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Graphical visualization of behavioural patterns in relation to indoor environment quality and energy use

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Abstract. In this paper, the authors provide a general overview on the methodological framework behind the monitoring and evaluation strategies of Mobistyle project that are used as reference for the demonstration cases. The strategies identify parameters that need to be evaluated during several phases regarding the impact (energy, IEQ, health, behavioural patterns) and the strategy (effectiveness of the process) of the project, and how these parameters can be numerically evaluated. In particular, the paper focuses on the graphical visualization method for behavioural patterns analysis in relation to indoor environment quality and energy use. The proposed approach is illustrated based on measured data from one Mobistyle Project case study i.e. a hotel for long term stay located in Turin, Italy.

1 Introduction

Today, the underlying global climate arguments for enhancing energy performances of the existing European building stock are well known. Decarbonising the European building stock is no longer only a question of technology, such as step-by-step deep renovation measures, but has become a task that involves the “real” energy consumers in buildings. In this context, the European Union has established a comprehensive approach that, next to the long-term goal of creating a nearly-zero energy/smart building stock, foresees triggering behavioural change as key strategy to reach EU’s energy saving targets. Until recent years, social sciences and humanities research has played less of a role in shaping European energy policy than Science, Technology, Engineering and Mathematics disciplines.[1]

1.1 Mobistyle project

A positive example in this direction is the ongoing Horizon 2020 Mobistyle project[2] (Motivating end-users behavioural change by combined ICT based tools and modular information services on energy use, indoor environment, health and lifestyle). The aim of the project is to raise awareness through a provision of attractive personalized information on user’s energy use, indoor environment and health, through information and communication technology (ICT) based services. (see Fig. 1)

Well aligned with literature recommendations [3,4] in the field of project management, Mobistyle project has developed an uniform and replicable evaluation strategy early on for overcoming unexpected evaluation challenges by mitigating risks in advance, leading to more useful results, and improving the optimization process of the project. The Mobistyle evaluation strategy is designed to evaluate the project’s effectiveness (estimating the extent to which the project’s outcomes meet its objectives) and the project’s relevance (identifying if the project’s goals are responding to the identified users’ needs). A key objective of the proposed evaluation strategy is to define methods that allow assessing the amount of energy saved during and at the final stage of the Mobistyle project. Variations due to other boundary conditions that impact the variation of energy uses should be isolated from the evaluation, such as strong seasonal variations, changes in occupancy, or other contextual factors e.g. investments in energy efficiency or conservation strategies that are not related to Mobistyle. (see Fig. 2)

In addition to energy use reduction, Mobistyle project is dealing with non-energy benefits related to indoor environmental quality and health. For including in the appraisal also these very important issues, the Mobistyle evaluation strategy also provides a framework to develop a Cost-Benefit Analysis, in order to assess the economic performance of the application of Mobistyle solutions in buildings where a central role is attributed to the users as active components of the system.

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To set up an effective evaluation process during the entire project, the proposed Mobistyle evaluation strategy consists of three monitoring periods (M0 – initial monitoring, M1 – feedback provision, M2 – optimized feedback provision) alternated with follow-up evaluation steps (E1 – benchmark definition, E2 – intermediate evaluation, E3 – final evaluation). Over time, monitoring periods and evaluation steps are planned to be implemented in 6 steps scheduled as illustrated in **Fig. 3**.

The Mobistyle evaluation strategy is providing a guideline for assessing the impact in the different Mobistyle testbeds during different project stages and a verification method whether Mobistyle goals were achieved.

From the overall developed Mobistyle evaluation strategy, this paper focuses in particular on the graphical visualization method for behavioural patterns analysis in relation to indoor environmental quality and energy use.

When identifying the baseline behavioural patterns, the interactions of the users with their surrounding shall be monitored and analysed. The evaluation process needs to be conducted with great caution, because it is analysing the implementation of an innovative and complex intervention in “living labs” during a long timeframe. These aspects could hinder complete demonstration of causation mainly due to motivators/triggers external to the Mobistyle intervention. Both quantitative and qualitative measurements maximize the accuracy of demonstration of causation. The following non-exhaustive list of measurements serves as guidance:

Quantitative measurements

- **Occupancy** (occupied/unoccupied [total person hours], number of occupants [persons]). Occupancy tracking can be done in a variety of ways e.g. movement and presence detection sensors, indoor localization of individual users using data from wireless sensor networks with portable nodes [5], people counting software using data from ceiling mounted cameras pointed straight down [6].
- **Operation of technical building systems, building components and home appliances:**
 - Home appliances and ICT products (energy use);
 - Heating system (room temperature heating setpoint; energy use – to be cross-checked with HDD, occupancy and normalised as needed);
 - Cooling system (room temperature cooling setpoint; energy use – to be cross-checked with CDD, occupancy and normalised as needed);

- Ventilation system (number and duration of window openings; energy use of mechanical ventilation system – to be cross-checked with indoor emissions generating activities e.g. cooking, shower, occupancy and normalised as needed);
 - Lighting system (energy use – to be cross-checked with length of day and occupancy and normalised as needed);
 - Solar shading system (number and duration of openings/closings – to be cross-checked with length of daytime, sky nebulosity, solar irradiance, occupancy and normalised as needed);
 - Domestic hot water system (energy use; water use – to be cross-checked with outdoor air temperature, occupancy and normalised as needed).
- **Health trackers and wearables:** There is a large variety of wearables on the market (e.g. [7]). The selection of the wearable technology shall be made based on the actual scope of the device, although it should monitor at least heart rate, physical activity and body temperature for usefulness and meaningfulness purposes;
 - **Analytics of MOBISTYLE tools** (e.g. time of sending notifications, length of use, number of questions asked through the ‘help’ sub-tool).

Qualitative measurements focus on adding meaning by creating a user perception layer on top of the quantitative measurements and shall cover occupant satisfaction, well-being, comfort, productivity/creativity and health (e.g. number of sick days, number of doctor visits, decreased effects of respiratory diseases, mental health) via questionnaires/ interviews.

The qualitative measurements generate easier to manage datasets than the quantitative measurements. The evaluation process has a straight forward approach in terms of identifying changes in behaviour meaning that the collected occupant feedback via questionnaires/interviews is directly analysed for the relevant periods.

For complete demonstration of causation, it is useful to cross-check quantitative and qualitative measurements as such adding meaning by creating a user perception layer on top of the quantitative measurements.

The quantitative measurements generate datasets that quickly amount to big-data levels. There are inherent difficulties in transforming and presenting these data in a coherent and comprehensible format without excessive simplification. Common approaches to visualizing these datasets include simple bar charts, time-series plots, and

scatter plots. Three-dimensional plots are also very useful for visualizing building performance data, however, can present issues when used in practice. These issues can be overcome by flattening the 3-dimensional plot, i.e. representing the third axis using a colour-coded scale, resulting in so called carpet plots.[8]

The analysis assumes that the data consist of a systematic pattern (usually a set of identifiable components) and random noise (error) which usually makes the pattern difficult to identify. Most analysis techniques involve some form of filtering out noise for making the pattern more salient.

Most patterns can be described in terms of two basic classes of components: trend and seasonality. The former represents a general systematic linear or (most often) nonlinear component that changes over time and does not repeat or at least does not repeat within the time range captured by our data (e.g., a plateau followed by a period of exponential growth). The latter may have a formally similar nature (e.g., a plateau followed by a period of exponential growth), however, it repeats itself in systematic intervals over time. Those two general classes of components may coexist in real-life data.

2 Methods

The proposed approach is illustrated based on measured data from one Mobistyle Project case study i.e. a hotel for long term stay located in Turin, Italy[9].

Data is collected from four guest rooms and the reception of the Hotel Residence L’Orologio, demonstration case in Turin, Italy. The apartments have an area of 36-39 m² and are comprised of 2-3 rooms per apartment. The following user interaction with technical building systems is monitored: heating and cooling setpoints of the fan-coil units, window (and door) openings, electricity use of fan-coil units and appliances. The specific case objective of this Mobistyle demonstrator is to monitor IEQ and electricity use for providing the hotel guests with feedback and guidance on how to reduce energy use and better control the heating/cooling systems. This shall be combined with suggestions regarding daily activities and encouraging energy efficient usage of appliances as additional information to increase user awareness, though these are not directly measured.

The usefulness of graphical visualization for behavioural patterns analysis is highlighted using the ‘BELOK Operation Analysis’ visualization tool [10].

For this paper measured data between 18 September 2018 and 19 October 2018 was cleaned and used for generating carpet plots.

3 Results

The data cleaning process was tailored for each data point based on a frequency of measurements as presented in **Table 1**:

Table 1 Frequency of measurement of data points

| Data point | Measurements | Frequency |
|--|----------------|-----------------------------------|
| Door openings | Open or closed | Continuously |
| Window openings | Open or closed | Continuously |
| Energy | kWh | Every 10 minutes |
| Power | kW | Continuously and every 10 minutes |
| Fan-coil actuator openings | Open or closed | Continuously |
| Thermostat temperature set point | °C | Continuously |
| Indoor air temperature | °C | Every 15 minutes |
| Indoor air temperature relative humidity | % | Every 15 minutes |
| Indoor air CO ₂ concentration | ppm | Every 15 minutes |

For each data point with numerical values the minimum, maximum and average values over the measurement period have been calculated and are shown in **Table 2**.

Table 2 Minimum, maximum and average values of data points with numerical measurements

| Data point | Min. | Avg. | Max. |
|---|--------|--------|---------|
| Energy (kWh) | 548 | 604.14 | 661 |
| Power (kWh) | 0.05 | 0.18 | 1.91 |
| T _{set point} (°C) | 17.78 | 22.71 | 40 |
| T _{indoor air} (°C) | 20.58 | 22.76 | 25.88 |
| RH _{indoor air} (%) | 34 | 56.52 | 79 |
| CO ₂ _{indoor air} (ppm) | 331.84 | 488.99 | 1565.44 |

The carpet plots generated based on measured data between 18 September 2018 and 19 October 2018 in one

of the four guest rooms are illustrated in **Fig. 4**, **Fig. 5**, **Fig. 6**, **Fig. 7**, **Fig. 8**, **Fig. 9**, **Fig. 10**.

4 Discussion

On the developed carpet plots the following aspects can be analysed:

- Window and door openings, **Fig. 4**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale with only 2 colours: beige for periods with closed door/window and black for periods with open door/window;
- Energy and power, **Fig. 5**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale for energy that ranges from 548 (beige) to 661 (black) kWh and for power from 0.05 (beige) to 1.91 (black) kW;
- Fan-coil actuator openings, **Fig. 6**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale with only 2 colours: beige for periods with closed actuator and black for periods with open actuator;
- Thermostat set point temperature, **Fig. 7**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale that ranges from 17.78 (beige) and 40 (black) °C;
- Indoor air temperature, **Fig. 8**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale that ranges from 20.58 (beige) to 25.88 (black) °C;
- Indoor air relative humidity, **Fig. 9**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale that ranges from 34 (beige) to 79 (black) %;
- Indoor air CO₂ concentration, **Fig. 10**, represented with the days of the year on the x-axis and the hours of the day on the y-axis using a colour scale that ranges from 331.84 (beige) to 1565.44 (black) ppm.

Before analysing behavioural patterns, the occupancy periods are most relevant to be identified. Considering the data points of Hotel Residence L'Orologio, the following measured data shall be cross-checked: door openings, windows openings, temperature set point, indoor air relative humidity and indoor air CO₂ concentration. For example, if only **Fig. 10** would be analysed the conclusions could be that the apartment was occupied only during periods with higher CO₂ concentration, however that is not the case when cross-checking at least with the window openings **Fig. 4**.

In terms of energy use, analysing both power, and energy, **Fig. 5**, provides a better understanding about individual events and how their impact accumulates over time. When analysing occupant behaviour power gives more insights on individual actions which can be related eventually to certain defined triggers (especially when thinking about the Mobistyle tools that shall be deployed) whereas energy gives the overview necessary for concluding if the expected results are met.

When analysing the indoor environmental quality, **Fig. 8**, **Fig. 9**, **Fig. 10**, the outdoor conditions can also be easily guessed i.e. warmer during the end of September 2018 and gradually cooled down in October with a need to turn on the heating at the end of the measurement period. It is recommended to develop similar carpet plots for outdoor air parameters during the same periods, for additional cross-checking leading to increased accuracy and minimised assumptions.

Although it takes time to develop the carpet plots, they can be analysed interactively (cursor over the carpet plot shows the exact measured value for a given date and time) covering periods of up to one year long. For the one-month period considered in this paper the tables containing the raw measured data have a bit over 610000 values and the tables containing the cleaned measured data have a bit over 220000 values. Having in mind this order of magnitude it is close to impossible imagining a behavioural pattern analysis of the measured data in any other way than by using such carpet plots.

5 Conclusions

Visualizing occupant behaviour parameters for certain periods enables identification of baseline occupant behaviour and specific patterns of use. This establishes a situation of knowing what to expect, thus facilitating evaluation processes aiming to identify changes in behaviour based on quantitative measurements. It is worth noting that these behavioural patterns are occupant dependent and as such in cases as the Hotel Residence L'Orologio the baseline needs to be identified for each occupant individually. In general, the longer the period of stay the more accurate the results of the analysis are. For very short stays (e.g. a few days long) the analysis needs to be handled with caution.

Cross-checking the quantitative measurements of the different data points is very critical for maximizing the accuracy of the gained insights. Otherwise, data can easily be misinterpreted and results invalid. Furthermore, cross-checking with qualitative measurements would most likely facilitate the complete demonstration of causation once the Mobistyle tools will be deployed in the Italian demonstration case.

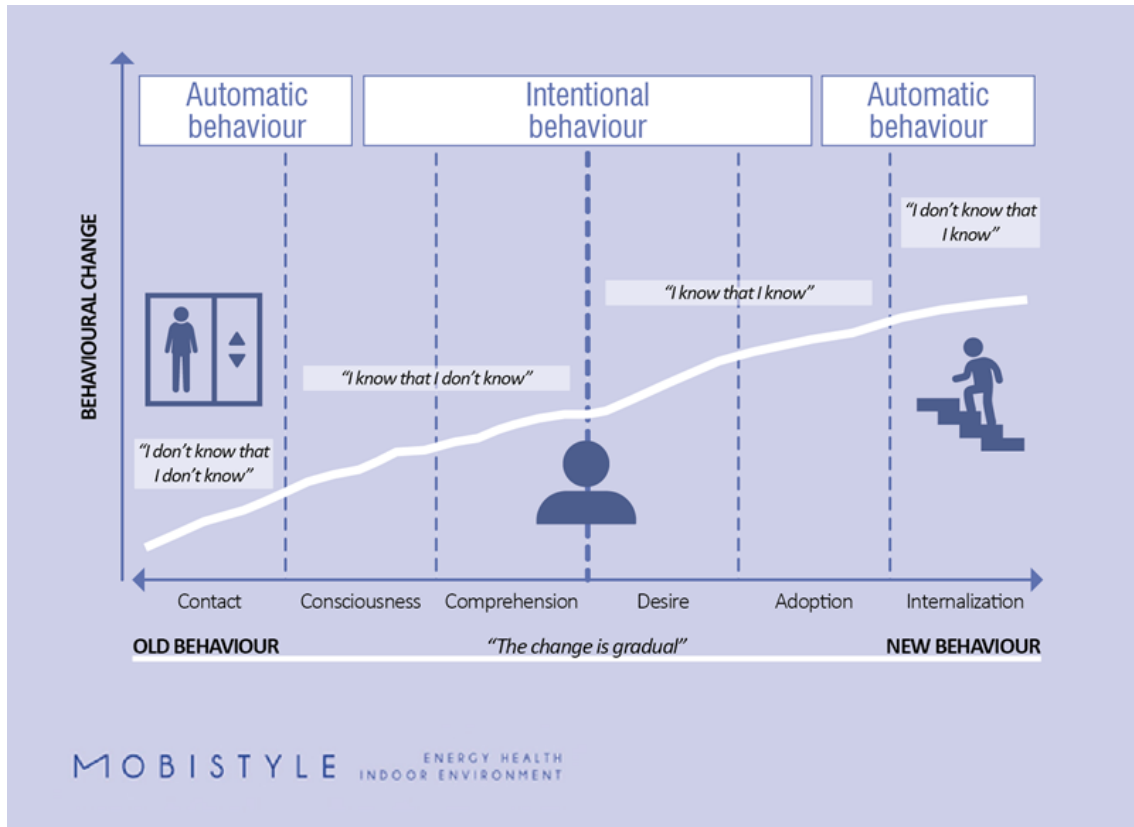


Fig. 1 Behavioural change objective – Mobistyle project

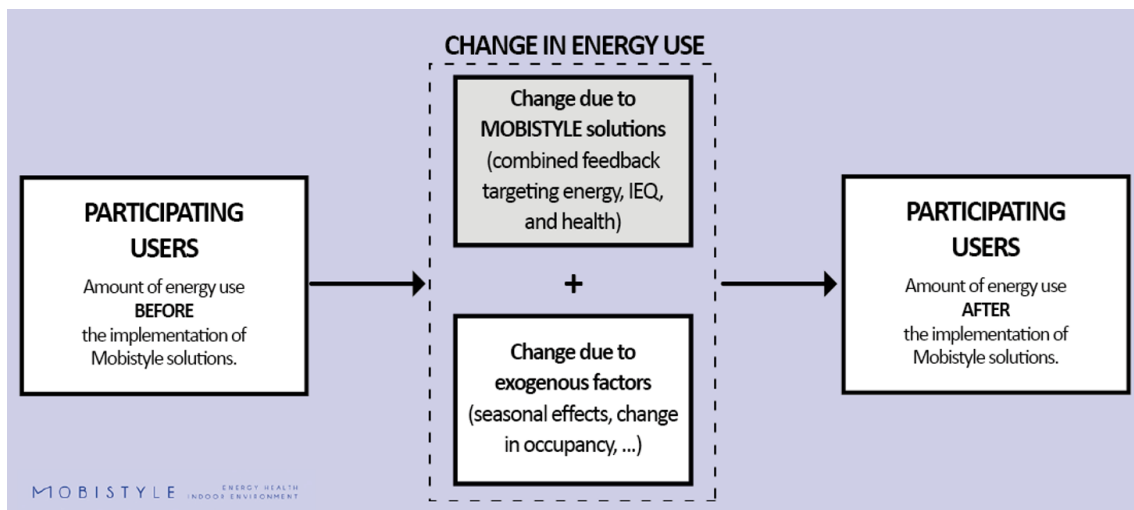


Fig. 2 Change in users' energy use – Mobistyle project

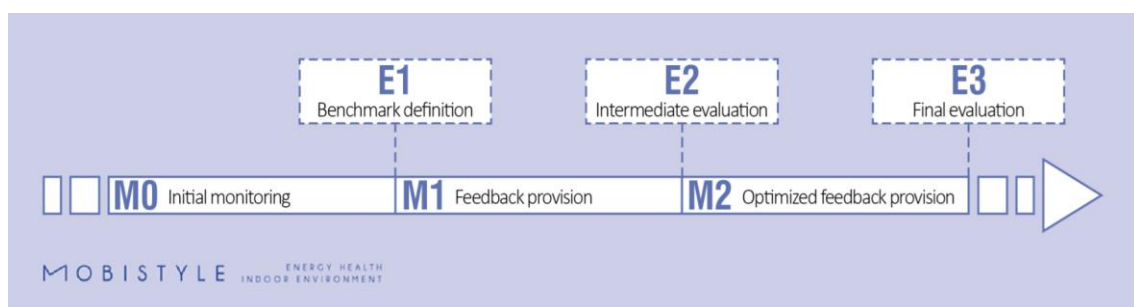


Fig. 3 The evaluation strategy – Mobistyle project

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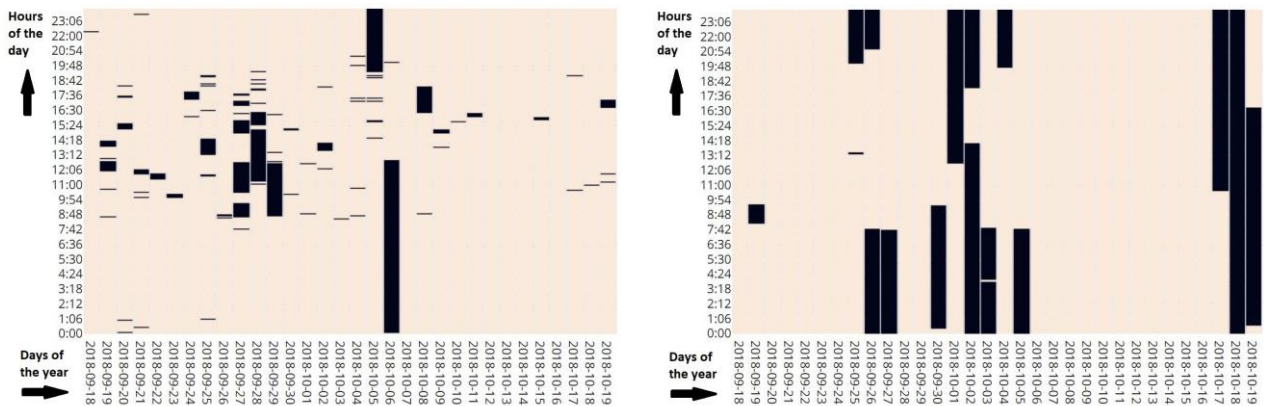


Fig. 4 Measured door openings (on the left) and window openings (on the right) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale has only 2 colours: beige for periods with closed door/window and black for periods with open door/window

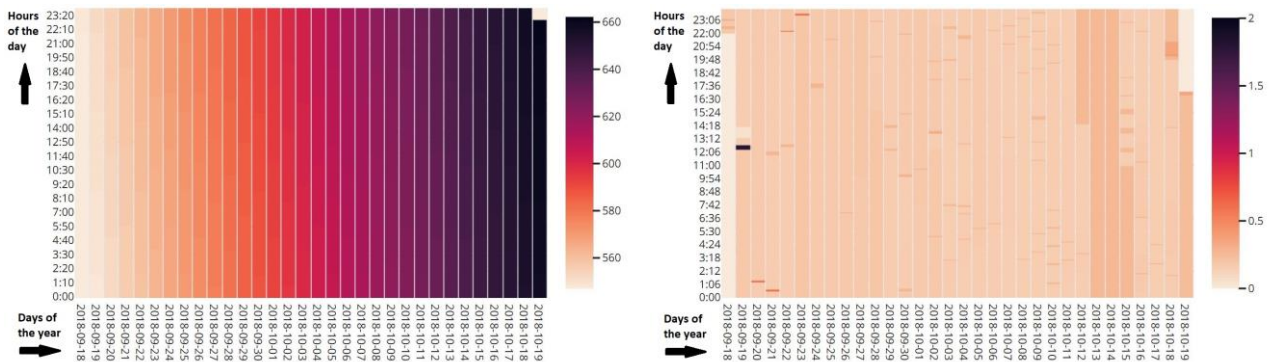


Fig. 5 Measured energy (kWh on the left) and power (kW on the right) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale for energy ranges from 548 to 661 kWh and for power from 0.05 to 1.91 kW

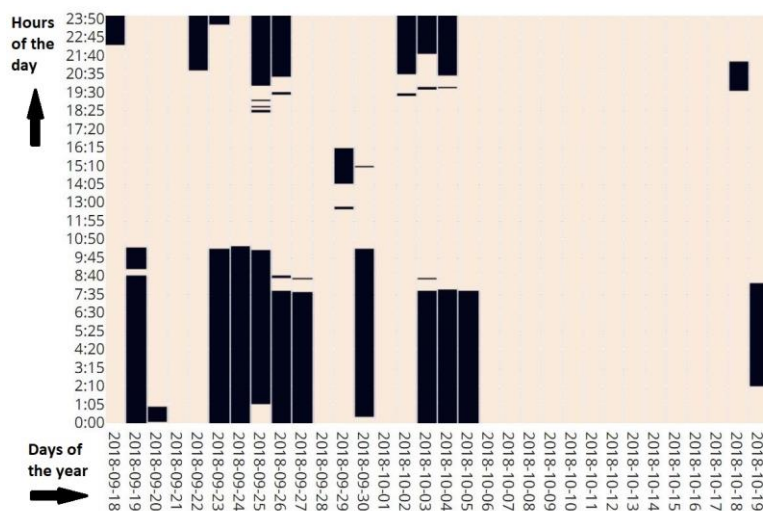


Fig. 6 Measured fan-coil actuator openings (0 closed, 1 open) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale has only 2 colours: beige for periods with closed actuator and black for periods with open actuator

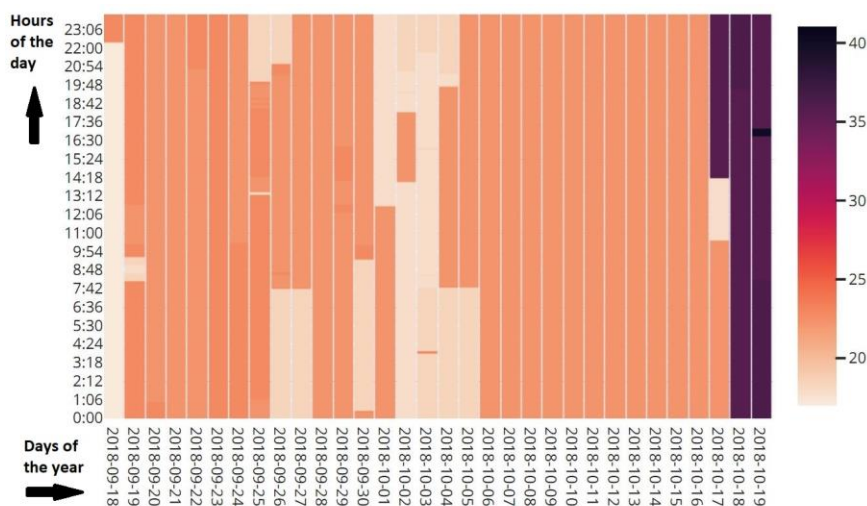


Fig. 7 Measured thermostat set point temperature (°C) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale for set point temperature ranges from 17.78 and 40 °C

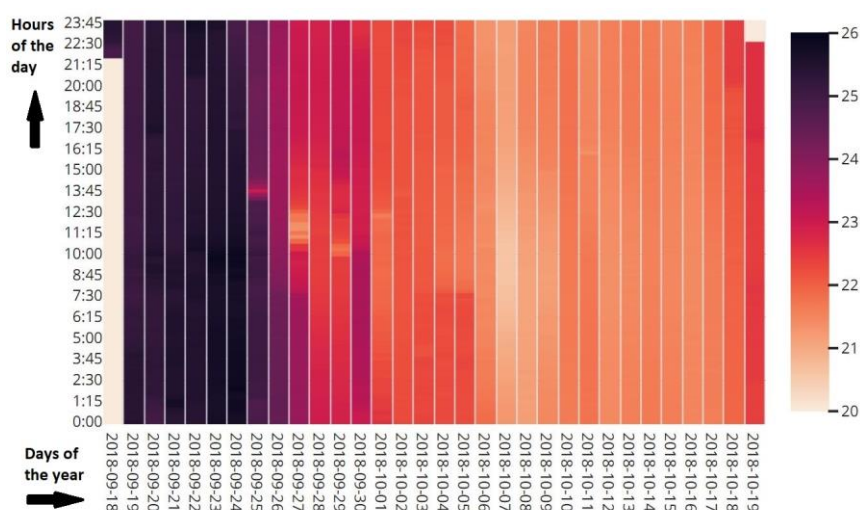


Fig. 8 Measured indoor air temperature (°C) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale for indoor air temperature ranges from 20.58 to 25.88 °C

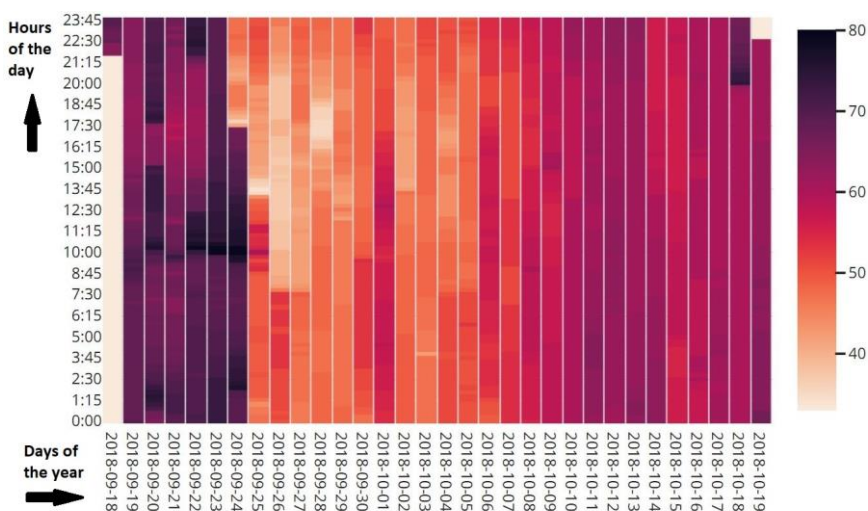


Fig. 9 Measured indoor air relative humidity (%) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale for indoor air relative humidity ranges from 34 to 79 %

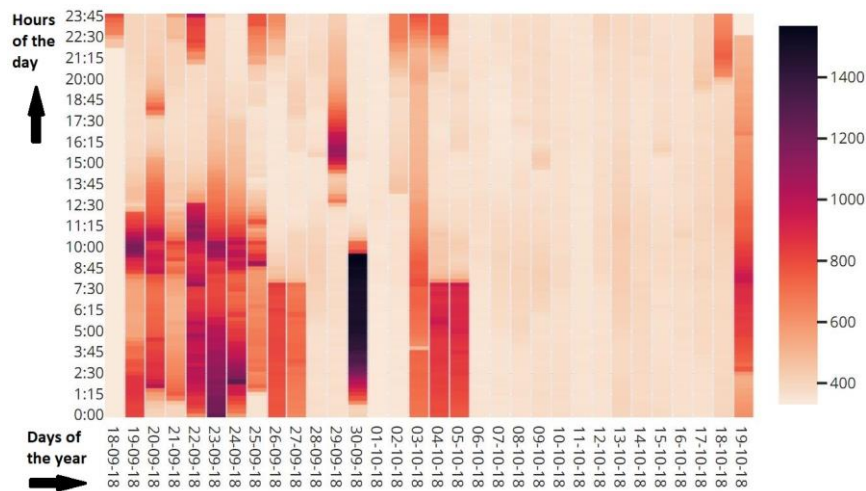


Fig. 10 Measured indoor air CO₂ concentration (ppm) between 18 September 2018 and 19 October 2018 in one of the four monitored guest rooms at Hotel Residence L’Orologio. The colour scale for indoor CO₂ concentration ranges from 331.84 to 1565.44 ppm

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