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# Review of Intelligent Control Systems for Natural Ventilation as Passive Cooling Strategy for UK Buildings and Similar Climatic Conditions

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**Abstract:** Natural ventilation is gaining more attention from architects and engineers as an alternative way of cooling and ventilating indoor spaces. Based on building types, it could save between 13 and 40% of the building cooling energy use. However, this needs to be implemented and operated with a well-designed and integrated control system to avoid triggering discomfort for occupants. This paper seeks to review, discuss, and contribute to existing knowledge on the application of control systems and optimisation theories of naturally ventilated buildings to produce the best performance. The study finally presents an outstanding theoretical context and practical implementation for researchers seeking to explore the use of intelligent controls for optimal output in the pursuit to help solve intricate control problems in the building industry and suggests advanced control systems such as fuzzy logic control as an effective control strategy for an integrated control of ventilation, heating and cooling systems.

## 1. Introduction

The UK government has targeted cutting emissions by at least 80% below 1990 levels by 2050 without sacrificing the economic growth [1]. In 2019, this was increased to a net zero target by 2050. Significant reductions are expected in the power and transport sectors, but the building sector also needs to be completely decarbonised to meet this target. The building stocks is responsible for 19% of annual emissions in the UK where energy used by heating, ventilation, and air-conditioning (HVAC) systems account for the biggest chunk of energy in buildings [2]. Improving the U-values of external walls by adding internal/external insulations is one of the most effective refurbishment strategies that have been incentivised by several governmental schemes, but these schemes face significant practical limitations and must be combined with other measures [3]. The currently planned level of refurbishment in the existing stock will reduce the energy demand of buildings, but they still fall far short of the carbon savings that is required in both domestic and non-domestic sectors. Furthermore, anticipated savings in heating demand will be increasingly offset by higher cooling demand. One study has been conducted on the stock modelling of air conditioning (AC) systems in the UK, and it has estimated that the market penetration of an AC system is likely to increase for the next two decades. The intensity of electricity consumption for cooling existing offices is estimated to be in the range of 31 to 41 kWh/m$^2$·pa [4]. Natural ventilation or hybrid ventilation systems are alternative design options that could reduce the cooling demand of buildings through a ventilative cooling mechanism.

The importance of natural ventilation in the future of sustainable buildings is becoming a well-known fact among the designers and academics. Guidelines and handbooks such

as natural ventilation in buildings; a design handbook, CIBSE AM10-Natural ventilation in non-domestic buildings; and CIBSE AM13-Mixed-mode ventilation [5–7] have been developed in the past few decades to standardise the design procedure and determine the most effective design features for different applications and climates. Despite this advancement in knowledge generation and standardisation of Natural Ventilation (NV) design, its application has been largely limited to residential buildings, and it has not been broadly adopted as the primary ventilation or cooling strategy in non-domestic buildings. Security, control and reliability [8], overheating risk [9], air quality, and noise issues in urban areas [10] are some of the known challenges of NV operations in commercial buildings. The automatic operation of NV in buildings using actuators on windows, dampers, doors, and roof lights is an evolving design feature that could tackle some of these issues. It could contribute towards the further utilisation of natural ventilation, especially in non-domestic buildings. A reported case of motorised vent in a school theatre and a case of automated windows in the atrium of a headquarter office building was studied.

The study showed that infiltration losses caused by excessive crack lengths in motorised dampers and inadequate sealing to high-level window vents resulted in an undesirable rise in heating energy usage at the school. When the workplace temperature rises over 23 degrees Celsius in the building, the automated systems open the atrium windows, sucking air in over the exposed ceilings. When the air temperature in any zone drops below 18 °C, the windows in that area are closed and then reopened when the temperature increases over 20 °C. During the day, all automatic windows are closed at a speed of 10 m/s, and at night, they are closed at a speed of 20 m/s.

The implementation of automatic NV was relatively successful in the above-mentioned cases, although infiltration loss due to poor sealing was reported as the main issue during operation. However, there also have been reports of ineffective implementation of these automated control designs where building managers had to switch off the automatic control system and resort to manual operation of windows and openings. Fundamental design shortcomings, control complexity, lack of coordination between NV and HVAC systems, and improper commissioning and fine-tuning are known to be the main sources of reported issues in operation [11,12].

There are opportunities to improve the effectiveness of automatic NV and NV cooling designs in buildings by adopting intelligent control systems. Several intelligent control systems such as the expert systems, generic algorithm, and artificial neural network were reviewed, and fuzzy logic presents a more effective control of NV and HVAC systems to avoid any possible increase in energy consumption of indoor equipments due to open windows or vents. This is particularly important in transitional seasons when the operation of natural ventilation and heating systems can overlap. In addition, optimisation algorithms such as genetic algorithm or neural network could be implemented for an optimised control of such systems to adjust the opening level and heating/cooling outputs in order to maintain acceptable air quality and comfort level with the least energy consumption. Artificial intelligence techniques could also be utilised to fine tune the operational settings of an integrated control system of NV and HVAC systems to prioritise energy or comfort depending on building use. This review aims to analyse the reported academic research in the literature on the intelligent control of natural ventilation as a passive cooling strategy for buildings. The paper also recommends the most effective control theories to maximise its benefits and overcome the issues around implementation.

Section 3 further discusses the cited paper in the literature around the proposed control theories for natural ventilation, stating its potentials and benefits, while Section 4 discusses the intelligent systems and control, with a focus on fuzzy logic. This order of sections has been chosen to emphasise the importance of both natural ventilation design and various control strategies for a successful implementation of NV in buildings of different types and climates.

## 2. Methodology

The analysis of the literature is regarded as a structured means to gather and synthesise previous research [13]. This study adopts a systematic approach as it identifies and critically appraises relevant research, as well as answers the question of the most effective intelligent control system after collecting and analysing data from said research. In identifying sources for this literature, multiple databases were adopted. The use of journals, books, and conference proceedings was explored for this study to extend the extraction of relevant literature. On Google Scholar, Research Gate, and Scopus, the keywords "Intelligent Control System," "Fuzzy Logic Control," "Natural Ventilation," and "Ventilative Cooling" were searched. The year of publication was not restricted in order to allow many publications. The initial search yielded a large number of publications across all the platforms used. Only articles published in the fields of environmental research, engineering, and control systems were used to refine the extraction due to their appropriateness and relevance in consideration of the purpose of this literature review. Abstracts were read first, and selections were made before reading the full text. Studies that examine the practical application of a specific intelligent control system (fuzzy logic control) were the focus. In this literature review, the validity and credibility of all sources is considered on the basis of conformity with the research intent and credentials of the author of the sources, along with a few from previous decades to introduce fundamental principles that remain until now. Most of the articles reviewed, including case studies, focused on the UK, following its goals to cut emissions by at least 80% by 2050. However, these control strategies can be adopted under any condition and all climatic features.

## 3. Natural Ventilation Design

### 3.1. Natural Ventilation Design Features

Natural ventilation design features are mostly passive elements that would be considered during the architectural design of a building in order to bring outside air into indoor space through openings. The driving force behind this air movement through the building could be wind pressure or a buoyancy effect due to temperature difference [10]. When wind (wind-driven NV) or buoyant forces (stack-driven NV) operate on one or more openings in the building structure, natural ventilation (NV) arises [10]. In a wind-driven natural ventilation, positive pressure from the windward side of the building pushes the air through openings mainly towards the leeward side, which has a negative pressure. This circumstance occurs mostly in double-sided or cross-ventilation where there are openings on both the windward and leeward sides of building. However, most of the buildings are partitioned into core and perimeter zones, and each zone has one or two operable windows only on one side of the building. In a single-sided/double openings indoor space, air mainly comes into the space through one of the windows with slightly higher pressure, and it leaves through the second window. Similarly, but with a slight difference, in a single-sided/single-opening indoor space, air is pushed into the space from one part of the open window, and it leaves from another part of it. The natural airflow movements in a single-sided/single opening office space in typical winter and summer conditions are illustrated in Figure 1. It is clear to see that cooler air comes into the space from the lower part of the open window, picks up the heat from occupants, lighting, equipment, etc., and then warmer air leaves the space from the upper part of the window. This air movement could be utilised for ventilation in winter and for both ventilation and cooling in summer.
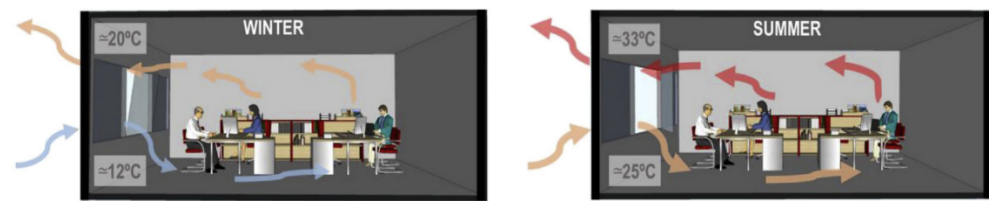
**Figure 1.** Single-sided natural ventilation of an office building in winter and summer [10].

In a buoyancy-driven ventilation design, warmer air moves upward because of the lower density. This stack effect could drive cooler air from outside to inside where it moves to the upper level of buildings as it heats up. The predicted temperature distribution based on CFD simulation results in a naturally ventilated multi-storey building is illustrated in Figure 3. Thermal stratification could be easily seen in this building at De Montfort University in Leicester where there is a 3 °C temperature difference between different floors. In reality, for most cases of natural ventilation, a combination of buoyancy and wind-driven ventilation is experienced. An example of such NV design in the Houghton Hall Office Building in Luton is shown in Figure 2. Upper-level vents in this building are open only from spring until autumn to utilise the stack effect for air movement, while in winter, they are closed. An assisted fan accelerates air movement when the atrium temperature is above 26 °C and the louvres are closed when rain or high wind is detected. It is noteworthy to mention that an aerodynamic effect might also need to be investigated as part of the design process, especially for tall buildings [14].
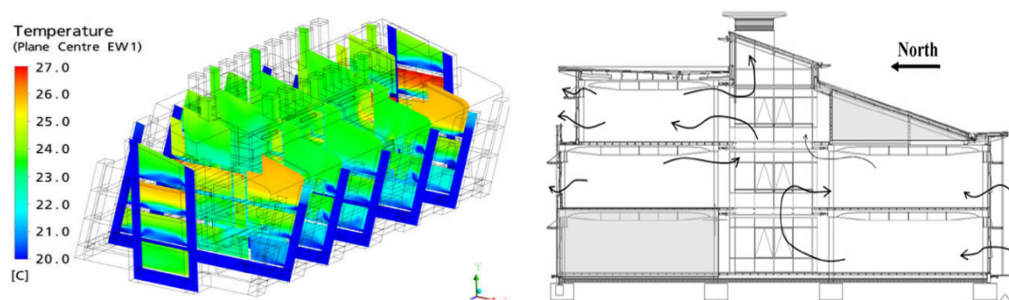


**Figure 2.** Buoyancy-driven NV design, (**Left**): Queens building at De Montfort University, Leicester, UK [15], (**Right**): Houghton Hall Office Building, Luton, UK [16,17].

The potential of NV in reduction of carbon emission in buildings greatly depends on climate and building types. Chen, Tong, and Malkawi [18] estimated NV potentials of 1854 locations around the world, and they found subtropical and Mediterranean climates as the most favourable places for NV designs. They also concluded that there are potentials for NV design with a night purge strategy for the desert climate of the Middle East with high diurnal temperature. For the temperate oceanic climate of the UK, they estimated an average NV hours of 2000 h per year, which shows it requires the right control strategy for an effective operation in parallel to active systems in buildings. Regarding building types, NV could be an ideal choice for residential buildings where occupants could adjust their clothing level depending on season, and precise control of indoor temperature is not that important. With increasing environmental awareness, designers are putting more effort into the implementation of NV in non-domestic buildings such as educational, office, and healthcare buildings. Kolokotroni, Perera, Azzi, and Virk [19] analysed the monitored internal/external data in naturally ventilated educational buildings, and the results have shown that natural ventilation coupled with exposed thermal mass could provide a comfortable condition inside the building. Similarly, several successful cases of naturally ventilated office buildings with an adequate comfort level for occupants have been reported in the literature [20–22]. Yun and Steemers [23] investigated the occupants' response in an office building in Cambridge, UK with and without night ventilation.

They suggested insect screens and tilted external louvres in front of openable windows to address security concerns and provide protection from heavy rain. In another study, Lomas and Ji [9] looked into the resilience of naturally ventilated buildings in NHS (National Health Services) buildings in the UK regarding their adaptation to climate change. It was concluded that although naturally ventilated buildings have less $CO_2$ emissions compared to their mechanically ventilated counterparts, the anticipated risk of overheating in NV designs is of more concern in healthcare buildings. Atkinson and the World Health Organization [24] developed a guideline for the design of natural ventilation for infection control in healthcare settings. Nevertheless, a widespread application of NV in healthcare buildings requires an advanced control of openings due to the need for the precise control of indoor conditions for patients.

The purpose of NV design in buildings is highly dependent on the climate types, and appropriate design features and control strategies need to be selected accordingly to improve the effectiveness of this feature. The ventilated cooling is an important aspect of NV in the tropical climates where temperature and humidity is high all year around. The generated air movement in this climate is usually enhanced with ceiling/stand fans to further reduce the time of the year when active cooling is needed. In addition, windows/vents need to be air tightly closed when an AC system is switched ON to avoid any waste of energy. Several studies in the literature demonstrated the feasibility of NV and hybrid designs in non-domestic buildings located in the tropical and subtropical cities in Thailand, Malaysia, Brazil, and South China [15,25–27]. On the other hand, in the temperate climates, NV is operational for a limited time during the year, usually from spring to autumn. The precise control of openings based on indoor/outdoor condition is necessary to avoid any discomfort for occupants or increased heating load. Gratia, Bruyère, and De Herde [28] conducted building simulations to investigate the performance of natural ventilation in buildings for the temperate climate of Western Europe. Ventilated cooling was found to be an effective design in this climate where architectural design plays an important role.

### 3.2. Appraisal of the Benefits of Natural Ventilation

There are potentials for natural ventilation (pressure differences generated by wind or buoyancy forces acting on one or more openings in the building) and hybrid ventilation (a ventilation system that alternates between natural and mechanical ventilation systems depending on the time of day or season of the year; it is also known as 'mix-mode ventilation') designs to be applied widely for the ventilation and cooling of indoor spaces for the range of building use in various climates. The benefit of this implementation is a reduction of building carbon emissions and energy saving compared to using mechanical ventilation (mechanical ventilation systems operate by forcing air into a building using fans, either positively or negatively) or AC systems. There are many studies in the literature that have attempted to estimate the energy-saving potentials of NV and HV designs using measurements or simulation-based approaches. The details of some of these reported investigations with their level of energy savings are listed in Table 1. The estimated energy saving ranges between 13 and 40% depending on assumptions made for the base case. Occupants' satisfaction has not been compromised in any of the reported studies, and even in some cases, comfort level has improved due to the more precise control of environmental conditions. The adopted design type and control strategies seem to be the main point of difference among these studies. It could be suggested that expected energy saving is more promising for integrated control of HVAC and NV with coordination of their operations.

**Table 1.** Reported studies in the literature on application of natural ventilation design in buildings.

| Building Type and Approach | Climate Type | Design Type and Control Strategy | Energy Consumption | Comfort Level | Reported Study |
|---|---|---|---|---|---|
| Numerical simulation and thermal modelling in a residential building | Hot-and-humid (Miami) and warm-and-mild (Los Angeles) | Reinforcement learning in an integrated NV and HVAC design | 13–23% lower compared to rule-based control strategy | 62–80% better compared to rule-based control strategy | [29] |
| Numerical simulation and experimental setup in a laboratory | Mediterranean climate of Crete, Greece. | Fuzzy logic control with genetic algorithm optimiser in an integrated NV, HVAC, and lighting design | 20.5% energy saving for heating and cooling, 66% energy saving for lighting | Occupants' discomfort has diminished | [30] |
| Mathematical formulation and thermal modelling of an architectural studio | Mediterranean climate of Izmir, Turkey. | Differential evolution optimisation for operation of NV design | 40% reduction in heating energy consumption | Acceptable comfort level maintained | [31] |
| Building simulation of a single storey house | Tropical climate of Kuala Lumpur, Malaysia | Model guide for comparison method for an integrated control of NV and HVAC | 31.6% less than typical HVAC system | Acceptable comfort level achieved | [32] |
| Thermal modelling of a three-storeys office building | Mediterranean climate of Istanbul and temperate climate of Stuttgart and Turin | Coupled air flow network and dynamic modelling | 13–22 kWh/m$^2$·a in Stuttgart, 32–36 kWh/m$^2$·a in Turin and 38–44 kWh/m$^2$·a in Istanbul | Comfort level has improved | [33] |

The benefits of NV and HV designs are not only limited to energy saving and reduction of building $CO_2$ footprints. Using natural means of cooling and ventilation in building over mechanical systems could enhance the thermal tolerance of occupants [10]. This perception of occupants is identified and quantified in adaptive thermal comfort models presented in ASHRAE 55 [34] and CIBSE TM52 [35] guides. Hence, the comfort perception of occupants in naturally ventilated buildings should be evaluated based on the above-mentioned adaptive comfort models rather than conventional PMV (Predicted Mean Vote)-based models. The concept of adaptive comfort for different climate types requires further attention and research. This plays a key role in the true understanding of benefits of NV over active cooling systems in buildings, which lies in the overall well-being of occupants beyond simple comfort indicators such as indoor temperature. The sense of comfort that is achieved through NV could be both more efficient and healthier than a refrigeration cooling system since the human body gets exposed to outside air directly and finds its thermal balance in closer harmony to the surroundings.

### 3.3. Manual vs. Automatic Operations of Natural Ventilation Systems

The operation of natural ventilation in buildings could be categorised into manual or automatic mode. In manual operation, occupants play an effective role who open and close windows based on their perception of air quality and comfort in the space. On the other hand, windows and vents could be controlled by actuators with necessary control system in places to adjust the opening level based on indoor/outdoor conditions. Nevertheless, there is usually a manual override control available for occupants to open or close windows based on their perception even in the automatic operation. The manual mode of NV is commonly observed in spaces where a limited level of transient discomfort due to overheating or draft is tolerated such as in residential or second-tier office buildings. Many studies in the literature [21,26] have attempted to investigate the window-opening

behaviour of occupants through field studies and measurements. Rijal, Tuohy, Nicol, Humphreys, Samuel, and Clarke explored the implementation of an adaptive window-opening algorithm for predicting thermal comfort, energy usage, and building overheating. Although the mean interior and outside temperatures were higher when the window was open than when it was closed, it was discovered that opening a window had a helpful cooling impact [21]. In a study conducted in Brazil, Sorgato, Melo, and Lamberts evaluated the impact of human behavior on window opening ventilation control and building thermal mass on energy consumption linked to HVAC systems in residential structures. The findings showed that buildings with medium thermal capacity have a better ability to give thermal comfort to people when properly ventilated. In addition, proper building ventilation enabled by automated ventilation management and medium thermal inertia caused a decline in HVAC system energy consumption [26]. Doca, Fabi, Corgnati, and Andersen [36] developed a probabilistic function based on field measurements to capture occupants' behaviour in naturally ventilated dwellings in order to predict the heating energy use more accurately. The results of similar field studies have suggested that the proportion of windows opened has a strong or significant correlation with outdoor temperature, indoor temperature/$CO_2$ concentration, season of the year, time of the day, and occupancy pattern [22,37]. There are also other factors such as wind speed and the probability of precipitation, which could also be determining factors in opening the windows. It was also indicated that the action of opening and closing windows is an important factor in investigating occupants' behaviour rather than just simply determining the status of window at each point of time [38]. Yun and Steemers [23] revealed that the activities of window control were constrained to the start of occupancy and the window state remained the same until the departure of occupants.

The automatic control of windows in buildings is a relatively new design feature that could enhance the performance of NV in both domestic and non-domestic buildings. The control logic is designed to imitate the occupants' window-opening behaviour and adjust the opening level automatically. There is a need for an integrated control of NV with other passive or active systems in the space to coordinate their operations and avoid energy waste and discomfort. Natural ventilation could be operational in parallel with mechanical ventilation in order to guarantee a certain outdoor flow rate. A hybrid natural ventilation/mechanical ventilation system was found to be a feasible design feature that is appreciated by occupants [15,39]. Lim et al. [40] conducted a simulation-based approach to investigate the performance of a window-mounted hybrid ventilation system, and they concluded that a $CO_2$ demand control system with an enthalpy-based control algorithm is the most effective control method for this hybrid system. In most cases, NV could bring enough outdoor air to satisfy the ventilation needs. However, its cooling benefits may not be enough when the outside temperature is too hot or internal gain is significant. In addition, there are transitional seasons when there could be both heating and cooling demands in the same space from morning until evening. Hence, there is a need for NV to be controlled in coordination with cooling and heating systems. A more advanced control algorithm such as fuzzy logic control or model predictive control could enhance the performance of such integrated NV and HVAC systems [41,42]. This integrated control system could also include shading and lighting systems to consider both visual and thermal comfort in adjusting window openings and louvres position [43].

## 4. Intelligent Systems and Controls

### 4.1. The Concepts of Intelligence and Control

Intelligence and control are closely related, and there is a specific and distinguishable meaning to the word "Intelligent Control". An intelligent system needs to identify targets and use them. Then, control is needed to direct the machine to these targets or to reject them. Therefore, any intelligent machine would be a control system. Since control is an integral part of any intelligent system, instead of "intelligent systems" or "intelligent machines", the word "intelligent control system" is often used in engineering discourse. The

phrase "intelligent control system" simply emphasises the control aspect of any intelligent system [44]. However, intelligent control systems (ICS) are systems that, under conditions of complexity, energy shortage, and origin of abnormal conditions, can control complex dynamic objects (CDO) no less effectively than they could be managed by highly competent practised operators [45]. In agreement with Ilyasoy and Valeeva, Sun and Finnie [46] noted that intelligent control is used to deal with complex situations that conventional methods cannot control. Rosenblat, Kneese, and Danah [47] also affirm that intelligent systems work to identify and implement actions by using probabilistic notions, even though they tend to be accurate or precise. The availability of intelligent systems also generates the assumption that researchers can have a more perfect solution.

### 4.2. Artificial Intelligence (AI)

Artificial intelligence is the field of technology that focuses on the development of electronics that can replicate human intelligence behaviours by studying, accessing, adjusting, and expanding knowledge and processing logic to find solutions and act proactively. Studying and developing AI algorithms have different objectives. The primary interest of scientists is to properly comprehend how problems are solved by humans. Engineers' goal is to use simulations to adopt AI algorithms to resolve issues in the actual world. Expert systems (ES), fuzzy logic (FL), artificial neural networks (ANN), genetic algorithms (GA), and hybrid algorithms that combine two or more algorithms are examples of AI algorithms developed for these applications. Each of these algorithms has its own capabilities that fit different engineering needs as well as unique goals for different application domains.

#### 4.2.1. Expert Systems

Intelligent systems that rely on rational reasoning to imitate the decision making of human experts are expert systems. They are based on classical set theory with sets of clear rules, and if–then statements form the rule base. The key benefit of ES is the ability to encode multiple knowledge experiences into its knowledge base in one knowledge domain. As such, ES will achieve the desired change in decision making based on a large knowledge base, which could never be accomplished by a single expert. The ability to understand its information structure and provide clarification facilities for its assumptions and decisions is the attribute that can differentiate ES from other AI algorithms, basically since its knowledge base is linguistically encoded. To constantly develop its knowledge base through rule inference and generalisation tools, more features have been added to ES.

#### 4.2.2. Artificial Neural Network

The structure of the artificial neural network is similar to the human brain. It consists of processing elements (neurons) interlinked through weighting links and organised in multiple layers with a nonlinear activation function. Every neuron represents the infinitesimal portion of the nonlinear surface of the system to be modelled, whereas the contribution of this portion to the overall surface is expressed by linked weighting ties. ANN's learning mechanism changes the weights of interconnected links to accommodate the nonlinearity of the system that offers machine learning capabilities to be modelled.

#### 4.2.3. Genetic Algorithms

The genetic algorithm (GA) emerged from a desire to model natural selection and population genetics biological processes, with the original goal of developing intelligent systems of learning and decision making. The GA has been widely used as an alternative optimisation technique to conventional methods since its introduction and subsequent popularisation. It is generally common to divide the application of GAs to control into two distinct areas: offline design and online optimisation. Offline applications have proven to be the most efficient and widespread. Owing to the difficulties involved with using a GA in real time and directly affecting the operation of the machine, online implementations appear to be very uncommon. GAs have been applied to the design of controllers and the

identification of systems. Either the parameters or the structure can be optimised in each situation, or possibly both. Fault diagnosis, stability analysis, sensor, actuator positioning, and other logical issues are other applications [48].

### 4.2.4. Hybrid Intelligent Systems (HIS)

In order to manage a computer program, HIS incorporates numerous information implementation systems, decision-making frameworks, and learning techniques. By the hybridisation of multiple approaches, this integration solves the limitations of individual techniques. Artificial neural networks, fuzzy inference systems, and genetic algorithms are three essential models utilised in most HIS. The combination of FL and ANN allows machine learning to benefit from human experience. Then, the knowledge base of neuro-fuzzy systems is increased to its maximum potential. GA is commonly used in offline high-level control, whereas neuro-fuzzy systems are used in the direct control loop.

Many experiments have shown the application of these intelligent systems to solve critical problems in other areas. Using the model predictive control process, Yüzgeç, Palazoglu, and Romagnoli [49] optimised the control activity of the short-term petroleum refining strategy. In the Linear Programming Intelligent Tutoring System (LP-ITS), Samy, Naser, and Al-Azhar [50] used an artificial neural network and an expert system to gain knowledge for the learner model in order to evaluate the learners' academic rate of efficiency and provide the adequate degree of challenge to solve linear programming difficulties. The learners' output projection accuracy is really high, implying that the artificial neural network is capable of making reasonable projections The assessment and implementation of congestion control using an expert-controlled system was also presented by Lee et al. [51], and the proposed approach was found to minimise the burden on experts by implementing an intelligent expert system that automatically predicts congestion and bypasses autonomous vehicles.

### 4.3. Fuzzy Logic Controllers

With these three factors, fuzzy logic controllers (FLC) offer a significant benefit against traditional control techniques: They can present nonlinear mapping surfaces using membership functions and inference mechanisms inherited from their structure; they are not dependent on mathematical modelling and rely solely on behavioural performance to define linguistic variables and rule bases; the fuzzy logic system deals with data that are inconsistent or ambiguous. In its form and mechanism of inference, it is similar to ES. However, classical sets are replaced in FL by fuzzy sets with gradual boundaries that allow gradual transition between sets. The use of fuzzy logic offers the ability to evaluate a broad range of tasks where facts, objectives, and constraints are complicated, poorly defined, and difficult to explain precisely mathematically. A fuzzy set is a class of objects in which elements have a degree of membership [52]. This theory has been widely used to incorporate imprecision and subjectivity in mathematical modelling, management, and control of processes. The promising results of this theory in the control and optimisation of machinery, power system, computer aided diagnosis, etc. have motivated researchers to explore its application in the built environment field. Levermore [53] has elaborated a set of if–then rules based on fuzzy logic theory to control the output of a heater to achieve comfortable indoor condition. The application of FLC has also been reported [54,55] for adjustment of shading devices in buildings to harmonise thermal and optical comfort levels and take full advantage of daylight for indoor illuminance. Dounis et al. [56] investigated the performance of a fuzzy reasoning machine for maintaining an acceptable indoor air quality in NV buildings. The results have shown that a satisfactory IAQ level could be achieved with good stability of control parameters. However, more input parameters should be included to simultaneously control thermal comfort and IAQ levels. The design scheme of a proposed FLC for the control of a naturally ventilated test room is illustrated in Figure 3. Crisp inputs of outside/inside temperature, rain, and wind velocity have been considered in this algorithm with the opening position of windows/vents being the crisp output. Where crisp input signifies input variables that are precise with strict boundaries,

and crisp output represents the deffuzified output variables, which are quantifiable. After fuzzifying the input variables using membership functions, the inference engine executes the fuzzy process and defuzzifies the output using a series of if–then rules. If–then rules are articulated rules that define the intended relationship involving inputs and outputs to be executed using fuzzy logic control, enabling a controller to be designed for a system with an uncertain transfer function.
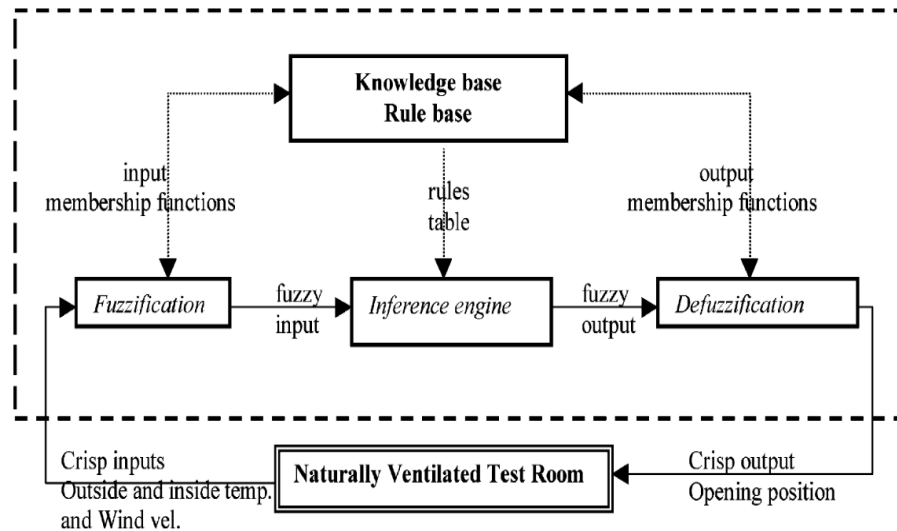


**Figure 3.** Basic configuration of fuzzy logic controller [57].

The quantities and changes of input and output variables are described in a number of membership functions (usually between three and seven) with linguistic labels. Typical membership functions describing inside/outside temperatures, wind velocity, and rain are illustrated in Figure 4.
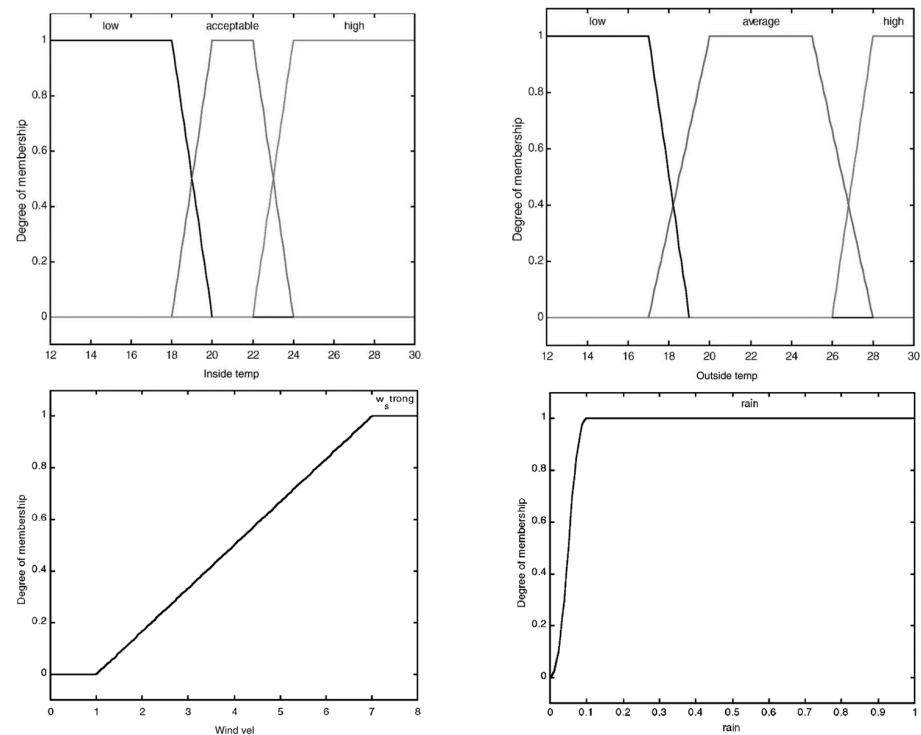


**Figure 4.** Membership function describing inside temperature (**top left**), outside temperature (**top right**), wind velocity (**bottom left**), and rain (**bottom right**) [57].

Eftekhari and Marjanovic [57] developed two fuzzy controllers with different numbers of membership functions for the operation of NV buildings, and the results showed that the models with a larger number of if–then rules were more responsive to changes. The FLC algorithm could be more complicated for integrated control of NV and HVAC systems. Dounis and Manolakis [41] adopted two separate defuzzification strategies in the control process to simultaneously operate heating and natural ventilation systems. Similarly, Dounis and Caraiscos [58] concluded that an intelligent coordinator such as fuzzy PI could be developed to prioritise passive techniques for achieving comfort in an integrated control of passive and active systems. In another relevant study, Kolokotsa et al. [59] developed an adaptive fuzzy PD controller to minimise energy consumption by eliminating overshooting and oscillation. Further research needs to be conducted regarding developing adequate sets of fuzzy crisps and if–then rules for the coordinated control of NV and HVAC system. Such research could pave the way for an actual implementation of this intelligent control system for NV operation in buildings.

### 4.4. Optimised Fuzzy Controllers

Optimisation techniques could be applied to improve the performance of fuzzy logic controller in an HVAC system in order to satisfy occupants' comfort with the least amount of energy consumption. Adopting an optimisation algorithm could be particularly effective where there are multiple inputs and outputs in an FLC system, and developing basic if–then rules could be cumbersome and inefficient. An optimisation engine could be developed to shift between different membership functions and prioritise passive designs for achieving comfort. Genetic algorithm is one of the biologically inspired methods for solving optimisation problems, which imitates natural evolution theory. GA has found its way into many sectors, and it improved the performance of processes and systems in the last century. This optimisation algorithm benefited the building industry as well through improving the design process and control systems in buildings. In particular, the coupled genetic algorithm model with linear or nonlinear control strategies such as FLC has shown promising results. Khan et al. [60] developed an adaptive FLC based on genetic algorithm to adjust the flow rate of chilled water and steam into an air handling unit. The proposed adaptive FLC outperformed the existing FLC in terms of steady-state error, rise time, and settling time. Similarly, Alcala et al. [61] employed GA for rule weighting derivation and the selection of FLC to develop an intelligent control for HVAC systems in buildings. Parameshwaran et al. [62] have also reported improvements in the energy efficiency of demand control and economiser cycle ventilation by coupling a GA optimiser with an FLC controller. This coupled controller of GA and FLC has been found an effective strategy for an integrated control of lighting, heating, and NV systems in buildings. Kolokotsa et al. [30] used the genetic algorithm optimisation technique to shift between membership functions of illuminance, PMV, window opening, $CO_2$, and heat output in order to satisfy occupants' expectations with the least energy consumption. Illuminance level and $CO_2$ concentration in the reported case study of FLC implementation with and without GA are compared to each other in Figure 5. It could be seen that these environmental conditions are closer to the defined settings for the fuzzy controller after GA optimisation.

Artificial neural network is another biologically inspired algorithm that imitates the function of the human brain to recognise patterns and infer rules as aforementioned. The ANN model could be trained and validated from the monitored data during operation of the system and the developed model could provide forecast of environmental conditions and system parameters to be fed into the FLC unit of the controller. Kolokotroni et al. [19] investigated various control strategies for passive ventilation and indicated that empirical models based on fuzzy logic reasoning and the neural network concept are more suitable for the operation/control of a building compared to theoretical control models based on thermophysical laws. In another relevant study, Marvuglia et al. [20] developed an FLC model fed by an indoor temperature predictor based on an auto-regressive neural network approach with external inputs. The results demonstrated the effectiveness of this combined

neuro-fuzzy model for thermal comfort regulation of office buildings. Chen et al. [63] adopted a transfer learning approach for a deep neural network model to overcome the limitation regarding the need for a large amount of data for the training of a neural network model and save system design and commissioning costs in new buildings. These promising results in the application of optimised FLC in buildings demonstrate the potential of such coupling of fuzzy logic with optimisation algorithms.
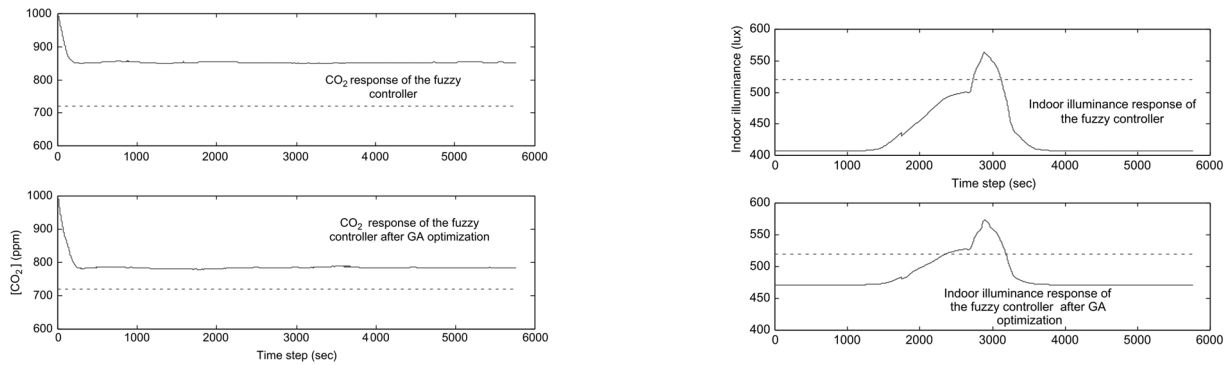


**Figure 5.** Example showing the comparison between $CO_2$ concentration (**left**) and illuminance (**right**) level in a fuzzy controller before and after GA optimisation [30].

There have been attempts to employ other optimisation techniques and machine learning approaches such as model predictive control (MPC), reinforcement learning (RL), differential evolution (DL), and particle swarm optimiser (PSO) for the control of passive and active systems in buildings. MPC optimises the control decisions of the system at the current time step while considering the future time steps. This control theory has found its applications in chemical processes and power systems. Chen et al. [40] investigated the performance of different control strategies for the operation of natural ventilation in five big cities in China. The results demonstrated that a fully automatic natural ventilation design integrated with the model predictive control (MPC) system is the most effective strategy with an estimated energy saving of 17 to 80%. The same group of researchers [29] attempted to synergise the operation of HVAC and operable windows in buildings using a reinforcement learning control strategy. The reinforcement learning control system demonstrated significant improvement over a heuristic approach in terms of reduction in cooling/heating energy consumption and discomfort hours. Elbi et al. [31] used the differential evolution (DE) method to optimise ventilation strategies in buildings. An estimated energy savings of 40% (compared to mechanical ventilation and manual opening) have been predicted for the implementation of this control theory in an architectural studio classroom. In another study, Fanti et al. [64] proposed a co-simulation architecture tool in which TRNSYS software used for thermal/ventilation modelling and particle swarm optimisation (PSO) for determining the window-opening threshold. The model has been tested for a case study of residential building in the Mediterranean climate, and the results indicated the reduction of energy consumption and overheating hours. Despite these positive results, these control theories are still at the research and development stage, and they need to be tested in experimental setup before being adopting for the control of passive or active systems in real buildings.

## 5. Discussions

The review of reported studies in the literature on the control of natural ventilation has suggested that NV could be an effective passive cooling design feature for many applications. Estimated energy savings of 13 to 40% were reported depending on the basis of comparison and building types. The comfort and air quality level in naturally ventilated buildings remained unchanged, or in some cases, they improved compared to MV buildings. These observations indicate that the application of NV could be more

widespread in both residential and commercial buildings. Although findings of several studies have shown the importance of implementing a well-designed control system for the operation of NV design, especially in non-domestic buildings. In residential applications, manual operation of windows and openings is more common where occupants adjust the opening level of windows depending on their perception of air quality and comfort.

Developing an adequate control system for the operation of natural ventilation is of high importance especially for non-domestic buildings. This is to make sure that outside air is being introduced into space at the right time and rate to avoid increasing the heating or cooling load of the HVAC system. In addition, occupants have less flexibility and access in adjusting their clothing level and openable windows in commercial buildings. This means that any fluctuation of temperature outside of the comfort zone due to a change in the outside temperature or ventilation rate could result in discomfort and diminishing productivity. Various design types and control strategies have been investigated in the literature to optimise the operation and control of NV as a passive cooling strategy in buildings. However, numerical simulation and thermal modelling approaches have been mostly adopted in these studies, and there is a lack of connection between these proposed theories and the actual design of NV in buildings. There is a need for the real implementation of automatic NV systems with intelligent control design. This could fill the existing gaps between theory and practice to find the most effective control strategies in real buildings.

It is unrealistic to assume that natural ventilation by itself could provide comfortable indoor space for any significant number of hours each year. The performance and operational strategies of NV are very mush dependent on other passive or active systems in the space including heating, ventilation, and air conditioning systems as well as lighting and shading control systems. Therefore, it has been argued that for many commercial applications of natural ventilations, there is the need for the coordinated control of NV with HVAC and shading systems. This emphasises the importance of implementing an advanced control strategy for the operation of NV with the right control interface and communications with other zone equipment and devices. Several studies in the literature have investigated the performance of fuzzy logic control for such an integrated control design. FLC was found to be an effective control strategy for an integrated control of NV, HVAC, and shading system where control decisions are made based on several input parameters translated into membership functions. It has also been shown in several studies that the performance of FLC could be improved by coupling it with optimisation techniques such as genetic algorithm and neural network.

Another important aspect regarding the wide-scale application of natural ventilation in building is the probabilities of different future weather scenarios. It is already getting difficult to limit overheating in the existing non-domestic buildings, and this could get worse as outside temperatures during the summer time are likely to increase. Retrofitting cooling systems to a building that did not properly consider future weather and had a poorly optimistic NV approach could be worse in carbon terms than designing it right in the first place. This issue could be more pronounced in the temperate climate such as the UK where traditionally buildings do not have cooling systems to cope with extremely hot weather conditions.

## 6. Conclusions

A review of existing knowledge on the application and control of natural ventilation as a passive cooling strategy for buildings has been conducted. This includes a theoretical context and practical implementation for researchers seeking to explore the use of intelligent controls for optimal output in the pursuit to help solve intricate control problems in the building industry and suggests advanced control systems such as fuzzy logic control as an effective control strategy for integrated control of natural ventilation, heating, ventilation, and air conditioning systems. The review found that there is potential to enhance the performance of natural ventilation, especially in non-domestic buildings. An advanced control strategy such as fuzzy logic control coupled with optimisation engine of neural

network could be an effective control system for such a design. It has been concluded that an automatic control of windows integrated with the control of heating and cooling systems could truly materialise the benefits of such a control design. This study is limited to UK buildings and other buildings with similar climatic conditions. The reviewed systems could be applicable to areas where there is a lot of heating and more need for availability of natural ventilation. For researchers and control engineers interested in exploring the application of intelligent controls for optimal output in the quest of solving complex control issues in the construction sector, this paper provides an excellent theoretical framework and practical implementation. This review is also valuable for people working in the related field for developing and improving such applications toward more sustainable building design. For future works, it is recommended to test the performance of such a control design in an experimental setup or in an actual case study with an integrated building management system. Successful implementation of an NV system in hybrid systems could pave the way for the widespread applications of this free source of cooling and ventilation in non-domestic buildings.

## References

1. The Committee on Climate Change Quantifying Greenhouse Gas Emissions—Committee on Climate Change. 2017. Available online: https://www.theccc.org.uk/publication/quantifying-greenhouse-gas-emissions/ (accessed on 5 May 2021).
2. UK GBC. Energy Efficiency in the UK's Buildings: Key Priorities for the New Government. 2017. Available online: https://www.ukgbc.org/wp-content/uploads/2017/09/UK-GBC-Aldersgate-Energy-Efficiency-Briefing.pdf (accessed on 5 May 2021).
3. Gillich, A.; Saber, E.M.; Mohareb, E. Limits and uncertainty for energy efficiency in the UK housing stock. *Energy Policy* **2019**, *133*, 110889. [CrossRef]
4. Building Research Establishment Study on Energy Use by Air-Conditioning: Final Report. 2016. Available online: https://www.bre.co.uk/filelibrary/pdf/projects/aircon-energy-use/StudyOnEnergyUseByAirConditioningFinalReport.pdf (accessed on 21 April 2021).
5. Allard, F.; Santamouris, M.; Alvarez, S. *Natural Ventilation in Buildings: A Design Handbook*; James and James (Science Publishers) Ltd.: London, UK, 1998.
6. CIBSE AM10. Natural Ventilation in Non-Domestic Buildings. 2005. Available online: https://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7m2AAC (accessed on 16 May 2021).
7. CIBSE AM13. Mixed Mode Ventilation, CIBSE Applications Manual AM13:2000. 2000. Available online: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I7nt (accessed on 16 May 2021).
8. Emmerich, S.J.; Dols, W.S.; Axley, J.W. Natural Ventilation Review and Plan for Design and Analysis Tools. 2001. Available online: https://doi.org/10.6028/NIST.IR.6781 (accessed on 19 April 2021).
9. Lomas, K.J.; Ji, Y. Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. *Energy Build.* **2009**, *41*, 629–653. [CrossRef]
10. Carrilho da Graça, G.; Linden, P. Ten questions about natural ventilation of non-domestic buildings. *Build. Environ.* **2016**, *107*, 263–273. [CrossRef]
11. Martin, A.; Fitzsimmons, J. *Making Natural Ventilation Work*; BSRIA: Bracknell, UK, 2000.
12. The Carbon Trust. A Natural Choice: Lessons Learned from Low Carbon Buildings with Natural Ventilation. 2011. Available online: https://www.carbontrust.com/media/81365/ctg048-a-natural-choice-natural-ventilation.pdf (accessed on 6 May 2021).
13. Tranfield, D.; Denyer, D.; Smart, P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]

14. Etheridge, D.; Ford, B. Natural Ventilation of Tall Buildings-Options and Limitations. 2008. Available online: http://global.ctbuh. org/resources/papers/download/291-natural-ventilation-of-tall-buildings-options-and-limitations.pdf (accessed on 11 April 2021).

15. Ji, Y.; Lomas, K.J.; Cook, M.J. Hybrid ventilation for low energy building design in south China. *Build. Environ.* **2009**, *44*, 2245–2255. [CrossRef]

16. Christine, E. *Walker Methodology for the Evaluation of Natural Ventilation in Buildings Using a Reduced-Scale Air Model*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2006; Available online: https://dspace.mit.edu/handle/1721.1/34415 (accessed on 9 May 2021).

17. Zhai, Z.; Johnson, M.; Krarti, M. Assessment of natural and hybrid ventilation models in whole-building energy simulations. *Energy Build.* **2011**, *43*, 2251–2261. [CrossRef]

18. Chen, Y.; Tong, Z.; Malkawi, A. Investigating natural ventilation potentials across the globe: Regional and climatic variations. *Build. Environ.* **2017**, *122*, 386–396. [CrossRef]

19. Kolokotroni, M.; Perera, M.D.A.E.S.; Azzi, D.; Virk, G.S. An investigation of passive ventilation cooling and control strategies for an educational building. *Appl. Therm. Eng.* **2001**, *21*, 183–199. [CrossRef]

20. Marvuglia, A.; Messineo, A.; Nicolosi, G. Coupling a neural network temperature predictor and a fuzzy logic controller to perform thermal comfort regulation in an office building. *Build. Environ.* **2014**, *72*, 287–299. [CrossRef]

21. Rijal, H.B.; Tuohy, P.; Nicol, F.; Humphreys, M.A.; Samuel, A.; Clarke, J. Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. *J. Build. Perform. Simul.* **2008**, *1*, 17–30. [CrossRef]

22. Zhang, Y.; Barrett, P. Factors influencing the occupants' window opening behaviour in a naturally ventilated office building. *Build. Environ.* **2012**, *50*, 125–134. [CrossRef]

23. Yun, G.Y.; Steemers, K. Time-dependent occupant behaviour models of window control in summer. *Build. Environ.* **2008**, *43*, 1471–1482. [CrossRef]

24. Atkinson, J. World Health Organization Natural Ventilation for Infection Control in Health-Care Settings. 2009. Available online: https://www.who.int/water_sanitation_health/publications/natural_ventilation.pdf (accessed on 12 April 2021).

25. Aflaki, A.; Mahyuddin, N.; Al-Cheikh Mahmoud, Z.; Baharum, M.R. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy Build.* **2015**, *101*, 153–162. [CrossRef]

26. Sorgato, M.J.; Melo, A.P.; Lamberts, R. The effect of window opening ventilation control on residential building energy consumption. *Energy Build.* **2016**, *133*, 1–13. [CrossRef]

27. Tantasavasdi, C.; Srebric, J.; Chen, Q. Natural ventilation design for houses in Thailand. *Energy Build.* **2001**, *33*, 815–824. [CrossRef]

28. Gratia, E.; Bruyère, I.; De Herde, A. How to use natural ventilation to cool narrow office buildings. *Build. Environ.* **2004**, *39*, 1157–1170. [CrossRef]

29. Chen, Y.; Norford, L.K.; Samuelson, H.W.; Malkawi, A. Optimal control of HVAC and window systems for natural ventilation through reinforcement learning. *Energy Build.* **2018**, *169*, 195–205. [CrossRef]

30. Kolokotsa, D.; Stavrakakis, G.S.; Kalaitzakis, K.; Agoris, D. Genetic algorithms optimized fuzzy controller for the indoor environmental management in buildings implemented using PLC and local operating networks. *Eng. Appl. Artif. Intell.* **2002**, *15*, 417–428. [CrossRef]

31. Elbi, D.; Ekim, H.F.; Dursun, O. Optimizing natural ventilation strategy in existing buildings using differential evolution: Case of architectural studio classrooms. In Proceedings of the 2016 IEEE Congress on Evolutionary Computation (CEC), Vancouver, BC, Canada, 24–29 July 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 3895–3900. [CrossRef]

32. Homod, R.Z.; Sahari, K.S.M.; Almurib, H.A.F. Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison. *Renew. Energy* **2014**, *71*, 639–650. [CrossRef]

33. Schulze, T.; Eicker, U. Controlled natural ventilation for energy efficient buildings. *Energy Build.* **2013**, *56*, 221–232. [CrossRef]

34. ASHRAE Standard 55—Thermal Environmental Conditions for Human Occupancy. 2017. Available online: https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy (accessed on 2 April 2021).

35. CIBSE TM52. The Limits of Thermal Comfort: Avoiding Overheating in European Buildings. 2013. Available online: http://app.knovel.com/web/toc.v/cid:kpTLTCAOE4/viewerType:toc/root_slug:limits-thermal-comfort (accessed on 7 May 2021).

36. D'Oca, S.; Fabi, V.; Corgnati, S.; Andersen, R. Effect of thermostat and window opening occupant behavior models on energy use in homes. *Build. Simul.* **2014**, *7*, 683–694. [CrossRef]

37. Andersen, R.; Fabi, V.; Toftum, J.; Corgnati, S.P.; Olesen, B.W. Window opening behaviour modelled from measurements in Danish dwellings. *Build. Environ.* **2013**, *69*, 101–113. [CrossRef]

38. Fabi, V.; Andersen, R.V.; Corgnati, S.; Olesen, B.W. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Build. Environ.* **2012**, *58*, 188–198. [CrossRef]

39. Perino, M. Short-term airing by natural ventilation—modeling and control strategies. *Indoor Air* **2009**, *19*, 357–380. [CrossRef]

40. Lim, Y.; Yun, H.; Song, D. Indoor Environment Control and Energy Saving Performance of a Hybrid Ventilation System for a Multi-residential Building. *Energy Procedia* **2015**, *78*, 2863–2868. [CrossRef]

41. Chen, Y.; Tong, Z.; Wu, W.; Samuelson, H.; Malkawi, A.; Norford, L. Achieving natural ventilation potential in practice: Control schemes and levels of automation. *Appl. Energy* **2019**, *235*, 1141–1152. [CrossRef]

42. Dounis, A.I.; Manolakis, D.E. Design of a fuzzy system for living space thermal-comfort regulation. *Appl. Energy* **2001**, *69*, 119–144. [CrossRef]

43. Sun, B.; Luh, P.B.; Jia, Q.-S.; Jiang, Z.; Wang, F.; Song, C. Building Energy Management: Integrated Control of Active and Passive Heating, Cooling, Lighting, Shading, and Ventilation Systems. *TASE* **2013**, *10*, 588–602. [CrossRef]

44. Antsaklis, P. *Defining Intelligent Control*; Report of the Task Force on Intelligent Control; IEEE Control Systems Society: New York, NY, USA, 1993.

45. Ilyasov, B.; Valeeva, R. *Agile Manufacturing: The 21st Century Competitive Strategy*; Elsevier: Amsterdam, The Netherlands, 2001.

46. Sun, Z.; Finnie, G. A fuzzy logic approach to experience-based reasoning. *Int. J. Intell. Syst.* **2007**, *22*, 867–889. [CrossRef]

47. Rosenblat, A.; Kneese, T.; Danah, B. *Understanding Intelligent Systems*; Data & Society Research Institute: New York, NY, USA, 2014.

48. Fleming, P.J.; Purshouse, R.C. Evolutionary algorithms in control systems engineering: A survey. *Control Eng. Pract.* **2002**, *10*, 1223–1241. [CrossRef]

49. YüUzgeç, U.; Palazoglu, A.; Romagnoli, J.A. Short-term Planning Model for Petroleum Refinery Production. *IFAC Proc. Vol.* **2010**, *43*, 308–313. [CrossRef]

50. Samy, S. Abu Naser Predicting Learners Performance Using Artificial Neural Networks in Linear Programming Intelligent Tutoring System. *Int. J. Artif. Intell. Appl.* **2012**, *3*, 65–73.

51. Lee, S.; Kim, Y.; Kahng, H.; Lee, S.; Chung, S.; Cheong, T.; Shin, K.; Park, J.; Kim, S.B. Intelligent traffic control for autonomous vehicle systems based on machine learning. *Expert Syst. Appl.* **2020**, *144*, 113074. [CrossRef]

52. Zadeh, L.A. Fuzzy sets. *Inf. Control* **1965**, *8*, 338–353. [CrossRef]

53. Levermore, G.J. *Building Energy Management Systems: Applications to Low Energy HVAC and Natural Ventilation Control*; E & FN Spon: New York, NY, USA, 2000.

54. Kristl, Ž; Košir, M.; Trobec Lah, M.; Krainer, A. Fuzzy control system for thermal and visual comfort in building. *Renew. Energy* **2008**, *33*, 694–702. [CrossRef]

55. Trobec Lah, M.; Zupančič, B.; Peternelj, J.; Krainer, A. Daylight illuminance control with fuzzy logic. *Sol. Energy* **2006**, *80*, 307–321. [CrossRef]

56. Dounis, A.I.; Bruant, M.; Guarracino, G.; Michel, P.; Santamouris, M. Indoor air-quality control by a fuzzy-reasoning machine in naturally ventilated buildings. *Appl. Energy* **1996**, *54*, 11–28. [CrossRef]

57. Eftekhari, M.M.; Marjanovic, L.D. Application of fuzzy control in naturally ventilated buildings for summer conditions. *Energy Build.* **2003**, *35*, 645–655. [CrossRef]

58. Dounis, A.I.; Caraiscos, C. Advanced control systems engineering for energy and comfort management in a building environment— A review. Renew. *Sustain. Energy Rev.* **2009**, *13*, 1246–1261. [CrossRef]

59. Kolokotsa, D.; Tsiavos, D.; Stavrakakis, G.S.; Kalaitzakis, K.; Antonidakis, E. Advanced fuzzy logic controllers design and evaluation for buildings' occupants thermal–visual comfort and indoor air quality satisfaction. *Energy Build.* **2001**, *33*, 531–543. [CrossRef]

60. Khan, M.W.; Choudhry, M.A.; Zeeshan, M. Multivariable adaptive Fuzzy logic controller design based on genetic algorithm applied to HVAC systems. In Proceedings of the 2013 3rd IEEE International Conference on Computer, Control and Communication (IC4), Karachi, Pakistan, 25–26 September 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 1–6. [CrossRef]

61. Alcalá, R.; Casillas, J.; Cordón, O.; González, A.; Herrera, F. A genetic rule weighting and selection process for fuzzy control of heating, ventilating and air conditioning systems. *Eng. Appl. Artif. Intell.* **2005**, *18*, 279–296. [CrossRef]

62. Parameshwaran, R.; Karunakaran, R.; Kumar, C.V.R.; Iniyan, S. Energy conservative building air conditioning system controlled and optimized using fuzzy-genetic algorithm. *Energy Build.* **2010**, *42*, 745–762. [CrossRef]

63. Chen, Y.; Tong, Z.; Zheng, Y.; Samuelson, H.; Norford, L. Transfer learning with deep neural networks for model predictive control of HVAC and natural ventilation in smart buildings. *J. Clean. Prod.* **2020**, *254*, 119866. [CrossRef]

64. Fanti, M.P.; Mangini, A.M.; Roccotelli, M.; Iannone, F.; Rinaldi, A. A natural ventilation control in buildings based on co-simulation architecture and Particle Swarm Optimization. In Proceedings of the 2016 International Conference on Systems, Man, and Cybernetics (SMC), Budapest, Hungary, 9–12 October 2016; IEEE: Piscataway, NJ, USA, 2016; p. 2621. [CrossRef]