Measurement and characterization of energy related behaviors and IEQ in residential buildings for physics-based building energy modeling using a wireless sensor network

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***Abstract*—We use a sensor network of 173 sensors to monitor the energy consumption, the indoor environment quality and local meteorological conditions of three collective residential buildings composed of 62 dwellings. In particular, 146 sensors were deployed in 8 apartments and 27 sensors in the buildings common areas. The collected data are used to assess the performances of the three buildings which have recently been undergoing heavy retrofit actions. It also aims to accurately characterize some of the occupants behaviors which directly impact the buildings energy consumption and the indoor environment quality such as the occupancy patterns, the windows opening for natural ventilation or the temperature set point. We observe different occupancy patterns depending on the number of people in apartments and their schedule. As expected, we also observe a strong seasonal variation of windows opening rates and consequently in natural ventilation. Averaged indoor temperatures over the heating season are much higher than the values used in regulatory simulation scenarios. Furthermore, besides the recent buildings energy retrofit there is a total absence of time-of-day dependent heating load control which may explain a large amount of the buildings energy performance gap.**

***Index Terms*—sensor network, building, indoor environment quality, energy, performance gap**

I. Introduction

As residential buildings account for a third of the overall energy consumption and greenhouse gas emissions in Europe [1], building energy modeling is an essential tool to reach energy efficiency goals [2]. In the energy modeling process, calibration is a mandatory step to obtain accurate and reliable energy simulations [3]. Nevertheless, the comparison between simulation results and the actual building energy behavior often highlights a significant performance gap [4] that may have various origins [5]. Among these, building operation description in energy models, especially energy usages, users' behavior and indoor environment quality (IEQ), play an important role in the reliability of simulations [6].

To render a more accurate building operation description and target performance gap reducing, using monitored field data are is a key solution [7]. Sensor networks are popular tools for in situ data collection and have been promoted by recent regulations over energy monitoring [8]. However, the literature shows that the many aspects of energy related behaviors and IEQ are difficult to target all at once and with a high level of detail [9,10], especially in residential buildings [11].

Therefore, the present study discusses results on the analysis of field data collected in a residential case study to characterize energy-related behaviors and indoor environment quality (IEQ) for physics-based building energy modeling and calibration. The case study is a three-building residence of social housings, and recently retrofited. Data collection covers building energy behavior – thermal and electricity, indoor environment, inhabitants' comfort, occupancy, occupants behavior and energy uses, and local weather. Data are collected through a wireless sensor network of 173 sensors, deployed on energy systems, in shared portions of the buildings and in an eight-apartment sample [12]. Collection is performed for over a year in house-

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holds and for three years at building scale. Analyses focus on occupancy, natural ventilation through window opening, and heating patterns.
The article is organized as follow: Section 2 introduces the case study. Section 3 details materials and methods for the sensor network and collected data processing. Analyses results are discussed in Section 4 along with a feedback on lessons learnt from the instrumentation process. Section 4 presents conclusions and future works prospects.

II. Building use case description

Building use case has three residential social housing buildings located in Paris (France) eastern suburb. Buildings comprise 63 apartments over a 4,600 m² living area. They were built in 1974 and underwent a full deep energy retrofit in 2021. The main energy-uses, heating and domestic hot water, are produced by a central geothermal energy system dedicated to the three buildings.
An eight-apartment sample is instrumented along with common portions of the buildings and building-scale thermal energy consumption. Description of the eight supervised apartments is given in Table I with the floor number, the related area, the orientation and the floor number. Buildings are later referred as B1, B2 and B3 in the present study. Instrumented households are referred with their floor such as B1/2 for the apartment on the second floor of building.

TABLE I
Description of instrumented apartments

Building	**Floor number**	**Area (m^2)**	**Orientation**	**Number of inhabitants**
B1	2	63	North-West	2
B1	3	50	North-East	1
B2	0	64	North-West	1
B2	1	53	South-East	1
B2	2	53	South-East	1
B2	5	50	South-East	1
B3	0	74	North-East	2
B3	2	64	North-West	1

III. Materials and Methods

A. Instrumentation plan and used sensors

The sensor network aims to characterize the main energy end-uses (electricity, heating and domestic hot water), indoor environment quality and energy-related behaviors. We installed 173 sensors in total, 27 of which are dedicated to the buildings common areas, with a data collection starting in February 2019. We also installed 146 sensors in a sample of 8 apartments, with an average of 18 sensors for each apartment and data collection starting from February 2021.
Electricity demand is measured in electrical switchboards, on smart electric meters and with smartplugs – only in apartments for the latter – at one-minute time-step. Thermal energy consumption, for heating and domestic hot water (DHW), is measured at building-scale with ultrasonic thermal energy meters at five-minute time-step. In apartments, thermal energy demand is characterized using temperature measurements at one-minute and half-hour time-steps for DHW and heating, respectively. Indoor environment quality is monitored with a half-hour time-step using a sensor combining temperature, humidity, CO_2 and luminosity measurements, along with sensors measuring the temperature of building envelope walls. At building-scale, temperature and humidity are hourly monitored. Energy-related behaviors are tracked with window-opening and presence detection – counting the number of passing in the range of the sensor. The former is event-driven and the latter is aggregated data half-hour time-step.
The local weather is monitored as well using a weather station with measurements of temperature, humidity, rainfall, solar irradiation, wind speed and direction.

B. Data collection and storage

The sensor network is entirely wireless. It relies on two different wireless communication protocols: LoraWan and GPRS. LoRa is divided between an operated network and a private network. The choice of a specific protocol depends on its characteristics, data acquisition requirements and available technologies for each type of sensor [12]. GPRS data communication is used for electrical measurements on electric smart meters and switchboards. Building-scale data acquisition along with smart-plugs relies on a LoRa operated network. All other sensors installed in apartments are using a private LoRa network.
Collected data are stored on a FTP server, in csv format.

C. Data processing

Data processing is divided into five steps. First, data are cleaned to only retain relevant information: date, time, type of measurement, and corresponding values. Collected data are then formatted. Because of the many different types of sensors and communication protocols, raw data are initially collected under different formats. Data filing is set to a single csv file for each measurement of each sensor, updated daily. Data quality is studied to assess data completion for the different sensors, identify relevant timeframes for data analyses and identify potential causes of data losses.
The fourth step of data processing unifies data time-step. Data aggregation is set to hourly time-step. Indeed, sensors have different acquisition time-steps, from one-minute to one hour. Therefore, the largest time-step is selected. Moreover, data analyses are performed to use analyses results for physics-based energy modeling where usage scenarios are mostly daily profiles with hourly time-step. These daily profiles are obtained by averaging data for each time-step.
Finally, specific types of data are modified. Window opening data are resampled prior to aggregation because of event-based data acquisition. Presence detection in apartments is modified to presence/absence. If any presence is detected, the apartment is considered with full occupancy. Otherwise, it is considered empty. DHW temperature measurements in apartments are processed to deduce DHW usage. Since DHW volume consumption cannot be measured onsite, averaged

daily consumptions for 40°C DHW usage are retrieved from studies from ADEME agency [13]. A 40°C threshold is applied to DHW temperature measurements: any data point over 40°C is considered as one minute of DHW usage. Data are summed at hourly time-step to retrieve daily profiles figuring DHW time usage for each hour. Then, daily mean consumptions are evenly distributed over the daily profiles. Data processing is performed using Python 3.7.

IV. Results and Discussions

A. Occupancy and natural ventilation

Building occupancy is expected to be a predominant energy driver since it leads to DHW consumption, window opening, dissipated power from appliances use, ventilation regulation and so on. Occupancy is deduced from presence detection in apartments, performed in the living room. Activity and presence of occupants in the different apartments largely differ from one apartment to the other. Comparing B1/2 (Figure 1(a)) and B1/3 (Figure 1(b)), presence in the former is quite consistent all along the day with small peak at lunch time and in the evening. In B1/3, there are two clear signs of activity in the apartment, in the morning and in the evening. Such differences can be explained by the number of people living in instrumented apartments and their respective schedule: B1/2 has a student with changing schedule and a working parent while B1/3 only has a full-time working adult. However, because presence detection sensors do not count how many people are present in the apartment at a given time, uncertainties remain for occupancy profiles of apartments with several occupants.

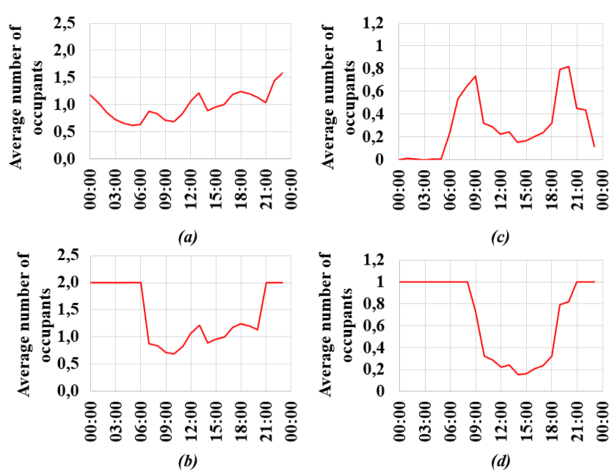


Fig. 1. Occupancy profiles for B1 floor 2 (a) and B1 floor 3 (b) before night correction and after night correction (c) and (d)

Natural ventilation is pictured by window opening. Window opening data are processed to result in daily profiles with an opening duration for each hourly time slot of the day. Daily profiles are then aggregated for each month. Window opening shows that this behavior is mostly season-driven as for the example of the living room in B1 floor 2 (Figure2). Windows are mostly opened during the summer period. This can be explained by the absence of AC units in the buildings. Furthermore, regarding the short time of opening during the heating season starting in October, window opening duration is expected not to have a very significant impact on heating energy consumption.

	May-21	June-21	July-21	Aug-21	Sept-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22
00:00	3	27	22	21	10	0	3	2	0	0
01:00	2	24	24	20	8	0	0	2	0	0
02:00	2	22	24	20	6	0	0	2	1	0
03:00	1	21	24	20	6	0	2	1	4	0
04:00	0	19	24	18	6	0	2	0	4	0
05:00	0	19	24	18	6	0	2	0	4	0
06:00	0	18	24	18	4	0	2	0	0	0
07:00	0	19	25	18	5	0	3	1	1	0
08:00	0	19	26	18	6	0	3	0	0	0
09:00	2	25	24	19	5	4	0	2	1	2
10:00	3	28	26	23	8	3	1	3	4	3
11:00	2	23	27	26	6	5	2	5	4	4
12:00	5	22	30	29	9	9	1	7	9	1
13:00	9	27	29	35	17	9	2	4	6	1
14:00	8	25	29	31	19	2	0	4	4	0
15:00	7	22	30	31	17	0	1	8	1	0
16:00	5	22	32	35	15	3	3	6	3	1
17:00	7	23	31	33	13	5	0	6	4	2
18:00	4	22	29	38	20	4	0	0	8	2
19:00	9	25	30	40	29	3	1	1	9	2
20:00	7	30	28	38	26	1	0	1	5	0
21:00	9	28	19	31	23	0	0	0	8	0
22:00	9	28	18	25	21	0	2	0	9	0
23:00	2	26	23	24	13	0	7	1	5	0
Total opening time per day (hours)	**1,6**	**9,4**	**10,4**	**10,5**	**5,0**	**0,8**	**0,6**	**0,9**	**1,6**	**0,3**

Fig. 2. Daily window opening profiles for each month from May 2021 to February 2022 – each cell shows the number of minutes of opening for each hourly time slot.

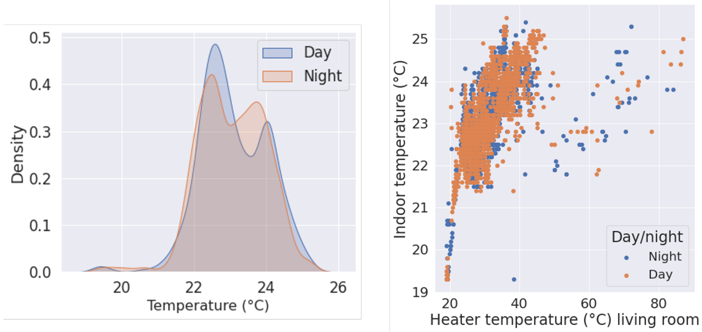
B. Heating patterns

Heating patterns are characterized using indoor air temperature and heaters temperature measurements.

Indoor temperature measurements show that obtained measurements are much higher than the recommended 19°C setpoint temperature. Indeed, apartments have an average indoor temperature from 21.2°C for B1/2 up to 25°C for B3/0 for the 2021-2022 heating season. Also, despite the fact the three residential buildings are just retrofited with a brand new heating system, analyses results show that there is no water logic management of the heating system. Indeed, there is no difference between day and night temperatures in the apartment (Figure3 (a)) which is also highlighted by the analysis of heaters temperature confirmed by the analysis of heaters temperature analysis (Figure3 (b)).

C. Field experiment feedback and lessons learned

Data analyses entirely rely on a field experiment. Implementing such a large sensor network highlighted several critical points for future work and replicability [12]. First, the installation conditions and environment are critical. Indeed, existing buildings were not necessarily built and designed to have such a diverse instrumentation solution installed. Although the energy retrofit updated many aspects of the



(a)

(b)

Fig. 3. Density curve for indoor temperature in B1/3 (a) and scatter plot of indoor temperature vs. heaters temperature in the living room of B1/3 (b) comparing day and night time measurements.

buildings, there are still data communication issues remaining because of the location of sensors, gateways and structure of the building. Also, the whole purpose of the study is to collect data in an occupied environment. This is a strong constraint as well, since many sensors can be moved or deactivated by building users, thus affecting data collection.

The sensor network uses technologies from the IoT market. These technologies are not developed to sustain such a demanding and detailed instrumentation plan. This resulted in several technological issues, malfunctions, and limitations regarding the measurements. Moreover, about half of the sensor network deployment was entrusted to a contractor, while the rest of the solution was installed and supervised by the research team. Comparing the two processes, it results that an internal management of the instrumentation requires strong technical skills and knowledge. However, it significantly ease and speed up the handling of technical issues, then preventing significant data loss. On the other hand, contractors provide a more "plug-and-play" service without constraints of installation. However, they do not control the whole chain of sensor network deployment as they often depend on other contractors for installation services. Hence, there is a major loss of time and data in the communication and operation process to set up the sensor network and fix technical issues.

Conclusions and Future Work

We used a sensor network of 173 sensors to monitor energy consumption, occupants behaviors and indoor and outdoor environment quality of three collective residential buildings composed of 62 dwellings for more than 2 years. In particular, we extensively instrumented a sample of 8 dwellings and the buildings common areas.

The main goal of the deployed sensors network is to assess the buildings energy performance after a heavy retrofit program, to compare actual performance to predictions and to understand the eventual performance gap using field data. Collected data enable us to characterize the occupants behaviors, a parameter of paramount importance for the buildings performance gap understanding. In particular, we extracted typical occupancy patterns, windows opening patterns and heating patterns. If occupancy patterns correspond to what is commonly reported in literature, we show a strong seasonal variation of windows opening patterns. In addition, measured heating patterns exhibit high indoor temperatures compared to values generally used in standard heating scenarios considered in energy codes and building thermal regulations in general which might explain a significant part of the performance gap.

The buildings monitoring as well as the data processing is still in progress and will enable us in the near future to automatically extract typical energy consumption and occupants behaviors patterns using automatic data profiles clustering [14]. Clustering results can then be embedded in building energy models to accurately assess their impact on the buildings overall energy consumption and the potential performance gap between simulations and measurements. In addition, the cross analysis of different measured quantities such as occupancy, indoor environment quality, outdoor weather conditions condition, energy related behaviors will enable us to derive finer and more realistic models for these different quantities.

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