A Sensor Network for Existing Residential Buildings Indoor Environment Quality and Energy Consumption Assessment and Monitoring: Lessons Learnt from a Field Experiment

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A sensor network for existing residential buildings indoor environment quality and energy consumption assessment and monitoring

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Abstract: Enhancing residential buildings energy efficiency has become a critical goal to take up current challenges of human comfort, urbanization growth and the consequent energy consumption increase. In a context of integrated smart infrastructures, sensor networks offer a relevant solution to support building energy consumption monitoring, operation and prediction. The amount of accessible data with such networks also opens new prospects to better consider key parameters such as human behaviour and to lead to more efficient energy retrofit of existing buildings. However, sensor networks planning and implementation in general, and in existing buildings in particular, is a particularly complex task facing many challenges and affecting the performances of such a promising solution. In the present paper, we report on a field experiment of a sensor network deployment involving more than 250 sensors in three collective residential buildings in Paris region for the evaluation of a deep energy retrofit. More specifically, we describe the whole process of the sensor network design and roll-out and highlight the main critical aspects in such complex process. We also provide a feedback after several months of the sensor network operation and preliminary analysis of collected data. Reported results path the way for an efficient and optimized design and deployment of sensor networks for energy and indoor environment quality monitoring in existing buildings.

1 INTRODUCTION

Residential buildings are one of the major energy consumers and greenhouse gas (GHG) emitters, with 38.1% of the final energy consumption and 36% of the GHG emissions in Europe (ADEME, 2015). Efforts have been made to reduce the impact of residential buildings on energy consumption with various codes, standards and thermal regulation mandatory compliance for designs of new buildings (ASHRAE, 2013; HARMONIE, 2017). However, given the slow turnover of the building stock in European countries, the effect of these regulations is limited (INSEE, 2017). Hence, existing building retrofit turns into a priority (ADEME, 2018). On the other hand, ambitious massive smart sensor networks plans (European Commission, 2019; European Parliament & European Council, 2009; French Ministry of Ecological and Sustainable Transition, 2016) have been launched in recent years to enhance buildings energy efficiency.

Smart sensor networks have been largely deployed in buildings for energy monitoring and operation (Bourdeau, Guo, & Nefzaoui, 2018; Fan, Xiao, Li, & Wang, 2018) or building energy consumption forecasting (Bourdeau, Zhai, Nefzaoui, Guo, & Chatellier, 2019; Jain, Smith, Culligan, & Taylor, 2014). Studies have used sensors to highlight and characterize the link between energy efficiency and inhabitants' behaviour (Li & Lim, 2013; Menezes, Cripps, Bouchlaghem, & Buswell, 2012; Pisello & Asdrubali, 2014), identified as one of the main source of energy performance gaps (de Wilde, 2014). Data collection solutions have also been proposed to supervise building energy retrofits (Ben & Steemers, 2014; Calì, Osterhage, Streblow, & Müller, 2016; CSTB, 2016; Jankovic, 2019). However, instrumentation solutions deployment is a complex task, facing many challenges and difficulties. Thus, it directly impacts on the quality of the analyses and the efficiency of related energy savings measures (Calì et al., 2016; Jankovic, 2019; Pisello & Asdrubali, 2014).

In this context, we present a feedback on a case study of a sensor network deployed in three existing collective residential buildings in France. The instrumentation takes part in a larger project that aims to study the impact of deep energy retrofit measures on the studied building energy consumption.

The present paper is organized as follows: we present the project case study in Section 2 ,then, we describe details of the instrumentation solution in Section 3. A feedback on the main critical points for sensor networks implementation in existing buildings is proposed in Section 4. Finally, Section 5 presents lessons learned from priliminary analysis of data collected after several months of operation of this experimental sensor network.

2 PRESENTATION OF THE CASE STUDY

In the present research project, a group of three existing social residential buildings – 63 apartments over a 4,600 m² living area – is considered for field experimentation. Buildings were built in 1974 in Paris (France) eastern suburb. Shared areas of the three buildings and a 10-apartment sample are instrumented for a period of three years, starting in March 2019. The ten apartments comprise surfaces from 50 to 75 m² distributed in the three studied buildings, on different floors and with different orientations. Apartment case studies have one to two occupants of various ages, professional occupation and living habits.

For all three buildings, heating and domestic hot water are provided through a heating substation located in one of the three buildings and served by a neighborhood gas furnace. Thus, heating settings and management are centralized. All appliances in apartments are electric appliances excepted for those using natural gas for cooking.

Case studies only had minor retrofit actions. They are now planned to undergo deep energy retrofit measures over an eighteen-month period in 2020-2021. Retrofit measures will be implemented on occupied site with tenants living in their apartments during the whole retrofit period. Retrofit actions in shared areas include i) the removal of the heating substation and the connection to a local urban heating network, ii) exterior thermal insulation and iii) installation of a new controlled mechanical ventilation. In the apartments, it includes renewal of the iv) radiators and of v) the whole glazing system.

3 INSTRUMENTATION METHODOLOGY

3.1 Instrumentation plan

The instrumentation deployed aims to provide a multi-scale and multi-targets wireless monitoring solution. It focuses on data collection at both building- and apartment-scale for energy consumption, outdoor and indoor conditions, and inhabitants' comfort and behaviour. Moreover, the installed sensor network needs to be as non-intrusive as possible. This is essential to ensure that the participants' comfort and living habits remain undisturbed to prevent any bias in the experiment.

3.1.1 Sensor characteristics and deployment

The sensors selection and deployment are performed in two different phases, to set a total number of 259 sensors and connected objects (Table 1). The first deployment phase covers shared areas and entire building level. It involves only 10% of the total number of sensors for 35% of the total cost. In this phase, sensors provision, installation and data communication are entirely managed by a hired contractor. Electricity consumption is monitored on the main electricity meters and switchboards targeting the overall and detailed shared areas energy consumption (lightings, lifts and ventilation) with a one-minute time-step. Electricity consumption of water pumps in the heating substation is also monitored. Building-scale thermal energy consumption is assessed using ultrasound thermal energy meters (Figure 1), with a five-minute time-step. Infrared presence detection sensors are positioned at the main entrance door of the three buildings and indoor temperature and humidity sensors are positioned on three floors of each building – ground floor, middle and last floor – for data collection with hourly time-step. Finally, a weather station is positioned on a nearby university building to monitor local air temperature, humidity, wind speed, wind direction, rainfall and solar irradiation data at 5-minute time-step. This first instrumentation step is now fully operational, exception made for the weather station which is currently being installed.

The second part of the sensors focuses on the characterization of apartments (aside from building-scale monitoring of domestic hot water consumption delayed to this second phase). Power demand is assessed with sensors installed on the main electric meter and switchboard, and smart-plugs to monitor all the main appliances of the instrumented apartments (one-minute time-step). Apartment-scale hot water consumption is assessed using contact-temperature sensors on hot water pipes (one-minute time-step) completed with data from already-installed remote reading volumetric meters. Also, heating energy consumption is deduced in a similar way using contact-temperature sensors on heaters (hourly time-step). Natural gas consumption, only used for cooking, is monitored with sensors installed on apartments gas meter (one-minute time-step). Indoor conditions and comfort should be captured using contact-temperature sensors positioned on exterior walls of the apartments and a sensor combining indoor temperature, humidity, luminosity, CO_2 and presence measurements (hourly time-step). Finally, occupants' behaviours should mainly be characterized through occupation data and using sensors for window opening-closing detection. This second deployment phase will start in November 2019.

Figure 1: Installation example of a thermal energy meter for heating energy demand monitoring

3.1.2 Communication network and online data collection

Data communication is mainly based on LoRaWan communication protocol – Long Range Wide-area network (Augustin et al., 2016). LoRa is a technology commonly used in IoT projects and wireless sensor networks deployed in smart buildings and smart cities contexts (Centenaro, Vangelista, Zanella, & Zorzi, 2016; Pasolini et al., 2018). It is relatively easy to implement, it provides information on the sensor status and it allows long-range data transmission even in areas with difficult access. LoRa technology is also cost-effective in terms of energy: it relies on radio waves with low communication rate and then low energy consumption.

Several implementation strategies have been selected for the two presented instrumentation phases. The first phase is using an operated LoRa network with two gateways installed onsite. Only the electricity consumption-dedicated sensors use a GPRS network because of the limitations of operated LoRa network in terms of bandwidth usage (Electronic Communications Committee, 2019) and the selected acquisition time-step. The second phase is processed differently and separated into three sub-phases. As for shared areas, energy monitoring is entirely managed – meaning provided, installed and operated – by a contractor. Other sensors are provided and configured by a different service company and installed onsite by the research team in charge of the project. Finally, a ten-sensor sample (those combining measurement of indoor temperature, humidity, luminosity, presence and CO_2 level for apartments) is entirely set up and installed by the research team. The LoRa network used is now a private network to bypass bandwidth usage constraints related to data acquisition time-step.

For all sensors, collected data are retrieved on a unique FTP server. The final format provides collected raw data with one csv file for each day and for each sensor. Information include the sensor identification and location, the type of measurements, the timestamp, the measured values and the units. Only data from the weather station are treated on a separated dedicated platform.

3.2 Instrumentation management process

Instrumentation overall management has a crucial impact on the success of the instrumentation and of the whole project. In the present study it can be divided into six different stages over an estimated timespan of one year and four months (started in October 2018 and expected to end in January 2020).

First is the accurate definition of the instrumentation specifications to meet the needs of the project, as detailed in Section 3.1.1. In parallel, a

Table 1: Characteristics summary of the deployed sensors

Sensor	Number at building scale (per building)	Number per apartment	Total number	Acquisition time-step	Communication protocol
Indoor temperature & humidity	3	/	9	Hourly	Operated LoRa
Presence	1	/	3	Hourly	Operated LoRa
Combined indoor temperature, humidity, luminosity, presence & CO_2 level	/	1	10	Hourly	Private LoRa
Exterior walls surface temperatures	/	2-5	32	Hourly	Private LoRa
Window opening detection	/	3-5	38		Private LoRa
Gas consumption	/	0-1	4	One-minute	Private LoRa
Electricity demand – main electric meter	2-3	1	17	One-minute	GPRS
Electricity demand – switchboard	0-1	1	11	One-minute	GPRS
Electricity demand – smartplugs	/	5-9	67	One-minute	Private LoRa
Heating energy demand – thermal energy meter & pulse sensor	1 + 1	/	3 + 3	Five-minute	Operated LoRa
Heating energy demand – radiators	/	3-5	36	Hourly	Private LoRa
Domestic hot water energy demand – thermal energy meter & pulse sensor	1 + 1	/	3 + 3	One-minute	Private LoRa
Domestic hot water energy demand – apartments	/	2	20	One-minute	Private LoRa

review of service providers offering adapted solutions is performed and apartments are recruited to participate to the instrumentation study. Once specifications are organized in a clear framework, they are submitted to identified contractors. Several rounds of discussions allow modifications on the specifications to adapt to the reality of the market and for service providers to refine their offer to meet the needs of the project to the best of their capabilities. Every round dismisses several service providers to select the most relevant ones. In the present case a total number of thirty-three service providers have been contacted for a short-list of ten and two final selected contractors. Once a contract is signed, sensors are ordered, delivered and installed under the supervision of the research team. Finally, when the sensor network is functional, data quality is checked. It ensures that all sensors are properly measuring and transmitting data, that there are no missing information or other issues and that the proper data format is displayed for future applications.

4 IDENTIFTICATION OF CRITICAL POINTS FOR SENSOR NETWORK IMPLEMENTATION

The planning and deployment of the proposed instrumentation solution has highlighted several critical aspects in sensor network implementation. These critical points arose from various issues encountered during the instrumentation process. These can be grouped into four categories with i) onsite installation conditions and environment, ii) characteristics and purpose of instrumentation, iii) service provider and iv) project tracking and management.

4.1 Onsite installation conditions and environment

Characteristics of the experimentation site have a significant impact on the feasibility of a monitoring project. As a first step, it is crucial to precisely identify the equipment and installations to be monitored. Equipment conditions are also important, as for security reasons some may not be monitored. Indeed, over the selected ten-apartment sample, seven electrical switchboards could not be equipped because of their obsolescence and have to be replaced for the experimentation. Sensor connectivity must also be considered since metal stairs and doors disrupt radio waves and then data transmission. Finally, the installation environment should be documented. For instance, several sensors do not use batteries but need a main power supply – thermal energy meters for instance. In the studied buildings, electrical installations were not adapted or even not existing where they were needed. Thus, additional costly actions were necessary to prepare the installation site.

The instrumentation solution described is also specific because all buildings remain occupied during the sensor network deployment and the whole experimentation. Then, the sensor network must as non-intrusive as possible. However, non-intrusive sensors imply higher costs because of specific technologies. Also, as the project mostly relies on collected data from apartments and occupants' behavior, it is necessary to recruit participants. Then, recruitment is a crucial step for the success of the research project, but is particularly time-consuming, requiring several rounds of presentations and visits (general presentation, door-to-door visits, phone calls and individual meetings). It also needs a well-prepared and transparent communication on the project. Project goals must be clearly stated, project actors must be identified, and inhabitants must find clear benefits in their participation. Finally, as most collected data are personal data, a specific attention should be given to related regulations and mandatory administrative actions (French Ministry of Economy, 2019).

4.2 Characteristics and purpose of the instrumentation solution

The introduced sensor network serves for a research project with specific needs. Therefore, it differs from usual commercial monitoring studies because it aims to investigate situations and details that would usually not be considered. More specifically, there are a wide range of acquisition time-steps (from one minute to one hour) and a large variety of sensors and measurements as presented in Table 1.

Consequently, such a complex instrumentation solution faces several challenges. Sensors are designed for standardized usage conditions depending on the environment of installation and usually with hourly acquisition time-step. However, specific implementation characteristics imply that the sensors must respect specific standards, such as for gas consumption metering (Zone-atex.fr, 2019). Moreover, having sub-hourly acquisition time-steps is reducing the expected battery lifetime. This needs to be considered while selecting sensor technologies as it is not always possible to change the battery of sensors (due to manufacturing standards). Also, sensor technologies and measurement characteristics (especially the acquisition time-step) are defining the communication protocol selected for the sensor network. Indeed, several IoT communication protocols are available on the market such as operated and private LoRa networks, GPRS, Sigfox (Sigfox, 2019) or Modbus (The Modbus Organization, 2019). However, they all have different characteristics, advantages and constraints. For instance, operated LoRa networks restrict bandwidth usage. Then having a one-minute time-step on large amounts of sensors is hardly possible. Private LoRa networks offer a solution but are more complicated to implement. Other solutions such as GPRS also raise different issues related to wireless monitoring technologies and electro-sensitivity.

4.3 Service providers and contractors

Through this study, service providers have been hired to provide an instrumentation solution adapted to the goals of the research project. On the French IoT market, there are many different contractors. However, they do not all provide the same delivery. Most commercial proposals focus on sensor provision but do not include set up and installation. Therefore, such contractors must partner with other companies to match the needs of a project. This often leads to many communication issues and delays. Furthermore, when a contract is established, all the terms must be carefully checked to ensure a smooth project process. Some points must be investigated and especially i) responsibilities and guarantees about the sensors/network and about the potential provision and installation delays, ii) maintenance details and conditions when included, and iii) what is done by the contractor with collected data during and after the contract validity.

Regarding technical aspects, it is necessary to ensure the service quality and expertise of contractors. Indeed, there is a significant difference between common "plug and play" sensors – such as for temperature or humidity sensors – and energy metering. The latter requires very specific knowledge on the technologies, installation procedures and data acquisition checking. Moreover, many contractors do not have such equipment and need to partner with other manufacturers. Contractors with a lack of expertise should be avoided to prevent many future issues such as with sensor calibration or equipment failures.

Finally, the budget management requires a detailed investigation. Indeed, there can be several unexpected expenditure items which function is not always explained by contractors and that can significantly increase the total instrumentation budget. This include for instance accessories, connectivity subscriptions, details of all-inclusive maintenance contracts, installation and setup, or site visits. From the ten complete commercial proposals received for the present project, the total budget could be divided into 38% for sensors provision, 20% for installation, 20% for set up and data treatment software/platform, 9% for communication system, 8% for maintenance and 5% for project supervision.

4.4 Project management

The overall project management, comprising supervision on the three previous subsections, is the key to a smooth sensor network deployment and optimal valorisation. Regarding the instrumentation, a detailed and precise tracking is mandatory to identify every sensor with sensor type, measurements, communication protocol, installation date and location. This ensure that any potential issue will be solved with the minimum amount of time.

Adapted and controlled communication is essential within the research team to prevent any loss of information and miscommunication. It also must be ensured with other actors and particularly with building occupants. Indeed, it is recommended to avoid any over-soliciting with inhabitants for obvious privacy reasons. Finally, as the present research project is a multi-disciplinary study combining several research teams, an optimal coordination is needed. Objectives and tasks should be clearly defined for each actor. People in charge also must be designated for optimal communication and project tracking.

5 PRELIMINARY DATA ANALYSIS FROM THE FIRST INSTRUMENTATION PHASE

The first instrumentation phase focusing on building common areas is fully operational. Thus, a statistical data analysis is performed on an observation window from 2019/02/19 to 2019/10/06 to highlight issues in collected data. Twenty sensors are considered including data for temperature & humidity (9 sensors – hourly time-step), passage counting (3 sensors – hourly time-step), thermal energy (3 meters – 5-minute time-step) and electric power demand monitoring (5 sensors – 1-minute time-step).

The main highlighted issue relates to missing datapoints. Over the given observation period, 92.7% of the expected datapoints are collected. Figure 2 compares the evolution of expected measurements (blue curve) and of the effective collection results (orange curve) with the variation of the percentage of acquired data (green curve). The major gap is due to a 17-day-long sensor malfunction in May 2019 for the electrical switchboard monitoring. Electricity demand data collection is therefore the category with the least collected datapoints (on Figure 3: 92.0% of the optimal target), followed by thermal energy monitoring (94% of data collected). Indoor environment and passage counting account for more than 99% of collected data. However, large amounts of missing energy measurements should also be transposed to time-scale analysis. Indeed, electric sensors provide one-minute time-step information. Hence, over a 230-day observation period, it would be equivalent a loss of less than 19 days of data and in the present case essentially concentrated on a specific period for one specific sensor.

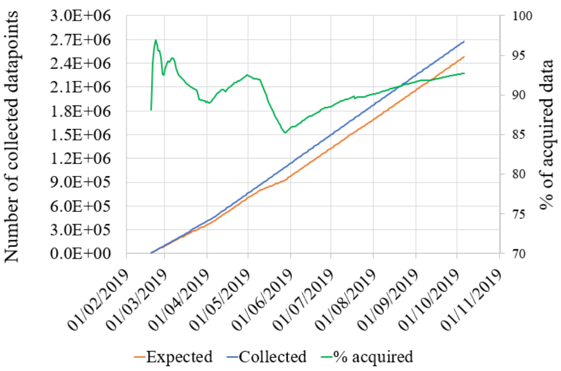

Figure 2: Evolution of collected datapoints (orange) compared to expected collected datapoints (blue) from 2019/02/19 to 2019/10/06

Other observed outliers are abnormal and additional measurements. Abnormal values are only found for energy demand monitoring, with overly high measurements or zero-values. The former represents 0.06% of total datapoints while the latter accounts for 6.8% of the amount of collected data and is almost exclusively related to electrical switchboard monitoring (99.9% of abnormal measures). Also, such measurements should be further analyzed from an energy-behavior point of view. Indeed, unexpected zero power demand can be related to data loss but also to potential power cuts that are part of the building energy behavior.

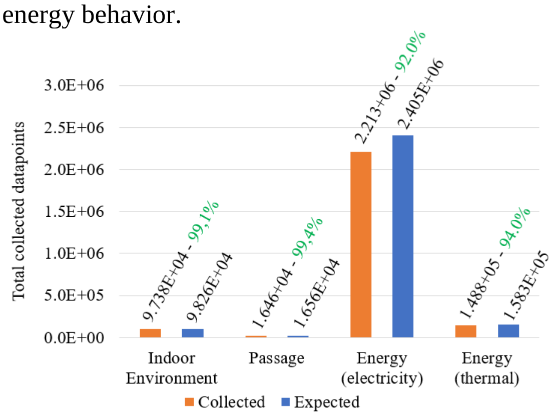

Figure 3: Comparison of collected datapoints (orange) compared to expected collected datapoints (blue) for the different monitoring categories

6 CONCLUSIONS AND FUTURE WORK

This paper presents the planning, deployment and supervision of a sensor network for existing residential buildings monitoring. The proposed solution is a multi-scale sensor network covering thermal and electrical energy consumption, indoor environment and comfort, inhabitants' behaviour and weather conditions, at various timescales from one-minute to hourly.

The instrumentation solution has been entirely planned and divided into two implementation phases. The first phase focuses on the monitoring of building shared areas and is entirely operational. The second phase considers a similar approach on a ten-apartment sample and will be deployed starting from November 2019. Details of both phases are presented with a description of sensor characteristics, communication networks and overall project management.

A feedback on the sensor network implementation from the first phase is proposed. It highlights several critical points to consider for similar future applications. These critical aspects are grouped in four categories with onsite installation conditions and environment, characteristics and purpose of the instrumentation solution, service provider and contractors and project management. A preliminary statistical analysis of collected data is also provided. It highlights the main encountered issues in data collection.

Data analysis should then be extended to measurements from the operation of the second instrumentation phase. Moreover, in order to ensure long-term measurement accuracy and to prevent future avoidable data loss and highlighted data collection issues, a long-term calibration study must be conducted. Finally, data analysis should be further conducted from an energy point-of-view. It would aim to highlight the specificities of building- and apartment-scale energy behaviours and investigate potential issues in building energy management.

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