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Integration of occupant voting systems and smart home platforms for collecting thermal feedback in indoor environments

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Integration of occupant voting systems and smart home platforms for collecting thermal feedback in indoor environments

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Abstract. The assessment of indoor thermal comfort is increasingly shifting from statistical to personalized models and therefore there is a growing interest in collecting feedback on occupants' perceptions and preferences. Occupant Voting Systems (OVS) are emerging as a widely used tool in Post Occupancy Evaluations (POE) but the level of occupants' interaction with these data collection devices, their scientific accuracy, and the integration of feedback data with building management systems, especially in residential buildings, still need to be further explored. This paper presents a study conducted on five dwellings, located in Italy, where smart home switches were used as feedback buttons to collect the thermal sensation of the occupants. These buttons were integrated into an open-source smart home platform, MOQA. The developed system is described in its technical features, highlighting the amount of information collected, the response rate and its interoperability with smart home systems. The results show that OVSs still have limitations in terms of occupant engagement and it is still rather complicated to correlate ratings with environmental variables. However, an easier integration, here described, with smart home systems would partially overcome these problems, turning the OVS into a useful tool for both users and research purposes.

1. Introduction

Although building-human interactions and building occupants' preferences are widely discussed topics in the literature [1], the term OVS was comprehensively defined by Khan et al. only in 2020 [2], referring to a system or method for collecting data on IEQ (Indoor Environmental Quality) using small, user-friendly devices placed inside the building, which allow occupants to provide real-time feedback on their perceived comfort [3]. Recent advances in Information and Communication Technologies (ICTs) have made OVSs a tool often combined with questionnaires, which have always been the standard for surveying occupants' opinion [4], if not a solution to replace them. Questionnaires can assess phenomena that might be difficult to measure with sensors and gather information on large samples. However, due to cognitive biases, misunderstood or misinterpreted questions may result in erroneous reporting, and self-reported behavior may not necessarily match the observed behavior. The literature comparing OVSs and questionnaires is rather scarce [5], but it can be stated that OVSs are more efficient than surveys when the focus is on collecting complaints rather than opinions. Potentially, the benefits of an OVS are higher because the data are quantitative and continuous, which is especially useful if the goals are HVAC system tuning, integration with smart buildings, information on building operation and maintenance, and occupant comfort. OVSs are non-intrusive and more engaging for occupants, leading to higher

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response rates compared to a traditional questionnaire, and can be installed in easily accessible locations such as hallways or common areas. Despite these advantages, the implementation of such voting systems is so far limited to commercial or office buildings but has not yet been explored in residential environments where, thanks to the spread of smart home platforms, IoT (Internet of Things) devices, such as smart buttons and smart switches, are becoming pervasive. Moreover, the limitations of continuous subjective occupant feedback are quite well known [6]:

- Limited data on different indoor environmental factors
- Limited flexibility compared to classical questionnaires
- Limited feedback granularity and discrete rating scales [7]
- Technical limitations such as connectivity issues, software bugs, or hardware malfunctions
- Usability issues: user-friendliness and right positioning
- Engagement level over long period of time
- Integration with building [8].

In this framework, this paper presents an innovative tool – MOQA: “Measure and Optimize the Quality of Architecture” – for the integration of OVS data collected via low-cost sensors with an open-source smart home platform. The limitations described above are highlighted by the data collected in the still ongoing monitoring of the thermal comfort of 5 public housing units in Rovigo (Italy), where smart buttons were freely available to occupants to indicate their thermal sensation. The data, although preliminary, confirmed the need for greater integration between feedback, users and building, described here in its technical component, which will be implemented in the second part of the monitoring.

2. Materials and methods

2.1. OVS architecture

The OVS had to be adaptable to a variety of users - kids, adults, and the elderly - and did not require the use of technological tools such as smartphones or personal computers. In addition, the OVS had to communicate via several communication protocols - Zigbee, Z-wave, Wi-Fi, etc. - to ensure wide compatibility with environmental and energy monitoring systems or smart home platforms on the market. Attention also had to be paid to the cost of the entire system. For these reasons the concept of single-button feedback was chosen and three Zigbee smart switches were used (Fig.1a). These buttons are usually employed as home switches for electric lighting but it is possible to intercept the signal they send once pressed and convert it into a trigger for custom automation.

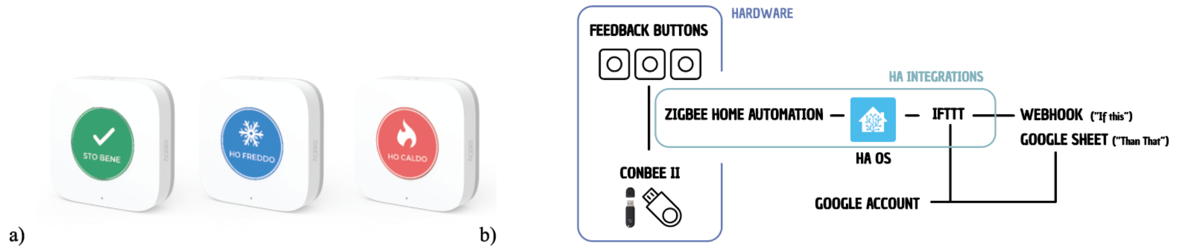

Figure 1. a) OVS: smart feedback buttons; b) OVS: architecture

The signal is here received by a universal Zigbee-USB Dongle, mounted on the Raspberry Pi (see Section 2.2) and reaches the smart home platform as "switch.turn_on" or "switch.turn_off" data. To create a backup of the system and facilitate the statistical analysis of the raw data by translating the "on-off" data into "date-time-thermal sensation", a secondary automatic procedure was implemented, aimed at creating a .csv file, then saved locally. This was done with the IFTTT (If This Than That) Web service which allows users to create chains of simple conditional instructions, called "Applets". Thus, for each physical button, an applet was created on the IFTTT Web platform that, given an initial condition ("if this"), types the desired information into an appropriately linked Google sheet ("than that"). The datetime are extracted directly from the "on-off" event recorded on the smart home platform; pressing the button indicates the corresponding thermal sensation. To properly define the "if this" condition, an IFTTT component was installed on the smart home platform as an integration (see section 2.2). An automation was then created to activate, through the "Webhooks" service, the applet created before every time the button was clicked (Fig. 1b).

2.2. Integration between buildings monitoring and OVS

The hardware-software package used as the core of the monitoring system (Fig.2) consist of a Raspberry Pi4 as the primary board, on which an open-source operating system, Home Assistant (HA), developed by an online community and refined by the authors, was installed. The potential of the system, also with regards to energy and environmental monitoring, is very high, as Home Assistant is able to connect and control almost all the smart sensors, services and devices in a home, regardless of their manufacturer. For this purpose, the installed version requires an additional hardware component, a Zigbee-USB dongle, to connect the environmental sensors and the implemented OVS system (section 2.1). The combination of the hardware and software components resulted in the MOQA prototype (Fig. 2a), which is designed to ensure maximum data interconnectivity. With reference to the OVS system, every time the feedback button is pressed, an automation queries all temperature/humidity sensors - one per room - and returns the data for each room and the average value for the whole flat. In this way, together with the procedure described in section 2.1 and 2.3, a stand-alone spreadsheet and a direct correlation between feedback and environmental data is created.

a) b)

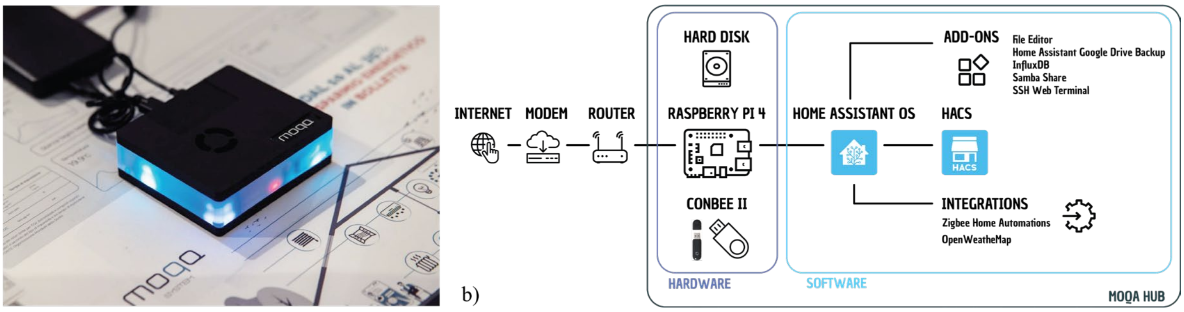

Figure 2. a) MOQA prototype; b) MOQA hardware and software components

2.3. Test buildings

The research project involved 5 apartments located in 3 different public housing buildings in Rovigo, Italy (45°04'25.2"N 11°47'20.3"E), built between the 1940s and the 2000s with low thermal performance. Some characteristics of the dwellings and inhabitants involved are listed in Table 1.

Table 1. Description of the flats and involved households

Flat n.	Building n.	Floor	Building Heating Energy use intensity [kWh/m^2.yr]	Flat orientation	Flat floor area [m^2]	Household composition
1	1	3rd (out of 3)	132.62	South+West	70	1 old lady
2	2	4th (out of 4)	156.93	South+West+East	76	Middle-aged couple
3	2	0 (out of 4)	156.93	East+West	80	Middle-aged couple + 1 son
4	1	1st (out of 3)	132.62	North	54	Mother and daughter
5	3	1st (out of 2)	178.69	South+North	87	Mother and son

The monitoring campaign is still ongoing; the analysis is here limited to the heating period of 2021-2022 (December to February). Figure 3 displays monthly averages of temperature and solar radiation across the 24 hours of the day. Data were obtained from Rovigo weather station (45°03'6.2"N 11°46'28.7"E).

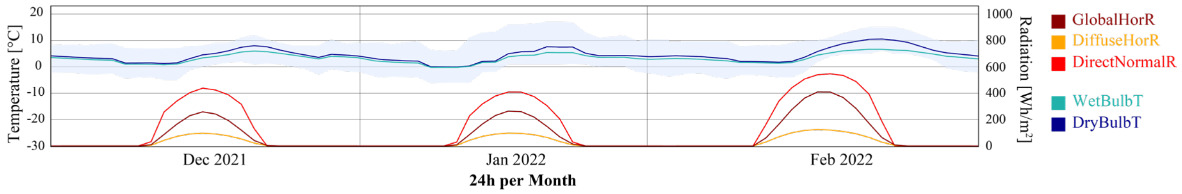

Figure 3. Outdoor weather conditions in Rovigo (IT) from 12-2021 to 02-2022

In this first phase of the study, the inhabitants were not shown any of the data collected and, except for the first presentation of the project, none of them were prompted to use the OVS. The objective was, in fact, to assess the level of interaction between the occupants and the system, without direct interference. The values measured by the indoor temperature and relative humidity sensors (Aqara WSDCGQ11LM, accuracy: ±0.3°C, ±3%) were compared with those of professional microclimatic monitoring station (accuracy: ±0.1°C, ±1%) installed in all the flats for 7 days each for calibration, confirming the validity of the measurements. Environmental data were collected every 5 minutes and at each time OVS was used (Section 2.2).

3. Results and discussion

3.1. OVS data

Figure 4 shows on a psychrometric chart the indoor temperature and relative humidity values when the OVS feedback buttons were pressed, during the winter period 2021-2022 (see Section 2.3). In Figure 4a, each shape - circle, diamond, cross, square, and filled 'x' - denotes a flat, while the colour indicates the type of thermal sensation perceived: blue for 'I'm cold', green for 'I'm fine', red for 'I'm hot'. The dashed lines with coloured contours represent PMV (Predicted Mean Vote) values for an air velocity of 0.2 m/s, clo=1, met=1.1, and mean radiant temperature of 20°C. These values are considered representative and/or obtained from the 7-day on-site parallel monitoring with the microclimate station.

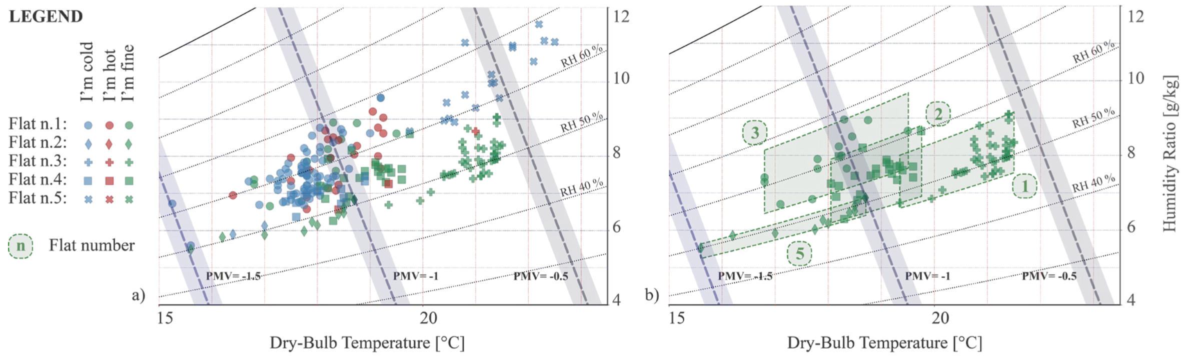

Figure 4. a) Psychrometric diagram showing temperature and relative humidity values - for different thermal sensations and involved households - recorded when the feedback button is pressed; b) comfort zones for different households

The figure demonstrates that it is very complicated to define a specific thermal comfort zone when monitoring only a few environmental parameters. Data are limited as well as the people involved, but considering, for example, flat 5, it is noticeable that occupants always feel cold, even in microclimatic conditions considered good or even warm by other users. Comfortable conditions are plotted in Figure 4b, which shows how comfort zones greatly differs from one household to another and how the PMV, in the figure always less than -0.5 and therefore indicating "slightly cool" to "cool" environment, cannot perfectly map the inhabitants' thermal sensations. These depend on factors that are not limited to temperature, humidity or the physical environmental parameters defined by the standards, but are also linked to the habits with which a person experiences his or her home [9]. Figure 5 shows the second limitation of OVS systems: the decreasing response rate over time. The five graphs, one per flat, show the trend in the number of feedbacks per day. The data, in this case, is not limited to the winter 2021-2022, but extends to January 2023 to better assess the curve. As already mentioned, no reminders were given to the users involved, nor were the results of their votes shown, leaving them free to use the smart buttons, which were always placed where the user preferred (often at the entrance of the houses).

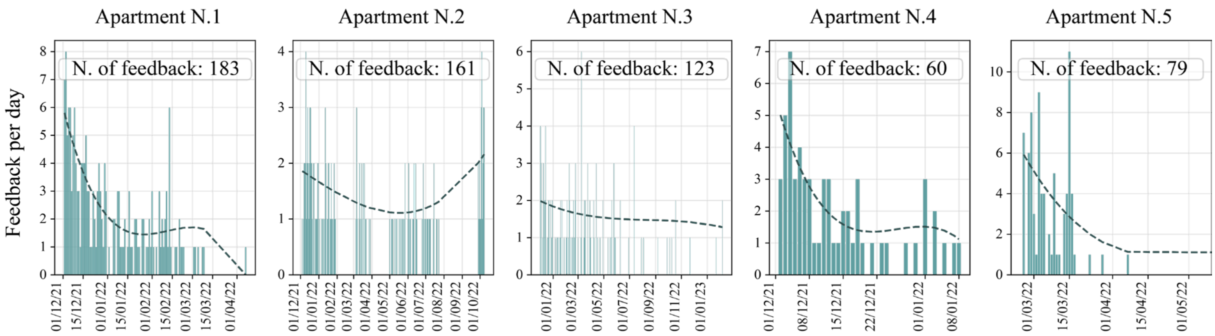

Figure 5. Number of feedbacks per day per flat and related trends

The total number of feedbacks varies among the case studies, without following any particular pattern related to the age or number of the inhabitants, but apparently depending on the individual's willingness to participate in the research. This decreasing level of engagement is evident in all the examined flats, except for flat number 3 where, due to technical problems, a second survey was needed in the summer, which may unintentionally have served as a reminder. However, it is not a coincidence that the number of feedbacks increases as the second winter season approaches. This supports the trend, already noted in the literature, that OVS is more used as a compliance tool rather than a way to testify a pleasant status.

3.2. Integration of feedback data into the smart home platform

This first period of experimentation also served to develop strategies aimed at overcoming the limitations of the OVS systems described in Section 1. The main challenges in measuring comfort using discrete scales concern the definition of target values, understanding whether the same size of steps necessarily leads to equal steps in perceptions, and the need for multidimensional and multi-domain assessments [7]. New IoT technologies, such as those previously described, fully address these challenges: for instance, it would be simple to replace the thermal sensation buttons described in point 2.1 with one or more physical or virtual buttons with a continuous scale (0-100%), such as those currently used for blinds controlling. It is also easy to integrate the results of surveys carried out via online platforms (e.g. Google Forms, Survey Monkey, Prolific, etc.) with which to collect metadata useful to better clarify the comfort ratings expressed via OVS. This allows for gathering information that cannot be obtained from a simple smart button, such as clothing and metabolic level. The usability problems of many OVSs are minimized by using a variety of physical or virtual feedback buttons that can be easily adapted to different users and that, given their independence from the power grid, can be freely placed in convenient locations within the living space or even worn by users. With tools such as MOQA, it is easy to collect feedback data but also to monitor environmental variables. They allow the most appropriate communication protocol to be chosen according to the case study, increasing data stability and reliability. In addition, this flexibility potentially allows cost-effective conveyance of energy consumption data, weather data, user behaviour data or any information on the Web into a single database. Connecting the OVS to a smart home system can also maximize the level of occupant engagement. Home Assistant, for instance, displays on the IP of the Raspberry on which it is running, an integrated and fully customizable graphical interface where users can see their ratings, an indication of the overall indoor environmental quality of the building, as well as real-time suggestions, based on the monitored data, to improve their comfort. Furthermore, through the same platform, it is possible to implement gamification applications and send notifications or reminders to motivate occupants. The

OVS system, perfectly integrated with the building, can finally, if connected to a smart HVAC system, provide the necessary data to adapt the heating and cooling system's operation to user preferences.

4. Conclusion

In this paper a new non-intrusive system for integrating OVS into broader monitoring of indoor comfort in residential buildings is presented. The system was tested in 5 flats, collecting preliminary thermal sensation data from 5 different households. The collected data demonstrated the well-known limitations of feedback buttons but allowed the authors to investigate how to integrate this data into smart home platforms, where other data can be conveyed and displayed. At this early stage of the study, the authors did not force occupants to interact with the OVS, merely collecting the number of feedbacks. It is well known that users are more likely to express feedback when they do not feel comfortable, rather than when they feel satisfaction. For this reason, in this case study, users were informed of the importance of using the OVS as many times as possible regardless of their thermal sensation, and the choice of smart buttons and their flexible positioning, chosen in accordance with users, was precisely intended to facilitate their use. While for offices there are already suggestions in the literature on how to place non-wearable OVS systems, for residential spaces the topic is yet to be explored. In the coming months, a higher level of interaction will be tested, providing occupants with the monitored data that has so far been obscured, in order to study how the feedback response rate may vary as the level of engagement changes and whether a smart home platform can help keep it high. Future tests will be conducted with larger populations of occupants, so far too few to generalize scientific results.

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