Do-it-yourself, low-cost building monitoring system

Olivier Steiger, Reto Marek
Lucerne University of Applied Sciences and Arts
Switzerland
olivier.steiger@hslu.ch

Abstract. Monitoring systems are essential for the energy-efficient and comfortable operation of buildings. However, today's monitoring solutions are relatively expensive in terms of purchase, installation, and maintenance. At the same time, there is a need for low-cost monitoring systems, especially for smaller buildings. To address this need, a novel do-it-yourself, low-cost building monitoring system based on open technologies has been developed. The system is intended to be assembled and put into operation by laymen in accordance with given instructions. Accordingly, all work stages must be simple and obvious. This paper describes the low-cost monitoring system and its prototype implementation.

1. Introduction
Monitoring is the generic term for the systematic recording and supervision of conditions and processes by technical means: Operating states of technical systems, electrical and thermal energy, water and fuel consumption, room conditions, user behavior. Monitoring systems are essential for the energy-efficient and comfortable operation of buildings. The objectives are manifold:

- Create transparency regarding optimizations in planning and operation.
- Determine the origin of the performance gap. I.e., deviations of actual consumption values from planning or target values.
- Ensure and maintain the desired building performance.
- Check the success of energy optimization measures.
- Create reliable foundations for further optimization steps.

Today's monitoring solutions are often quite expensive due to hardware, installation, and maintenance cost. At the same time, there is a need for low-cost monitoring systems, especially for smaller buildings.

In this paper, a low-cost building monitoring system based on open technologies is presented. All instructions and software relating to the solution are available on a dedicated website [1]. The system consists of several commercially available measuring devices and an open-source software for data aggregation and visualization. Furthermore, detailed instructions for assembling and using the system are provided. The monitoring solution records energy consumption (electricity, water, heat) and comfort values (room temperature, air quality, humidity). With the new solution, interested persons / bodies / associations will have a simple and cost-effective insight into the parameters relevant to the energy consumption and comfort of their buildings. The target price for hardware and software, installation, data transmission and visualization is well below CHF 1’000.-
The remainder of this paper is organized as follows. Section 2 provides an overview of the state of the art. In Section 3, the architecture and components of the proposed system are described. In Section 4, first test results that have been obtained with a prototype implementation are presented. Finally, Section 5 concludes the paper with some prospects.

2. State of the art
In this section, the state of the art with respect to low-cost monitoring solutions for buildings is reviewed. In addition to scientific literature, available products and community efforts have been surveyed, as these provide valuable insights into the current market situation.

Cost-effective monitoring systems have been investigated in several publications. In one paper [2], an energy consumption measuring plug is described which monitors and controls energy usage of domestic appliances in real-time. The design is based on low-cost, commercially available hardware for voltage and current measurement. A similar solution is presented in [3]. In another publication [4], a low cost, non-intrusive home energy monitoring system is introduced. The design employs open-source hardware based on the Arduino architecture and off-the-shelf sensors for electrical current measurement. In [5], a real-time based power monitoring system that measures the energy consumption within households and uploads the data to the cloud is proposed. Power usage data is extracted from conventional energy meters via the electrical LED interface. In [6], an IoT device that has been developed for monitoring electrical energy consumption in a building is introduced. It consists of three off-the-shelf modules including an electrical energy sensor, an Arduino Nano microcontroller, and a commercial Serial-to-Wi-Fi board. In [7], a software platform is proposed for low-cost, energy-efficient, and secure building energy management and control of multiple buildings from a remote-control center over the Internet.

Various community efforts have also been dedicated to low-cost monitoring solutions for buildings. The Open Energy Monitor [8] is a community project for measuring electricity, temperature and humidity with open-source hardware and software. The basis for this is a Raspberry Pi-based measurement system. The system can be extended by various current and comfort measurement sensors as well as a web app for data processing and visualization. Babelbee [9] is an open-source, do-it-yourself electric power meter with an associated open-source data visualization software. A similar, Arduino-based solution has been developed by foobarflies [10]. Finally, several companies have recently provided proprietary building monitoring solutions for low-cost applications.

Many of the aforementioned solutions are limited to electrical measurements. Thermal energy, fuel consumption and room conditions are not considered. Also, it is often not possible to incorporate existing measurements into the monitoring, e.g., from energy meters. Finally, monitoring data are generally represented as time-series (i.e., raw data), along with some basic statistics such as mean, standard deviation and histograms. Recent studies have shown however that more complex and application-oriented visualizations are expected in practice [11].

3. System overview
In this section, the architecture and components of the proposed low-cost building monitoring system are described.

3.1. Architecture
The architecture of the low-cost building monitoring system is depicted in Figure 1. The monitoring data stem from three different sources:

- **LoRaWAN sensors.** This is the preferred data transmission path. It allows for data collection in (near) real-time, e.g., for quarter-hourly or daily values. Individual measuring devices (sensors) are connected to the public LoRaWAN-network “The Things Network” [12], either directly or via a local gateway. The use of TTN is free of charge, the integration of new measuring devices is simple. Also, TTN offers cloud storage with a capacity of seven days. This prevents data losses in case of temporary outage of the lcm software.
Figure 1. Architecture of the low-cost building monitoring system. The monitoring data stem from three different sources: (i) LoRaWAN sensors; (ii) CSV import; (iii) Time-series database. Data from LoRaWAN sensors are transmitted over The Things Network and stored on the TTN-cloud for max. 7 days. All data are aggregated and visualized using the custom-made “lcm”-software.

- **CSV import.** It is further possible to import monitoring data from comma-separated values (CSV) files. This is often used to read in metering data from utilities or real estate companies.
- **Time-series database.** Finally, it is possible to read data from an influxDB time-series database [13]. This is typically used in order to input data from third-party systems such as Building Automation and Control Systems.

All data are then saved, aggregated, and visualized using the custom-made “lcm”-software (Section 3.3).

### 3.2 Measurement devices

Measurement data can generally not be tapped from existing electricity and heat meters. The main reasons are that numerous different meter types are in use (from electromechanical to smart), and that their communication interfaces – if any – are not unified and often accessible to the utilities only. Therefore, it was decided to make the low-cost monitoring system as self-sufficient as possible. This means that required measurement data will generally be collected on site using easy-to-install, wireless measurement equipment.

To minimize cost, non-invasive measuring devices are used whenever possible. This reduces the cost of installation because it can be done by the end-user, and no power lines or water pipes need to be disrupted. For current measurement, inductive probes are available. The situation is more complicated when it comes to heat measurement. Non-invasive measuring methods are possible. However, these are usually expensive and depend on the heat transfer medium, pipe diameter, material etc.
In the present prototype implementation of the low-cost monitoring system, the following measuring devices are supported. These are used “as is”, i.e., without any further calibration.

- Room comfort sensor Avelon – Wisely Standard → Room temperature, humidity
- Room comfort sensor Avelon – Wisely Carbonsense → Room temperature, humidity, air quality (CO₂-concentration)
- Climate sensor Dragino – LHT65 → Outdoor temperature, flow temperature of central heating system
- Impulse counter nke WATTECO – Flash’O → This is used to readout legacy meters. E.g., electricity consumption, heat consumption, water consumption.

### 3.3. Monitoring software

The custom-made monitoring software “lcm” of the Lucerne University of Applied Sciences and Arts consists of several data evaluation modules and configuration functions. Each module carries out a different evaluation of the monitoring data. I.e., each module is dedicated to different applications or optimization measures. An overview of all available modules is provided in Table 1.

In addition, the lcm software supplies configuration functions for the integration of the measuring devices (Section 3.2) and the definition of the building to be monitored. The software has been developed in the programming language \( R \). It is publicly available (incl. source code) on the development platform GitHub [14].

| Module | Purpose | Visualizations | Required measurements |
|--------|---------|----------------|-----------------------|
| Room > Temp vs. Hum | Comfort analysis regarding humidity and temperature (overheating, mold problems, dry air in winter) | Humidity vs. room temperature, Mollier-h,x-Diagram | Room temperature, Relative humidity |
| Room > Room vs. Outside Temp | Reduction of overheating hours | Room vs. outdoor temperature | Room temperature, Outdoor temperature |
| Room > Air Quality | Comfort analysis regarding indoor air quality (often problematic in bedrooms) | CO₂ vs. time, Lower and upper quantile | Room air quality (CO₂) |
| Room > Temp Reduction | Reduction of heating energy by lowering the room temperature | Room temperature vs. time, Mean value, setpoint, deviation | Room temperature |
| Flat > Electricity | Analysis and reduction of electricity consumption | Daily consumption vs. time, Standby consumption | Electricity consumption flat |
| Flat > Heating | Analysis and optimization of heating energy consumption | Heating energy per year/month | Heating consumption flat |
| Flat > Hot Water | Analysis and optimization of hot water consumption | Hot water consumption per year/month, Hot water consumption flat |
| Central > Heating Signature | Analysis of the heating signature | Heating signature (actual), Energy consumption central heating | Outdoor temperature |
| Central > Heating Curve | Analysis and optimization of the heating curve | Heating curve [actual], Energy consumption central heating | Outdoor temperature |

Table 1. Overview of the data evaluation modules of the monitoring software “lcm”.

### 4. Results

Thus far, the low-cost monitoring system has only been tested with anonymized data from a single apartment house. The building is located in Central Switzerland and comprises four flats. Each flat is inhabited by a family. The test data correspond to a measurement period of two years. A live demo of the system using the aforementioned data is available online [15].

An exemplary screenshot of the lcm GUI is depicted in Figure 2. The screenshot shows monitoring data from Flat A. These are visualized using the data evaluation module “Room > Temp vs. Hum”. All available modules are accessible on the left part of the GUI. In the main display, data are represented in two diagrams: room temperature vs. relative humidity, and Mollier-h,x-diagram. The green area defines temperature-humidity pairs that are considered to be comfortable (“comfort zone”).

With this representation, it is easy to pinpoint measurements that are outside of the targeted comfort zone. Similarly with the other modules, it is possible to visualize data in a concise and purposeful way. Furthermore, the software provides recommendations regarding the interpretation of the measurement data and possible optimization measures. Note that these recommendations are static and do not take into account the actual measurements.
Figure 2. Screenshot of the monitoring software “lcm”. The screenshot shows monitoring data from a single flat. These are visualized using the data evaluation module “Room > Temp vs. Hum”. All modules are accessible on the left. In the main display, data are represented in two diagrams: room temperature vs. relative humidity (left); Mollier-h,x-diagram (right). The comfort zone is depicted as green area. Various parameters can be adjusted on the left and on top of the diagrams. On the bottom, recommendations regarding the interpretation of the measurement data and possible optimization measures are given.

5. Conclusions and future works

The low-cost monitoring system described in this paper provides a low-threshold way to collect and visualize monitoring data in a purposeful way. It provides a flexible solution that allows one to quickly try out and prototype things, i.e., to adapt the monitoring application to one’s own wishes. Also, it is intended to be assembled and put into operation by laymen (e.g., the end-user himself) in accordance with the instructions provided on the project website [1]. Thus, no manufacturing of the system by our institution is necessary, nor is this foreseen.

Note however that the proposed solution has only reached an early prototype stage so far and thus needs to be refined in several ways. First, the system should be validated with a larger number of buildings. In this way, it will be possible to gain valuable, practical experience and refine the solution accordingly. Also, software bugs must be eliminated, the documentation should be further refined, and additional features should be added, e.g., support for multi-building projects.

In addition to the above, some more fundamental challenges shall be addressed in the future:

- Automatic plausibility checking and error correction of the monitoring data.
- Implementation of additional data evaluation modules. E.g., optimization of cooling and ventilation systems.
- Automatic data interpretation, e.g., using machine learning approaches.
- Generation of case-specific optimization recommendations.
- Advanced visualizations, e.g., derived from our previous work [11].

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