ACTIVE CONTROL SYSTEM BASED ON THE APPLICATION OF PASIVE SOLAR ARCHITECTURE MEASURES

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1. Introduction

The quality of indoor environment in buildings is directly connected to the productivity and health of occupants as well as to the energy efficiency of the building. In such a context the provision of satisfactory internal conditions is an issue that has implications on a socio-economic scale (Fisk, 2000, Sobocki, 2006) reaching beyond the scope of construction related professions. Nonetheless, the problems concerning design and regulation of the indoor environment can be addressed directly and efficiently on the level of the building design and management. Buildings as artificially created objects can be split into two distinct but codependent entities – building envelope and indoor environment. In contrast to the external environment, indoor environment for people represents a place of control on the physiological as well as psychological level. Because these two environments are not discrete but in constant exchange of energy, mater and information (Krainer, 1993), the function of the building envelope is to enable the desired indoor conditions with regard to the external climatic conditions. Quality indoor environment provided with the formulation of an appropriate building envelope is at the base of bioclimatic design and passive solar architecture (PSA). Building performance (Fig. 1) can additionally be raised by correct use of installed devices (e.g. heating and cooling systems) and especially by providing automated regulation to the functioning of the whole building (Košir et al., 2006). Automated control systems represent a solution to a complex problem of balancing the user demands with external climatic conditions with respect to the comfort and energy use criteria. The end result of such applications is the design of healthy and comfortable internal environment with low energy consumption and not the other way around (Krainer, 2008).

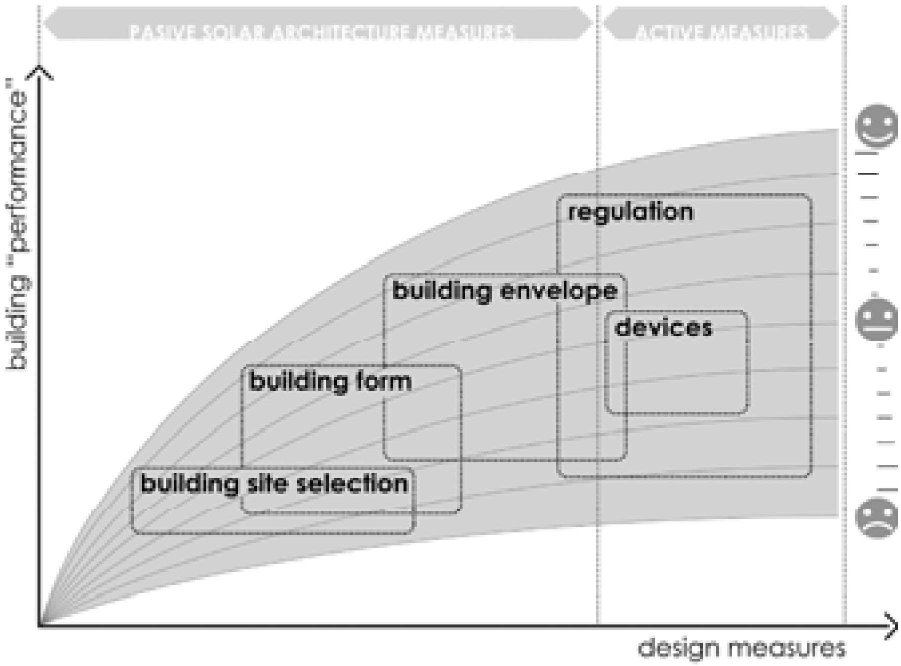

Fig. 1: Synergetic effects of design measures have a decisive influence on the final "performance" of buildings.

The Integral Control system of Internal Environment (ICsIE) (Košir, 2008) presented in the paper represents a holistic regulation system based on the presumptions of bioclimatic design with the utilization of PSA measures. The system regulates thermal, visual and olfactory parameters of an occupied office at the Faculty of Civil and Geodetic Engineering, University of Ljubljana in Ljubljana, Slovenia. The regulation is achieved through the use of internal and external sensors, which monitor the corresponding environmental conditions. The system then directs the appropriate actuators according to user demands and current external conditions. ICsIE is designed around a fuzzy logic and conventional PI (i.e. proportional-integral) controllers linked into a cascade system. The priority of the ICsIE is the use of PSA measures prior to mechanical interventions synchronised with user demands, therefore integrating user satisfaction as well as energy efficiency into the core of the system.

2. Integral Control system of Internal Environment

With the creation of artificial living and working environments people formulate systems that enable us to function more efficiently and comfortably in the socio-economic system of our civilisation. No mater how advanced these environments are, they are never separated from the greater natural environment, but are a vital part in the link between humans and our environment. Because indoor environment is inseparably linked to the external climatic conditions and internal user demands, it represents a complex system of energy, mater and information exchange. With adequate level of control and energy input a meta-stable state of indoor conditions can be maintained and with it also the functioning of human society. The indoor environment of buildings can be described as a cross-section of thermal (Szokolay, 2008), visual (Szokolay, 2008), olfactory (CR 1752, 1998), acoustic (Szokolay, 2008) and ergonomic (Pheasant and Haslegrave, 2006) factors, which jointly form the perception of indoor environment. The control over qualitative and quantitative aspects of each factor is crucial in the formulation of good and healthy indoor environments. Due to the interconnection of different aspects of indoor environment (e.g. thermal and visual impact of solar radiation) a holistic approach is necessary. Nonetheless, the number of factors influencing the regulation of indoor environment can be reduced, if they are classified according to the level of their dynamics. Therefore, acoustic and ergonomic aspects can be described as relatively static and can be successfully controlled by passive measures on the level of building envelope (e.g. sound insulation) or space geometry (e.g. appropriate furnishing). On the other hand, visual and thermal comfort and air quality are constantly changing with regard to the external conditions and user behaviour. In accordance to these presumptions the ICsIE (Košir, 2008) is focused on the control of work plane illuminance (daylighting and artificial illumination), thermal conditions for heating and cooling seasons and natural ventilation.

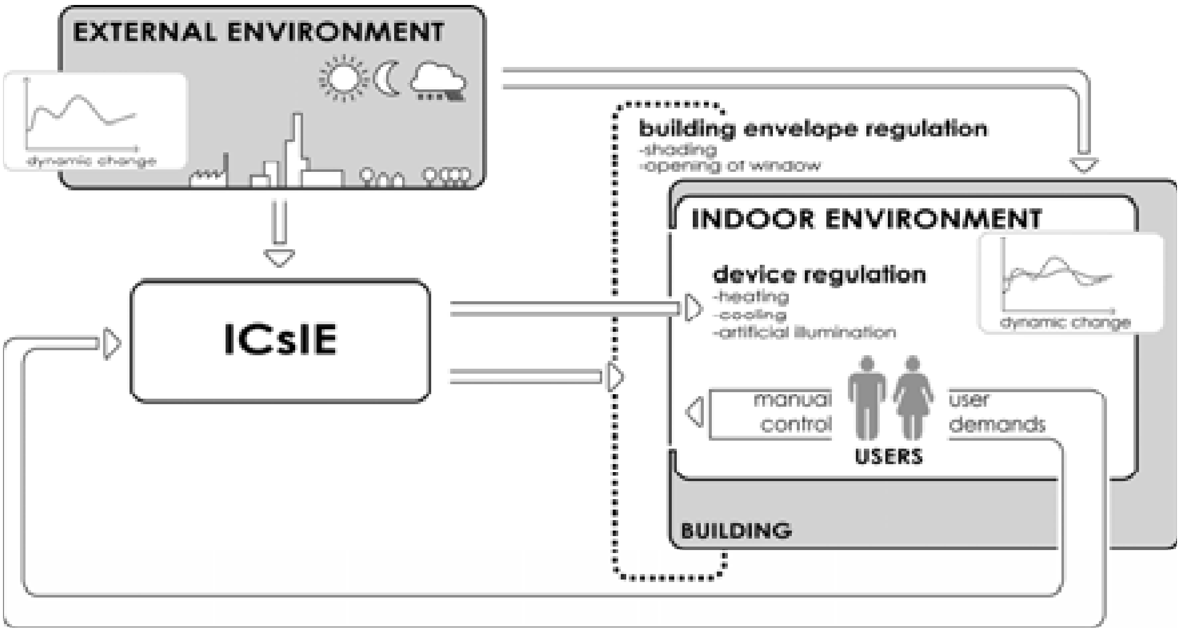

Fig. 2: Conceptual diagram of the ICsIE's relation to the building, its users and external environment.

Because of the dynamics of the external weather conditions and the current state of building technology we can rightly say that the majority of interactions between external and indoor environments will pass trough the transparent parts (i.e. windows) 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 stark contradiction with the external conditions. These contradictions demand a highly flexible and responsive control system which can be attained with correctly designed and regulated building envelope and supplemented with installed mechanical and electrical devices (Fig. 2.). In the case of buildings the control is in the majority of cases manual or of an ON-OFF type. Both types have proven to be inadequate in attaining a sufficiently responsive regulation (Krainer, 1993). On the other hand, if an advanced control system is applied, it is often only on the level of a single sub-system (e.g. heating control, daylight responsive illumination) and not for the whole building, thus neglecting the interactions between different parts of indoor environmental control. Traditionally, automated regulation is achieved with the use of conventional PID (i.e. proportional-integral-derivative) or PI controllers which are very common in the control of industrial processes. Although such control systems are very efficient, it can be extremely complicated to design and tune them correctly in the case of highly complex systems, such as the regulation of indoor environment. A possible solution to this problem is, as in the case of ICsIE, the application of hybrid regulation systems where conventional PI controllers are used in a cascade system with fuzzy logic controllers (Košir, 2008) (Kristl et al., 2007). 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.

The ICsIE system presented in the paper was designed for the control of three key aspects that constitute the basis of a comfortable and energy efficient internal environment. The system regulates internal work plane illuminance, thermal conditions for heating and cooling seasons and natural ventilation. Regulation is achieved with the use of an elaborate array of internal and external sensors, which monitor the environmental conditions. In the external environment the following parameters are measured: air temperature (M_{ET}), relative humidity (M_{ERH}), illuminance (M_{EIL}), direct solar radiation (M_{SR}), reflected solar radiation (M_{RSR}), wind speed (M_W), wind direction (M_{WD}) and presence of precipitation (M_P). In the indoor environment the measured parameters are: air temperature (M_T), relative humidity (M_{RH}), work plane illuminance in two work places (M_{IL1} and M_{IL2}), CO_2 concentration (M_{CO2}), heating energy consumption (M_H) and cooling energy consumption (M_C). The ICsIE directs the available actuators according to the set-point values of internal parameters in relation to the current external conditions. The system prioritizes according to the energy effectiveness of an action (e.g. shading has a priority over mechanical cooling in the case of thermal regulation).The priority of the system is the use of passive solar architecture measures (PSA) prior to mechanical interventions synchronized with user demands. For the regulation of internal illumination the system can use six external venetian blinds to control daylighting and conventional ceiling suspended office fluorescent lights as artificial illumination. In the case of thermal regulation (heating and cooling) the ICsIE can use venetian blinds for the regulation of solar gains, ceiling mounted low temperature radiant panels for the supply of heating or cooling energy and automated window for night time cooling; the same window is also used for ventilation purposes. The process level of the system is built around a programmable logic controller (Mitsubishi A2SHCPU(S1)) that performs all of the appropriate actions in correlation to the defined regulation rules. Supervision of functioning and communication with the programmable logic controller is enabled through a special interface application installed on a standard PC.

2.1 Heating and cooling control

Thermal conditions in the office can be regulated by controlling the solar gains (shading or exposing the window) or by heating or cooling the room by activating the radiative panels. During cooling season also the cooling by ventilation is available. It is possible during times when external temperature (M_{ET}) is lower than internal set-point temperature (ST_T). In general the ICsIE favors the use of PSA measures, which means that active heating or cooling is activated only if regulation of solar gains or cooling with ventilation is inefficient. Because solar gains are regulated in the same way as daylighting (e.g. trough positioning of blinds), the system operator has to choose whether the system is in illuminance priority or thermal priority mode. In general, when users are present in the office the preference is set to the control of dayligting, as humans are more susceptible to the changes in illuminance levels than to the changes in temperatures.

Input parameters to the thermal control of the ICsIE consist of measured data, defined set-point parameters and constants that influence the regulation of the indoor thermal environment (Fig. 3). The set-point temperature value can be set arbitrarily by the system operator. In the case of experiments conducted with the ICsIE, ST_T was defined according to the recommendations defined in the CR 1752 standard (CR 1752, 1998), i.e. 22.0 °C for heating and 24.5°C for cooling. The goal of the system is to maintain M_T as close to ST_T as possible. If the system is in thermal priority mode, the first available action is the regulation of solar gains with the venetian blinds. This action can be used in the heating as well as in the cooling mode with opposite functionality (i.e. shading in the cooling mode and exposing the window in the heating mode). In both cases, the system 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 (cooling mode) or retracts (heating mode) the 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 building specifics. The system also incorporates time delay constants (T_D) that regulate the interval in which only one movement of the blinds can be performed. Time delays are used to prevent constant movement of actuators that would be disturbing to users. Similar time delay interval (T_H) is applied between the activation of solar gains regulation and the activation of other actuators. If the indoor set-point temperature is not reached with the regulation of blinds or if the system is in the illumination priority mode, additional actions are taken to regulate indoor thermal environment (i.e. heating/cooling panels are activated). Fig. 3 represents in detail the cooling part of the thermal regulation control loop of the ICsIE.

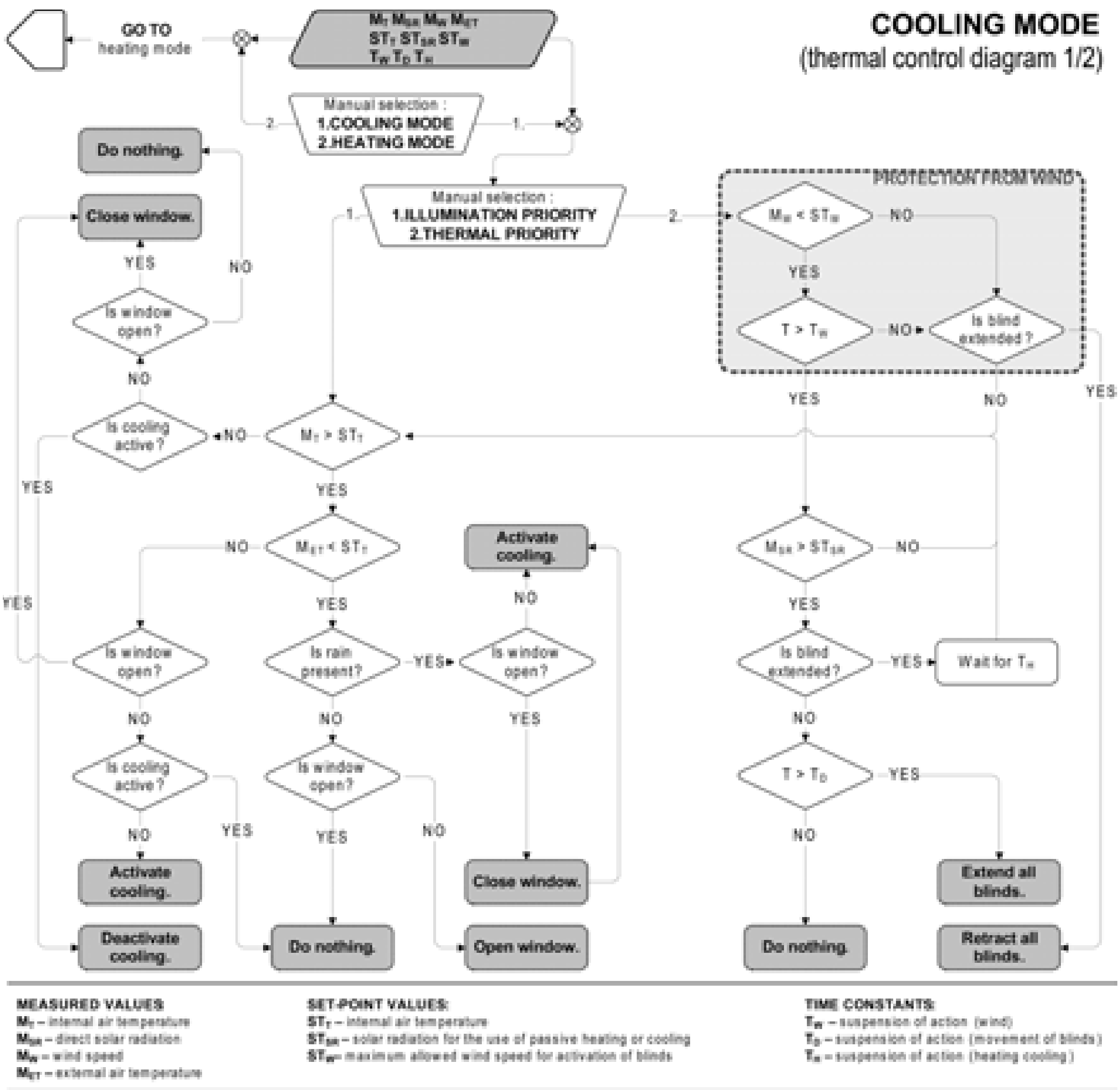

Fig. 3: Flow chart representing the cooling mode of the thermal regulation control loop of the ICsIE.

2.2 Illuminance control

Internal measured illuminance (M_{IL}) of the office is determined from two sensors positioned on the work places situated in the office. The value of M_{IL} is derived by calculating a weighted average of the spot measurements (M_{IL1} and M_{IL2}). To control the daylighting in the office the ICsIE can individually control six external venetian blinds. These can be either fully retracted (e.g. window is unobstructed) or completely extended (e.g. window is shaded). When all of the blinds are extended, the blades can be positioned at four different angles in steps of 30° from horizontal position (i.e. 0°) to vertical position (i.e. 90°). Each blind can be retracted individually, but the blades of all of the extended blinds are regulated simultaneously. If the office is insufficiently day lit, the system can activate additional artificial illumination.

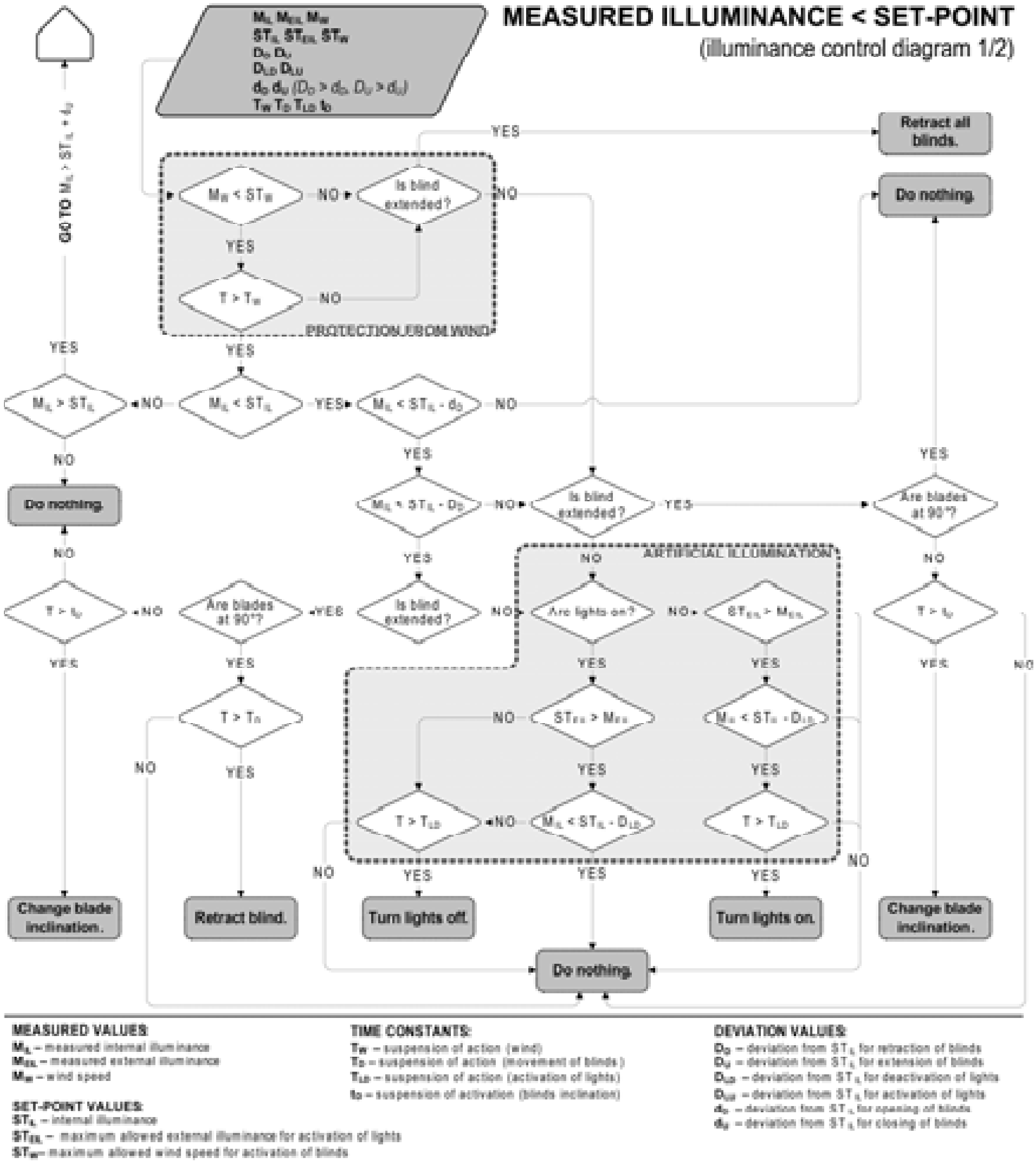

Fig. 4: Flow chart illustrating the functioning the illuminance control of the ICsIE when M_{IL} is smaller than ST_{IL}.

The illuminance control loop of the ICsIE (Fig. 4) was designed on the experiences gathered through experiments conducted with the control system KAMRA (Trobec-Lah et al., 2005). During the experimentation with the KAMRA system it became obvious that because of quickly changing external illuminance conditions the movements of shading devices have to be limited in order to avoid annoying the users. Because of this a compromise regarding the ICsIE's accuracy and user acceptability was necessary; therefore, we used time delay constants and deviation limits. The system applies a series of values that define acceptable deviations from the set-point illuminance ST_{IL}. If M_{IL} is in the defined zone, the system does not react. Deviations are defined separately for the upper and lower threshold levels, as lower work plane illuminance is more problematic for the visual efficiency than the higher one. In the case of the ICsIE three pairs of deviation values are used for each individual actuator reaction. For the movement of blinds, a value of parameter D_D defines the lower limit (e.g. ST_{IL} - 80 lx) of the acceptable deviations while parameter D_U defines the upper limit (e.g. ST_{IL} + 100 lx). Separate parameters are also defined for the blade movements (d_D, d_U) and for the activation of artificial illumination (D_{LD}, D_{LU}). Additionally, the activation of actuators is also restricted by the time delays. For each of the actions a time interval is defined, in which only one movement can be performed (Fig. 4). This is of great importance, because the external and consequentially the indoor daylight levels can fluctuate very rapidly and with large amplitudes. The responsiveness of the ICsIE is greatly dependent on the values of the described deviation parameters and time intervals. In general, the smaller time intervals and deviation values, the more responsive the system will be, but at the same time the blinds will move more frequently.

2.3 Air quality control

Determining air quality in enclosed spaces is a very complicated task because of the multitude of different possible harmful chemicals that are hard to detect and even harder to remove. However, if the only source of contaminants in the internal air is human metabolism, the level of CO_2 concentration is a simple but effective indicator of its quality (CR 1752, 1998). Supervision of the amount of CO_2 present in the internal atmosphere and adequate ventilation can effectively eliminate potential discomfort problems related to air quality**.** In the case of the ICsIE ventilation of the office was executed with an automated opening of a window linked to a CO_2 concentration sensor (M_{CO2}). The same window is also used for passive cooling by the thermal control loop (Fig. 3). In order to avoid conflicting situations between the two control algorithms, the priority is always set to the air quality control, because user health, comfort and effectiveness represent a more efficient building system as a whole (Kristl et al., 2007). Opening of the window is suspended only when the external precipitation sensor (M_P) detects rain or snow.

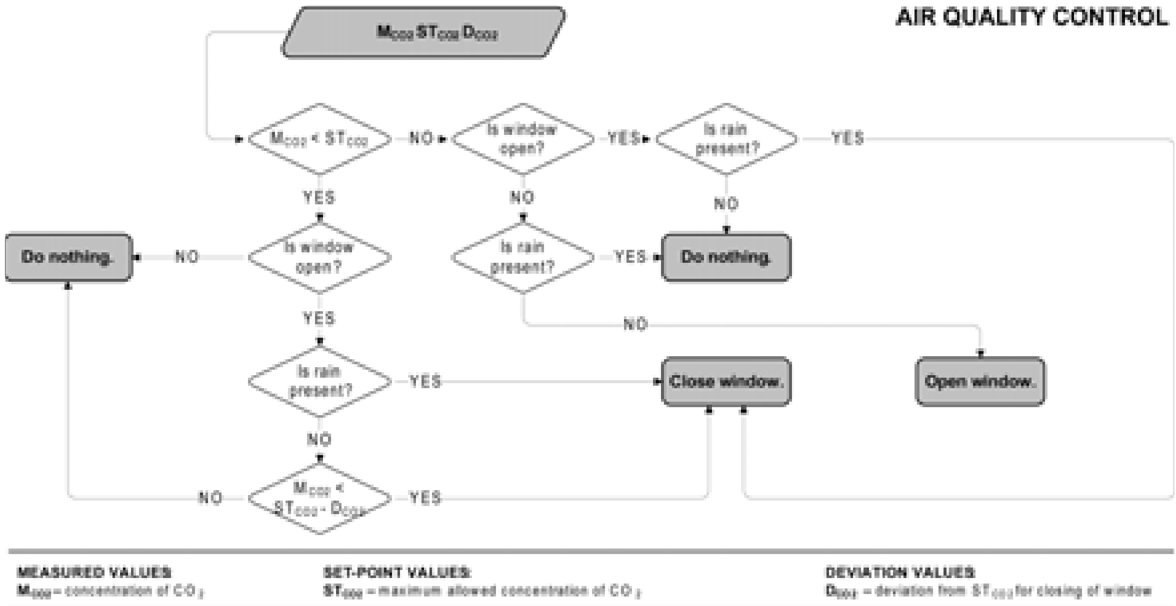

Fig. 5: Flow chart illustrating the functioning the air quality control of the ICsIE.

Compared to the illuminance and thermal control loops of the ICsIE, control of the air quality exhibits lower level of complexity (Figs. 3, 4 and 5). The quality of the indoor air is regulated according to the measured concentration of CO_2 (M_{CO2}) that is compared to the maximum allowed concentration (ST_{CO2}). When M_{CO2} exceeds the defined value of ST_{CO2}, the system opens the window. The window remains open until the level of CO_2 in the room is reduced by the defined deviation value (D_{CO2}). The ICsIE also executes time dependant cyclical openings of the window that are not linked to the CO_2 concentrations in the office (e.g. the window is opened every 120 minutes for the duration of 10 minutes). The idea behind such operations is not to wait that the maximum CO_2 concentration is reached, but rather to maintain relatively constant levels of air quality. The entire flow chart diagram of the ICsIE air quality control is presented in Fig. 5.

3. Operation of the ICsIE

The ICsIE was designed between 2007 and 2008 and installed in the office of the main building of the Faculty of Civil and Geodetic Engineering in late 2008. During the operation of the system in the winter of 2008/2009 preliminary experiments were executed to eliminate defects in the design and glitches in the programming and functioning. After some initial problems with the functioning of the actuators, the system was put into continuous operation in spring of 2009.

3.1 Configuration of the test office

The test office equipped with the ICsIE is a typical cellular office with the floor space of 38.80 m^2 and a volume of 163.40 m^3, with a western oriented window of a total glazing of 11.40 m^2. Considering its size the office has a relatively large window area (≈ 30 % of its floor area, and ≈ 38 % of the external wall area) but a small level of occupancy (0.05 persons/m^2), as there are only two work places in it. The window of the office is segmented into six individual units, each unit equipped with the above mentioned motorized external venetian blinds. The upper right (as seen from the inside of the office) window is automated and is used for ventilation and passive cooling of the office. Heating and cooling panels mounted to the ceiling of the office are connected to the central heating and central cooling plant of the Faculty of Civil and Geodetic Engineering building. The basic geometry of the office can be seen in Fig. 6.

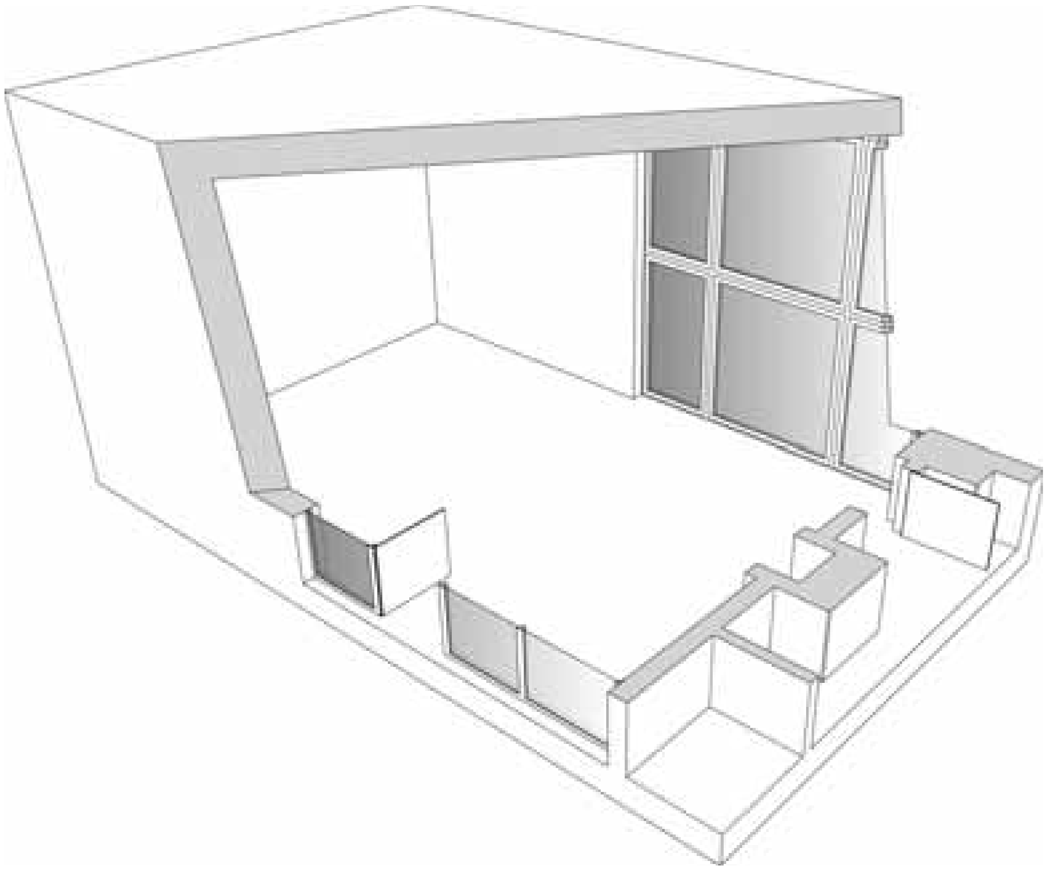

Fig. 6: Basic geometry of the office equipped with the ICsIE control system.

3.2 Experiment: Illuminance control, 7th of March 2011

Typical operation of the ICsIE is that during week days the system is in illuminance priority between 7:00 and 18:00. After that the system switches to a reduced regime (i.e. no illuminace control, reduced internal temperatures control). During weekend days the system is typically in thermal priority mode or dormant (regulation of blinds is deactivated). Fig. 7 represents a typical early spring experiment where the system was in illuminace priority mode with deactivated artificial illumination, which means that internal illuminance was regulated strictly by the venetian blinds. ST_{IL} was set to 500 lx with acceptable deviation values of parameters D_U set to +100 lx and D_D set to -50 lx (Fig. 7). Deviation parameters for the rotation of the blind blades were set symmetrical ($d_D = d_U$) to ±50 lx (not depicted in Fig. 7), while time restriction constants were set to T_D = 300 s and t_D = 120 s. The ST_{IL} value was taken from the recommendations for office environments defined in the ISO/CIE 8995-1 standard (ISO/CIE 8995-1, 2002). Weather conditions on the presented day were extremely sunny and stable, which can be observed from the solar radiation (M_{SR}) curve depicted in Fig. 7. Due to the western orientation of the office the direct solar radiation influences the internal illuminance of the office only after the sun passes to the western part of the sky hemisphere. Internal illuminance was too low during the morning hours when additional artificial illumination would be necessary to reach the desired value of 500 lx. After 13:00 the office was adequately daylighted until 17:00, when the intensity of the sun dropped due to the setting of the sun. During this time the ICsIE successfully regulated the internal illuminance with the positioning of the blinds (POS_{BL}) and rotation of its blades (POS_{BLA}). The POS_{BL} line depicted in Fig. 7 represents the movement of six individual venetian blind units, where the value of 1000 represents all of the blinds being retracted, while each additional step corresponds to one blind unit being extended. All of the blinds were extended around 15:15. At this time the position of the blades (POS_{BLA}) was horizontal (0°). Each additional step was then executed in 30° increments. The POS_{BLA} line depicts this rotational movement of blades where the value of POS_{BLA} = 0 corresponds to 0° and POS_{BLA} = 900 corresponds to 90°. Temporary drops in the level of internal illuminance during the movements of blinds are caused by blind movement which can be executed only with blades at 90° position (POS_{BLA} = 900). The presented experiment illustrates the efficiency of the ICsIE's illuminance control, as it was successful at following the ST_{IL} value accurately and with less than 4 movements of blinds in one hour.

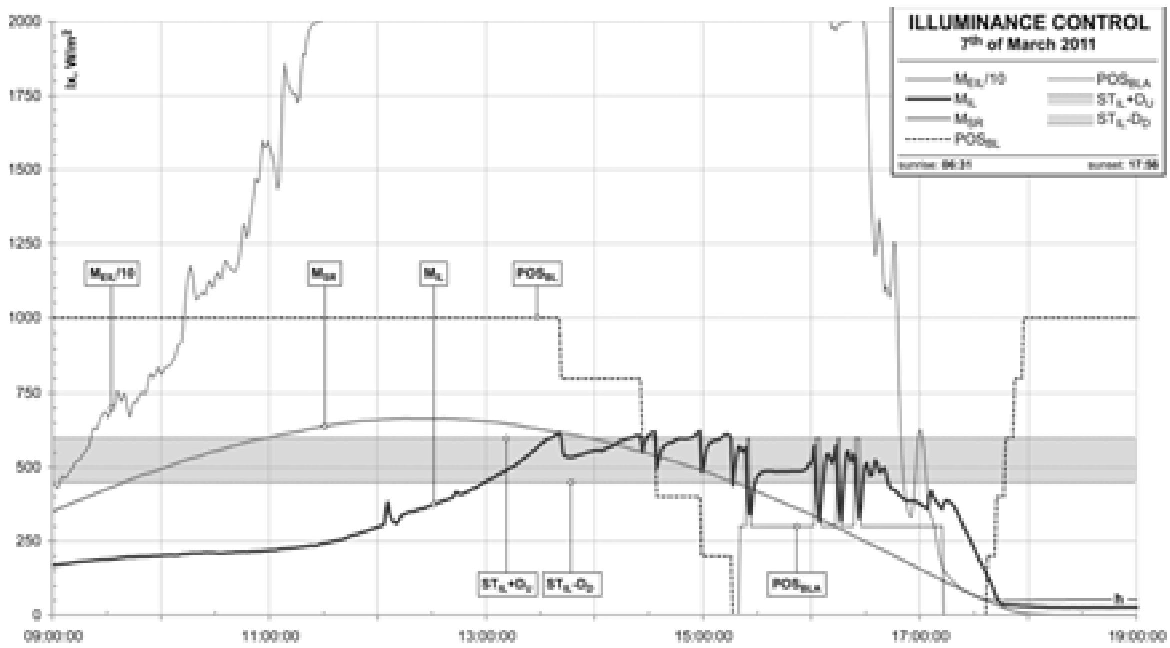

Fig. 7: Illumination control on the 7th of March 2011; the ICsIE illuminance control was active between 07:00 and 18:00, artificial illumination was turned off. The diagram depicts the following values: internal set-point illuminance with defined deviations ($ST_{IL}+D_U$, $ST_{IL}-D_D$), internal illuminance (M_{IL}), external illuminance divided by factor 10 ($M_{EIL}/10$), direct solar radiation (M_{SR}), position of individual blinds (POS_{BL}) and inclination ob blades (POS_{BLA}).

4. Conclusion

The ICsIE was designed and executed as a full scale, real time automated control system that would be able to effectively control the living and working indoor environments of buildings. The system is installed in an occupied office at the Faculty for Civil and Geodetic Engineering in Ljubljana, Slovenia. The system is focused on providing greater user comfort and consequentially in working and school environments also greater efficiency at working and learning. In the context of user satisfaction lower energy consumption of a building is a secondary concern and must not interfere with providing good and healthy internal environmental conditions (Krainer, 2008). Nevertheless, this does not mean that a building with such system can be energy inefficient, but that striving for reduction of energy consumption must be coordinated with the goal of better indoor environmental conditions (Košir, 2008). In the case of ICsIE this is achieved through the application of bioclimatic principles and use of PSA measures to achieve simultaneous positive effects in the field of user comfort as well as energy efficiency. ICsIE is a system that controls the most dynamically changing aspects of indoor environment (illuminance, thermal conditions and air quality), while acoustics and ergonomics were not controlled due to their relatively static nature. Regulation is achieved trough the use of internal and external sensor arrays that monitor the indoor environmental and the external climatic conditions. According to the reference values of indoor controlled values (user demands) and the external possibilities, the system guides the appropriate actuators to a proper state. The system is executed as a cascade fuzzy logic/PI control system for the regulation of heating, cooling and illuminance and as a conventional PI controller for the regulation of natural ventilation.

During the operation the ICsIE has been successful at synchronizing the controlled aspects of internal environment and has maintained them in the desired range around the set-point values. Illuminance control has been successful in following the defined set-point values of the indoor work plane illuminance. Through experimentation the appropriate values for the deviation limits around the set-point value and time delays have been defined. With these values properly defined, the ICsIE is able to regulate the level of indoor illuminance with relatively few movements of the blinds (i.e. typically ≈ 5 movements in 1 hour). Low number of blind alterations is crucial as to prevent annoyance to the users. Thermal control of the indoor environment was also successful at keeping internal temperatures in the desired range. The most surprising was the efficiency of the nigh-time passive cooling, where reduction of 4 to 5 K in indoor air temperatures was achieved when the office was naturally ventilated through an automated window. Quality of the indoor air has been controlled by automatic natural ventilation. The system is capable of sustaining indoor CO_2 concentrations continuously below the upper threshold of 1000 ppm. In most cases the window was opened only for the duration of 5 minutes in order to reduce the concentration of CO_2 in the office by 50 ppm. According to the occupants' feedback the ICsIE could be deemed a success, as manual interventions into the functioning of the system were rare. The same conclusion can also be drawn from the experimental data where good results were achived even with daylighting, which is the hardest to control due to its unpredictable and highly dynamic nature.

5. References

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

Sobocki, P., Jönsson, B., Angst, J., Rehnberg, C., 2006. Cost of depression in Europe. Journal of Mental Health Policy and Economics. 9, 87-98.

Fisk, W. J., 2000. Health and productivity gains from better indoor environments and their implications for the U.S. Department of Energy. Lawrence Berkeley National Laboratory.

Krainer, A., 2008. Passivhaus contra bioclimatic design – Dedicated to em. Univ.-Prof. Dr. Ing. habil. Dr.h.c. mult. Karl Gertis on the occasion of his 70th birthday. Bauphysik. 30, 393-404.

Krainer, A., 1993. Building Science and Environment-Conscious, Design Module 1: Design Principles, 7 Toward Smart Buildings. European Commission TEMPUS Joint European Project JEP-1802.

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

CR 1752, 1998. Ventilation for buildings – Design criteria for the indoor environment, European Committee for Standardization, Brussels.

Pheasant, S., Haslegrave, C. M., 2006. Bodyspace: anthropometry, ergonomics, and the design of work – 3rd ed., Taylor & Francis, Boca Raton.

Košir, M., 2008. Integral regulating system of internal environment on the basis of fuzzy logic, PhD thesis, University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana.

Kristl, Ž., Košir, M., Trobec-Lah, M., Krainer, A., 2007. Fuzzy control system for thermal and visual comfort in building. Renewable energy. 33, 1-12.

Trobec-Lah, M., Zupančič, B., Krainer, A., 2005. Fuzzy control of illumination and temperature comfort in a test chamber. Building and Environment. 40, 1626-1637.

ISO/CIE 8995-1, 2002. Lighting of indoor work places, International Organization for Standardization, Brussels.