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# Adaptive Building Envelope: An Integral Approach to Indoor Environment Control in Buildings

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Additional information is available at the end of the chapter

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## Abstract

The problem of energy consumption of buildings is complex and multidimensional, as it is a cross section of building envelope performance, indoor environmental conditions and user demands and preferences. In order to fulfil the EU goal stated in the 2020 climate and energy package and beyond, the implementation of high-performance buildings is crucial. Part of the solution is properly designed, flexible and adequately controlled building envelope that can contribute to reduced energy consumption and to increased occupancy comfort. In the presented chapter first, a structured treatment of the indoor environment formation is proposed that can be used in order to define appropriate fields of interventions when designing building automation systems. Furthermore, interaction between adaptive building envelope elements, indoor and exterior environment is discussed and elaborated. Second, the conventional and artificial intelligence control approaches used in building automation are discussed and commented, whereas advantages and disadvantages of each group are discussed. At the end, an example of building automation system designed on the principles of a holistic treatment of indoor environment in buildings is presented. The discussed system was designed at the Faculty of Civil and Geodetic Engineering using a combination of conventional and artificial intelligence control methods.

**Keywords:** building automation, building envelope, Indoor environment, daylight control, thermal control, ventilation control

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## 1. Introduction

During the last decades, it has become obvious that the overall influence of human civilization has planetary consequences, which are most pronounced through climate change, resource

depletion and energy shortage. The situation was additionally intensified with the onset of global economic crisis. One of crucial links in reducing environmental impacts is attaining higher energy efficiency and lower greenhouse gas emissions (GHGs) of the building sector. In the EU, buildings are responsible for roughly 40% of the EU's final energy consumption and GHG emissions [1]. Similar situation applies for the USA [2], with slightly different but nonetheless similar shares in other parts of the world as well (e.g. 28% in China, 42% in Brazil, 47% in Switzerland [3], and 53% in Singapore [4]). In fact, buildings are one of the largest global end users of energy, but they also have an extremely large untapped potential for energy savings. In the EU, this potential is estimated at 11,630 GWh (i.e. 1509 Mtoe) by 2050 [5]. Therefore, they are at the forefront of the EU's struggle to develop a low-carbon economy and reduce its dependency on imported energy while at the same time to limit its environmental impact.

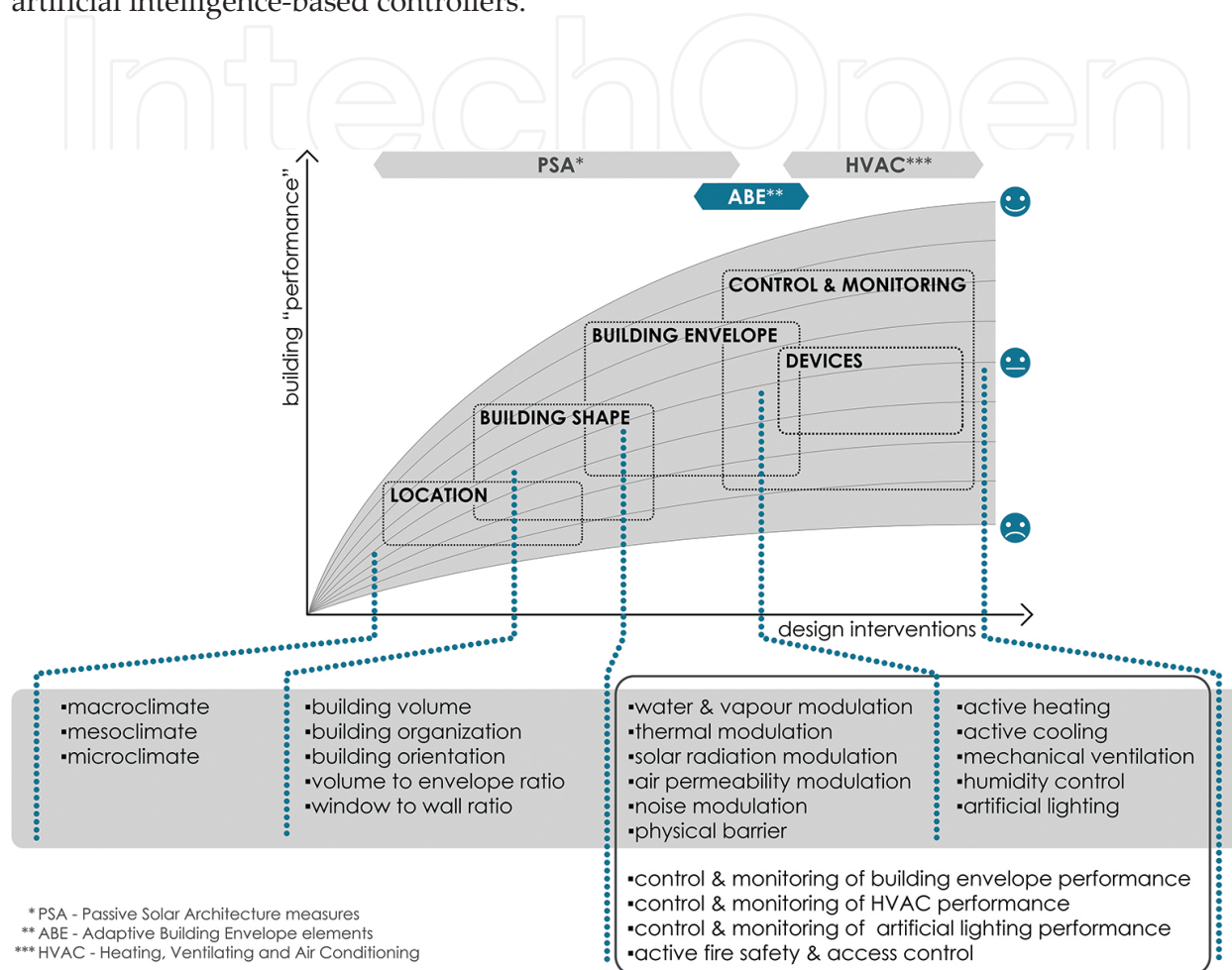
The main focus of the EU's policy on energy and climate was stated in the 2020 Climate and Energy Package [6]. The goals stated in the aforementioned document were reduction of 20% in GHG emissions from the 1990 levels, 20% improvement in energy efficiency and supplying 20% of EU energy from renewable energy sources. The importance of buildings, especially the operational energy consumed by buildings during their life time, is highlighted through a series of EU Directives, of which the most crucial are the Energy Performance of Buildings Directive-recast (EPBD-r) [7] and the Energy Efficiency Directive (EED) [8]. The main objective of the EPBD-r is the formulation of national legislation of member states in which energy performance of buildings is prescribed, monitored and encouraged through multiple mechanisms for new developments as well as for renovation projects. The primary goal, put forward in the EPBD-r, is that by 2020 all newly constructed buildings in the EU will be nearly Zero-Energy Buildings (nZEB). In other words, this means that buildings should have very high energy performance and that the energy they consume for heating, cooling, lighting, ventilation and preparation of domestic hot water should be mostly from renewable energy sources produced on-site or nearby [7]. The exact implementation of minimum performance criteria for achieving nZEB is left to each member state, which is why they can vary and are often hard to directly compare [9]. For the renovation projects the nZEB criteria are not obligatory, as renovations have to be executed in a cost-effective manner considering the presumed costs of the renovation as well as savings resulting from the energy renovation through the expected life cycle of the building. Nevertheless, in some cases the nZEB criteria are also achievable for the renovation projects. From the practical viewpoint, the goal of nZEB can be achieved through conventional means of thermally insulating building envelopes, by proper overheating control and by providing energy-efficient heating, cooling and ventilating building services (HVAC) as well as through energy-efficient lighting systems. Proper design and coordination among different building elements and systems are crucial, as best results can be achieved through multidisciplinary integrated approach resulting in expected performance. In other words, building automation systems (BASs) can ensure proper functioning and coordination among different building elements and installed electrical and mechanical systems [10]. The result is lower energy consumption and thus better utilization of installed systems. The importance of BAS as well as monitoring and metering in buildings is also emphasized in the EPBD-r, which encourages member states to promote, where appropriate, the installation of active building control systems [7, 11]. To this end, a dedicated standard,

EN 15232 [12], was developed in the EPBD set of European standards, defining terminology and methods for determining the impact of BAS on the energy performance of buildings. The potential of BAS for reducing operational energy consumption in buildings is relatively substantial, as was shown by Rubinstein et al. [13] and Lee et al. [14] over a decade and a half ago. Nevertheless, the overall achievable energy savings with the implementation of BAS are still poorly understood due to its multidimensional nature connecting energy consumption, user comfort and level of implemented control [4, 15].

As we have seen, in regard to the implementation of automation in buildings, the EU legislation focuses only on the potential of attaining energy savings with the utilization of BAS. Consequently, the influence on user comfort and well-being is disregarded, despite numerous studies showing that satisfaction of building users with the quality of indoor environment can have substantial impact on the energy consumption in buildings [3, 16, 17]. In fact, the influence of improved indoor environment in buildings has direct and indirect impact on building user health [18] and productivity [19, 20] and thus also on the greater socio-economic context of human society. In general, higher quality of indoor environment results in fewer instances of sick building syndrome (SBS), allergic reactions, asthma and communicable respiratory infections [17, 21, 22]. Inappropriate thermal conditions in buildings are the main cause of user discomfort [17] but have also been linked to cardiovascular problems if inhabitants are not exposed to regular fluctuations of indoor temperatures [23]. On the other hand, exposure to adequate levels of daylight is crucial for the regulation of human circadian rhythm [24] and has been linked to improved mood, reduced stress and fewer symptoms of seasonal affective disorder (SAD) [17] as well as higher productivity and better learning efficiency [19, 20]. All this is not surprising as in the developed world people spend more than 90% of their lives indoors [25], most of this in buildings, which is why the quality of indoor environment is probably the single most important environmental factor in human health. Hence, the design and performance of buildings are crucial for modern urbanized societies. Solutions such as smart buildings, high-performance buildings [26, 27] or active buildings [28] are a possible answer to the challenge posed to the designers by interconnectedness of energy efficiency, user well-being and comfort [17]. Such buildings, in contrast to the nZEB, put building users in the centre of the design process, while at the same time, they strive to be energy efficient, thus providing healthy and comfortable indoor environment with the lowest possible energy consumption and not the other way around [10]. Central to the design of high-performance buildings is the bioclimatic approach, which is focused on the users as well as energy efficiency of buildings [10, 15]. Crucial for the bioclimatic approach is the utilization of passive building features (i.e. passive solar architecture (PSA) features [29]), which enable appropriate utilization of climatic conditions to facilitate comfort and energy efficiency in buildings (**Figure 1**). Additionally, in high-performance buildings, Adaptive Building Envelope (ABE) elements (e.g. movable shading, automated natural ventilation) must be applied in order to enable adequate level of control and functionality of interactions between indoor and exterior environment. Building automation can be used to efficiently harmonize and regulate among PSA, ABE elements and HVAC systems (**Figure 1**) [30] to simultaneously achieve the goals of higher indoor comfort and lower energy consumption. Nonetheless the problem is extremely complex and non-linear and characterized by high noisiness of the processes that need to be



addressed by BAS [4]; consequently appropriate control approaches have to be selected in order to achieve desirable results. It was shown by Dounis et al. [15] and Shaikh et al. [4] that in general advanced control methods like fuzzy logic and neural controllers are more suited for BAS applications than conventional controllers (e.g. on/off controllers). Thus, the trend in experimental and commercial applications of BAS is shifting towards widespread use of artificial intelligence-based controllers.



**Figure 1.** Conceptual representation of synergetic effects in the design of high-performance buildings that crucially influence the quality of the final outcome of a project.

Below the complexity of indoor environment automation via building-wide integration will be described. Special focus will be on indoor environment, ABE elements and user demands. The objective is to outline a broader picture and provide background information regarding the specifics, limitations and feasibility issues of implementing BAS. Basic characteristics of conventional and artificial intelligence controller-based BAS systems will be discussed, whereas special attention will be given to the advantages and drawbacks of each group. At the end, a simple experimental system for automated control of indoor environment implemented at the University of Ljubljana, Faculty of Civil and Geodetic Engineering (UL FG), will be presented. Its structure and functioning will be described and thus illustrating the application of the presented holistic treatment of the indoor environment.

2. Indoor environment in buildings

Indoor environment is formulated with the creation of the building envelope—a separator that divides the interior from the exterior and thus creates an artificial human habitat. We perceive our surrounding environment on two distinct, but nonetheless interconnected, levels. One is dependent on the cultural and social predispositions, while the other is based on the physiological and psychological response of each individual. Culturally conditioned perception of the surrounding physical environment is strongly dependent on the individual upbringing and therefore connected to history and social environment [31]. It is determined by each individual’s expectations, impressions, influences and wishes about the indoor environment; these are, of course, extremely subjective but nonetheless the result of individual’s social context (e.g. society as a whole, family and friends). The psychophysiological response of the human body to the environmental impulses is on the other hand much easier to predict [32], although it still varies to some extent from one individual to another due to gender, age, health and fitness. Human sensory interpretation of surrounding environment starts with the environmental impulses received by our body’s sensory system. From here, the information is passed to the brain that interprets these sensory impulses as properties of the environment.

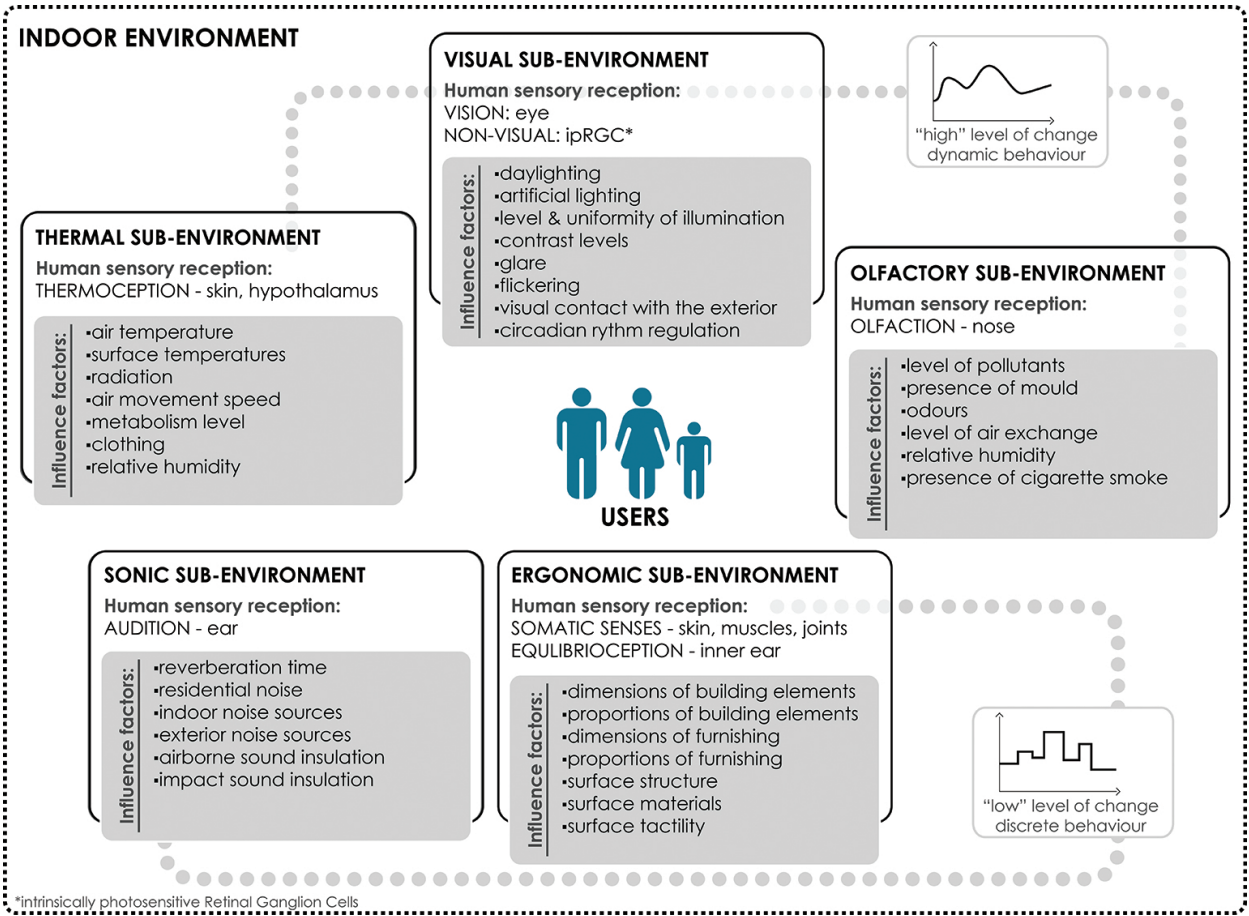


Figure 2. Indoor environment as a cross section of five sub-environments with corresponding human sensory reception system as well as major influential factors to be considered when designing indoor environments in buildings.

Sensory interpretation of the environment can therefore be reversely connected to a specific sense or group of senses (e.g. visual impulses can be linked to vision). This simple classification of different environmental impulses with human sensory reception system can be used to systematically structure the environmental influences on the building users according to the human psychophysiological response. Consequentially, five sub-environments can be defined: thermal, visual, olfactory, sonic and ergonomic environments (**Figure 2**). Together they form the wholeness of the indoor environment. The proposed classification can be implemented in the building design as well as in the implementation of BAS, thus defining the fields that are best suited to automated control in order to enhance the quality of indoor environment and subsequent user well-being and satisfaction. For each sub-environment, crucial influence factors can be identified. These factors govern to greater or lesser extent the human response to the environment and therefore the perception about its quality. Because some of the influence factors are interconnected and interdependent (e.g. daylighting and thermal comfort), an extremely complex picture of the indoor environment emerges [17, 33, 34].

The main problem of the proposed user-oriented approach in the design of BAS is its complexity and the number of possible interactions between the external environment, building envelope and indoor environment with the user-defined demands and wishes. In order to reduce the amount of considered influence factors, a selection according to the importance in regard to the user comfort should be executed. Additionally, it is also prudent to include in the design of BAS and ABE the control of only those influence factors that cannot be satisfactorily resolved by conventional building techniques. In this context, the ergonomic and, to some degree, the sonic sub-environments are less prone to unpredictable and highly dynamic changes. In other words, a large majority of comfort issues stemming from the dissatisfaction of users with aspects of sonic and ergonomic sub-environments can be solved on the level of building and/or interior furnishing design. It is true that some aspects of sonic sub-environment can also be actively controlled, like active noise cancelation systems [35] or automatically controlled movable absorbers to control room reverberation [33], but still such applications are relatively rare in comparison to other building automation issues. In comparison, the thermal, visual and olfactory sub-environment factors are characterized by extreme dynamics of change, high unpredictability and consequentially high risk for user dissatisfaction, having at the same time large energy savings potential [3, 4, 26]. Therefore, the issues connected to the control of thermal, visual and indoor air quality (IAQ) will be further discussed. This, of course, does not mean that during the design of BAS and ABE, sonic and ergonomic sub-environments should not be considered. Especially potential negative interactions, like in the case of automated natural ventilation, when opening the windows can cause the increase in the noise exposure of the occupants and consequential dissatisfaction with the indoor environment.

## 2.1. Thermal sub-environment

Indoor thermal sub-environment is predominantly the result of external macro- and micro-climatic characteristics of a building's location. The external seasonal and diurnal fluctuations in temperatures and solar radiation are the principal influences behind the formulation of

internal thermal conditions, although the effects of external climate can be to some degree mitigated by building envelope design and HVAC systems [29, 31, 33]. In the majority of contemporary buildings, the predominant influence on indoor thermal sub-environment is the solar radiation [29] that drives the thermal environment of a building. Solar radiation is either beneficial as passive heat source during heating season or unwanted because it leads to overheating during cooling season. In addition to the influence of the solar radiation, the thermal sub-environment of a building is also dependent on the thermal exchange with the exterior (i.e. transmission and convection heat gains or losses) as well as on the building usage (i.e. indoor heat gains from appliances and metabolic heat of occupants). In some instances, when buildings have high occupancy rates and large amount of installed appliances (e.g. offices, hospitals), they become mostly dependent on the internally generated heat [33]. In such buildings, also called internal load-dominated buildings [29], the climatic conditions have far smaller influence on the overall formulation of the indoor thermal sub-environment.

Human thermal comfort in indoor environments can be linked to a multitude of influences, such as air temperature, humidity, mean radiant temperature, metabolic activity and clothing (**Figure 2**), but all these factors are linked to the human vasomotor control mechanism [34]. The vasomotor control mechanism, in relation to the surrounding thermal conditions, regulates the flow of blood in the skin and underlying tissue in order to maintain the deep-core body temperature approximately at 36.5°C. For the designers of buildings, HVAC systems and BAS, the main problem is how to correlate between influence factors that influence to larger or lesser degree the vasomotor control response and therefore human satisfaction with specific thermal sub-environment. Many measurement systems of indoor thermal sub-environment parameters have been proposed during the last decades [34], with the most complex being the PMV index [36] proposed by Fanger in the 1970s. The PMV index links indoor air temperature, humidity, air movement, mean radiant temperature, metabolic rate and clothing factor to the human thermal sensation. Although the PMV index is an extremely useful tool, it has its limits [37] and poses in connection to the automation of building additional problems from the practical standpoint, as it is difficult to acquire appropriate data (especially mean radiant temperature, metabolic rate and clothing factor), although there have been successful applications in BMS (see [15, 38]). Alternatively, less complex indicators of indoor thermal sub-environment can be utilized. One of them is the idea of thermal neutrality that links the trend of change in external temperatures to the indoor temperatures deemed acceptable by a large number of people [39]. Thermal neutrality inherently includes the influence of seasonal thermal adaptation of users and is therefore linked to certain locale as well as culture. In the end, even just a simple measurement of dry bulb air temperature can be used for BMS applications [30] if a building has a relatively uniform radiant environment and limited indoor air movement (e.g. no draft due to ventilation system or insufficiently air sealed envelope).

## 2.2. Visual sub-environment

Adequate performance of visual tasks during activities in buildings is one of key occupant demands. Therefore, proper formulation of visual indoor sub-environment (**Figure 2**) is crucial



in building design. It can be split into visual and non-visual effects of light on the human body, with daylighting as crucial element, as it is preferred by users over artificial illumination [17], as well as necessary for the regulation of biological processes [40, 41]. While artificial illumination is inevitable for the functioning of modern societies, it is no substitute for daylighting, as exposure to natural light is central to the biological functioning of our bodies [40]. The spectral composition and direction (i.e. light from the side as well as from the top) of daylight are decisive for the activation of intrinsically photosensitive retinal ganglion (iPRG) cells and consequential regulation of human circadian rhythm [24, 41] and have to this day for all practical reasons still not been matched by artificial lighting. In addition to the circadian regulation, daylight is also crucial in the process of synthetization of vitamin D and resulting in better absorption of calcium in human bodies, therefore reducing the risk of osteoporosis and rickets [42]. The beneficial influence of daylight goes even further, as studies have shown that schoolchildren in classrooms with adequate daylight had 20% better results in mathematical tests and were by 26% better in reading abilities in comparison with those that were in non-day-lit classrooms [19]. Similar results have also been found for office environments [20]. Other studies have also shown that there is a link between daylight and sales in shops [42]. In regard to the visual performance, daylight is highly valued by building users, so much even that they are willing to tolerate higher levels of visual discomfort from daylight than in the case of artificial illumination. For the majority of visual tasks performed in buildings, the most important criterion is the amount and uniformity of horizontal illuminance measured on the working plane [24, 33]. On the other hand, the most common problem connected to the use of daylight in working and living environments is the occurrence of glare due to the influence of direct sunlight and/or placement of high luminance objects in the field of view [34, 41]. As daylight in buildings is provided through the building envelope, the design as well as the control of transparent parts (i.e. windows, skylights and shading devices) is essential for indoor visual comfort of users. Especially, the level of shading control is crucial because it influences the aspects of visual (i.e. glare, illuminance levels and view) as well as of the thermal sub-environment (i.e. overheating and passive heating control). In the end, all modern buildings have a need for artificial illumination in order to facilitate adequate visual conditions in times when daylight is not available. The coordination between daylight and artificial illumination is vital for the reduction in electrical energy consumption, as control and coordination over daylight and lights can result in savings in the range from 30 to 60% [43]. Visual sub-environment parameters in buildings are probably the hardest to adequately regulate using BAS [30] but at the same time promise the largest long-term social and healthcare dividends [17].

### 2.3. Olfactory sub-environment

The indoor atmospheric conditions in buildings as a whole are very poorly understood and many times neglected, despite strong indications of multiple links between IAQ, occupant health and comfort [21, 22]. The influence factors governing the formation of the olfactory sub-environment can be divided into two groups: the sensible factors which can be perceived by the human olfactory sensory system (e.g. stale air) and the nonsensible factors in the form of harmful chemicals undetectable to humans (e.g. radon gas) [44, 45]. The sources of harmful substances in the indoor air are mostly the materials used in the building elements, furnishing,

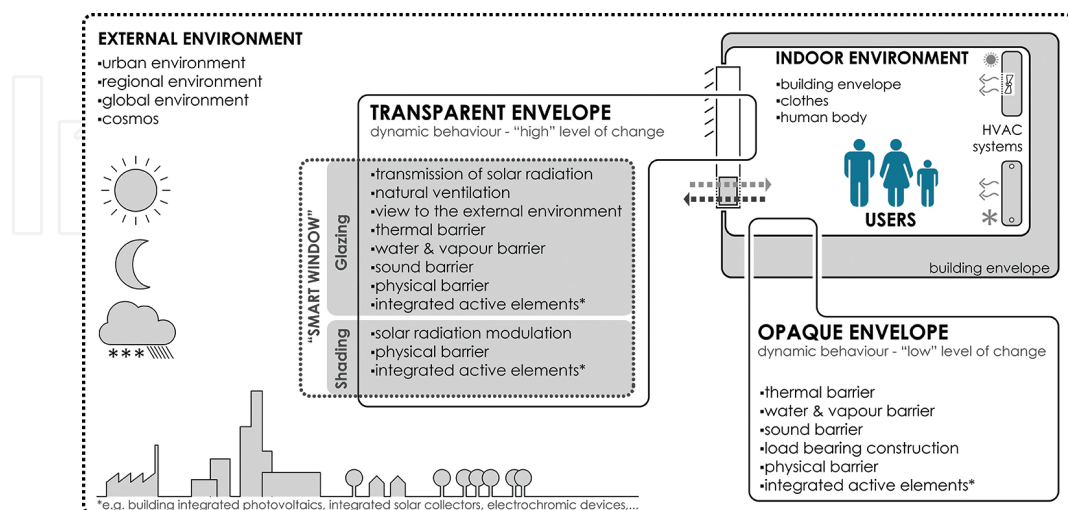


improperly designed and maintained ventilation systems and external natural and artificial sources. Because the influence of chemicals and their combinations on the humans are poorly understood [45], the most prudent cause of action is to remove all known and potentially harmful substances from the indoor environment. Presuming that all such sources have been removed from the indoor environment, we can conclude that the primary sources of dissatisfaction with the IAQ are organic substances present in the air [22] and occupant metabolic by-products [44] (**Figure 2**). Exemption to this presumption are indoor environments where the removal of hazardous chemicals is impossible (e.g. industrial environments dealing with toxic substances) or where the contaminant is present in the external environment [46] and is therefore the result of the location of a building. In order to maintain adequate levels of IAQ in buildings, ventilation is used either in the form of natural, mechanical or combined ventilation that periodically exchanges indoor air with external fresh air. The level of air exchange and the method [19] of ventilation (natural or mechanical) have been shown to drastically influence the occurrence of the SBS symptoms (e.g. asthma, respiratory inflammation and headache), allergic reactions and communicable respiratory infections. On the basis of available studies, Sundell et al. [22] conclude that SBS symptoms are drastically reduced if the ventilation air flow rate is higher than 25 l/s per person. This ventilation air flow rate is higher than the minimum required values in many standards and guidelines [22, 44], which causes a concern in regard to the contemporary buildings that are designed to be energy efficient and therefore often use minimum ventilation rates in order to conserve energy [10], thus neglecting occupant comfort. From the standpoint of BAS design, the most practical control strategy is demand-side ventilation, either mechanical or natural, controlled according to the CO<sub>2</sub> concentration [30] in the indoor air. Although humans cannot sense the presence of CO<sub>2</sub>, it can be reliably used [44] as an indicator of air quality, where values above 2000 ppm should be avoided, as at such levels the majority of users already report problems with concentration and occurrence of headaches. Regarding the method of ventilation, studies on user comfort show a slight preference towards natural ventilation [17, 19], although it negatively influences energy use. Therefore, for better performance of naturally ventilated buildings, BAS can be used to coordinate between heating, cooling and natural ventilation [30].

### 3. Adaptive building envelope

Indoor environments in buildings are at the same time separated from and connected to the external natural environment via building envelopes, which enable the exchange of energy (e.g. heat), materials (e.g. air) and information (e.g. view) between the two [31]. Therefore, building envelope is an interface that connects the two dynamic and unpredictable environments. Traditionally, the function of building envelope was seen as a separator, limiting the influence of undesired external climatic conditions on the indoor environmental conditions. However, such interpretation is insufficient, as the interaction between the two environments is equal in importance, if not even more important [47]. This duality of demands represents a problem for the design of building envelopes. As static solutions (i.e. conventional PSA) are not flexible enough to provide adequate level of flexibility demanded from modern high-

performance buildings (**Figure 1**). To facilitate higher level of functionality, ABE elements (**Figure 1**) are used in order to enable dynamic and flexible interaction between interior and exterior. In the future, the whole building envelope might become adaptable and/or morphable [48], like in the case of hypothetical “polyvalent wall” proposed by Mike Davis [27], which would combine the benefits of opaque building elements with the functionality of the transparent envelope and integrate them with the HVAC systems. However, due to the limitations of current technology, building envelopes of today must be divided into two distinct types: transparent and opaque envelopes (**Figure 3**). For the most part, the ABE elements and technologies are focused on the transparent envelope, which is characterized by high level of energy, matter and information exchange (**Figure 3**) and therefore presents the most dynamic part of a building. On the level of realization, this mostly means the application of movable shading elements, automated natural ventilation, electrochromic glazing, smart windows [49], light deflectors, shading elements with integrated solar collectors [50] or PVs, etc. Although ABE elements are featured in modern high-performance buildings, the usage of adaptable envelope elements in buildings is nothing new. A very good example of ABE application in traditional architecture is the Japanese house, which exhibits high level of envelope adaptability due to its movable “shoji” screens and “amado” shutters. The main difference between traditional and modern ABE systems is in the level of control, where traditional solutions relied on manual control with high margins of error, while modern ABE elements must be automated to satisfy the increasingly high demands of users regarding accuracy. Automation of ABEs also enables increased energy efficiency because it eliminates or reduces the energy wasted due to unwanted user behaviour, like keeping lights on and blinds down during daytime or leaving windows open while the air condition is active [3, 17]. Therefore, some sort of automation is inherently present in the ABEs of high-performance buildings, while the best results can only be achieved with building-wide integration, via BAS, of all systems (i.e. ABE, HVAC and lighting), crucial for providing acceptable indoor conditions.



**Figure 3.** Building envelope as an interface between external and indoor environment and corresponding primary functions of the transparent and the opaque part.

4. Control approaches for BAS

The history of building automation and the development of smart buildings are closely tied to the advances in modern telecommunications and computer technologies. The first implementations of “building intelligence” can be traced back to the early 1980s in Japan and the USA, where oversupply of office spaces pushed developers to provide advanced telecommunication services in order to attract tenants. Automation in such buildings was primarily focused on the provision of information technology, although rudimentary automation of building services such as HVAC was also implemented [35]. The limitations of such a narrow view of building intelligence soon became apparent, as it became evident that smart buildings are much more than just telecommunications. The importance of responsiveness to environmental as well as spatial and business change was shown to be of extreme importance. Therefore, the focus shifted from technological centered solutions to the all-around building performance [35], including the performance and comfort of occupants [17] as a central part of high-performance buildings. In this context the automation of building elements and systems became a central point of research and development due to its large potential to affect user comfort, energy consumption [14, 26] and thus also increased productivity. Despite this, the field of BAS implementation was, and still is, predominantly driven by the application of existing technologies [51] and far less by the introduction of advanced control techniques, although there are signs of shifting trends [4], predominantly due to the nature of the problem characterized by high unpredictability, complex models, noisiness of the system and non-universal solutions.

Controller type	Mathematical model necessary	Suitable for complex BAS	Adaptable (i.e. learning)	Complexity	User interaction
Conventional approaches					
on/off	No	No	No	Low	No
PID	No	Yes*	No	Low	No
Optimal, predictive and adaptive control	Yes	Yes	**	High	No
Artificial intelligence approaches					
FLC	No	Yes	No	Low	Yes
ANN	No	Yes	Yes	Medium	Yes
ANFIS	No	Yes	Yes	Medium	Yes
MPC	Yes	Yes	No	High	No
MACS	***	Yes	***	Medium	***

\*Generally poor performance in cases of non-linear and noisy systems.  
\*\*YES for adaptive control.  
\*\*\*Depending on the used control approach.

Table 1. Comparison of major advantages and drawbacks of described conventional and AI controllers.

The problem of automated control of indoor environment and ABE systems is characterized by relatively large complexity. With the integration of HVAC and lighting, the complexity of the controlled system is additionally increased and is further complicated by the unpredictability of external weather conditions and user behaviour. All this poses a challenge to the control system designer as the choice of control type determines to some degree the success of the implemented BAS. The majority of BASs are centralized and to some degree integrated with the building systems as well as the building itself. The focus was traditionally on achieving minimum energy consumption, although, as shown herein, it has shifted to user comfort with minimum possible energy consumption [10, 17]. Various building control approaches can be used in order to control the performance of a building. Although the type of controller can be arbitrary, it has been shown [15] that at least to some level the choice is influenced by the complexity of the implemented automation. In other words, it could be claimed that what is being controlled also determines the type of a controller, which can roughly be categorized into conventional and artificial intelligence (AI) approaches. The following overview of the two groups of controllers is a general introduction outlining and comparing the basic features (**Table 1**), while a more in-depth state of the art can be found in Refs. [4, 15, 17].

#### 4.1. Conventional approaches

The conventional control approaches to building automation originate primarily from industrial applications and were the first to be studied and used for BAS. The primary concern was mostly the control over energy consumption and indoor temperatures, although user comfort can also be controlled using conventional approaches. This group primarily includes on/off (i.e. thermostats) and PI (i.e. proportional-integrative) and PID (i.e. proportional-integrative-derivative) controllers [52]. The simple on/off controller is the most rudimental controller that was and still is used in indoor temperature regulation. An inherent problem of such an approach is the inevitable overshoot of the regulated value and consequential wastage of energy as well as possible user dissatisfaction. In general, such control performs poorly and is incapable of achieving optimal control of indoor environment [4], especially in situations where complex systems like daylighting and ABE elements are to be satisfactorily regulated. Nonetheless, building automation using on/off controllers can be a suitable solution when the overshoot is not a problem, like in the case of indoor temperature regulation where due to a large thermal capacity of buildings and consequential long oscillatory periods of indoor temperatures occupants can adapt to the temperatures if they are kept within reasonable margin around the set-point value (e.g.  $\pm 2$  K). An improvement over the on/off controllers can be achieved with the application of PI and PID controllers, which are closed-loop controllers with constant parameters with no direct knowledge of the system that is controlled. In general, their application in the control of industrial process is successful and widespread. In BAS applications, they perform adequately in cases of linear systems and when the controlled process is relatively stable and without extensive noise (e.g. ventilation and HVAC systems) and disturbances from the environment. Otherwise, they have been shown, like in the case of work presented by Li et al. [53], to perform relatively poorly due to problems stemming from their inability to perform in noisy and non-linear systems that are characteristic for certain



aspects of building automation (e.g. daylighting). Using PID controllers in cascade configurations and incorporating feed-forward controllers [54] can enhance their performance in BAS. Successful implementation of PID control in building automation was also achieved by hybrid systems using PID controllers in conjunction with AI control approaches [30, 55]. In the end, improper gain selections can cause PID controllers to become unstable. They are also harder to optimally set up in cases of highly dynamic systems, which can result in slower transient response and larger overshoot than in comparable AI control techniques, as it was demonstrated by Menghal and Jaya Laxmi [56].

As an alternative to PID and on/off controllers, the designers of BAS turned to the use of optimal, predictive and adaptive controllers [15, 54, 57]. These controllers are not “black-box” controllers as in the case of PID and on/off controllers. Thus, they require a mathematical model of a building, as in the case of optimal and adaptive controllers, or a model of future disturbances (e.g. the impact of solar radiation), as in the case of predictive controllers. The need for such a model presents an obstacle in the case of BAS application, as building thermal and visual behaviour models are extremely complicated and non-linear. Furthermore, each model differs from building to building due to specifics in their geometry, construction type, location, etc., practically making each controller solution unique. Although the application of mathematical model in case of BAS is achievable in some instances, like for thermal control, as it was shown by Škrjanc et al. [58], it is hard to achieve and therefore uneconomical in other cases like daylighting, as demonstrated by Logar et al. [59]. Additionally, the usage of optimal, predictive and adaptive controllers is further limited by the notion that user interaction with the controller settings is limited and that such controllers are highly susceptible to noise due to parameter estimations [15]. Despite the above-stated shortcomings, it must be stressed that experimental systems have shown very good results [60], although practical implementations are almost non-existent due to extremely complicated application [4]. More importantly, the adaptive controllers in conjunction with fuzzy logic (adaptive neural fuzzy-inference system – ANFIS) are considered as one of the most promising approaches to building automation [15].

## 4.2. Artificial intelligence approaches

The study of alternative approaches to building automation gained ground in the 1990s, as the limitations of conventional controllers for the application in BAS became evident. The focus shifted to AI approaches that include among others fuzzy logic controllers (FLCs) [55, 61], artificial neural network controllers (ANNs) [62], adaptive fuzzy neural network controllers (ANFISs) [63], model-based predictive control (MPC) [64] and multi-agent control systems (MACSs) [58]. All these control approaches have gained in popularity with researchers as well as in practical applications, because they have certain advantages over the conventional control techniques and are at least in some cases better suited for the implementation in BAS. In fact, according to a survey conducted by Shaikh et al. [4], MPC, MACS and FLC are the most frequently employed control approaches in BAS, followed by the on/off conventional control systems. The FLCs have been successfully applied to many control problems like process automation and robotics and are especially suited to control systems where there is no detailed mathematical model of the process or where the development of such a model would be



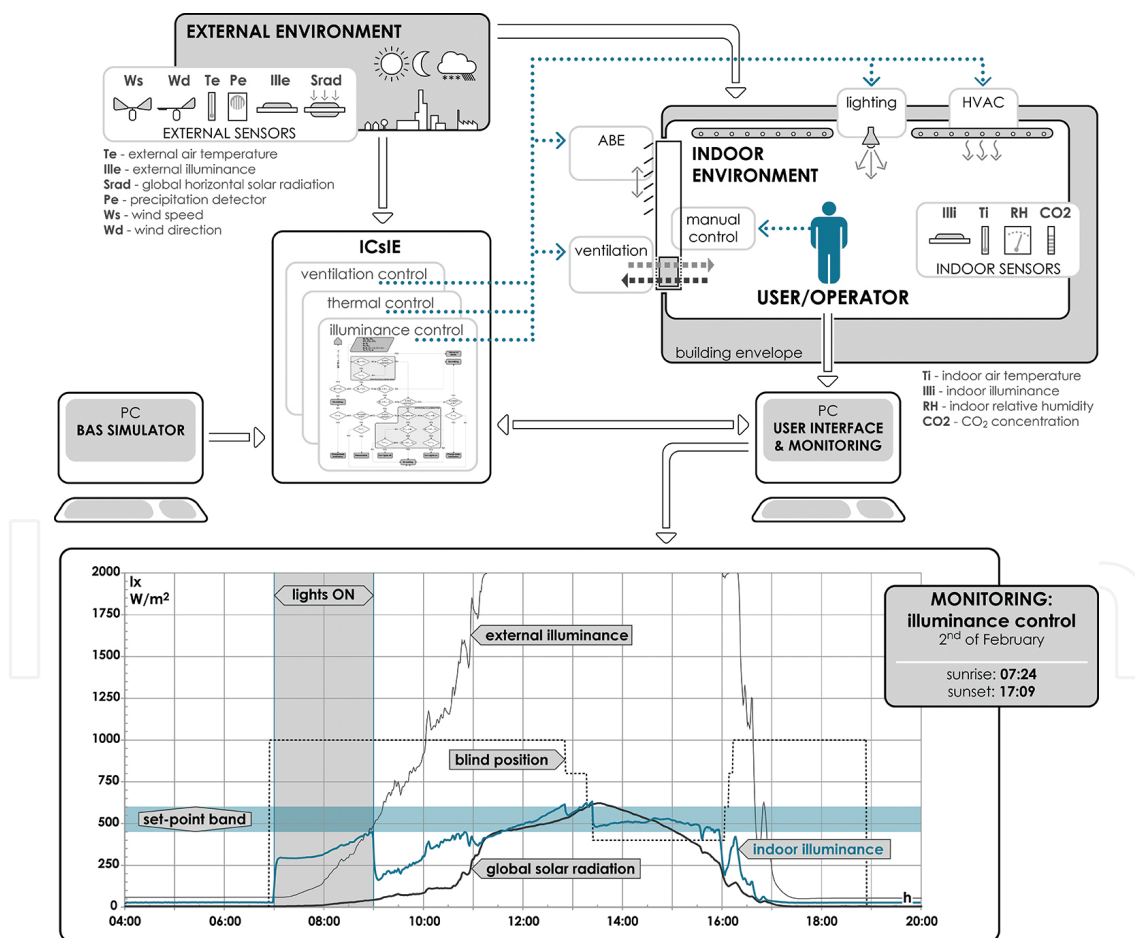
uneconomical. FLC controllers can successfully cope with imprecise data as a consequence of unknown model or imprecisions from gathered sensor data [65, 66]. Their main advantage is the use of linguistic variables with which descriptive expressions can be mathematically modelled [65] and expert knowledge can thus be used transparently and more intuitively in order to control the system actuators. Nonetheless, it has to be mentioned that the application of expert knowledge for the setting of FLC can also present a problem as such tuning process does not guarantee optimal performance due to trial and error approach and the subjectivity of the “expert”. The problem can be surpassed by the application of adaptive techniques applied in ANFIS, by computer simulation-based optimization [67] and by using tuning techniques like genetic algorithms applied by Guillemin and Molteni [68] for a self-tuning FLC-based BAS. Because fuzzy systems have the ability to map non-linear building system characteristics by applying if-then statements that pair each combination of input variables to the desired output parameter, they are suitable for the control of highly non-linear and complex functions. FLCs have also been used in hybrid systems along with conventional PID controllers [30, 55, 65], effectively utilizing the advantages of conventional and AI control. Fuzzy logic has been successfully applied to control ABE elements and HVAC systems as well as to energy management and comfort control in buildings with promising results [4, 61, 65], comparable to or outperforming conventional approaches. A study by Ulpiani et al. focused on the comparison of thermal performance of an energy-efficient building controlled by on/off, PID and FLC-based BAS and demonstrated that FLC outperformed both conventional techniques by achieving up to 67% lower energy consumption with simultaneous higher average thermal comfort index [69].

In a similar manner to FLC, ANN and ANFIS, controllers can be used for building automation as they are based on an artificial system of neurons mimicking the human brain and its learning abilities [62]. The main advantage of ANN controllers is the possibility of the controller to perform self-tuning and therefore learn and adapt to changes in the building environment without expert knowledge from a system operator. Such tuning process can be executed if and when sufficient data about controlled system behaviour are available and the controller is trained by a training algorithm [70]. A generic scheme of an ANN model is composed of an input layer and a hidden layer, both with multiple neurons and a single-neuron output layer. In order to achieve adequate functioning of the ANN controller, usually a training phase is conducted, which is used to adopt a learning algorithm with pre-prepared data sets [63, 70]. For the ANFIS controllers, the ANN structure utilizing artificial neurons is introduced to the fuzzy logic control system where the nodes in the hidden layer of the ANN perform the purpose of membership functions and fuzzy rules. Another method to building automation that has gained in popularity in recent decades is the MPC which utilizes a model of a controlled system to predict future development. Therefore, the control actions of an MPC BAS are gained by optimizing the objective functions in regard to predicted future functioning of the system [64]. This is a great advantage in automation of buildings where thermal inertia, unpredictability in occupancy schedules, variations in energy prices and weather forecasts can be taken into account to perform an optimization in accordance with predicted future developments. Although such control approach is based on the principles of conventional control techniques (i.e. predictive control), it is listed in the literature mostly under AI approaches (e.g.

[4]) and is usually used in conjunction with AI controllers. While MPC controllers have been proven to outperform other methods, the computational costs and the complexity of the building model can be considerable and therefore impose a limitation to the application of MPC, as highlighted by Afram and Janabi-Sharifi [71]. However, the benefits in potential energy savings and enhanced indoor comfort can be substantial. Because BASs have grown in complexity, the resulting controllers can become extremely complex, which results in a system that is inflexible and hard to design as well as to modify. To solve this problem, MACS can be used by splitting the whole problem of the indoor control in buildings into smaller manageable controller-agents [15]. These are used to perform a certain operation and are then guided by the coordinator-agent to the optimal solution. A MACS-based BAS can utilize multiple control approaches (e.g. FLC, ANN) to solve specific control tasks [58, 72]. These are coordinated and optimized by a set of rules that can be actively changed through a learning process.

### 4.3. BMS application example

Integral control system of indoor environment (ICSIE) is an experimental BAS implemented in an occupied office of the main building of the UL FGG. The office has two work places, a



**Figure 4.** Conceptual representation of the ICSIE structure, presenting the sensor array, control level, user interface, utilized actuators and monitoring of performance. The diagram in the bottom of the figure presents the performance of the visual control loop on a typical late winter day.

floor area of approximately 40 m<sup>2</sup> (i.e. occupancy of 0.05 persons/m<sup>2</sup>) and a large western-oriented window with 11.40 m<sup>2</sup> of glazing. The transparent part of the external envelope of the office is a typical double-glazed window with aluminium frames segmented into six individual units. Each segment is equipped with external motorized louvres that enable the adaptive changing of optical characteristics of the transparent envelope (i.e. shading and daylight regulation). One of the six window segments can be opened and is therefore motorized and utilized for automated natural ventilation and nighttime cooling of the office. In addition to the ABE elements of the building envelope, the office is equipped with a heating and cooling system comprising of 12 ceiling-mounted low-temperature radiative panels connected to the building's heating and cooling plant. When daylight is insufficient, the office can be illuminated by six ceiling-suspended, typical office fluorescent luminaires. The conceptual diagram of the ICsIE with the sensors, process level, supervision and data acquisition level as well as with the installed actuators is presented in **Figure 4**. The installed sensors are used to monitor indoor (i.e. temperature, illuminance, relative humidity and CO<sub>2</sub> concentration) and exterior (i.e. direct solar radiation, illuminance, temperature, wind speed and direction and precipitation) environmental parameters necessary for the control of the installed actuators in order to regulate indoor thermal, visual and olfactory sub-environment parameters. In the case of visual sub-environment, the controlled parameters are the working plane horizontal illuminance and the vertical eye level illuminance. The vertical illuminance is used to measure the potential non-visual effects on the occupants [24] as well as an indicator of possible glare which can occur during the evening hours because of the low sun elevation. For the control and assessment of thermal conditions in the office, a simple measurement of the internal dry bulb temperature is used in connection to the control of solar heat gains controlled by the external louvres, while for the ventilation of the office, the CO<sub>2</sub> concentration is the decisive parameter.

The BAS is designed around an industrial programmable controller that executes the necessary operations according to the desired set points inputted by the user/operator through dedicated interface software installed on a PC (**Figure 4**). The controller is divided into three control loops: the illuminance, thermal and ventilation loop. Although the three loops are treated individually, the interaction between them is regulated according to the priority set by the operator. The system can either be in thermal or visual priority. In either case, the IAQ is always a priority action, meaning that the ventilation is regulated according to the CO<sub>2</sub> concentration in the office. Switching between thermal and visual priority is not automated as there is no occupant detection system installed in the ICsIE. Therefore, the system operator defines the state of the system either manually or by defining the schedules that determine the operation of the systems. Typically, this means that during office hours the system is in visual priority, while during weekends, holidays and during nighttime, it switches to thermal priority. In the end this means that during visual priority the louvres are not available as an actuator to the thermal regulation loop, while in the opposite situation, the indoor illuminance is ignored. All control loops are designed similarly but with different levels of complexity, as illuminance and thermal control algorithms are far more complex than the ventilation one [30]. Hierarchically speaking, in all three control loops, activation of the ABE elements has priority over the HVAC and lighting system, in order to utilize the bioclimatic potential of the building before using mechanical or electrical systems. The user interface and the monitoring of BMS functioning

are executed in the SCADA Factory Link (Supervisory Control and Data Acquisition and Human Machine Interface) environment, which enables the control over the functioning of the system as well as the storage and analysis of the recorded data and corresponding system responses.

4.3.1. Controller structure and setup

The ICsIE is executed as a hybrid control system combining conventional and AI control approaches. A conventional PI controller is used in a cascade configuration with the FLC controller in case of visual and thermal control loop, while the ventilation is controlled only by a simple on/off controller. Such configuration was proven successful in a pilot experimental system executed at UL FGG [55]. The FLCs of the ICsIE were developed using the IDR BLOK [73] software package advanced process control algorithms for fuzzy logic controllers, applying a fuzzy-inference system in the Takagi-Sugeno form that returns a crisp value as an output. For the visual control FLC, the input variables are the set-point value ( $ST_{iii}$ ) and the error variable ( $ER_i$ ), which is determined as a difference between measured value of indoor illuminance and the  $ST_{iii}$  set by the operator. The  $ST_{iii}$  is defined in the range between 0 and 1400, while the  $ER_i$  is set between  $-300$  and  $300$ , where 0 corresponds to measured illuminance being equal to the  $ST_{iii}$ . The output of the corresponding fuzzy decision matrix is defined in the range between 0 and 100, where the value of 100 corresponds to completely closed and value 0 to retracted louvres. The output crisp value of the FLC is communicated to the auxiliary PI controller that executes the necessary modifications of actuators in respect to their current position. The possible actions executed by the ICsIE are the retraction or extension of louvres, change of blade inclination in  $30^\circ$  increments from horizontal (i.e. blades open  $-0^\circ$ ) to vertical (i.e. blades closed  $-90^\circ$ ) position, or the activation of lights. The number of possible louver positions is determined by the responsiveness of the actuator, where the actuator motor

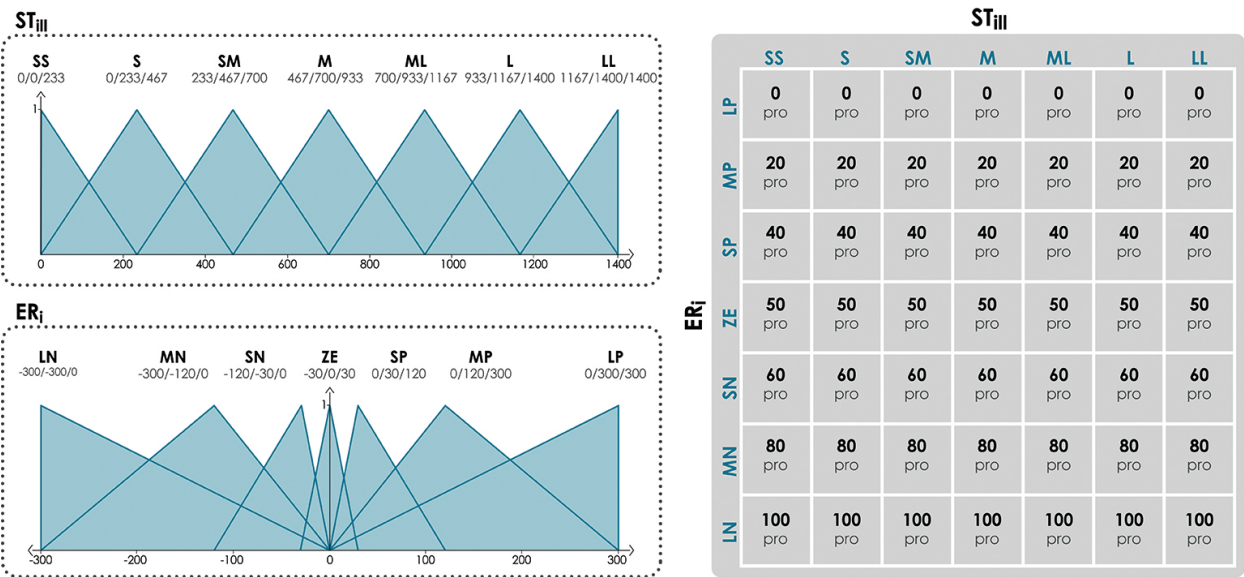
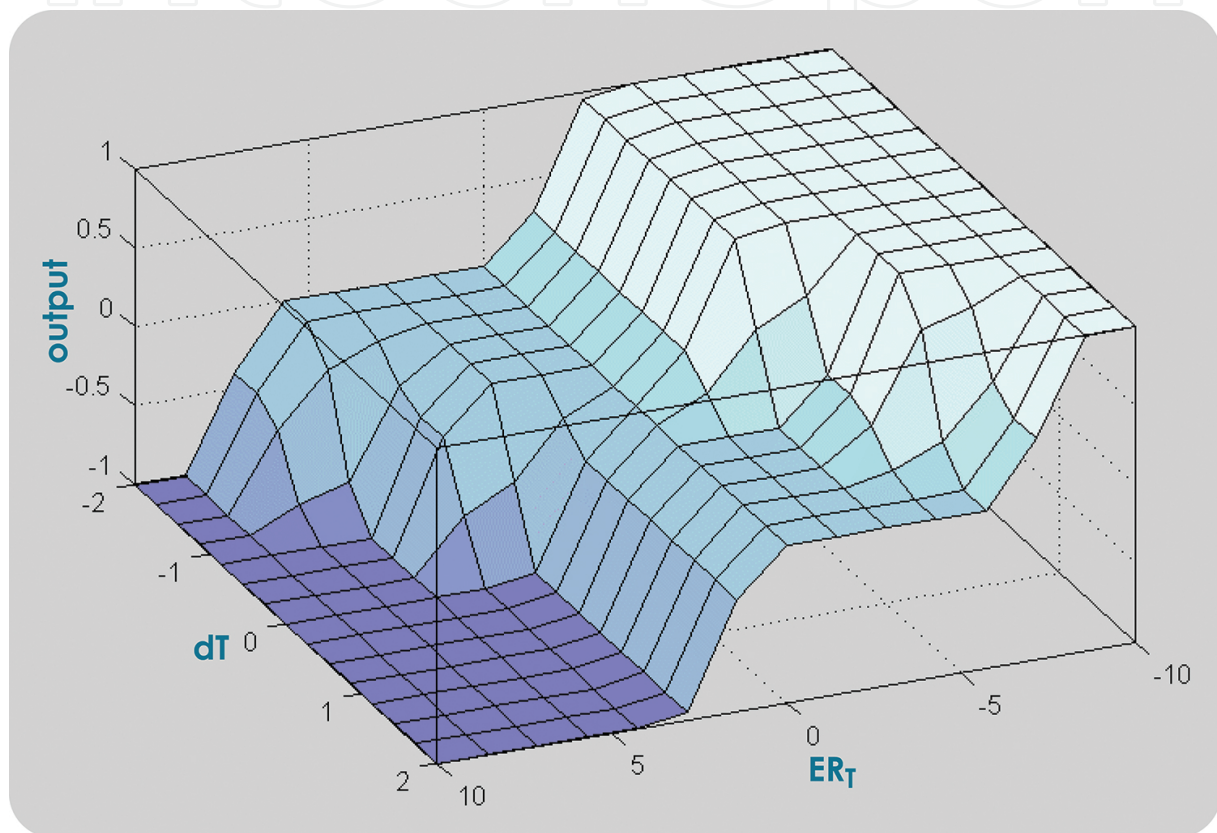


Figure 5. Membership functions  $ER_i$  and  $ST_{iii}$  and the corresponding decision matrix of the visual control FLC of the ICsIE.



enables the setting of the blade inclination only in the completely extended state. Although the blades of the shading device can be set at an arbitrary angle, the  $30^\circ$  increment was chosen as a compromise between flexibility and accuracy of the mechanical drive of the louvres. If the  $ST_{ill}$  is not reached even if all of the louvres are retracted, the system activates artificial illumination using a simple on/off controller. The lights can be activated only if all of the louvres are retracted, the system is in visual priority and the indoor measured illuminance is lower than  $ST_{ill}$ . The membership functions and the decision matrix of the visual FLC are presented in **Figure 5**.



**Figure 6.** The input-output characteristics of the thermal control FLC of the ICsIE.

Similar structure of FLC as in visual control is also implemented in the case of thermal control loop, where the two input variables to the fuzzy controller are the indoor temperature derivative ( $dT$ ) and the error ( $ER_T$ ) determined by the difference between set point ( $ST_T$ ) and measured indoor dry bulb temperature. As in the case of visual control, the Takagi-Sugeno fuzzy-inference system was used applying triangular membership functions of the input variables. The if-then rules of the decision matrix are determined using AND logical operator, while for the de-fuzzification of the output variable, the weighted average is used. The input-output characteristic of the thermal controller is presented in **Figure 6**, where it can be seen that the output values are defined between  $-1$  and  $1$ . The output value of  $0$  means that the office is in “free run”, meaning that neither heating nor cooling is needed. If the output value



is  $-1$ , the ICsIE is in cooling mode, while in case of  $1$ , the system is in heating mode. In both cases firstly, the possibility of using passive measures (i.e. shading and natural ventilation) is checked. The output actions are the movement of louvres (if the system is in thermal priority) and activation of active heating or cooling via the ceiling-mounted radiative panels. In case of cooling, an additional output is available in the form of convective cooling using natural ventilation, which is enabled during times when the external temperatures are lower than indoor  $ST_T$  value (e.g. during nighttime). Before activating active heating or cooling, the system has to determine whether the heating or cooling plant is active. This is determined by activating the heating/cooling circulation pump and measuring the cooling or heating medium temperature for a short period of time (i.e. 5 min). If the medium is of an appropriate temperature, active cooling or heating can be used. In the opposite case, the BAS disables the circulation pump in order to prevent damage. Therefore, it has to rely solely on the passive measures. The implementation of the described protocol was necessary as there is no communication between heating and cooling plant of UL FGG building and the ICsIE, since the plant is controlled manually by the building caretaker. Additionally, the operator can override the system and manually set whether the ICsIE is in cooling or heating mode. This can be done on-line for each day or it can be determined through schedules, where a winter (i.e. heating) or summer (i.e. cooling) season can be defined, while during the transitional period (i.e. spring and autumn), the system decides whether heating or cooling is necessary. The user demands regarding indoor thermal (i.e. indoor temperature) and visual (i.e. indoor work plane horizontal illuminance) comfort parameters are not crisp values, but rather a range of values around a set point that define the acceptable deviation around the target value. Therefore, in the ICsIE, the operator defines a range of values that are acceptable (e.g.  $ST_{ill} - 50$  lx and  $ST_{ill} + 100$  lx), and if the indoor measured value is in the defined dead band, the system does not modify the actuator states. This limits the number of actuator movements that can be potentially annoying to the occupants and it reflects the comfort definitions in the standards and regulations [36, 44]. In contrast to the visual and thermal control, the ventilation controller of the ICsIE is a simple on/off controller designed to open or close the automated window in correlation to a maximum allowed  $CO_2$  concentration ( $ST_{CO_2}$ ). The window is opened when the  $ST_{CO_2}$  value (e.g. 1000 ppm) is reached and it closes when the indoor concentration is reduced by a defined value  $d_{CO_2}$  (e.g. 200 ppm). As already mentioned, the ventilation control is always in priority mode and is suspended only in case of detected precipitation in order to prevent rain and snow from entering the building.

The visual control of the ICsIE was developed using experiments and expert knowledge [55]. Although there are better and more objective methods to tune the FLC [15], the trial and error approach was chosen as there were substantial data available on the functioning and setup of a FLC for a previous BAS system developed at UL FGG and presented by Trobec Lah et al. [66] and Kristl et al. [55]. The final implemented version of the visual FLC configuration was based on consecutive testing in real-time conditions of selected 12 controller setups from the previous experimental BAS controller. The functioning of each was evaluated and compared and the best performing controller was then fine-tuned and used as an ICsIE visual FLC. In contrast, the configuration of the thermal FLC was determined through simulations on a mathematical model based on energy balance equations simulated in the Matlab/Simulink environment. The

thermal model presented and developed by Škrjanc et al. [65] was used to define the thermal FLC setup using trial and error method supported by data gathered from the aforementioned experimental BAS system. Such approach was relatively time consuming, especially in the case of illuminance control, where trial and error tests were conducted in real time using real BAS. Thus, the need for a quicker and easier way to set the FLC rules was identified. Therefore, a BMS simulator (**Figure 4**) was developed mirroring the functioning of the control system as well as the thermal and visual response of the controlled indoor environment. The simulator was developed using Matlab/Simulink and Dymola/Modelica environments and enables the operator to quickly test different controller alternatives using real weather input files. Thermal simulations integrated into the simulator are based on the abovementioned model developed by Škrjanc et al., while the visual model was developed as a black-box model on the basis of data gathered through the functioning of the ICsIE as presented by Tomažič et al. [67] and Logar et al. [59]. Although the simulator is not vital to the performance of the ICsIE, it is still a useful tool as it enables fast testing and tuning of new FLC setups.

#### 4.3.2. Performance of the ICsIE

The ICsIE has been in almost continuous operation since 2009. Although at the beginning of the operation, there were certain problems with the functioning of the actuators, the overall performance can be described as successful. The ICsIE was able to fulfil its primary objective in controlling the indoor user comfort parameters in desirable limits and consequentially improving the comfort levels in the office. In case of visual environment of the office, the system was able to regulate the indoor illuminance by controlling the shading devices and therefore daylight penetration. If external conditions were favorable (i.e. adequate levels of external illuminance), the indoor daylight conditions were successfully managed only by relatively few movements of the shading device (typically less than five movements per hour). An example of indoor visual environment control can be seen in **Figure 4**, where indoor illuminance control on the 2<sup>nd</sup> of February is presented. If the time period from 11:30 to 16:00 is observed, it can be seen that the ICsIE was capable of guiding the indoor work plane illuminance in the desired set-point band defined in the range from 450 to 600 lx. When the upper limit of the set-point band was reached, the system extended a louvre. During the considered day, only three louvres were necessary in order to control the indoor illuminance (**Figure 4**). In the evening (after 16:00), when the sun was setting, the external illuminance was quickly decreasing and with it also the indoor illuminance. The ICsIE tried to compensate this by successively retracting the louvres, but this was inadequate. Lights were not activated as the system was already in the off-work mode when the automated activation of lights was disabled. During morning hours, the system switched from thermal to visual priority at 7:00. A few minutes prior to that, all louvres were retracted, thus enabling daylighting. Nonetheless, during the morning hours, the external illuminance was too low to provide adequate daylighting and consequentially the ICsIE activated the office lights, which were on, until the occupants manually disabled them at 9:00 (**Figure 4**). In the instance of thermal regulation, the ICsIE was also able to guide indoor temperatures around the defined  $ST_T$  with acceptable typical deviations not exceeding  $\pm 1.5$  K. On the other hand, the indoor thermal comfort was still inadequate during certain days of the cooling season, when in case of high external temperatures and high levels of solar radiation

during afternoon the office overheated despite shading and active cooling. The reason for inadequate thermal conditions is not in the functioning of the BAS but in the building itself. The office in question is oriented to the west and therefore exposed to high levels of solar radiation during evening. Additionally, the external building envelope has high thermal transmission (external wall U value is  $1.29 \text{ W/m}^2\text{K}$ ; window U value is  $2.9 \text{ W/m}^2\text{K}$ ) and is therefore susceptible to overheating. The effectiveness of passive cooling with nighttime ventilation was also demonstrated, as 4–5 K reduction in temperatures was achievable with its use. The effect of the ICsIE on the reduction in energy use of the office cannot be objectively evaluated because there is no comparable reference office in the UL FGG building to compare its performance. Despite this it can be at least speculated, in accordance with the work conducted by Firlag et al. [49], Ulpiani et al. [69] and the EN 15232 [12] standard, that even some basic automatization of building performance and systems results in measurable energy savings.

## 5. Conclusion

The challenges posed to the building industry by the need to reduce energy consumption and GHG emissions of buildings, while at the same time striving to increase occupancy comfort, are extremely complex. They cannot be solved only by conventional architectural measures, especially in cases of high-performance buildings where high standards of user comfort are demanded with simultaneous energy efficiency. A viable solution to increase the performance of future buildings is the application of BAS-controlled ABE. The potential of BAS for increasing energy efficiency of buildings was also recognized by the EU in the EPBD-r [7]. Additionally, Firlag et al. [49] demonstrated through simulations the influence of BAS on energy performance, where it was shown that manual control of window shades has almost no impact on the reduction in energy consumption, while even the most rudimental type of automated controller can achieve a reduction in a range from 11 to 13%. Although the application of AI control methods in building automation does not guarantee better performance in comparison to conventional approaches, it can still be concluded from the extensive body of work presented in the paper that AI techniques are at least better suited, if not a priori more efficient. Comparison between FLC and conventional control in the example of energy-efficient building, conducted by Ulpiani et al. [69], demonstrated that FLC-based BAS can outperform other controllers with 31.4–67.8% lower energy consumption. Through the paper the importance of occupant comfort was highlighted and supported by overview of the subject of indoor comfort and its influence on overall performance of the building and its occupants. Even though the influence of indoor comfort can be hard to evaluate and even harder to automatically control, especially in the case of highly changeable parameters such as daylighting, an example of such BAS was presented through the case of the ICsIE developed at UL FGG. The presented system was focused on the control of indoor thermal-visual and air quality conditions of an occupied office. On the level of applied control techniques, a combination of FLC and PI controllers was used, while for natural ventilation control, a simple on/off controller was applied. The indoor temperature, horizontal illuminance and  $\text{CO}_2$  concentration were

used as controlled variables, while other comfort parameters (e.g. mean radiant temperature, glare) were omitted due to the complexity issues. The results presented confirmed the ability of the system to satisfactorily control the indoor environmental conditions. Especially in the case of the illuminance control, the executed controller was successful as it was capable to control the indoor daylighting with relatively few actuator movements and it reduced the activation of lights, thus optimizing daylight usage [24]. The main shortcoming of the ICsIE identified through its design and testing is the process of controller tuning. Especially in the case of FLC setup, the applied trial and error method was time consuming, and even though substantial data on the functioning of a similar system [55, 65, 66] were available, the process was lengthy and prone to mistakes. Therefore, a more objective and faster process would enable easier adaptability of the system to other situations and buildings.

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