A Comprehensive Review of Adaptive Building Energy Management Systems Based on Users' Feedback

P. Nafisi Poor, P. Javid

Abstract—Over the past few years, the idea of adaptive buildings and specifically, adaptive building energy management systems (ABEMS) has become popular. Well-performed management in terms of energy is to create a balance between energy consumption and user comfort; therefore, in new energy management models, efficient energy consumption is not the sole factor and the user's comfortability is also considered in the calculations. One of the main ways of measuring this factor is by analyzing user feedback on the conditions to understand whether they are satisfied with conditions or not. This paper provides a comprehensive review of recent approaches towards energy management systems based on users' feedbacks and subsequently performs a comparison between them premised upon their efficiency and accuracy to understand which approaches were more accurate and which ones resulted in a more efficient way of minimizing energy consumption while maintaining users' comfortability. It was concluded that the highest accuracy rate among the presented works was 95% accuracy in determining satisfaction and up to 51.08% energy savings can be achieved without disturbing user's comfort. Considering the growing interest in designing and developing adaptive buildings, these studies can support diverse inquiries about this subject and can be used as a resource to support studies and researches towards efficient energy consumption while maintaining the comfortability of users.

Keywords—Adaptive buildings, energy efficiency, intelligent buildings, user comfortability.

I. INTRODUCTION

LIVING systems develop survival strategies through an evolutionary process. The utilization of this strategy and morphological properties of nature in non-biological sciences is called "Biomimetics" and it is being used widely in engineering. Nowadays the interest in this particular field is growing rapidly, believing that these properties are able to bring novel approaches to building technologies and cause significant improvements in overall performance. New technologies adapt themselves to the changing environmental conditions, perform multiple functions and are coming in the form of de-centralized controls for occupants [1].

The concept of adaptiveness begins with the biological insight that the human being is a comfort-seeking animal, willing to have interaction with the environment in ways that secure his/her comfort [2]. This biological fact leads to a principle called "Adaptive Principle" which dictates that people will always respond to environmental or more

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specifically thermal changes to make sure their comfort is restored [3]. These reactions are known as adaptation. The adaptation principle indicates that a person is not a passive receiver of sense impressions but quite the opposite, and acts as an active participant in dynamic balance with the thermal environment. Therefore, people together including their physical and social environment need to be considered as a "Dynamic system". Significant distancing from this dynamic system's neutral state, whether as a result of a change in an individual's requirements or a change in the thermal environment, is likely to cause "Discomfort" while on the other hand, if the changes are towards the neutral state, it is likely to result in "Comfort" or in other words, thermal pleasure. Based on this theory, comfort and discomfort are dynamic in character [2].

This paper aims to understand the basics of adaptation, the reasons we need adaptive and flexible energy management systems and, analyze related works in this area of research. So, this document is organized as follows: The following section gives an overview of adaptive systems and studies the basics and roots of adaptation in order to understand the main concepts, Section III explains the reasons why adaptive energy management systems are becoming so popular and necessary, Section IV describes user feedback-based systems to understand their workflow, Section V studies related works in the field of adaptive energy management systems based on user needs and feedbacks and, following a comparison between these works on Section VI, the main conclusions of this study are listed in Section VII.

II. ADAPTATION

Adaptation can be described as a set of learning processes, so people might be expected to adapt well to their usual environments and they feel hot when the temperature is higher than "usual" and the same for feeling cold [2]. This usual temperature is also referred to as "reasonable" in [2] and [4], and they tried to develop standards and guidelines for the interpretation of this reasonable temperature which will be elaborated further in Section III.

A. Adaptation Actions

In general, when the conditions are not in favor of an individual, a set of conceivable adaptive actions in response to warmth or coolness may occur that can be listed in five categories [2]:
- Changing the rater of internal generation,

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- Changing the rate of body heat loss,
- Changing the thermal environment,
- Choosing a different thermal environment,
- Changing the body's physiological comfort conditions.

These actions do not necessarily take place individually and one may try to do a mixture of these and also, they may not be noticeable for instance when an individual feels cold, he may put on a small piece of clothing or change the temperature of the room for one degree.

B. Circumstances and Restrictions

Each human is unique, not just in sensing and perception of thermal comfort [5] but in many other fields. These differences create circumstances and circumstances lead to restrictions in terms of adaptation. There are many restrictions caused by various circumstances but three of them are the most important since they have more influence on the process of adaptation:

1. Climate: climate affects many aspects of human life including the daily pattern of work and rest, people's eating habits and diets, their way of wearing and clothing, the design of the buildings, and further, the way of using and living within the building.
2. Wealth: different levels of society may influence people's expectation of their environment, for instance, rich people usually expect to have comfort ranges different from the poor and therefore their perception of adapting to the environment has narrower borders.
3. Culture: the culture of a nation will influence the styles of their buildings and the style of using them. Furthermore, the culture has a direct impact on the way people dress both inside and outside the building.

In addition to this list, there are other restrictions one may face in terms of adaptation like working conditions and social context, thermal control managed by others, fashion, gender, health, and even personality [2].

III. Adaptive Energy Management Systems

Premised upon the aforementioned data, there are various types of people with many differences, therefore considering a unit standard for all of them may not be as efficient as it is supposed to be especially, when it comes to energy consumption and energy management. Global energy consumption has been ascending over the past 50 years.

Developing low consumption and high-efficiency appliances had approximately no small part in reducing the consumption and production of greenhouse gases. It is important to consider that the fast growth of ubiquitous comfort services leads to higher power consumption [6].

Considering the dynamic nature of humans and energy consumption statistics over the past years, we can conclude that a different type of energy management is needed, an adaptive energy management system. Based on research conducted by Shizouka University, adaptability is the key feature of next-generation energy management [6]. Not only this, but other studies have indicated that standards such as ASHRAE [7] or Bedford either overestimate or underestimate a user's thermal comfort vote [8]-[13]. For instance, research done by Sharples and Malama in Zambia demonstrated that the ASHRAE has overestimated the lower limit by 2.7 degrees [8]. Also, when thermal units are managed by a constant set point, usually with a narrow bandwidth, the designer has to make assumptions about factors such as clothing or activity in order to find a suitable set point which cannot be accurate at any time [5]. In addition, the dynamic nature of humans is also one of the main reasons that demands adaptability in energy systems. Humphreys and Nicol noted that the comfort temperatures resulted from different field studies vary notably from one another and based on these results, thermal comfort needs to be considered as a part of a self-regulating system. In their study, they also mention that adaptive model and good ergonomic practice are quite the opposite since good ergonomic practice makes the user adapt to the environment while a good adaptive design provides sufficient adaptive opportunities and ensures that the environment is managed by the occupant [2]. Another study related to this field is done by Erickson and Cerpa, they report and analyze the results of one-year-long longitudinal surveys in six different countries around the world and named it Thermovote. Based on their surveys, they managed to categorize people in four clusters depending on their thermal comfort. Their clusters show that about 42% of people do not feel comfortable on "neutral" temperature [14]. These are the reasons why in recent years, researchers showed interest in developing automatically adaptative energy systems to the occupants [5].

Following the mentioned results, it can be concluded that a good adaptive system takes occupants' feedback into its consideration. A research conducted by Carriera et al. proves this theory. They indicate that an intelligent control situation that includes occupants' opinions in its factors is potentially capable of minimizing the consumption of energy while keeping the occupants comfortable [15].

IV. User Feedback-Based Systems

Since occupants' dissatisfaction with the indoor environment is recognized as one of the main causes of an interaction between BMS and occupants [16]-[19], one of the best ways to include occupants in the cycle of energy management is by analyzing their feedback.

The general concept is that a system or researcher - depending on whether the work is taking place in the real-world or just in theory – collects data on the thermal environment and the simultaneous thermal responses of the subject(s). These responses are usually evaluated by asking the occupants to vote upon their current thermal condition. After that, statistical methods are utilized in order to combine thermal variables such as room temperature, air velocity, and humidity, then based on that analysis, the system predicts a thermal comfort condition for future situations [5].

There are three ways of incorporating the feedback of the occupant(s) in an adaptive system:

1. Collecting the information directly from the user,
2. Collecting the information from the heating/cooling unit which is operated by the user,

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3. Collecting the information from physiological responses of human body.

The first case is the most common way of considering occupants in energy management and takes place when the occupant pushes a button or clicks on an option to tell the system that it is too hot or too cold [5]; this way of including occupants in the loop is also called OVS (Occupants Voting Systems). This term was first coined by Jung and Jazizadeh [20].

The options provided for the occupants are not limited to two (too hot, too cold) and can be added up to seven options [21].

Although more options might lead the system to measure more accurately, having various options together is more probable to confuse users and it usually needs users to respond to a series of questions that consumes more time and effort [22]. In addition to this factor, one of the main limitations of OVS is inconsistency. The reasons that cause this matter are:
1. Insufficient thermal scales,
2. Not taking other factors such as variation in clothing or physiological and psychological aspects into consideration,
3. Inaccuracy in measuring indoor thermal conditions such as temperature [23].

Another limitation of using votes is the need for occupants' dedication. Kim et al. [24] mention that users' participation was a challenging task in the process of collecting data in order to make personal thermal comfort profiles.

Besides voting, another way of collecting users' opinions is survey. In this way, researchers record users' opinions by having them filling a questionnaire asking them whether they are satisfied with the environment or not. The main problem with this method is that it is usually limited to a few weeks or months due to the challenges in gathering and analyzing human contributed data [22].

The second case happens when heating or cooling is operated by the user. In this case, the system considers this as a user wish since he/she tends to start the heating or cooling which means he/she does not feel comfortable [5].

Both of these cases require the system to measure, record, and learn the user's preferred temperature in order to predict the conditions for the next days. This learning process is done interactively based on the Reinforcement Learning (RL). Here a brief explanation of RL is provided for better understanding.

A. Reinforcement Learning (RL)

RL is a subgroup of machine learning and its origin goes back to 1960 and 1970 [25].

RL includes an agent, that learns by itself what actions need to be taken in an environment and it gets rewarded for its actions [26]. This process usually includes trials and errors from the agent as it tends to learn what actions lead to the highest rewards. In building energy management system, the reward can be efficient energy consumption, user satisfaction of a combination of both. Fig. 1 represents this interaction of an agent with its environment [25].
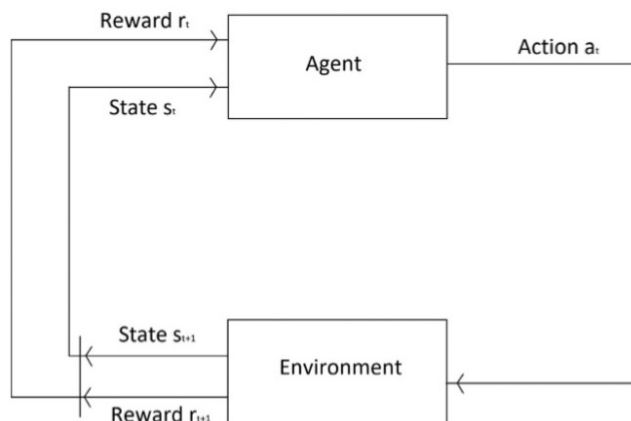

Fig. 1 Agent-Environment interaction

The third method is called PSS (Physiological Sensing System) and has gained a lot of attention recently. In this case, the system tries to monitor human bio-signals to reduce the need for direct interaction. The base theory of this method is that thermal comfort is a cognitive inference, depending on physical, physiological, and psychological factors and can be obtained when physiological efforts for regulating the thermal conditions of the body are minimized and the core body temperature is maintained in a close range [27]. These processes that aim to regulate the temperature of the body are called thermoregulation processes and are composed of an adjustment in blood flow to the skin, sweating, increase or decrease of heartbeat rate [28] shivering, etc. PSS systems tend to use these to measure human's thermal comfort and consider them as feedback to the environment [23].

The following section analyzes related works to the field of energy management system based on users' feedback.

V. RELATED WORKS

Murakami et al. [29] conducted a field experiment on energy consumption and thermal comfort in an office environment controlled by occupants' requirements. They mentioned that the main reason why the thermal environment in an office is not always at its optimal conditions is that air conditioning systems are managed without considering the occupants' needs. Based on that, they developed a system in which occupants could communicate their opinions. Their system is composed of two parts named "Client" and "Server". The client refers to users' personal computers and an application is installed on them. This app consists of three columns, Request, Thermal comfort and, Thermal sensation. On request tab, users can choose between the options of Want Warmer and Want Cooler, on the second tab they have seven options from Very comfortable to Very uncomfortable and finally on the last tab, they have again seven options from "Hot" to "Cold" in terms of thermal sensation.

Server as its name explains is the main source of calculations and its duty is to analyze the opinions and transfer the results into the HVAC system. They applied their system in an open plan office located in Osaka, Japan from August to September and confirmed that 20% more energy was saved

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compared to usual conditions.

Costa et al. [30] proposed a system called "3i buildings" which stands for Intelligent, Interactive and Immersive buildings. They believed that intelligent buildings are one of the important trends of the next generation's buildings that use smart controls to fulfill occupants' needs. Based on this theory, they developed a software consisting of three layers: Presentation, Management, and Communication. The presentation visualizes the building in 3D form using BIM principles so that the manager is able to see all the facilities and zones, the management layer allows him to manage the facilities and the Communication layer is responsible for gathering occupants and systems' information and share them with the manager. They did not explain how occupants are able to communicate their opinions in their paper and also, based on their workflow, the system decides whether the opinions need to be considered or not. They implemented their system in three cases including Luz's hospital, Lisbon aquarium, and, Norte shopping mall. After their experiment, they noted that the results were "Very Positive".

Brooks et al. [31] scaled-up the research, done by Goyal et al. [32] concluding that a rule-based system called MOBS (Measured Occupancy-Based Set back) controller had similar performance compared to a much more complex system in terms of both energy consumption and indoor climate conditioning. Brooks et al. tested MOBS in Pugh hall of the University of Florida in six days starting from 00:00, April 21st to 23:59, April 26th. The way intended to collect users' feedbacks was a web-based survey. They emailed occupants a link to an online questionnaire, asking them to give feedback on their air quality and overall comfort in the past five minutes. Users could answer both on a quantitative scale from 1 to 5 and on a qualitative scale from "Very comfortable" to "Very fresh". In addition to that, this system was occupied by a PIR sensor with binary (Presence/Absence) results for detecting the presence of a user. After three waves of the survey, they could reach 37% in energy saving resulted from the reduction of airflow during unoccupied periods. They mentioned that significant savings can be achieved without using expensive and complicated hardware and algorithms.

Sierra et al. [33] used a different way of including users into the energy management system. Their idea is based on the theory of intelligent buildings, mentioned by Krainier in 1996 [34] explaining that, an intelligent building is highly adaptable to the changing conditions of its environment. They considered the fact that each person is different in terms of personal perception of comfort; therefore, they tried to develop a system that is highly flexible. They proposed an intelligent system architecture that contains one main computer, responsible for monitoring, visualizing and, recording parameters, and local controllers that are in charge of the regulatory functions. To make the system flexible and adaptive, the central computer contains a database to record and monitor the information concerning users' preferences. The reason their work is different from the others is that they do not ask for direct feedbacks of the occupants; instead, they provide humidity and temperature panels in various rooms and let users adjust them to what he or she thinks is the ideal comfort conditions. When a user makes a change in temperature or humidity, the main computer records this behavior and saves it to its database for future predictions. To calculate these data, they used neural network of the self-organizational maps of Kohonen (SOM) type that clusters all the user's demands and removes whatever requirements which are not relevant to the main cluster. They implemented their system in the building of the Ministry of Education located in the city of Neuquen, Argentina. After the application of the system, they performed a survey, asking users to tell their comments about the building's performance. The outcomes were positive: 75% of users were very satisfied with their conditions, 20% were just satisfied and 5% were not satisfied at all. Although they included energy-saving rules and conditions in their system, they did not mention any energy saving compared to normal building conditions but they mentioned that their work uses an open architecture and has the potentiality to be developed further in terms of energy management.

Carriera et al. [15] analyzed and reviewed some previous works done in this field and came to the conclusion that most of those works lack robustness. They explained that in most cases, the system cannot understand exactly how much should the temperature change or how much discomfort the user is experiencing. Following this conclusion, they based their idea on robustness and proposed a system in which users are able to change the temperature by 1 °C, and the system works based on the majority of votes in order to obtain the most efficient satisfaction and energy efficiency. They mentioned that their goal is to understand how much discomfort the majority of occupants are able to support for reducing the consumption of energy. Their system tracks the occupants using Radio Frequency Identification (RFID) card reading to understand the occupancy status and the number of occupants. To include occupants in the cycle of energy management, they use a web-based platform that lets users submit their votes and comments about the thermal condition. After the majority of the users submitted their votes, the system gathers them all, identifies the pattern in them, and learns these patterns for making decisions. For the learning segment, they used MacKay algorithms [35] that use unsupervised machine learning and are able to separate the data into clusters and to determine the set point. They also did not mention any quantitative data about energy saving but based on their analysis and statistics, the system might be able to save up to 20% of energy without disturbing occupants' comfortability.

Purdon et al. [36] tried to follow the same way as [31] that leads to simplicity rather can complexity. They conducted research on current Model-Based Systems (MBS) and analyzed their results. What they found was that those systems are able to perform well in terms of both user satisfaction and energy efficiency but they require complicated algorithms and expensive components. To address this issue, they developed a model and sensor-free HVAC controlling system that uses direct occupant feedback for adjusting the temperature. The system contains two sources of information:

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1. The building control and management software (BMS),
2. The application installed on users' mobile devices.

Like the system proposed by [29], their architecture is also composed of two parts: the main server and the application. The main server gathers the information both from occupants and BMS to calculate the optimal temperature and sends the results to the HVAC system. It collects the indoor and outdoor temperature from BMS and Wireless Sensor Networks (WSN) that measure environmental parameters. In case the BMS does not provide the information for the system, it uses online sources for gathering information about the outdoor temperature. The application installed on users' phones provides them a platform to share their opinion about thermal conditions. In addition to voting, this app illustrates a pie chart of the thermal preferences of all other people in the building for a user to consider when voting. This application is only developed on iOS and it is just a prototype based on their paper. Further, they mentioned that besides the mobile app, they also installed a PC application in order to survey people about their current thermal comfortability. The options provided for users to vote were not clearly explained in their paper but they noted that the options vary from -3 which represents a high level of discomfort to 3 which represents a high level of comfort. Based on this information it can be understood that they provide seven options for users to vote. They implemented their system in a university campus which is considered an office building and could reduce the energy consumption to 50% compared to normal use, with minimal modifications on thermal comfort and without using complex systems and algorithms.

Lam et al. [37] also followed the same path but in a more comprehensive way. They analyzed previous researches and works, related to their field and came to the idea that previous efforts have two main problems, first they depend on an existing thermal comfort model from the built environment (PMV) which is proved to differ from real-time occupants comfort zones based on aforementioned studies and secondly, those works need occupants to keep submitting their feedbacks every time. Although it may increase the accuracy of the system, it has the potentiality to discourage one from submitting in the long term. To address these issues, they introduced a system that uses a smartphone application for occupants to submit their votes but with a prior feature. According to their paper, this application is able to record the votes and along with the current environmental data such as indoor temperature to create a personalized profile for each occupant. They developed an OPTC (Occupant-Participatory Thermal Comfort) server to save the data which are gathered from an occupant. This framework has four main modules:

1. Event monitor module: Responsible for collecting data both from environment and occupants
2. Temperature-comfort correlation model (TCC): Responsible for developing a correlation between current thermal conditions and comfort zone of each occupant
3. Set point optimization module: responsible for calculating the optimal set point based on TCC
4. Building controller module: Responsible for communicating the optimal set point with BMS

They performed a simulation in two different scales. Firstly, they took a classroom with different occupants' profiles, and secondly, they used the academic calendar of the Hong Kong Polytechnic University to simulate their work on a large scale. After the simulation, they could achieve 18% reduction of energy consumption using their framework.

Jazizadeh et al. [38] recognized the same challenges as [37] and tried to develop a user-led thermal comfort framework using decentralized systems. Their framework has four objectives:

1. Integration of context dependent data of occupants in the loop of HVAC system by using participatory sensing
2. Learning occupants' preferences and develop personal profiles
3. Taking control of the HVAC system in order to provide the desired environment
4. Solving challenges in the way of developing such system with minimal interference

Like [36], their system also creates a profile for each occupant and maintains its information for long term operation of HVAC and providing comfortable conditions. Using decentralized or room-based as opposed to zone-based systems gives the system the ability to modify the conditions of each room based on each occupant's comfort zone. They analyzed current ways of collecting data from occupants and tried to combine them with standard scales such as ASHRAE, Bedford, and McIntyre. They noted that using a rigid combination may need the user to answer to many questions and cause confusion and complexity; therefore, instead of providing users with options, they used a slider with snapping abilities. By sliding to left or right, users can communicate their preferences and sensation with the system. After collecting the votes, the system stores the votes on each occupant's profiles to maintain it for future modifications. They implemented their system in an operational office building on the University of Southern California which is a three-story building and has 60 permanent occupants in addition to 2000 temporary occupants such as students. After the evaluation of the system, they could reduce the daily average airflow by 39% compared to the legacy systems.

Ghahramani et al. [39] also did the same job as [38] and developed a knowledge-based approach that combines occupant's preferred thermal comfort temperature and zone level energy consumption and decides the most optimized setpoint for HVAC system. This framework uses fuzzy logic to create personalized discomfort profiles. They introduced personal discomfort as a function of zone temperature setpoints. In their framework, occupants can submit their feedback through a mobile application that uses sliders instead of providing various options to choose from. This User Interface (UI) as mentioned previously makes it easier for users to interact with the system. They also fed maximum and minimum values for the personal discomfort variable which is updated by recording users' feedback in order to find the minimum energy consumption and minimum airflow rate. They chose the University of Southern California as their

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testbed and performed an experimental evaluation that led them to reach 12.08% energy saving. According to their paper, this result was an addition to a 39% energy saving on their previous work.

Li et al. [40] tend to use the third way of analyzing users' feedbacks. They believed that understanding occupants' thermal sensation is an essential factor in the operational settings of HVAC and also it needs to be tested and evaluated in real-time. Following these ideas, they developed a system for analyzing facial infrared thermography. Their system contains three parts:

1. A computer vision to recognize human face and excavate the data from it,
2. Statistical methods to remove unnecessary data and analyze the temperature of raw skin,
3. Machine learning methods such as random forest classification for developing personal comfort prediction models and record unique facial features.

The main reason they chose facial skin temperature as their targeted bio-signal is that human face has a higher density of blood vessels compared to other surfaces which leads to a larger skin temperature variation [41]. The second reason for choosing face was the fact that human faces are not covered by pieces of clothing – separate from special conditions- and besides easier recognition, the transferred infrared energy can be directly analyzed by the thermal camera. After implementing and testing their system, they concluded that 85% accuracy in thermal comfort can be predicted using facial thermal sensation with their framework.

Ghahramani et al. [42] proposed a novel Human-Centered thermal Comfort Modeling (HCCM) technique that adapts its parameters in response to variations in individuals' thermal preferences. In their paper, they conducted a brief review of previous related works and came to the conclusion that the majority of those developed models miss the components for recognizing changes in time in thermal comfort. They noted that time-dependent variations were not mathematically studied in previous works. Premised upon this conclusion, they introduced their model which is able to dynamically adapt itself based on occupants' comfort requirements such as performing a change in the environment in an online learning fashion. It is categorized as online because it learns based on each input data. They clustered the raw data into three sets:

1. Uncomfortably warm,
2. Comfortable,
3. Uncomfortably cool.

After collecting and clustering the data, their system uses a Bayesian network to combine all the results and identify comfortable environmental conditions. They implemented their system in several offices in the University of California (USC) campus buildings which has a dry summer subtropical climate. The results from this implementation and the procedure mentioned previously on the data gathered from 33 test subjects showed an accuracy of 70.14% in determining the thermal comfort of occupants. They also mentioned that their results showed higher accuracy compared to all previous models.

The following section compares these works together to evaluate their results.

VI. COMPARISON

Based on the results, mentioned in each of those papers, it can be concluded that Ghahramani et al. [39] could reach the highest in energy saving. Using their knowledge-based system, they could achieve 12.08% more savings compared to their previous work which sums to 51.08%. In addition to their work, the system developed by Purdon et al. [36] is also a considerable system. They could achieve a 50% saving in energy. This percentage is so close to the result achieved by [39], but the superior point is that Purdon et al. were able to achieve this result using a simple rule-based system based on user feedback. Although it has to be considered that their result is compared to usual energy consumption in their university and this "usual" usage of energy for sure has a massive influence on their result, achieving such savings without using complex devices and algorithms, makes their work more valuable.

In terms of accuracy in providing satisfaction and comfortability for users, Sierra et al. [33] reached the highest satisfaction rate, 95% of satisfaction. Also, they mentioned that 75% of occupants were "very satisfied" which is an in-value result. Another considerable point of about their work is that, unlike others, they did not ask for direct feedback and developed their system in a way that it is able to understand user's comfort or discomfort by analyzing their behavior in response to thermal conditions. According to [24], one of the main limitations and challenging parts of including users in the loop of energy consumption optimization is users' participation. Sierra et al. excluded users' direct feedback and will not face this challenge which helps the process significantly.

Besides [33], the system developed by Li et al. [40] is also valuable. The reason why their work is in-value regardless of choosing the highest rate in satisfaction is that they took a step forward in the field of user-feedback based energy systems and used a totally passive way of monitoring users. By scanning the facial temperature of users, they could achieve 85% accuracy in thermal comfort in their work which is a highly acceptable rate considering the use of most recent and newborn technologies.

Table I organizes all mentioned papers based on their energy savings and the method they used to receive feedback from users.

VII. CONCLUSION

This paper presented an overview of adaptation and ABEMS, followed by a review over recent projects done in this field. Finally, a comparison between the mentioned works was presented.

It can be understood from the results of the works listed in this paper that, minimal energy consumption with maximum user comfortability is possible thanks to the recent technologies such as machine learning and WSN and the fact

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that projects developed, based on this theory, can be considered as the next generation of BMS projects with the high potentialities. In addition, one of the interesting results of this research was that achieving highly satisfying results both for users and engineers, does not necessarily need complex systems and algorithms, quite the opposite, it is achievable using simpler systems.

TABLE I
COMPARISON OF WORKS BASED ON ENERGY SAVINGS

Reference	Method	Energy Savings
Murakami et al. [29]	Mobile Application	20%
Costa et al. [30]	Not mentioned	Not mentioned
Brooks et al. [31]	Web-based survey	37%
Sierra et al. [33]	Users' reaction to the thermal condition	Not mentioned
Carreira et al. [15]	Web-based platform	20%
Purdon et al. [36]	Mobile Application	50%
Lam et al. [37]	Mobile Application	18%
Jazizadeh et al. [38]	Mobile Application	39%
Ghahramani et al. [39]	Mobile Application	51.08%
Li et al. [40]	Facial skin temperature	Not mentioned
Ghahramani et al. [42]	Mobile Application	Not mentioned

It was also concluded that asking for direct feedbacks is becoming unnecessary and recent technologies including developed thermal cameras are making it possible for BMS to understand the user's needs and learn from them.

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