


## Article

# Balancing User Comfort and Energy Efficiency in Public Buildings through Social Interaction by ICT Systems

Alessandro Franco 

Department of Energy, Systems, Territory and Constructions Engineering (DESTEC), University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy; alessandro.franco@ing.unipi.it; Tel.: +39-050-2217154

Received: 29 July 2020; Accepted: 26 August 2020; Published: 28 August 2020



**Abstract:** Energy efficiency, indoor environmental quality, and comfort in public buildings has received increasing attention in recent years as it can contribute to maintaining safety conditions and to the reduction of conventional fuels consumption, energy costs for building owners, and greenhouse gas emissions. People are an integral part of any building energetic ecosystem as, according to some estimates, they spend a great part of their life in indoor spaces. On one side, occupants are responsible for the energy consumption of the building and for this reason the “psychology of energy saving” has received attention since the 70s up to recent results. On the other hand, strategies for energy efficiency should not jeopardize occupants’ health and quality of life. While general awareness of the value of environmental variables has increased in the last few years, this interest has recently been further exacerbated by the spreading of the well-known COVID-19 pandemic. In fact, as most countries have started planning post-lock-down activities, there is a growing concern regarding how social distancing measures can be enforced in shared buildings and strict indoor air quality control can prevent airborne virus transmission in crowded spaces. The paper discusses the perspectives of increasing the level of social interaction of building users through the systematic use of Information and Communication Technologies (ICT), and in particular, some specific platforms. The ICT system, taking information from the occupants in a concerted way, can be an important instrument to collect data, coming both from physical sensors and from people to develop a multi-objective control strategy for the Heating, Ventilation, and Air Cooling (HVAC) systems in order to obtain energy savings whilst balancing user comfort and healthy conditions.

**Keywords:** ICT systems; social interaction; indoor environment quality; energy efficiency; gamification techniques; soft sensors; restart after COVID-19

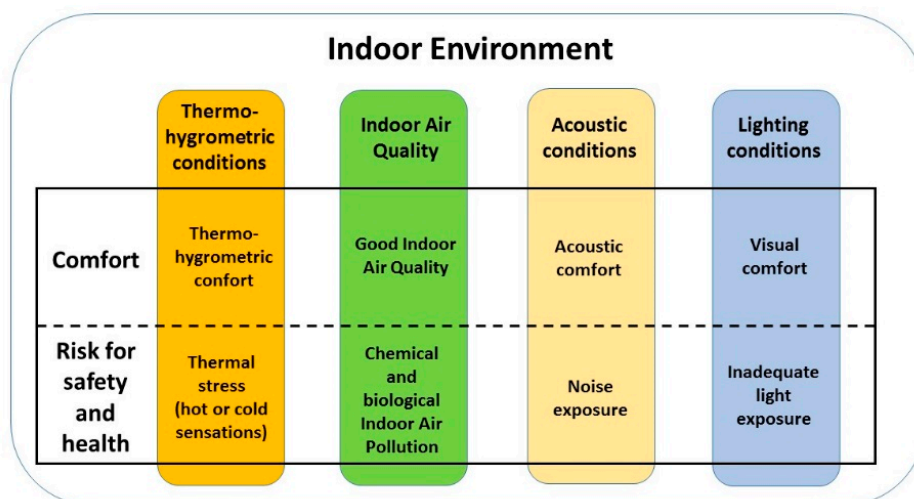
## 1. Introduction

In the last years, a relevant number of studies and projects have been funded and a lot of research activities have been carried out to develop automated management systems aimed at maintaining adequate Indoor Environmental Quality (IEQ) standards and at reducing energy consumption in public buildings for different uses (offices, educational buildings, supermarkets, hospitals, etc.).

Energy efficiency in the civil sector is receiving increasing attention as it can contribute to the reduction of conventional fossil fuels consumption, energy costs for building owners, and greenhouse gas emissions. The topic is particularly considered, since the beginning of the present century, as well exposed by Kolokotsa et al. [1]. In the EU, buildings account for about 40% of the overall energy consumption, in the most developed countries, as stated by Klein et al. in [2]. Precise statistics have been gathered on this important topic also by the European Union and by the US Department of Energy; for example, in the “Buildings Energy Data Book” [3].

The objective of the great part of the studies is to minimize the energy consumption of the Heating, Ventilation, and Air Cooling (HVAC) system, while preserving the comfort perceived by occupants of the building. The elements that are controlled are in general the indoor temperature, the relative humidity, and the concentration level of the various pollutants (e.g., CO<sub>2</sub>). The control system interacts with the HVAC systems, controlling the temperature or modifying the air exchange rate and all the remaining elements in order to guarantee the well-being conditions.

The topic is diffusely discussed in a lot of recent papers and textbooks; for example, by Norbäck in [4], by Fantozzi and Rocca in [5], and by Chang et al. [6]. Figure 1, rearranged from [5], furnishes a specific overview of the concurrent elements that influence well-being conditions in indoor spaces.



**Figure 1.** Concurrent elements that influence well-being conditions in an indoor environment.

Most of these studies have been carried out under the assumption that the building characteristics and all the other dynamics affecting energy consumption and occupants' comfort are precisely known or, at least, they can be modelled with a sufficient accuracy [6].

People are an integral part of any building energetic ecosystem as, according to some estimates, they spend about 80% of their life indoors, as expressly stated in [1,7]. Occupants are indirectly responsible for the energy consumption of the building, as well evidenced in the document of the European Energy Agency [8].

For this reason, the “psychology of energy saving” has received attention since the 70s, such as Winett et al. [9] and Brohmann et al. [10]. On the other hand, strategies for energy efficiency should not jeopardize occupants' health and quality of life, as well evidenced by Castilla et al. in [11]. In recent times, the “psychology of energy saving” has received growing social attention, being one of the main topics considered by “Fridays for future”, the movement that since 2018 protests against the lack of action on the climate crisis connected to the abundant use of fossil fuels and carbon technologies.

Energy consumption in public buildings is largely dependent on whether or not a building energy management system is responsible for this system functioning. Best practice projects provide innovative methods of public building energy management implementation by use of Information and Communication Technologies (ICT). Energy efficiency improvement is achieved through the change of building users' behavior, the energy data collection and analysis, the optimal setting of consumption patterns, and making remote control of the building's electronic unit.

Considering a building, and in particular a public building, energy management systems should be ideally designed, both to guarantee the required comfort level and to minimize the energy consumption for service-plant operations [12]. The two objectives might often be in conflict, as an improvement

of the comfort level typically asks for higher energy consumption. Such a problem, with conflicting objectives, requires multiple optimized trade-off solutions, as also discussed in [13].

The problems seem to be increased by the satisfaction of comfort level perceived by occupants. This is mainly determined by three concurrent factors, namely thermal comfort, acoustic and visual comfort, and air quality [14]. Obviously, those factors have a significant impact on human productivity, learning ability, health, and happiness and now on health security too. If the energy aspect is not really considered by the occupants, the comfort perceived is highly subjective. Good Indoor Air Quality (IAQ) requires an adequate ventilation rate, control of airborne contaminants, and maintenance of acceptable temperature, relative humidity, and CO<sub>2</sub> concentration level. This often requires additional energy consumption of the HVAC unit, as discussed by Zhang et al. in [15].

A new problem is represented today by the “safety question”, consequent to the recent pandemic emergency COVID-19. A wide variety of systems and methodologies have been proposed in the literature to address energy savings in residential and commercial buildings, while satisfying occupants’ comfort and the required IAQ conditions. These proposals are based on different but complementary perspectives, and often take an inter-disciplinary approach—a detailed survey is provided by Dounis et al. [16].

A deeper involvement of the occupants in the air quality control and in the energy management system of the building will be required in the future. This means that the pervasive supporting system will lead people towards energy-aware and comfort behaviors, taking into account the user feedback also on the perceived comfort in the surrounding environment.

The user, along with the whole community of the building occupants, will (partly) be in charge of the IAQ control and energetic efficiency of the system that they daily live (work) in, and will feel more and more responsible for it. In practice, the user will be pushed towards wise behaviors as they will participate in the “control” of the system, via ordinary personal devices like smartphones, tablets, and desktops. Therefore, the direct involvement of occupants in the process will be surely increased. Specifically, energy management systems should be able to directly and continuously interact with occupants, receiving feedback from them in different ways. In addition, occupants should often feel that they are having full control of the external environment.

The idea is to motivate and support citizen’s behavioral change to achieve higher comfort levels and energy efficiency by taking advantage of the recent development of Information and Communication Technologies (ICT) (e.g., personalized data-driven applications, gaming, and social networking) or Internet of Things (IoT). The topic is surely of interest in the recent literature, as stated in [17], where the authors provide an IoT upgrade for a smart and scalable HVAC control for commercial buildings.

A viable option for obtaining a strong interaction between the control system and the occupants of a building is the development of platforms based on ICT. The use of ICT platforms or apps is common today in several fields and their use could be interesting in connection with the optimum design problem of balancing energy efficiency, safety, and comfort. Such a platform must be constructed with the capability of acquiring data from physical sensors like temperature, humidity, and CO<sub>2</sub> concentration, and from the people and must include a multi-objective control system that will interact with the HVAC system, to balance safety requirements (related, for example, to the control of maximum occupation level), occupants’ comfort, and energy savings in the controlled building.

The ICT platform can be important to complement the existing comfort and energy management systems, usually based on utilization of physical sensors, of temperature, humidity, and CO<sub>2</sub>, like proposed by the same author in [18], and will take advantage from the interaction with the occupants, who will act as both “sensors” and as “actuators”. As sensors, they will provide information about their perceived comfort by interacting with the platform and possibly with the other occupants. The control system will take into account the inputs from the occupants as well as measurements collected by sensors (which will include smartphones, capitalizing on their multiple in-build sensing capabilities) deployed in the building, so as to find the best trade-off between global perceived comfort and energy

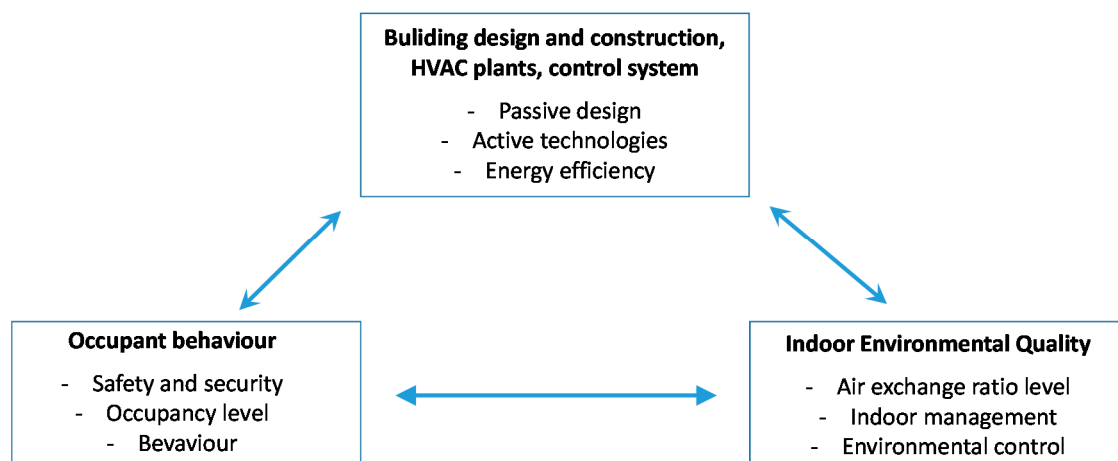
saving. The execution of the devised control strategy may ask for involvement of the occupants as actuators [5].

For instance, the strategy could determine the need of turning off the HVAC system or of a regulation of it. Within the platform, Miscellaneous Electric Loads (MELs), defined as all non-main commercial building electric loads, which normally are not controlled by the energy management system, will also take a prominent controllable role, as they constitute a significant portion of the energy consumption. The idea of the proposed ICT platform will rely also on soft sensors and Non-Intrusive Load Monitoring (NILM) techniques, as well as on the involvement of the building occupants. This aspect, analyzed by De Paola et al. [19], represents one of the main proposed advancements with respect to the state of the art. In today's world of technological advancements, utilizing the latest ICT and IoT hardware will help people optimize their IAQ and the required energy consumption, as well as help more people to understand the importance of this topic and the complexity of the control of air quality in public crowded buildings.

## 2. The Future Challenges of the Indoor Air Quality (IAQ) Control Systems after COVID-19 Pandemic Events: The Direct Involvement of the Occupant through Social Interaction

Design strategies for sustainable buildings should also promote healthy indoor environments with high quality standards. Some papers in the recently available literature contain a review of the coupling among building design methods, indoor environmental quality, and occupant behavior. Those focus the attention on defining the limits of adaptation on the three aforementioned levels to ensure the energy efficiency of the whole system and a healthy environment.

Šujanová et al., in [20], promote a kind of “virtuous circle” among building design and operation of the active plants, mainly the HVAC system, occupant behavior, and Indoor Environmental Quality (IEQ), as described in Figure 2. Prevention of health impacts due to indoor air pollution is discussed in other papers, like [21]; increasing intake of outside air and changing air more frequently are two of the possible options.



**Figure 2.** The complex design of a public building (rearranged from Šujanová et al. [20]).

A number of European research projects funded under the European Commission's Horizon 2020 program are proactively finding solutions to improve energy efficiency in public buildings of different end-uses. The problem is analyzed in several European projects, completed in the period 2009–2014, such as BESTEnergy [22], HOSPILOT [23], SEEMPUBS [24], KNOHOLEM [25], A2PBEER [26], SMARTSPACES [27], and SENCULT [28].

Comfort is traditionally associated with parameters such as temperature, humidity, light intensity, and air quality in general. Regarding the indoor air quality assessment indicators, it is certainly important to mention Fanger's study [29]. Fanger, similarly to what was previously done for the

evaluation of thermal comfort, introduced a subjective indicator of comfort. According to the theory exposed by Fanger, factors affecting thermal comfort are the air temperature, the mean radiant temperature, the relative humidity, the level of clothing, the activity level, and the air velocity.

The Fanger comfort equation can be expressed in synthetic terms as

$$M - W = (C + R + Esk) + (Cres + Eres) \quad (1)$$

where, on the left side of the equation,  $M$  is the metabolic rate,  $W$  is the work done by the person, while on the right side, the two groups of terms represent the “skin” and “breathing” terms, respectively. In particular,  $C$  and  $R$  are the heat transfer by convection and by radiation from the clothing surface,  $Esk$  is the evaporative convective heat exchange,  $Cres$  and  $Eres$  are the respiratory convective and evaporative heat exchange.

The theory proposed by Fanger more than 30 years ago is interesting for giving some quantification of comfort quality of the internal environment, even if it considers only thermos-hygrometric variables. Fanger defined, in particular, two indices, called PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied). The first index, PMV (Predicted Mean Vote), gives a subjective thermal reaction of a large group of persons according to a psycho-physical scale in which seven different levels are represented. An index that predicts the value of the mean votes of a large group of persons on the thermal sensation scale (psycho-physical), in which seven points are evidenced from cold (−3) to hot (+3), considering the value 0 as the neutral condition (normal).

In general, the PMV is directly correlated to the value of the Effective Temperature (ET), an empirical value derived from people’s observations or physiological effects, that combines the effect of air temperature, humidity, and air movement

Several different equations are proposed in the literature to estimate PMV. For sedentary or quite sedentary activities, for example, considering  $W$  reduced the value of PMV and can be calculated as a function of  $C$  and  $R$ , is strictly dependent on the temperature level of the indoor space under analysis.

$$PMV = a(C + R) + b \quad (2)$$

where  $a$  and  $b$  are constants.

The second index, PPD (Predicted Percentage of Dissatisfied), establishes a quantitative prediction of the number of thermally dissatisfied persons among a large group.

$$PPD = 100 - 95 \exp(-0.03353 PMV^4 - 0.2179 PMV^2) \quad (3)$$

The model proposed by Fanger permits the understanding of the direct connection between thermal comfort and the actual value of the temperature and humidity in the internal environment, conditions maintained with the operation of HVAC systems, and consequently it is well understood the connection with energy consumption. However, temperature and humidity are strictly correlated with the real occupation of the indoor spaces.

In recent years, different IAQ indicators were proposed for the evaluation of IAQ in buildings, with more specific attention to different elements, like the concentration of various pollutants. Those are discussed in recent papers by Wei et al. [30], Cony et al. [31], and Luo et al. [32].

A more comfortable and safe working environment has a positive effect, boosting productivity in some activities (for example, students in university classrooms or employers in public offices). Nowadays, it is also complemented with ergonomics, and after the relevant pandemic experience of COVID-19, with an accurate safety control of the indoor environment in order to prevent airborne virus transmission and to maintain quite low levels of pollutants (like  $CO_2$ ).

Most of the existing systems evaluate comfort by using sensors for measuring some of the above-mentioned parameters and this will be surely maintained, but the contribution of the people inside must be surely relevant, both to control the actual state (for example the occupation of the

spaces) and to improve the comfort. However, comfort is a quite subjective element and depends on the different perception of everyone. In addition, such perception is also affected by the current individual, health, and psychological status.

This is evident, for instance, from the different clothes people dress in, in the same environmental conditions. Thus, comfort should be measured in terms of individual satisfaction with thermal, acoustic, visual, aesthetic, and ergonomic parameters, as well as air quality.

The maintenance of specific comfort level, as well as the control of IAQ, has in some cases a negative impact on energy consumption (for example, to maintain air quality, a relevant value of air heat exchange rate is required). This satisfaction is affected by some factors such as the health state, habits, and type of activity. The individual satisfaction can be acquired only through a strong interaction with the occupants. Furthermore, all above factors become unimportant if the occupants are not present in the office/building. Thus, detecting the presence of occupants is extremely important. Presence can be either detected by means of proper “sensors” or inferred through, for example, smartphones, tablets, laptops, Personal Computers (PCs), attendance recorders, or in an indirect way by means of physical measurement (for example of CO<sub>2</sub>).

On the other hand, direct acquisition of parameters characterizing the occupants’ satisfaction eliminates the need for a general comfort model even if it introduces another relevant problem, as individuals perceive different levels of comfort and, often, these levels are in conflict. For instance, some occupants could consider the temperature in the building too low, while some others could consider it too high. If the group of occupants cannot control separately the various environmental parameters like the temperature, then a trade-off among the different individual satisfactions of these occupants and energy efficiency need to be achieved. The control system of the HVAC system will be designed so as to take into account all the objectives, which are typically in conflict to each other. Thus, the optimization process will not result in a single optimal solution. Instead, the control system will suggest a set of possible solutions with different trade-offs among the objectives.

These solutions will be first filtered by considering contextual factors and constraints, such as maintaining safety and healthy parameters and some non-subjective elements, such as the meteorological forecasting (if the weather will be sunny and warm is not relevant if the indication of a user is concerning a cold sensation). Finally, the filtered options will form the set of possible choices for the occupants during the actuation phase that determines feedback on the operation of the HVAC system.

Unlike many energy management systems presented in the literature, a control system based on this strong interaction with the occupants does not require a model of the building. Instead, it dynamically builds a “just-enough-accurate” model, which is sufficient to provide optimal decisions.

In this perspective, employing humans—in addition to, or even instead of, sensors—to assess the health and comfort level will allow the reduction of hardware and deployment costs. Furthermore, to limit the number of energy meters, innovative strategies for non-intrusive appliance monitoring will be also employed. These strategies aim to detect the power consumption of individual electrical appliances, or parts of a circuit, by analyzing the variations in the aggregate power absorbed by the circuit. Furthermore, “soft sensors” will be used for determining the presence/absence of occupants in the building. Soft sensors can be easily implemented by exploiting devices already available in the building for other purposes (e.g., smartphones, tablets, laptops, PCs, attendance recorders, card-enabled doors, etc.) and, hence, they have a reduced cost. Information provided by soft sensors, in conjunction with platform–occupant interactions, can considerably improve the control strategies for the HVAC system, with the result of energy savings. With respect to the former methods, the founding idea is of a deep involvement of the occupants in the management system of the building, relying on them as both sensors and actuators. This means that the pervasive supporting system will lead people towards energy-aware behaviors, taking into account the user feedback also on the perceived comfort in the surrounding environment. The user, along with the whole community of the building occupants, will (partly) be in charge of the energetic efficiency of the system they daily live in, and



will feel more and more responsible for it. In practice, the user will be pushed towards wise behavior as they will participate in a social game/community via ordinary personal devices like smartphones, tablets, and desktops.

Using an adaptive multi-objective controller, the involved people will become in-the-loop control components. Furthermore, the integration with the existing energy management system will be flexible, depending on the possibility to practically drive in-place devices. Yet another level of flexibility is given by the fact that a thorough energetic model of the building is not mandatory for the multi-objective controller. As a consequence of this high degree of adaptability, energy savings become achievable potentially in any context. Moreover, the proposed solution for control and optimization does not require significant investment; its adoption is almost effortless.

Finally, the occupants' habits, in some specific cases, to increase energetically wise behaviors will also bring benefits out of the public building environments, thus achieving further beneficial effects, like major productivity for the motivation of working in a "good" environmental situation and energy savings. As an important concept in such a kind of project's setting, in which humans are expected to act as both sensors and actuators, some stimuli, incentives, or training would be required to adopt the desired behaviors. Employing traditional learning techniques, such as a training course, is expensive and usually poorly effective. Instead, the engagement could be easily obtained by means of modern persuasive methods, such as a specific form of social gaming, for achieving the following objectives:

1. Collect the satisfaction and comfort level of occupants about the environmental conditions.
2. Motivate occupants to become active parts of the methods applied and engage with the applications used for sensing their preferences.
3. Motivate occupants to be actively involved in the decision processes implemented via the multi-objective control system, by means of a cooperative group approach.
4. Drive the occupants toward following correct behavior and practices that lead to improvement of the environmental quality and the energy efficiency.

The specific features that characterize the multi-objective controller must be defined. In particular, the conflicting objectives, the inputs of the controller, and the desired output have to be identified. Such work will allow an appropriate optimization scheme to be applied in a dynamic and complex environment with emphasis on optimization and control design requirements operating under a "big data" environment with many different "sensors" being able to provide information to the system. The analysis will have to take into account the possibility for the users to act not only as sensors but also as actuators. In this context, the requirements for optimizing the users' "obedience" in performing the actions suggested by the control/optimization system must be analyzed.

### **3. The Potential Role of ICT Systems (Platforms) and Human Interaction for Combining IAQ Control, Human Comfort, and Energy Consumption of HVAC System**

A surely viable option for obtaining a strong interaction between the control system and the occupants of a building could be represented by the development of platforms based on Information (Internet) Communication Technologies (ICT). The use of ICT systems (platforms or app) is common today in a lot of fields and their use could be interesting in connection with the optimum design problem of balancing energy efficiency, safety, and comfort.

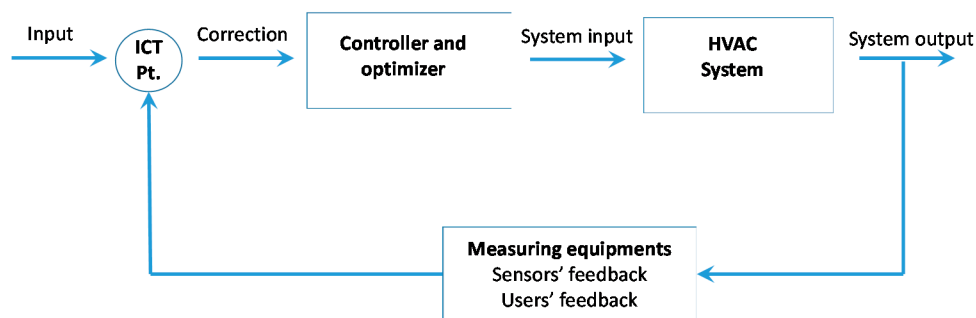
Such a kind of platform must be constructed with the capability of being able to acquire data from the people and based on a multi-objective control system that will balance safety requirements, energy savings, and occupants' comfort in the controlled building.

One of the most critical limitations of the platforms for energy efficiency in buildings proposed in the last years has been just their cost, according to [16]. Indeed, those platforms require a large number of sensors, energy metering systems, and actuators for controlling the main relevant parameters and the energy consumption in the buildings. Thus, although these systems have resulted to be very effective in terms of energy saving, the cost of the infrastructure deployment has always prevented

their wide spread. On the other hand, other systems just have focused on teaching correct behaviors to the consumers without any control action on the building. Although these systems are not expensive, their effectiveness in practice has to be quite low.

Nowadays, the platforms can be based on the use of ICT technologies, saving a lot of money connected with the use of physical sensors (for temperature, humidity, lighting, acoustics, and air pollutants, such as CO<sub>2</sub> concentration and volatile organic compounds in general).

The platform that can be designed will interact with the occupants as well as with the control system and with all the sensors already installed in buildings and to complement it; a possible architecture is shown in Figure 3. The occupants' engagement can be achieved by using specific apparatuses or by means of personal devices (e.g., smartphones, tablets), via communications mediated by specific human–computer interfaces.



**Figure 3.** The logic of the Information and Communication Technologies (ICT) platform for feedback coming from both sensors and users on the Heating, Ventilation, and Air Cooling (HVAC) system.

The ICT platform must be able to interact with the control system of the HVAC and possibly of other systems, taking into account the inputs from the occupants as well as measurements collected by the various sensors (both physical sensors, like temperature, humidity, and CO<sub>2</sub> concentration, often available, and data coming from smartphones or personal devices, capitalizing on their multiple in-build sensing capabilities) deployed in the building. The beneficial effect of using this ICT platform could be the following:

- The use of the data of the ICT platform will substitute an accurate model of the building and the occupant behavior, thus saving potentially several person-years in developing appropriate models, which in any case would only reflect the system state at the time of development. By embedding learning and self-adapting capabilities, the platform intrinsically, and during its operation, will continuously build a “just-enough-accurate” model for the building/occupant behavior, which will be sufficient to determine optimal decisions.
- It must reduce the risk that occupants can override the decisions of the ICT platform and/or not to adopt its recommendations; the control system will be able to compute the optimal decisions, while maximizing the likelihood that the occupants adopt them. To this aim, an iterative procedure based on the learning and self-adapting mechanisms embedded in the control system is required. Such a procedure will provide the control decisions to the occupants, will compute how much the occupants' actions are consistent with these decisions, and will calibrate the decision-making mechanism so as to “close the gap” between decisions and occupants' actions.
- Energy awareness will be boosted by the interaction of each occupant with the platform through gamification techniques—wise behaviors, resulting in greater energy efficiency, will naturally emerge as a consequence of the participation to this kind of “social game”. Thus, the occupants will not perceive the platform as a master/teacher but rather as a playmate. The increase of awareness will be measured directly by evaluating the occupants' behavior over time, while interacting with the platform.



- The interaction between the ICT platform and the occupants will be designed so as to minimize the impact of energy-saving strategies on the daily work. The platform should surely contribute to create a more comfortable working environment, thus boosting productivity. The impact of using the ICT platform on the daily work will be evaluated by comparing the levels of productivity before and after the adoption of the platform in some case studies considered for experimentation.

The interaction between the occupants and the control system could permit some possible optimization strategies, not only concerning the HVAC system, but for organization too. For example, in some particular cases of offices or service buildings, it could be possible to cluster occupants with similar profiles. For instance, we could discover that a number of users in a building prefer to work without an air conditioning system. Thus, exploiting the comfort profiles, the placement of the occupants could be, in some particular cases re-organized based on similar comfort perception rather than on similar working activities. Moreover, clusters will allow us to determine possible “outliers”, i.e., occupants with a comfort perception different from the majority.

Finally, the behavior of the various occupants will be shared socially within the same building and/or among different buildings (e.g., buildings belonging to the same organization). The aim is to share virtuous behavior and show that high comfort levels and energy savings can be obtained by constructive social interactions without decreasing the level of comfort perceived by each occupant.

The positive impact of such a kind of platform can be important in publicly owned buildings and buildings for public use. It could be interesting to evaluate the impact of the platform in terms of energy consumption reduction, consumer understanding, and engagement in energy efficiency.

Further, it is possible to evaluate how and how much the approach based on a strong social interaction between the platform and the occupants will increase their energy awareness. In some specific contexts like public offices, the actions of the occupants of buildings affect significantly the overall consumption by controlling MELs connected to the electrical grid, such as computers, copiers and printers, controlling overhead and task lights, and in some cases, the thermal environment via thermostats, personal fans and heaters, and shades and operable windows; this increase in awareness can allow for the saving of considerable energy amounts.

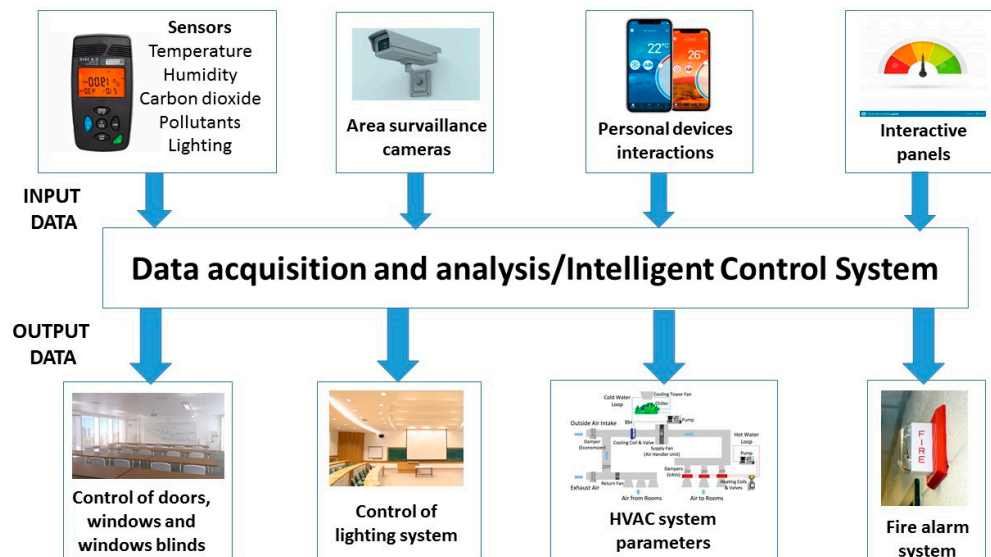
To stimulate the interaction of the occupants with the ICT platform, each occupant will be involved in a kind of social game. The social game will be designed so as to achieve the three following main objectives. First, the game will allow the collection of the individual satisfaction of each occupant with the different parameters defining comfort, thus making the occupants as an interactive part of the gaming strategies. Second, it will drive the occupants to act as actuators of the strategies determined by the multi-objective control system using a cooperative, rather than a coercive, approach. For instance, the game will provide a number of possible options to the occupants, with different potential impacts. The occupants will have the opportunity of deciding among the proposed options, thus having the perception of being actively involved in the decision process. Third, the strategy of the game will drive the occupants to follow correct behavior and practices for increasing energy efficiency. They will naturally emerge as a consequence of the participation in a kind of “social game”. Thus, occupants will not perceive the platform as a kind of “controller” but, rather, as a playmate. In this sense, the building ICT will ensure an optimized environment and energy management by supporting design, monitoring, and control with self-learning capacities. For occupants, ICT will provide user information, enhancing comfort and optimal indoor conditions, as well as enabling real time communication and interactions with the control system in order to prevent problems.

#### **4. A Specific Proposal for the Construction of a Specific ICT Platform for Assisting the Control System and Retrofitting of HVAC for Indoor Spaces**

In the previous section, the author has discussed the possible development of a specific ICT platform aimed at balancing the objective of maintaining conditions of IAQ and comfort, and maintaining an adequate energy efficiency in public buildings, through a strong interaction with the occupants. The question is always open, and a lot of solutions could be available, but some ideas concerning

its structure are here defined. The proposed ICT platform is complementary to the existing energy management systems and will take advantage from the interaction with the occupants.

A possible architecture of the system including the platform for the collection and elaboration of the data coming from the sensors and from the occupants is represented in Figure 4.



**Figure 4.** A possible scheme of the ICT-based control system and of the possible interactions.

As stated in the introduction, the people inside the indoor space can act at the same time as sensors and as “actuators”, being active subjects in the intelligent control system.

As sensors, they can provide information about their perceived comfort level or by other relevant elements concerning the environmental quality, by interacting with the platform and the other occupants within a kind of social game. The control system will take into account the inputs from the occupants as well as measurements collected by sensors (which will include smartphones, capitalizing on their multiple in-built sensing capabilities) deployed in the building, like those for temperature, humidity, and CO<sub>2</sub> concentration, so as to find the best trade-off between IAQ, global perceived comfort, energy saving, and maintaining safe conditions too.

The platform could be arranged according to the following characteristics, basing on some general indication that can be extracted by the existing general guidelines:

- (1) It must be organized to let different IT components collaborate in a harmonious way, under the coordination of a multi-objective controller, and implement the core components according to a SOA (Service Oriented Architecture) vision.
- (2) It will exploit data gathered from real sensors and from people that act as indirect sensors, making use of information generated by energy consumers, e.g., through social networks or captured from sensors.
- (3) It will pay special attention to the effective involvement of occupants by dedicating adequate effort to the design of proper human/computer interfaces (mostly for mobile devices) on one side, and to the shaping of a “gamification” strategy for supporting a social game on the other side. These applications range from apps for smart phones and tablets to serious games to empower consumers to stimulate collaboration and enable full participation.
- (4) It must be applied in different operating conditions, addressing different kinds of public buildings in different countries and with different functions (a bank, a hospital, commercial centers, administration offices), adopting different energetic solutions. Strictly speaking, it should

be deployed and validated in real life conditions in publicly owned buildings (including administrative offices, social housing) and buildings in public use or of public interest.

- (5) It will be paired to a new business model. The envisioned business model proposes the adoption of an ICT platform as a collection of services (mostly IT ones) provided by specialized companies that will be in charge of pairing energy management systems already present in public buildings with the required IT infrastructure. IT components will be basically used in the form of services, available “in the cloud” (more precisely, in the form of Software-as-a-Service (SaaS)).

Concerning the last points, cloud computing solutions typically ask for minimal investments, with no need of planned amortization. Moreover, data on the actual energetic features of the building, collected by the ICT platform, can then be analyzed offline to understand whether more concrete actions may be sustainable from an economic point of view too. In this perspective, validation should provide socio-economic evidence for ICT investment in the field and include detailed plans for sustainability and large-scale uptake beyond the project’s lifetime. Specific attention should be given to development and testing of “cleanweb” solutions, which not only bring opportunities for consumers, but also represent a promising investment field.

Obtaining the aforementioned purposes, the development of such a kind of ICT platform requires a number of different competencies on energy engineering, control engineering, sensor networks, approximate reasoning, social sciences, social networks, psychology, recommender systems, gamification techniques, human–computer interface and User Experience (UX) design, and service-oriented architectures, which are all necessary to achieve the ambitious objectives of the idea.

One of the most relevant objectives of the ICT platform is to obtain control of the indoor air quality parameters and achieving a control of the level energy consumption, and consequently of energy production and emissions connected to the public buildings. To attain this objective, the ICT platform exploits three different mechanisms that work synergically:

- (1) A multi-objective control system, which elaborates strategies for controlling the operation of the HVAC system in order to reduce the energy consumption, preserving the perceived comfort of the building occupants. The system will intensely exploit the interaction with the occupants, who act as both sensors and actuators. The control system will elaborate strategies for the operation of the HVAC system with the objective of saving energy, which will be shared with the occupants by gamification techniques. We expect that the control actions will be less and less intrusive with time passing.
- (2) A greater consumer energy awareness boosted by the interaction of each occupant with the ICT platform through a kind of social game; wise behaviors, resulting in greater energy efficiency, will naturally emerge as a consequence of the participation in the game. Especially in old non-automatized buildings, 20–50% of total energy use is controlled or impacted by occupants, as in Šujanová et al. [20]. Thus, an increased awareness can impact significantly on energy saving. Further, the correct behaviors in terms of energy use learned by the interaction with the ICT platform at work will be also transferred to the domestic use, thus producing a further energy saving with beneficial effects on the reduction of production and emissions.
- (3) A greater consumer understanding on how comfort perception can be also affected by their own behavior. As stressed in the previous parts, comfort perception and corresponding satisfaction are subjective. However, the perceived comfort is often influenced by wrong behaviors. For instance, some individuals tend to dress just for fashion in light clothes and then complain that they are cold, asking for an increase in the room temperature. The ICT platform can be also arranged for advising those persons that their perception is very far from that of the other occupants and will suggest possible causes and solutions. Thus, the comparison between the perceptions of the single individual and of the majority of the building occupants will boost each occupant to follow correct behaviors for trying to make their comfort satisfaction similar to the ones of the

other occupants. In the context of the social game, this will be supported by pointing out that complaints of an individual are penalizing the overall team in terms of energy efficiency. Hence, the ICT platform will try to teach to each occupant that comfort perception can be affected by using correct behaviors, so as to achieve a shared uniform group or social comfort perception.

## 5. Evaluation of the Beneficial Effects with Reference to a Specific Case Study

In order to show the potential of a positive interaction among the various occupants and the control system for the HVAC, the potential of the methodology has been analyzed, referring to a real case. This is represented by a classroom building of the School of Engineering of the University of Pisa, in Pisa. In this case, students' attendance is based on pre-pandemic schedules of classrooms.

The meteorological conditions are the ones obtained in the last year by an in-house weather station, located within the Engineering School area. The characteristics of the classroom building under analysis is reported below. The last reconstruction of the building is dated 2004; the building is constructed with brick masonry walls, with average vertical-wall thickness of 35 cm. Window-to-floor area ratio is about 0.15. The surface is about 2400 m<sup>2</sup>, and the volume is about 10,080 m<sup>3</sup> with one floor. Nine classrooms are present in the building for a maximum of 1424 available seats. Figure 5 shows the typical profile of occupation along the year 2010 in a typical pre-COVID-19 situation.

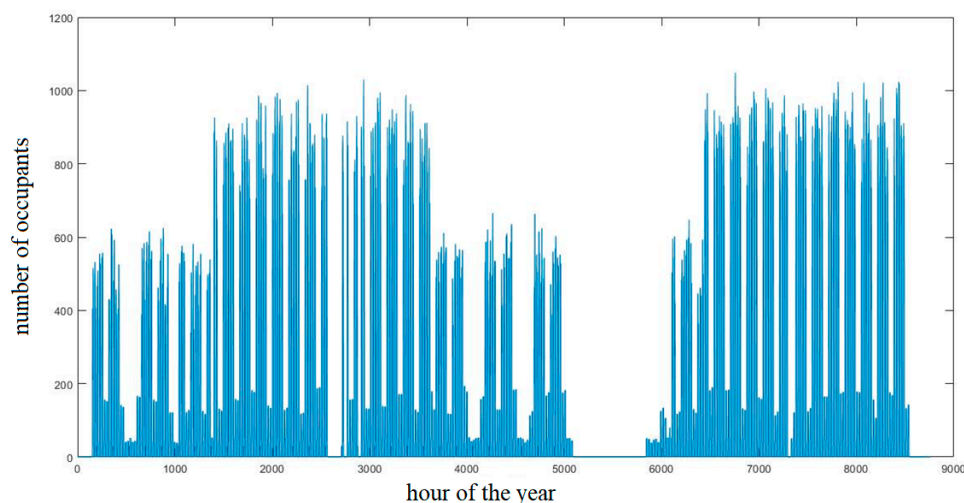


Figure 5. Profile of students' presence in Building F (School of Engineering, University of Pisa).

Figure 6 provides the temperature dispersion in the various hours of the year in the building. Cold and hot seasons for the operation of the HVAC system are evidenced with the black vertical lines. Considering this, Figure 7 put in evidence the evaluation of the PPD indicator, calculated according to Fanger's model [29]. According to this, it can be evidenced that in some cases the temperature appears to be quite high (in particular, during the winter season) or quite low (during the hot season) and the value of PPD is shown.

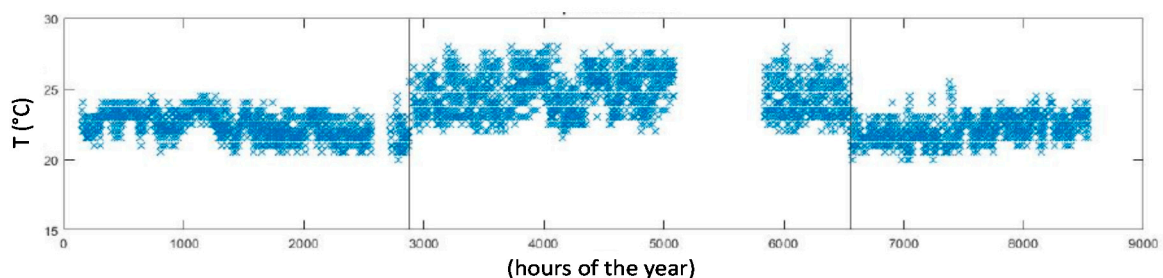
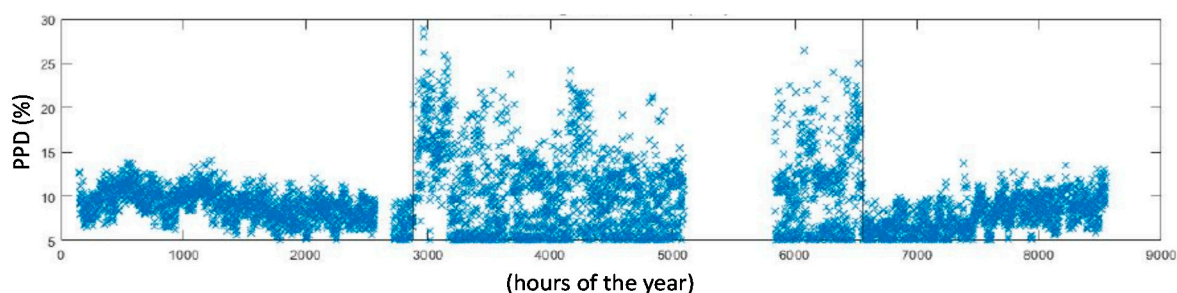


Figure 6. Values of the temperature in the buildings during the various hours of the year.



**Figure 7.** Values of the Predicted Percentage of Dissatisfied (PPD) index obtained according to Fanger's index [29] in the various hours of the year.

Considering the possibility of reducing the PPD values, as reported in Figure 6, mainly operating on the heating and cooling systems operation in the phase in which the PPD indicator is over the value of 10%, a relevant amount of energy saving is possible. Considering the use of a simplified thermal model of the building and using a demand-controlled ventilation rate directly correlated with the number of occupants, as described in [33], this can be estimated in the range between 15 and 30%, in dependence of the climatic condition, with respect to the energy consumption estimated in a typical year of operation.

Another interesting point of the proposed ICT platform is the fact that the analysis of a building during a relevant period of time could permit the definition of a “just-enough-accurate” model for the building/occupant behavior and for a building dynamic simulation, that can be constructed only using data and without any necessity for defining a physical model of the system.

The final considerations are in the perspective of the post-COVID-19 pandemic systems, as HVAC systems for public building services are going to become more and more advanced in response to the urgency of accurate IAQ control. A new social perception of indoor environments is emerging, with immediate consequences on the design, operation, and maintenance of HVAC systems. Schools and universities, shut almost worldwide during the epidemic emergency, should be promptly re-opened, to avoid a long-term impact on students, not only from the educational point of view, but also from the social and psychological standpoints. As the crowding index of educational buildings are typically high, to comply with new hygienic-sanitary rules, the air changes with fresh (uncirculated) air are going to be increasingly demanding in terms of energy usage. This issue calls for new energy-management solutions, to face the health emergency without disregarding the equally important climate emergency.

## 6. Conclusions

People that operate in indoor spaces, like students in classroom, employers in office buildings or workers and consumers in public buildings in general, are at the same time, both the prime beneficiaries of proper control management of IEQ conditions and the main players in devising the best pathway to maintain environmental quality and promote energy savings. This is the founding idea of the paper, that proposes the development of a cross-disciplinary ICT system (platform), intended to drive the move from an opportune trade-off between “indoor air quality”, “comfort”, “energy awareness”, and control of “safety” conditions. The problem has been already explored in the past, mostly towards the concept of “energy wisdom”, intended as a crucial element to get sustainability.

In practice, by leveraging sensing devices and information from the occupants in a concerted way, a multi-objective control system will attain energy savings whilst balancing user comfort and safety conditions. This objective must be now combined with other objectives concerning the need of strict air quality control, in order to prevent safety problems for the occupants, related to the control of the correct occupation of the spaces, to the maintenance of idoneous environmental parameters, to prevent problems related to smoke and fire and comfort condition (acoustics, light, temperature, humidity, and pollutant concentration). The platform, operating with a lot of data coming from physical sensors

and people, will act as a kind of glue of a social community formed by the occupants of the building (workers or users). The interaction within the community will supply inputs to the control system used for applying control strategies aimed at controlling the indoor air quality level, reducing energy consumption, and at increasing the satisfaction of the occupants.

With respect to the state of the art, the added value of the proposed methodology for a post-pandemic scenario can be summarized as follows:

- The platform considers several systems operating in the building (HVAC, lighting, MELs, e.g., computers, and ICT equipment, physical sensors, personal equipment like smartphones or tablets), and applies multi-objective optimal solutions to minimize the energy consumption, maintaining the correct levels of comfort and safe air quality for the users.
- The platform relies on gamification techniques, to promote the cooperation of the occupants and increase their understanding and engagement in IAQ control and energy efficiency.
- Users are actively involved in the process, acting as both (human) sensors and actuators.
- The ICT platform does not require an explicit and accurate model of the building and of the occupants' behavior, being based only on the data acquired.
- An intrusive and expensive monitoring system is not necessary for deployment and operation of the ICT platform. Soft sensors can pair with traditional sensors, and smart solutions can be applied whenever possible.

The main critical element is to motivate the occupants to interact with the ICT platform, but it is possible to think that the recent problem related to the COVID-19 pandemic could motivate people to contribute in a more effective way with respect to the recent past. The occupants can interact with the platform using a mobile app deployed on their smartphones or tablets, or a web application, and they can act as both sensors and actuators. As sensors, they provide information about their perceived comfort, by interacting with the platform and the other occupants, within a kind of social game. As actuators, they collaborate with the platform to implement the devised strategy.

Evaluation of the impact of the ICT platform in terms of energy savings, costs, usability, maintenance, and intrusiveness have to be specifically evaluated. It is difficult to quantify the positive effect of this interaction and the possible amount of energy saving that can be achieved by the synergic action of the various elements. Indeed, it strongly depends on the building features and use, and in the case of active participation of the users. Considering that in a case study analyzed of a building classroom of Pisa, the reduction of the PPD index can be obtained with an estimated reduction of the energy required for the operation of the HVAC system is expected to be certainly between a lower bound of 15% and the upper bound of 30%. The proposed ICT platform, promoting the active contribution of users for defining an optimized control strategy for the HVAC system, can contribute to reduce the costs related to the control system and sensors.

**Funding:** This research was funded by the University of Pisa (PRA 2018–19, project no. 2018\_38).

**Acknowledgments:** The author would like to acknowledge the University of Pisa, for the financial support given for the publication and Michele Rocca, at the University of Pisa, for the ideas expressed in his public dissertation for Ph.D. examination, that gave origin to the present analysis.

**Conflicts of Interest:** The author declares no conflict of interest.



## Abbreviations

ET	Effective Temperature
HVAC	Heating Ventilation and Air Cooling
IAQ	Indoor Air Quality
ICT	Information and Communication Technologies
IEQ	Indoor Environmental Quality
IoT	Internet of Things
IT	Information Technologies
MEL	Miscellaneous Electric Loads
NILM	Non-Intrusive Load Monitoring
PC	Personal Computers
PPD	Predicted Percentage of Dissatisfied
PPV	Predicted Mean Vote
SaaS	Software as a Service
SOA	Service Oriented Architecture
UX	User Experience

## References

- 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]
- Klein, L.; Kwak, Y.J.; Kavulya, G.; Jazizadeh, F.; Becerik-Gerber, B.; Varakantham, P.; Tambe, M. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. *Autom. Constr.* **2012**, *22*, 525–536. [CrossRef]
- Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. Buildings Energy Data Book. 2011. Available online: <https://ieer.org/resource/energy-issues/2011-buildings-energy-data-book/> (accessed on 28 August 2020).
- Norbäck, D. Future Directions of Research on Indoor Environment, Indoor Air Quality (IAQ), and Health. In *Indoor Environmental Quality and Health Risk toward Healthier Environment for All. Current Topics in Environmental Health and Preventive Medicine*; Kishi, R., Norbäck, D., Araki, A., Eds.; Springer: Singapore, 2020.
- Fantozzi, F.; Rocca, M. An Extensive Collection of Evaluation Indicators to Assess Occupants' Health and Comfort in Indoor Environment. *Atmosphere* **2000**, *11*, 90. [CrossRef]
- Chang, S.; Yang, P.P.J.; Yamagata, Y.; Tobey, M.B. Modeling and design of smart buildings. In *Urban Systems Design: Creating Sustainable Smart Cities in the Internet of Things Era*; Yamagata, Y., Yang, P., Eds.; Elsevier Inc.: Amsterdam, The Netherlands, 2020; Chapter 3.
- Yang, R.; Wang, L. Development of multi-agent system for building energy and comfort management based on occupant behaviors. *Energy Build.* **2013**, *56*, 1–7. [CrossRef]
- European Energy Agency. Achieving Energy Efficiency through Behaviour Change: What Does It Take? Technical Report. May 2013. Available online: <http://www.eea.europa.eu/publications/achievingenergy-efficiency-through-behaviour> (accessed on 27 August 2020).
- Winett, R.A.; Kagel, J.H.; Battalio, R.C.; Winkler, R.C. Effects of monetary rebates, feedback, and information on residential electricity conservation. *J. Appl. Psychol.* **1978**, *63*, 73–80. [CrossRef]
- Brohmann, B.; Cames, M.; Gores, S. Conceptual Framework on Consumer Behaviour—With a Focus on Energy Savings in Buildings. IDEAL-EPBD Project Report (2009) for the EU Under the Intelligent Energy Europe Pr. 2009. Available online: [http://www.ideal-epbd.eu/download/conceptual\\_framework.pdf](http://www.ideal-epbd.eu/download/conceptual_framework.pdf) (accessed on 27 August 2020).
- Castilla, M.; Álvarez, J.D.; Berenguel, M.; Rodríguez, F.; Guzmán, J.L.; Pérez, M. A comparison of thermal comfort predictive control strategies. *Energy Build.* **2001**, *43*, 2737–2746. [CrossRef]
- Yang, R.; Wang, L. Multi-objective optimization for decision-making of energy and comfort management in building automation and control. *Sust. Cities Soc.* **2012**, *2*, 1–7. [CrossRef]
- Nguyen, T.A.; Aiello, M. Energy intelligent buildings based on user activity: A survey. *Energy Build.* **2013**, *56*, 244–257. [CrossRef]

14. Wang, L.; Wang, Z.; Yang, R. Intelligent multiagent control system for energy and comfort management in smart and sustainable buildings. *IEEE Trans. Smart Grid* **2012**, *3*, 605–617. [CrossRef]
15. Zhang, H.; Arens, E.; Huizenga, C.; Han, T. Thermal sensation and comfort models for non-uniform and transient environments, Part III: Whole-body sensation and comfort. *Build. Environ.* **2010**, *45*, 399–410. [CrossRef]
16. 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]
17. Pnga, E.; Srinivasan, S.; Bekiroglu, K.; Chaoyang, J.; Sua, R.; Poolla, K. An internet of things upgrade for smart and scalable heating, ventilation and air-conditioning control in commercial buildings. *Appl. Energy* **2019**, *239*, 408–424. [CrossRef]
18. Franco, A.; Leccese, F.; Marchi, L. Occupancy modelling of buildings based on CO<sub>2</sub> concentration measurements: An experimental analysis. *J. Phys. Conf. Ser.* **2019**, *1224*, 012016. [CrossRef]
19. De Paola, A.; Ortolani, M.; Lo Re, G.; Anastasi, G.; Das, S.K. Intelligent Management Systems for Energy Efficiency in Buildings: A Survey. *ACM Comput. Surv.* **2014**, *47*, 1–38. [CrossRef]
20. Šujanová, P.; Rychtáriková, M.; Mayor, T.S.; Hyder, A. A Healthy Energy-Efficient and Comfortable Indoor Environment, a Review. *Energies* **2019**, *12*, 1414. [CrossRef]
21. Mujan, I.; Andelkovic, A.S.; Muncan, V.; Kljajic, M.; Ruzic, D. Influence of indoor environmental quality on human health and productivity—Review. *J. Clean. Prod.* **2019**, *217*, 646–657. [CrossRef]
22. BESTEnergy—Built Environment Sustainability and Technology in Energy, ICT-PSP Project (Ref: 238889). 1 February 2009–31 June 2012. Available online: <http://www.bestenergyproject.eu/> (accessed on 27 August 2020).
23. HOSPILOT—Intelligent Energy Efficiency Control in Hospitals, EU Project (Ref: 238933). 22 March 2009–29 February 2012. Available online: <https://cordis.europa.eu/project/id/238933> (accessed on 27 August 2020).
24. KNOHOLEM—Knowledge-Based Energy Management for Public Buildings through Holistic Information Modeling and 3D Visualization, FP7-ICT Project (Ref: 285229). 1 September 2011–31 August 2014. Available online: <https://cordis.europa.eu/project/id/285229> (accessed on 27 August 2020).
25. SEEMPUBS—Smart Energy Efficient Middleware for Public Spaces, FP7-ICT Project (Ref: 260139). 1 September 2010–31 August 2013. Available online: <https://cordis.europa.eu/project/id/260139/> (accessed on 27 August 2020).
26. A2PBEER—Affordable and Adaptable Public Buildings through Energy Efficient Retrofitting, FP7-NMP Project (Ref: 609060). 1 September 2013–28 February 2018. Available online: <http://www.a2pbeer.eu/> (accessed on 27 August 2020).
27. SMARTSPACES—Saving Energy in Europe’s Public Buildings Using ICT, ICT-PSP Project. (Ref: 292773). 1 January 2012–31 December 2014. Available online: <https://cordis.europa.eu/project/id/292773> (accessed on 27 August 2020).
28. SENCULT—Efficient ENergy for EU Cultural Heritage, FP7-ENVIRONMENT project (Ref: 260162). 1 October 2010–31 March 2014. Available online: <http://www.3encult.eu/> (accessed on 27 August 2020).
29. Fanger, P.O. Introduction of the olf and the decipol Units to Quantify Air Pollution Perceived by Humans Indoors and Outdoors. *Energy Build.* **1988**, *12*, 1–6. [CrossRef]
30. Cony, L.R.S.; Abadie, M.; Wargocki, P.; Rode, C. Towards the definition of indicators for assessment of indoor air quality and energy performance in low-energy residential buildings. *Energy Build.* **2017**, *152*, 492–502. [CrossRef]
31. Wei, W.; Ramalho, O.; Derbez, M.; Riberon, J.; Kirchner, S.; Mandin, C. Applicability and relevance of six indoor air quality indexes. *Build. Environ.* **2016**, *109*, 42–49. [CrossRef]
32. Luo, N.; Weng, W.; Xu, X.; Hong, T.; Fu, M.; Su, K. Assessment of occupant-behavior based indoor air quality and its impacts on human exposure risk: A case study based on the wildfires in Northern California. *Sci. Total Environ.* **2019**, *686*, 1251–1261. [CrossRef] [PubMed]
33. Franco, A.; Schito, E. Definition of Optimal Ventilation Rates for Balancing Comfort and Energy Use in Indoor Spaces Using CO<sub>2</sub> Concentration Data. *Buildings* **2020**, *10*, 135. [CrossRef]

