the user's preferences. The user or system operator can decide whether illumination or thermal regulation is a priority. As a general rule the preference is set to the optimization of dayligting when the office is occupied, as humans are more susceptible to the changes in illuminance levels than to the changes in temperatures.

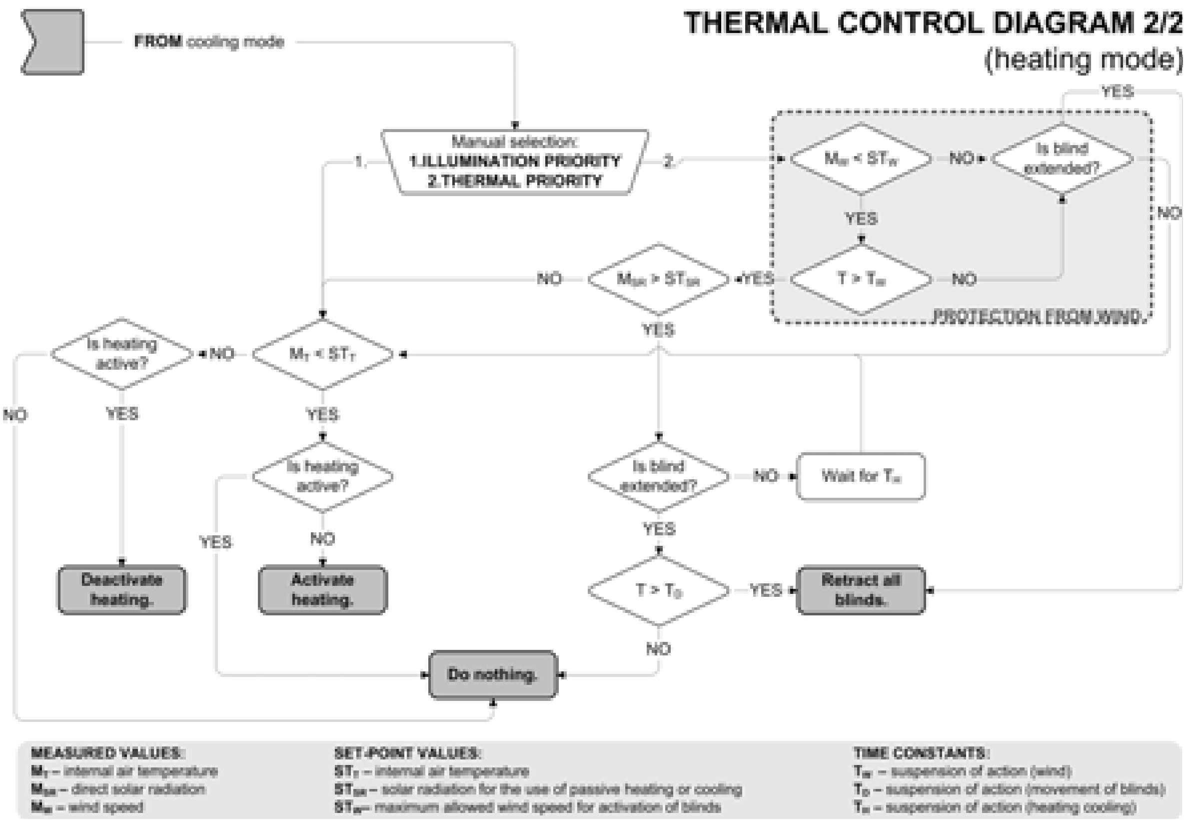

Fig. 2. Flowchart presenting thermal diagram of the ICsIE – heating mode.

For clarity purposes thermal control loop of the ICsIE can be divided into cooling (Fig. 2.) and heating (Fig. 3.) parts, although both are integrated into one control loop. Further, the functioning of the control process could be differentiated according to the measures at disposal of the regulating system. ICsIE can regulate internal thermal environment with passive and active measures. Passive measures consist of control of solar gains by means of shading (i.e. cooling mode) or exposing (i.e. heating mode) the transparent part of the building envelope and by passive cooling of the internal air ventilation achievable when the measured external air temperature (M_{ET}) is lower than the set-point internal air temperature (ST_T). With regard to the active measures the system relies on the already mentioned ceiling panels for heating as well as for cooling. The utilization of passive measures for achieving the desired effect is always a priority for the ICsIE. Because the control of solar gains is executed in the same way as the regulation of internal natural illumination, the system operator defines whether illumination or thermal regulation is a priority of the system (Fig. 2. and 3.). When illumination control is selected as a priority, the cooling or heating of the internal environment is achieved by active measures and cooling by air exchange with external environment because regulation of solar gains is not at the disposal of the thermal control loop. In the opposite case the system can also regulate the thermal aspects of the internal environment by shading or exposing the glazed part to the external environment.

The input parameters necessary for the regulation of thermal comfort are the desired indoor air temperature (ST_T) for the time when the office is in use (e.g. 22.0°C ± 1.0°C) as well as the temperature for the reduced regime (e.g. night-time, weekends and holidays). If the ICsIE is in thermal priority mode, the first action at disposal is the regulation of solar gains via the operation of venetian blinds. This action can be undertaken in heating as well as in cooling mode with opposite effect, i.e. shading in cooling mode and exposing the window in heating mode. In both cases, the ICsIE compares the measured direct solar radiation (M_{SR}) with the set-point solar radiation value (ST_{SR}). If M_{SR} is larger than ST_{SR}, the system extends (i.e. cooling mode) or retracts (i.e. heating mode) all automatically controlled blinds. It has to be stressed that the ST_{SR} value is different for the cooling and heating season as well as heavily dependent on the characteristics of the building. To prevent wind damage to the blinds a safeguard control procedure is in place (Fig. 2. and 3.). If a defined wind speed (M_W) is exceeded (e.g. 10 m/s), the blinds are retracted until the wind subsides. The system also utilizes time delay constants (T_D, T_W, T_H) that regulate the interval in which only one action can be performed (e.g. T_D defines the time interval between two movements of blinds). If the desired set-point temperature is not achieved during the defined time constant (T_H) for heating or cooling regulation, the system activates additional measures (i.e. heating/cooling panels). During the cooling season, in addition to shading and activation of cooling via radiative panels, the office environment can also be cooled by exchanging the inside air with the exterior air when the external air temperatures are lower than the internal ones ($M_T > M_{ET}$). This is manly possible in summer time over the night and during the morning. If the cooling with the ventilation does not reach the desired ST_T in a defined time, the controller closes the window and activates the cooling panels. During cooling season attention has to be paid to the internal relative air humidity, because surface condensation on the cooling panels can occur. The ICsIE incorporates a safeguard (not shown in Fig. 2. and 3.) that monitors the internal level of air humidity. If a critical level is reached the cooling panels are deactivated and surface condensation is avoided.

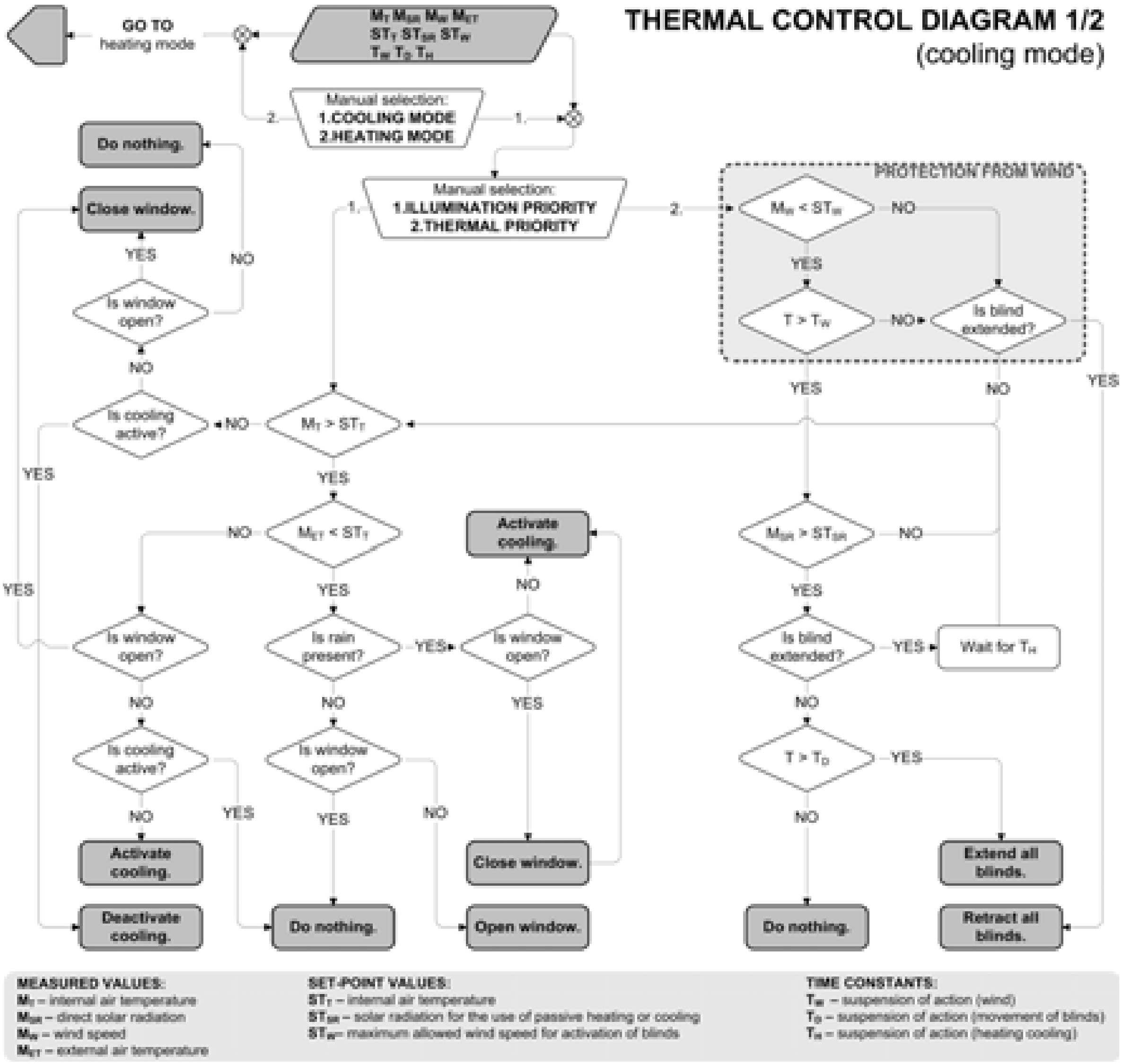

Fig. 3. Flowchart presenting thermal control of the ICsIE – cooling mode.

4. Conclusion

The system was designed and executed as a full scale, real time testing facility. The focus is on providing greater user comfort and consequently greater efficiency at working and learning. In this context lower energy consumption of a system is a secondary concern and must not interfere with providing quality internal environmental conditions. That does not mean that the building can be energy inefficient, but that the striving for energy efficiency must be coordinated with the efforts for attaining greater comfort. The ICsIE regulates internal illuminance, thermal environment and natural ventilation of an office in the building of Faculty of Civil and Geodetic Engineering. The presented paper describes in detail only the thermal aspects of the regulation system and their relation to the dynamical utilization of direct solar gains in buildings. Regulation is achieved through the use of internal and external sensor arrays that monitor the internal environmental and the external climatic conditions. According to the reference values of set-point internal temperature (i.e. user demands) and the level of direct solar radiation (i.e. external conditions) ICsIE guides the appropriate actuators (in the case of solar gains regulation these are the external venetian blinds) to the necessary state. Because the system favours passive measures (i.e. shading during cooling season) over active ones (i.e. cooling with ceiling panels), it means that energy effectiveness of the system is incorporated in the basic functioning of the whole system.

Regulation of solar gains with the ICsIE is achieved by actively regulating the position of external blinds according to a pre determined (defined by system operator) value of appropriate level of direct solar radiation. The system behaves differently when there is a need for cooling than in times that heating is necessary as functionality is reversed (i.e. shading in summer and exposing the window in winter). For proper and effective regulation of solar gains the most crucial element is the definition of appropriate values of direct solar radiation (ST_{SR}) for the activation of shading or exposing of the window. The definition of this value is heavily dependent on building specific characteristics as well as on other environmental parameters and must therefore be case specific. Through experimentation (experiments not presented in the paper) with the ICsIE a more consistent regulation of internal thermal conditions was demonstrated for cooling as well as for heating seasons. The main advantage of the described system was in the higher user comfort with regard to the visual, thermal and olfactory environments as well as coincidental lower energy usage of the test office. Lower energy use was primarily due to the automated regulation of passive measures that enable higher responsiveness of building systems and elements to the occurrence of unfavourable conditions in the internal or external environment.

References

[1] A. Krainer, Passivhaus contra bioclimatic design. Bauphysik, 6 (2008) 393-404.

[2] A. Krainer, M. Košir, Ž. Kristl, M. Dovjak, Passive house versus bioclimatic house. Gradbeni vestnik, 3 (2008) 58-68.

[3] M. Košir, (2008). Integral regulating system of internal environment on the basis of fuzzy logic – doctors thesis, University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana.

[4] ISO/CIE 8995-1, (2002). Lighting of indoor work places, International Organization for Standardization, Brussels.

[5] S.V. Szokolay, (2008). Introduction to architectural science: The basis of sustainable design – 2nd ed., Architectural Press, Oxford.

[6] CR 1752, (1998). Ventilation for buildings – Design criteria for the indoor environment, European Committee for Standardization, Brussels.

[7] J. Dul, B. Weerdmeester (1998). Ergonomics for beginners: a quick reference guide , Taylor & Francis, London.

[8] M. Košir, Ž. Kristl, A. Krainer, Parametrical study of fuzzy control approaches for regulating thermal and optical flows, EuroSun 2006: Conference Proceedings. International Solar Energy Society (2006) 1-9.

[9] Ž. Kristl, M. Košir, M. Trobec-Lah, A. Krainer, Fuzzy control system for thermal and visual comfort in building, Renewable energy, 4 (2007) 1-12.

[10] M. Košir, Ž. Kristl, A. Krainer, Control system for integral regulation of internal building conditions, Energy and the Environment (2008) 391-400.