HBIM: Low-cost Sensors and Environmental Data in Heritage Buildings

A guide for practitioners and professionals

HBIM Project – April 2018

About

This guide is intended to introduce the heritage conservation professional to the use of low cost sensors to capture environmental data in occupied heritage buildings, for the purposes of enhancing the heritage preservation practice with the capability for real-time monitoring and analysis of the buildings state.

The first part of this document is an introduction to the applications of sensors and data capture in buildings, followed by a more detailed discussion of the particular variables to be captured and the technology available. The second part is a guide to choosing equipment, deployment, and using the captured data, with recommendations for best practice.

Contents

Introduction

The professional practice of conserving occupied historical buildings, usually undertaken under the patronage of national conservation bodies and other foundations, often relies on a professional surveyor personally visiting the building to assess its state and detect potential issues, as well as communication with the occupants regarding their use of the buildings and what issues they can detect.

The recent advances in low-cost environmental sensors and data analytics have paved the way for automation to enter this practice. Low-cost sensors can be used to simplify parts of the conservation practice, enhance others, and introduce more sophisticated possibilities to it; by enabling continuous remote monitoring of the state of the property, and providing insights through advanced analytics on the recorded data. In the simplest scenario, an internet-connected wireless sensor kit can alert the conservation practitioner when undesirable conditions are detected, and make the data available for an analytics software package to diagnose the source of the issue.

Such low-cost environmental sensors have experienced a surge in development and demand in recent years, leading to an increase in the availability of user-friendly solutions that can be deployed in such contexts without great difficulty [1], which has the potential to push this technology out of the academic bubble and into conservation practice. This guide is intended to introduce the heritage conservation professional to the use of low cost sensors to capture environmental data in occupied heritage buildings, for purposes of monitoring and analysis of thermal performance measurement, diagnostics, and internal comfort. It will introduce the various areas where such sensors and data are applicable, the available commercial or open-source solutions for using them, and the practical considerations related to deployment and usage.

Environmental Data in Heritage Buildings

The use of sensors in buildings have grown quickly with the surge of interest in the Internet of Things and sensor technology, finding all manners of applications from simple monitoring of conditions to smart buildings that learn the occupant's preferences and adapt accordingly [2]. In terms of actual practice, the biggest application for data capture in buildings is perhaps the monitoring of energy efficiency and thermal performance. Studies monitoring conditions in buildings and their energy usage to analyse thermal and energy performance have been taking place since the 1970s [3] [4]; others looked at the hygrothermal properties of walls [5], some heating controls [6], and yet more on solar permittivity [7].

In heritage buildings, the same concerns regarding energy performance and sustainability are present, perhaps even more pressing given the restrictions on refurbishment and operation; but there is also the issue of the building's health, and the preservation of heritage features. A large body of research and published knowledge on the climatic and environmental effects on heritage buildings and structures exist, with preventative conservation representing a significant portion of it [8]. It is perhaps safe to say that we know what causes buildings to decay and what solutions are available in general, yet the practice of conservation in occupied heritage buildings is quite limited practically, perhaps due to the difficulty of operating in an occupied building.

Sensors and other data capture solutions can be an effective solution to this issue, automating away the expensive manual inspection, and providing remote management capabilities to facilitate timely intervention and reduce the time cost on professional conservationists. As part of the HBIM project, a report on monitoring the effects of climate change on heritage buildings has been produced, detailing the expected effects, their signs, and what technology can be used to monitor them [8]. This report follows through by providing guidance on monitoring campaigns and deployment.

What follows is an introduction to the applications of capturing environmental data in heritage buildings, with examples of previous efforts in each area, and guidance on the requirements for deployment in each case.

Thermal Performance

Monitoring the thermal performance, or energy efficiency of the building, is key to ensuring the building remains sustainable in the future, and planning any required intervention effectively. For heritage buildings, there is the added incentive that bad energy performance in buildings often exposes the building's elements to deterioration and damage [9]. In short, the objectives of this analysis are:

1. Ensure the energy usage and carbon footprint of the building remain sustainably low
2. Ensure the heat loss is kept at a minimum
3. Monitor the performance of the building for issues that cause a deterioration in this performance.

As this aim is mostly shared with most of the residential building stock, existing standards and guidances cover this ground extensively, such as the Technology Strategy Board's Guidance on Building Performance Evaluation, and the Energy Saving Trust's Professional Guide To Testing Housing For Energy Efficiency.

In the most basic way, the measurement setup in this case requires sensors that monitor internal and external temperature, plus heating energy, in several representative locations in the house [3], as well as the measurement of performance and energy use of any mechanical ventilation units. External weather conditions other than temperature are also important, but aside from external temperature, these can often be taken from a publicly available data source. If simulation software is intended to be used, or intervention planning is required, in-situ u-value testing is also important [10].

Depending on the method of analysis, the required data can be daily averages, hourly averages, or 5min (or less) samples. As the only reliable method of acquiring averages is to take high granularity samples, TSB guidance mandates that readings should be taken at intervals of no more than 5 minutes.

The output data can be used in several ways to measure performance:

1. Standard high-level metrics such as kWh/°C
2. Degree-day analysis
3. PRISM, STAR, and other calculation methodologies. Ready tools for these exist, providing as an output a measure of the energy efficiency of the building.
4. Heat loss coefficients, description of the dynamics of heat loss, solar permittivity, air tightness, and infiltration/ventilation loss, produced by dynamic models (required the original interval<=5min samples)
5. Hygrothermal properties of particular elements of the building (walls/ceilings). Require sensors on both sides of the element, preferably in more than one location.

Indoor Comfort

The comfort of the occupants is obviously the best predictor of how they operate or modify the building [11], and any changes to an occupied building must take this into account to be sustainable.

Indoor comfort has many factors; thermal, acoustic, and visual, but all of them can be monitored with sensors. The most complicated one is thermal comfort, which has an element of subjectivity and is affected by metabolic rates and clothing, but a number of well-tested models and standards exist to predict it based on temperature and humidity data [12].

Thermal comfort has been a frequent point of study when sustainability is investigated in heritage buildings [13]; some researchers have investigated how the original design of heritage buildings meant to adapt to thermal comfort requirements, in order to modify them to contemporary standards [14]. There is also a more archaeological interest in the topic, regarding heritage architecture from the point of view of their objectives for the internal thermal state, defined by some authors as architectural atmospheres [15].

Air Quality

Air quality is also a common target of monitoring. Sensors for this purpose detect the concertation of particular chemicals in the air, such as CO2, CO, Methane, ISo-Butane, ..etc. The objective of collecting this data can be to monitor the air quality in the interest of human health, or to monitor the presence of compounds that indicate or cause problems to the health of the building itself [16].

Fault Detection

Fault detection can be characterised as a continuous, automatic version of the same calculations taken for any of the previous objectives. The aim here is to detect significant (negative) changes in any of the detected metrics, indicating the presence of an issue causing undesirable conditions. Much research has been devoted to this, and various projects and case studies on instant notification and advice to occupants have been published [17] [18]. In particular, ventilation and humidity issues, as well as air quality ones, are often seen to be the most critical [19].

To equip a heritage building for fault detection, the set up varies based on the kind of expected fault, but can simply be identical to that of the relevant analysis in one (or more) of the previous sections. The detection part can be carried out manually, or extra software setups can be employed to detect and notify of changes.

Another possibility is to employ techniques from the field of Anomaly Detection, where the data is analysed without reference to any analysis or physical interpretation, and significant changes are flagged mathematically, by detecting a change in the nature of data variation and relationship between different sensors/variables. A study in the site of ancient Pompeii used 26 temperature and humidity sensors to monitor an area with archeologically valuable frescos, and employed a similar method to detect issues with excessive temperatures in certain locations [20]. Another study in the Cathedral of Valencia (Spain) used a similar methodology to monitor the conditions around certain fresco paintings as well, and managed to detect issues leading to the formation of efflorescence [21].

Sensors and Variables

There are generally four classes of variables that are used to monitor the state of a building directly, depending on the objectives. This list is certainly not a complete one, and many other variables can be used during analysis to enhance the results or extract information in an indirect way, such as occupancy information.

Climate/thermal information

Temperature and humidity, sometimes known as micro-climate data, were among the first variables to be sensed and employed for monitoring heritage buildings, perhaps due to the sensors being some of the simplest and most widely available. Researchers employ this data to diagnose condensation risk [18], make sustainability projections [13], prevent excessive corrosion to murals [22], and plan retrofitting action [23].

In addition to localised indoor sensors, it is often required to have data on the external weather around the building. This can be acquired using the same kind of sensors (with some caution), but specialised climate stations usually offer more robust, higher quality data on a wider range of weather variables. Commercial examples of this are plentiful, and their deployment and connection to a cloud server can be quick and painless if assisted by the services of a weather data service, such as those of Weather Underground, which offer cloud sync and backup services for a variety of climate stations in return for access to the data. This offers the possibility of simply using the data available through an already deployed weather station available through one of these services.

Figure 1 Personal climate station

Another possibility is to use official government meterological station data. The UK Met Office offers this kind of data to researchers and other practitioners subject to a simple registration and approval process, including weather forecasts and adapted measurements at local points near any centre of population.

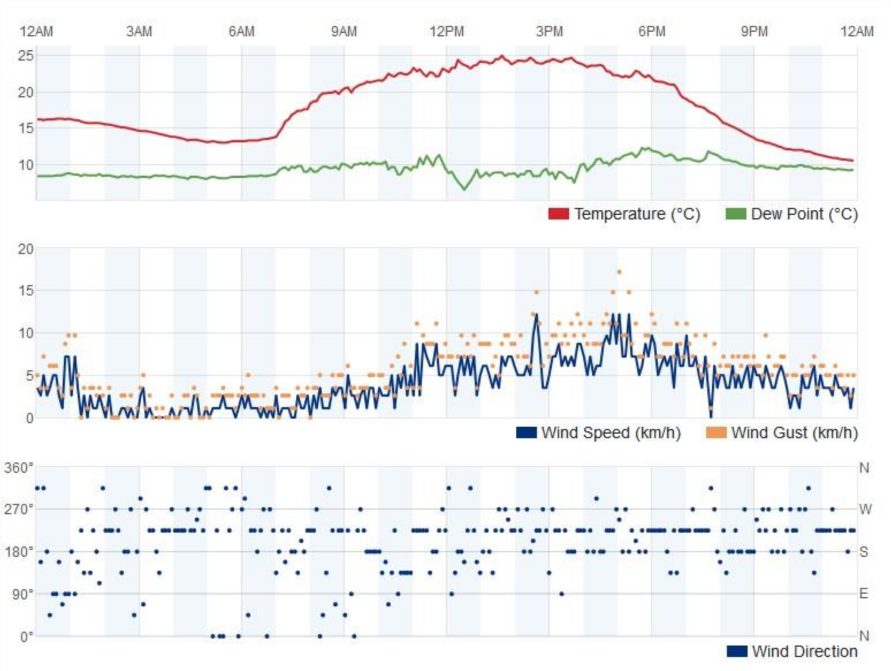


Figure 2 Some of the data recorded by a climate station

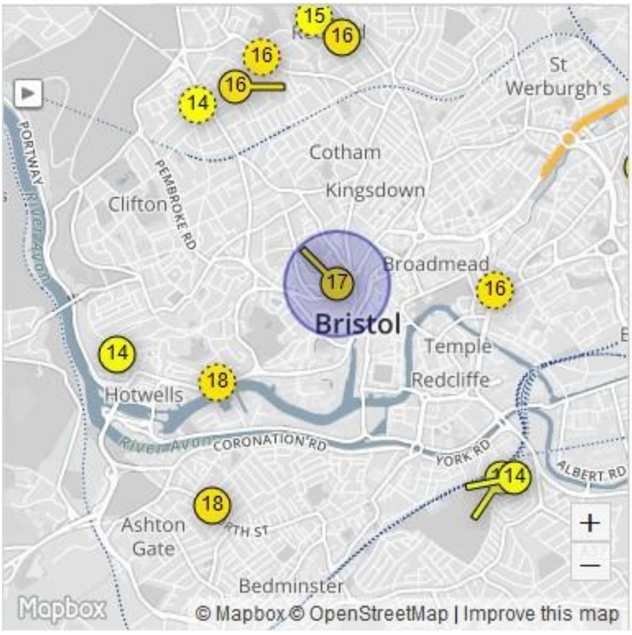


Figure 3 Map of public data WeatherUderground stations in Bristol, UK

Air

The chemical contents of air around and inside a heritage building is also a likely target for sensory monitoring with widely available sensors (though less so than microclimate ones).

Two sensors are most prominent in this case, CO2 and VOC sensors.

CO2

Other than the aforementioned direct uses, CO2 values are a good indicator of metabolism, and are often cited as a potential proxy for occupancy measurement [24] [25], as well as air change rates [26] [27]. Changes in CO2 levels can indicate a change in the number of occupants, or their state of activity (e.g. sleep), which provides context for interpreting energy performance and diagnosing issues. In addition, the rates of decay of the CO2 content in a building can indicate the air tightness, and on a longer period can be used to detect issues with sealing and ventilation.

VOC

Volatile Organic Compounds (VOC) sensors detect the presence and concentration of one or more of organic compounds that evaporate easily into room air, and are considered pollutants, such as Methane, ISo-butane, and Ethanol. The presence of these compounds in non-trivial quantities can cause detrimental effects to human health.

Energy and HVAC

The energy usage of the building or particular appliances, particularly HVAC ones, can possibly be monitored with a simple sensor, based on the type of meter or appliance in use, and is mostly needed for analysing energy and thermal performance, and calibrating simulations. This is important for monitoring and optimising heating and cooling control issues, which affect the health of the building and its sustainability greatly.

Meters

Monitoring the energy meter counter, whether Electric, Gas, or Heat, can be quite difficult or quite easy depending on the metering types installed, which vary considerably across the properties of even a single local authority [28]. In general there are four ways to log the monitor reading: serial logging, optical pulse counting, optical detection, magnetic detection, and smart meter download.

Serial logging

Certain energy meters are already equipped with the facility to send readings periodically to a logging device through a wired serial port or infrared interface. Communication between the meter and the logging device is standardised through IEC-62056-21 [29], which is not proprietary, and thus many commercial devices exist to communicate over it.

Figure 4 Electric energy mete with a serial port, and an EmonGLCD device using it

As these devices require the implementation of a specific protocol they are less widely available than more generic loggers (discussed below), and more expensive.

Pulse counters

A more frequently found interface on meters is the optical or infrared pulse. This is simply a small LED that emits a light pulse for every increase in energy over a certain threshold (e.g. 1 pulse/100kwh). Pulse counters that can be attached to the meter to count these pulses and log them are perhaps the most popular way to monitor meter readings.

Figure 5 Meters equipped with an optical output

Figure 6 Pulse counter mounting on a meter

The issues that can be expected here relate to data format and logger installation. Though the pulse output is widely available on meters, they are often not designed in such a way to facilitate the attaching of an optical receiver head, and thus adhesives and other solutions are used, and are a frequent source of problems.

Regarding data format, as the optical counter only receives a difference reading (e.g. 100kwh over previous reading), at non-regular intervals, extra hardware or extra processing is required to convert that into a synchronised, time-defined numerical format. In addition, should there be an interruption in the logging for any reason, information is lost, and no knowledge of the energy usage during the data loss period is preserved.

Optical and Magnetic Detection

Older meter types not equipped with either of the optical pulse or serial interfaces can be monitored by detecting the turning of their mechanical dials. For meters where a red spinning arrow is used (often found in old gas meters), an electronic color detector can detect the crossing of the arrow; or a magnetic detector can detect the spin of the least significant digit on the meter reading.

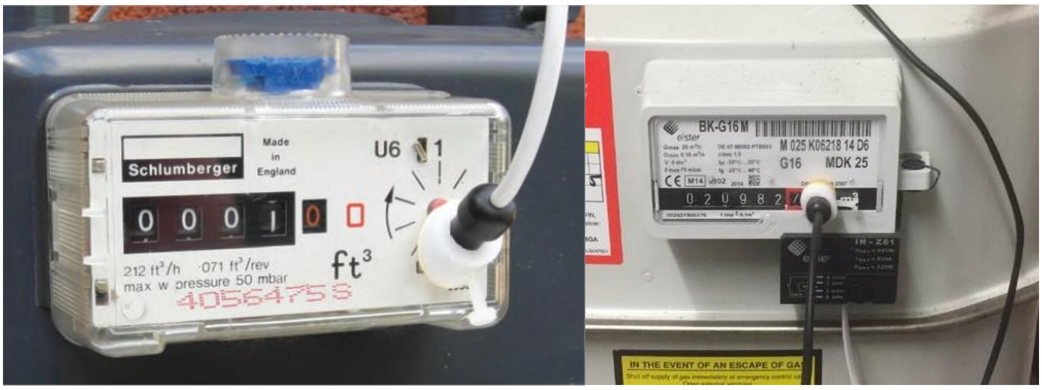


Figure 7 Optical and Magnetic detectors fitted on gas meters

Often devices for this purpose have an optical pulse output, in order to make use of the same hardware designed for newer meters. A good example, popular in the UK, is the Magpeye from Sinergy Meters

Figure 8 Magpeye Opto, an optical detector for arrow-type meters

Smart meters

In theory, this is the original objective of smart-meters; but the reality is less practical. A smart meter often transmits readings to a local monitor device at high frequencies (<1min), which can of course record them and make the data available easily. But as smart meter deployments differ greatly, there is as of yet a lack of standard, direct ways of accessing this data, which means a smart meter is either no different to a normal one, if it has the usual interfaces; or worse if it does not [30].

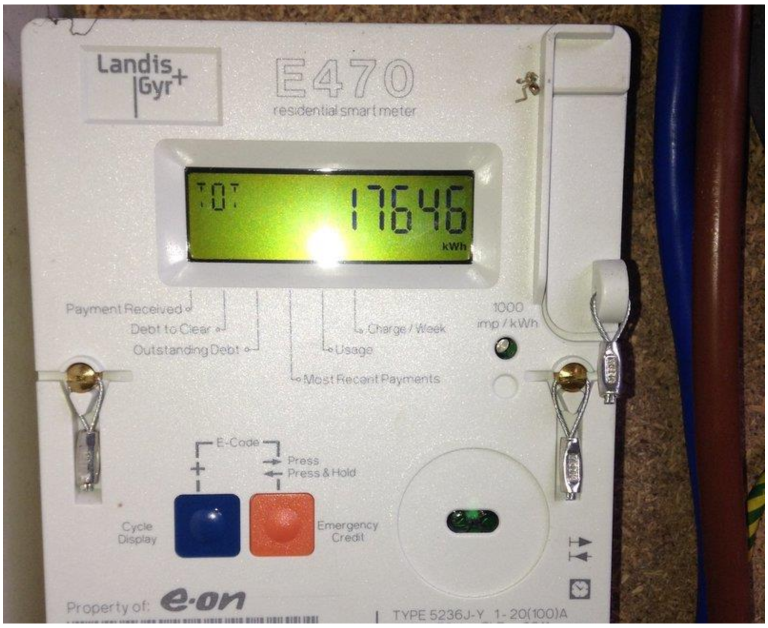


Figure 9 UK Smart meter equipped with a pulse output

This is likely to change as smart meter penetration grows and companies and researchers face the challenge of accessing the data, but so far this is still unclear.

Point metering

All of the options above are used to measure the energy usage of the building at the meter level, but for certain purposes, such as the calibration of energy simulations, the specific energy usage of the heating/cooling system is required. This can be acquired by using instruments dedicated for this purpose, or disaggregating metering data.

Electric

In the case of electric systems, plug-through and clamp-on power meters can measure the electric power flowing through a certain point, which can be used to measure the electric usage of the relevant system. Where it is plugged through a wall-socket (unusual for a central system, normal for portables), a plug-through meter is certainly cheaper. These are plugs that are placed between the appliance and the socket, and are cheap and effective.

Figure 10 Example plug-through meters

Clamp meters can be used to measure the power flowing to the system through a point in the wiring. This works for virtually any system, but is not as trivial to install, as it requires access to wiring that may be concealed in the wall, and sometimes removal of the outer insulation.

Figure 11 Clamp-on CT power meter

Gas flow meters

For a gas boiler, the flow of gas is more difficult to monitor. In general this requires the installation of inline flow-meters into the piping, or the use of clamp-on ultrasonic ones, which are less accurate but significantly easier to install and maintain. In both cases, these options are much more expensive than the electric counterparts, and must be compliant with certain safety standards [31] due to their proximity to a flammable substance.

Figure 12 Flow and Heat meters, external (left) and internal (right)

The output of these sensors can either be in cubic meters or in kWh, based on whether the type installed is a flow or heat sensor, but they work in the same way, albeit heat metering ones add a temperature sensor. As the required value is that of energy, not gas volume, it is tempting to go for the heat type, but as calorific values in UK gas networks are relatively stable [32], the difference isn't very important.

Disaggregation

Installing point metering equipment of the types mentioned in the previous section is significantly more expensive than meter reading equipment, and requires skilled installers. In addition, smart meters still offer the promise of providing high granularity data at the meter level even cheaper and easier, in most of the building stock. As a result, it is highly desirable to depend on this type of data rather than install point-metering equipment, which is possible to do in some cases using mathematical and data processing methods.

The problem of disaggregation for single point-metering is to calculate the consumption of a single appliance or system provided only with the sum of usage from all appliances or systems in the building (meter data) [33]. This is done through either statistical methods, which analyse the likelihood of a certain system being active at a certain point in time based on other information [34]; or through pattern-recognition methods, which try to detect the profile of change resulting from the use of a particular system [35].

For electric metering, this field of research is quite active, currently crossing the maturity barrier into commercial deployment. For gas systems on the other hand, statistical methods perform well if given temperature data, but only at very low granularities (e.g. daily consumption). Higher granularity disaggregation is still an open problem, but experiments within the HBIM project have shown significant success.

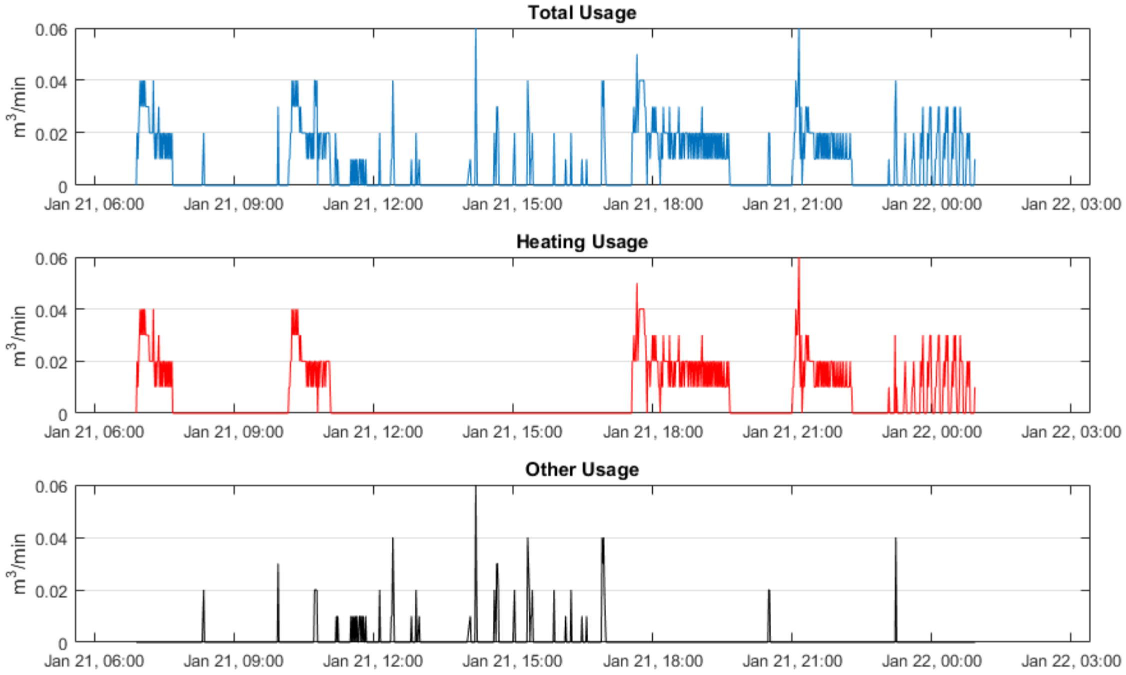


Figure 13 Example of pattern-based gas disaggregation

Other variables

Many other variables can be captured with cheap sensors, but are mostly of indirect or contextual use. For example, occupancy data can be used to provide context on occupancy routines and likely reasons for changes in other variables, such as temperature and humidity changes due to heating and cooking. This information can be captured in several ways, with varying levels of detail.

Another easily measured variable is luminance, which can be recorded with lux sensors. That said, the results are highly predictable based on the position of windows, building rotation, and existing lighting appliances, so this information is perhaps more useful as an indicator of curtain settings or room use.

Sensor Hardware Solutions

Though details of individual system blocks may differ, the architecture of a data acquisition system is generally constant, consisting of three major blocks; the local sensor network, consisting of sensors and data loggers; the cloud server, and the client, where data is consumed for processing and response.

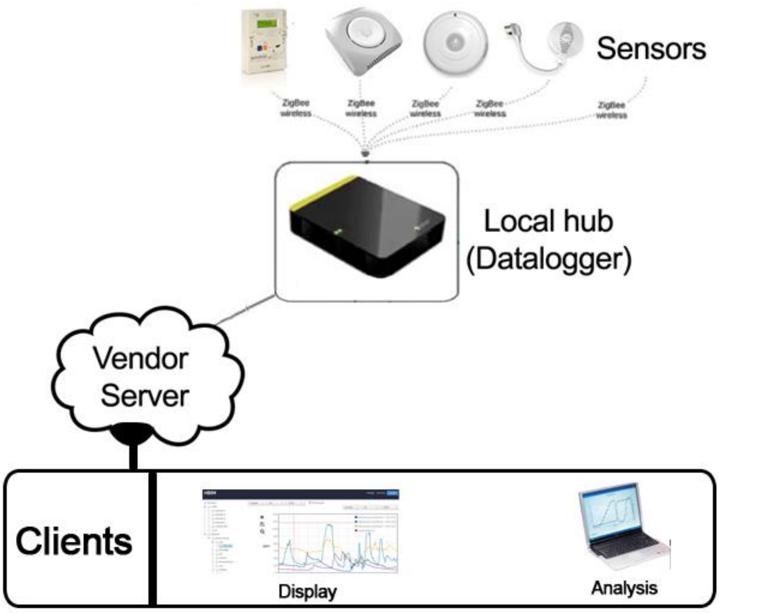


Figure 14 Standard data collection architecture

At the building level, there are two essential elements: the actual sensing device, such as a temperature or humidity sensors, and the data logger, which takes readings from the simple sensor device at any instant of time and stores them in the configured format. Given the need to add many sensors to the same building, and that of internet access to the read values, two more components are now essential; the communication system between the sensor and the data logger, and the local server administering these sensors and handling communication between the data logger and the cloud server.

Once the data is on the cloud, a software solution is often required to view the data and navigate it, monitor readings, calculate basic statistics, and analyse it. This often takes the form of a web application in the case of wireless sensors.

Unit Sensors

Many different formats exist for different scenarios; one example is the complete data logger-included sensor; which is essentially a self-contained data capture system, with a sensor, data logger, and possibly local server. Commercial examples include TinyTag, WiMoto, LilyPad, D-Link, and many more.

Figure 15 Examples of commercial self-contained sensors

This type of sensor is convenient to install, requiring no setup for communication to a hub or wireless pairing, but is not made to be part of a group of sensors, and is often not aware of a building as a unit.

Installation of the sensor is usually simply a matter of configuring the wireless connection (if any) and data logging settings, but this step must be repeated individually for each sensor, or in the case of the non-connected version, data will have to be collected manually with a USB cable or microSD card.

Consolidating the data from several such sensors can be done with the help of an open-source server (discussed below) with some extra configuration, but once the number of required sensors moves beyond the few, it is likely more cost effective to use a solution with a local network, already equipped for connecting a number of sensors on the same site.

Wireless Hub sensors

The more common scenario in a building is that of the simple sensors with communication boards, which transmit readings wirelessly to the data logger without storing them locally. Often the data logger will be a complete Unix system, housing a version of the software intended for the cloud server, with pre-processing, backup, and some graphing/analysis capability. Naturally, this is difficult to run on batteries, which makes it dependent on a socket and internet connection. The communication system in this case can be based on any of a number of standard protocols, such as Zigbee, Z-Wave, Xbee, RF, and many more.

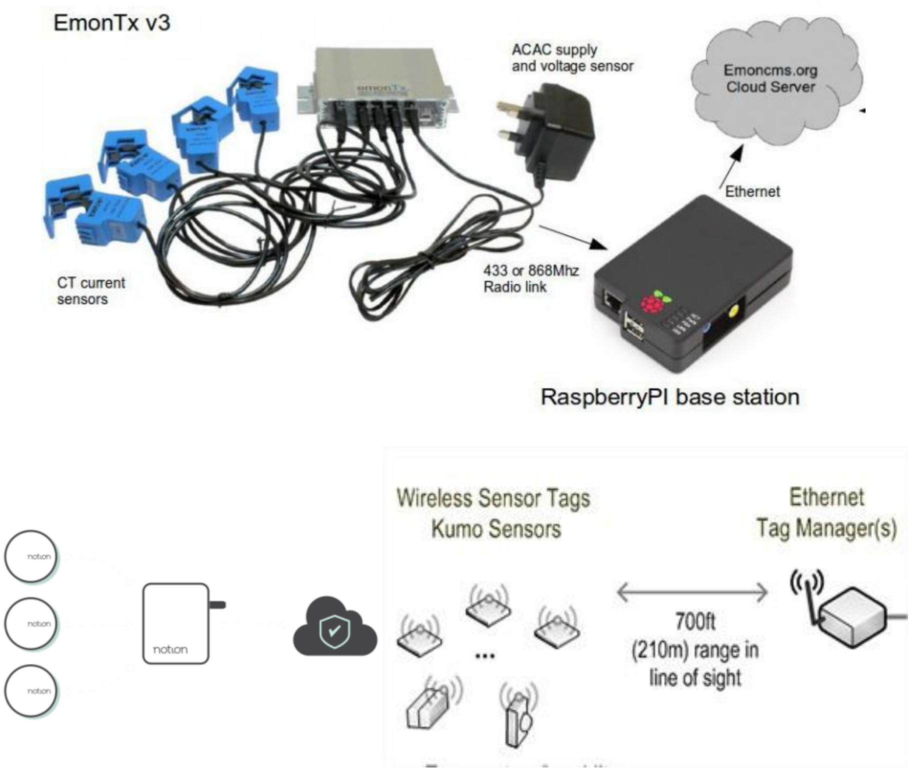


Figure 16 Examples of commercial sensor kits based on a central data hub (Emon, Notion, Kumo)

Installation

There are countless examples of such systems for various purposes, all with the same architecture regardless of purpose, and the configuration process is more or less the same:

1. Plug in and switch on the hub (could be called bridge, logger, local server, …etc depending on vendor)
2. Put hub in join/pair/discovery mode using a hardware button or software interface (phone/web).
3. Plug batteries into sensors and switch them on.
4. If not automatic on startup, put the sensor in join/pair/discovery mode using the hardware button.
5. Use interface to input additional information about the sensor, such as its name, location, and other configuration parameters.
6. Repeat for each sensor

Depending on the manufacturer, this process can take different forms, such as scanning a QR code on a sensor or pressing two hardware buttons at the same time.

Placement

The placement of sensors could be very important to the quality of data. For air temperature sensors, the chosen location should be out of sunlight, at average human height, away from heat sources and cold draughts coming through windows, doors, or ventilation vents. The principle is to keep it in an airflow representative of that of the room.

Humidity sensors should be placed following the same guidelines as those of temperature ones, but also away from moisture sources, such as tumble dryers, sinks, and showers.

Air component sensors should be placed at mid average human height, and be exposed to the air of the room, away from corners or closed places.

Fitting and fixing the sensors

Another issue in installing wireless sensors relates to the fitting of the sensors on the walls. For heritage buildings, screws and nails may be undesirable. Adhesives and glues can be a safer alternative, but may yet cause damage to the fabric of the building once removed. There are no standard recommendations for this problem, but caution is advised.

Coverage and location issues

Wireless sensors themselves can be moved with ease into any location in the building, but the data logger hub is usually tied to the availability of a power socket and broadband connectivity. In the case of residential buildings equipped with a wifi router, this problem may have already been solved by the occupants in the best way they could; Wifi router position needs to be optimised to provide wireless coverage to most of the building, and the same is true of the sensor hub.

Figure 17 Hub plugged into broadband router

That said, this is not always the case. Depending on the size of the house, location of the sensors, material of the building, and communication technology, the wireless range of the sensors can vary wildly.

Wireless kits based on Zigbee, Z-Wave or similar technologies often cite a range of between 50 and 200m in direct line of sight [36]. This figure is hugely optimistic, as line of sight connections are rarely available in a building. Indoors, the usual figure is 15-30m [37], but the actual distance is highly unpredictable. Where range is a pressing issue (in a large building or similar), range extenders (also known as signal repeaters) can be used. These are not available with all wireless sensor kits, which is a consideration to be taken before a choice of kit is made. The practitioner is advised to test their range requirement beforehand if possible, and check for the availability of range extenders, and the practicality of installing them when sockets are needed.

Internet Connectivity

Access to a reliable internet connection is required for effective remote monitoring and data upload. This may or may not be available at the building itself, which requires different arrangements. An often used resort is portable 4G routers (dongles), which use the existing cellular network.

Figure 18 Typical portable 4G router

There are several factors that must be taken into account when this choice is taken: first, connectivity between the 4G router and the hub must be possible. Many hubs can only operate over an Ethernet connection, whereas 4G routers are often equipped to create a wifi network only.

Second, coverage must be checked. Cellular connections may suffer in lower floors or rural locations, although this is much less of a concern in modern times.

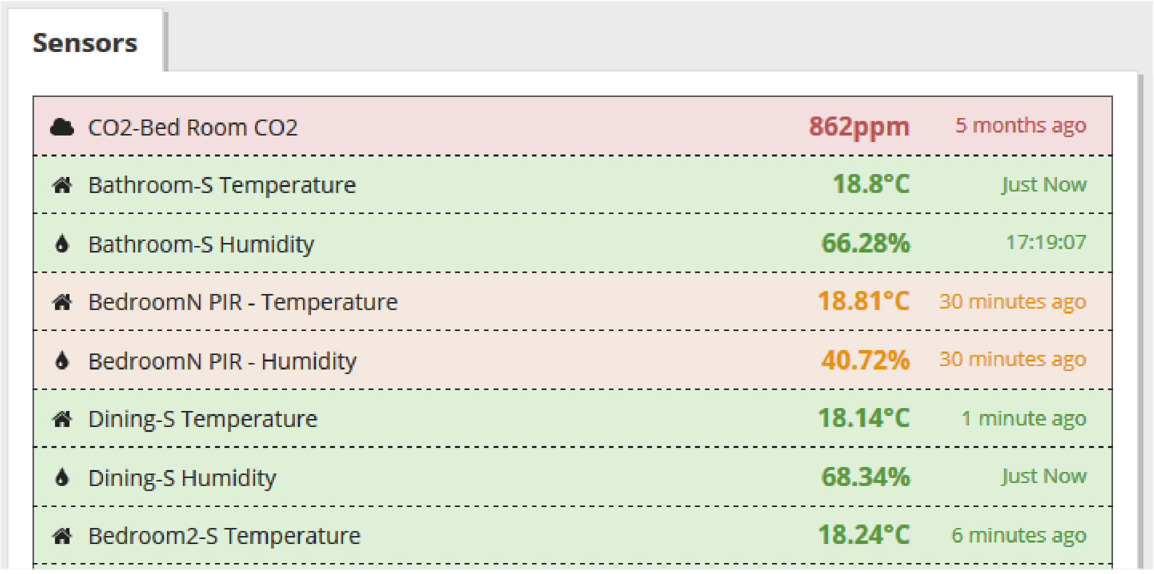
Finally, billing arrangements must be sustained, with sufficient monitoring. This is often overlooked because cellular subscriptions often send sufficient notification to subscribers that maintaining subscription isn't pre-planned. In this case notifications are sent to a machine, and deliberate checks are needed.

Reliability

Whilst this may not seem to be the case, wireless sensing is well known to be difficult to work with, especially in the dynamic environment of an occupied building. A recent survey of Building Performance Evaluation professionals in the UK [38] found that the equipment used for monitoring was a common cause for complaint, in many areas: It is expensive when compared to other industries carrying out similar work, the battery life is often abysmal, communications between the devices is frequently lost, and random software malfunctions are common; resulting in data loss and repeated unplanned visits to monitoring sites.

Health Monitoring

Essentially, compared to a wired sensor, the wireless network is exposed to many more possible sources of error. Given the known unreliability of wireless sensors, continuous monitoring and maintenance is of utmost importance. Technical methods to detect anomalies in the data and flag its loss automatically exist, but in actual data servers the most used method is that of time alerts. If a sensor hasn't reported in a certain time length, an alert is dispatched.



Sensors

CO2-Bed Room CO2	862ppm	5 months ago
Bathroom-S Temperature	18.8°C	Just Now
Bathroom-S Humidity	66.28%	17:19:07
BedroomN PIR - Temperature	18.81°C	30 minutes ago
BedroomN PIR - Humidity	40.72%	30 minutes ago
Dining-S Temperature	18.14°C	1 minute ago
Dining-S Humidity	68.34%	Just Now
Bedroom2-S Temperature	18.24°C	6 minutes ago

Figure 19 Health monitoring on the HeatingSave dashboard

Cloud Server

The fundamental function of the hub, or data logger, is to store the data on the on-board disk space or local secondary storage. When remote access is required, the hub has to be equipped to send the data periodically through an internet connection, and a cloud server needs to be available to receive the data and store it. Vendors of hubs with this capability will almost always have a cloud service, but in many cases this is not free, and unlike the sensors is sold on a subscription basis. Alternative open source solutions exist, but usually require substantial technical expertise to install and manage.

Web Applications

Once the data is on the server, the user can download it and manage it through their software package of choice, but often it is desirable to view and monitor the incoming data with more ease, which is why web applications (and sometimes phone apps) are usually hosted on the cloud server receiving the data.
Many companies seem to provide their own web application for the server, to monitor sensor readings, graph them, navigate them, and export them in the required format. More sophisticated servers will dispatch alerts based on certain events, and others implement programmable APIs for communication with analysis and automation packages. For the basic purposes of viewing and graphing, the provided application is usually sufficient, but open source packages with more advanced options are available at the expense of extra configuration and setup effort.

Wired setups

Wired sensor setups are typically based on MBUS [39], which is a European standard for remote metering; or Modbus [40], which is an industrial standard serial communication protocol, redeveloped in the early 1980s but actively used and maintained by a dedicated organisation.
In either case, sensors and meter reading devices are wired to the data hub, either directly or through intermediate hubs.

Sensors in a wired setup following either of those standards are often called slaves, with hubs being called masters. Each slave needs to connect to a master in order to pass on its data, and each master must have enough ports for a connection to all its direct slaves in an unattended setup.

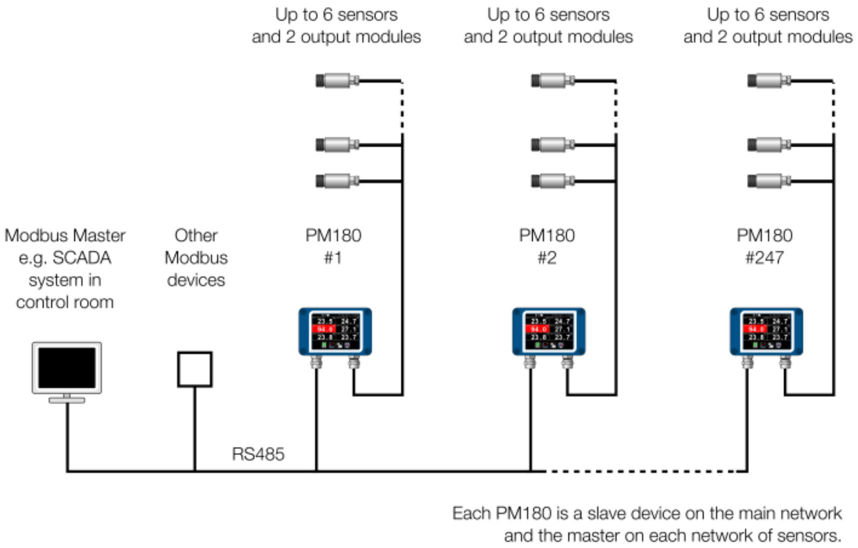


Figure 20 Example of a Modbus network employing the Calex Electronics PM180 hub

Wired setups are quite cumbersome to install and setup, not only for the requirement of technical competence, but for the need to manage wire connections running through the building. Fixing wires to walls is a relatively simple solution, but may require unacceptable damage to buildings, can be unacceptable to occupants, and could be aesthetically displeasing, while still requiring a significant amount of labour.

Figure 21 Wires clipped to wall

An alternative is to wire the sensors through the existing power line wiring infrastructure, which requires a competent electrician, a significant amount of time, and may not be possible to do noninvasively. In addition, a historic building may not always have the required infrastructure, or its outdated status could be a hindrance to this.

At the hub, data from the sensors is collated and recorded locally, but if it is required for this data to be sent remotely (e.g. on the internet), usually a computer device is required to interface with the hub, get the data, and then upload it normally. If cloud access is needed, network configuration is not trivial and requires technical competence and administrator access to the local network, which adds further cost and complexity to the wired option.

That said, for a small number of sensors, possibly in the same room, these issues may not be too difficult, and may be a better option than wireless sensors, which are infamously unreliable. Wired sensors on the other hand rarely fail once correctly configured, and have been known to be included in industrial configurations for years without fail.

Commercial and Open-source options

There are plenty of choices of commercially available sensor solutions available for the practitioner. A few examples are listed to showcase the range of availability and the recommended selection criteria.

TinyTags

The TinyTag product line is a UK-manufactured line of industrial-grade, highly reliable data loggers with integrated sensors. The product range offers sensors for most needed parameters, each of them logging the data to an on-board memory. The data can be downloaded by physically wiring the sensor to a laptop or PC and using the provided software locally.

Figure 22 Example TinyTag Devices

The company does offer wireless versions operating over an RF link, but the radio receiver is required to be connected to a running PC with a local version of the company's software, which can technically be configured for remote access over the internet, but that requires a significant level of technical competency, and administration access to the local internet connection.

Figure 23 Radio TX TinyTag data logger

HOBO pendants

HOBO pendants are another well-known line of sensors and data loggers, working in essentially the same way as TinyTags, which means they also require physical access to download the data. Some HOBO offerings include Bluetooth connectivity, making it easier to carry out this task.

Figure 24 HOBO Pendants

Ambiance

Ambiance is a relatively new sensor solution for buildings, combining temperature, humidity, presence, and lux sensors in one package, running over a LoRaWAN connection.

The LoRaWAN network is a type of low-energy low-signal rate network dedicated for IoT devices. When a nearby gateway is available (mostly the case in urban areas), this gets around the need for local internet connections, and performs well in terms of indoor signal penetration. The battery life of this type of sensor tends to be long (3 to 5 years in this case).

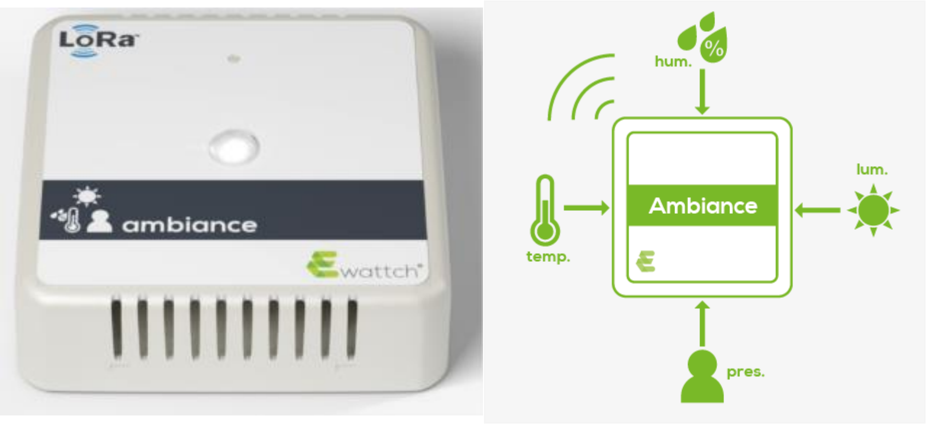


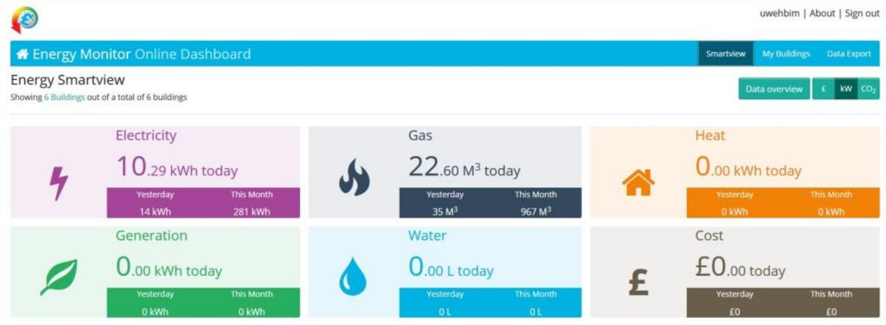
Figure 25 Ambiance sensor

Ambiance comes with a full package of cloud server and web app management software, making it a complete, convenient solution when no other sensor types are required.

[HeatingSave]

HeatingSave is a UK-based company providing complete solutions for building energy monitoring. Their hardware offering includes a wide range of sensors for all types of variables, with a central Ethernet-connected hub, and range extenders. The provided software allows data navigation and export, and quick monitoring of the status of sensors.

Figure 26 HeatingSave sensors and hub



Energy Smartview

Showing 6 Buildings out of a total of 6 buildings

Electricity
10.29 kWh today
Yesterday 14 kWh
This Month 281 kWh

Gas
22.60 M³ today
Yesterday 35 M³
This Month 967 M³

Heat
0.00 kWh today
Yesterday 0 kWh
This Month 0 kWh

Generation
0.00 kWh today
Yesterday 0 kWh
This Month 0 kWh

Water
0.00 L today
Yesterday 0 L
This Month 0 L

Cost
£0.00 today
Yesterday £0
This Month £0

Figure 27 HeatingSave Dashboard

HeatingSave is remarkable in providing extensive remote management capabilities, and a versatile data export interface, but requires some experience and technical support to set up effectively.

[OpenEnergyMonitor]

OpenEnergyMonitor (also referred to as EMON) is an open-source solution for monitoring energy and environmental parameters. The hardware offering combines a number of different types of sensors, available from different manufacturers, with range extenders, hubs, wireless loggers, and more. The software side is a powerful web application for remote management and monitoring of sensors and data, with a programmable interface for extensions, and a highly customisable function.

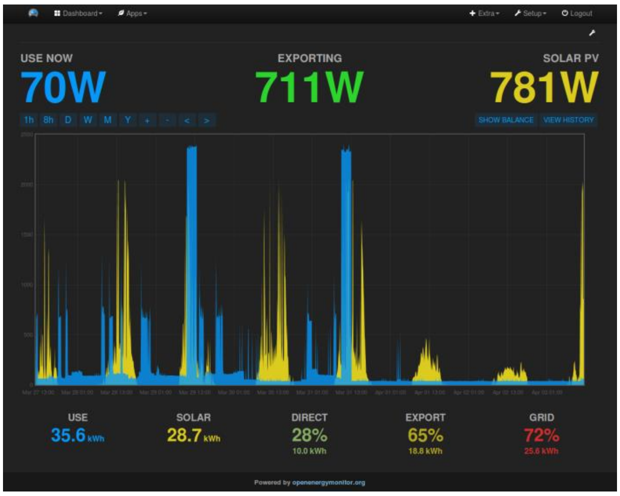


Figure 28 Snapshot of EmonCMS dashboard

EmonCMS can be used to manage data coming through different sensors, not designed by the OpenEnergyMonitor project, but this is not always trivial, and may require some significant technical expertise to implement.

Figure 29 emon sensors and hubs

For purposes of energy monitoring, the OpenEnergyMonitor project offers midway wired solutions, consisting of mini hubs that collect the data through wires from a number of nodes, then send it wirelessly to the central hub (or base). This strikes a certain balance between the reliability of wired setups and the convenience of wireless ones.

Comparison

Below is a comparison table between several commercial solutions, intended more as a guide on selecting products, rather than examining the particular listed options.

	Wireless	Sensors / Devices				Fitting	Cloud Service	Web App	PC Required
		T-RH	Energy	Air	Extend				
TinyTag	YES	YES	YES	YES	NO	None	No	Desktop	Yes
Emon	YES	YES	YES	NO	YES	None	Yes	Yes	No
HeatingSave	YES	YES	YES	YES	YES	None	Yes	Yes	No
HOBO Pend	NO	YES	YES	YES	NO	adhesive	No	No	Yes

The HBIM Platform

The HBIM Platform offers a centralized, cloud-based way of carrying out the management, visualization, and analysis of data, replacing or supplementing the web application offered by vendors. This section offers examples of its use and capabilities for this purpose.

The concept of the portal is to offer structured viewing-friendly information management capabilities for heritage information (historic significance, transformation over time, interpretation, curation, and preservation), as well as data management and automated analysis of real-time acquired environmental data (temperature, humidity, CO2, ..etc). For the purposes of monitoring and analysis, it brings the whole lifecycle together in a modular expandable architecture, allowing heritage professionals to focus on the results, rather than the arduous process of moving data from one program to another.

Real-time Data View

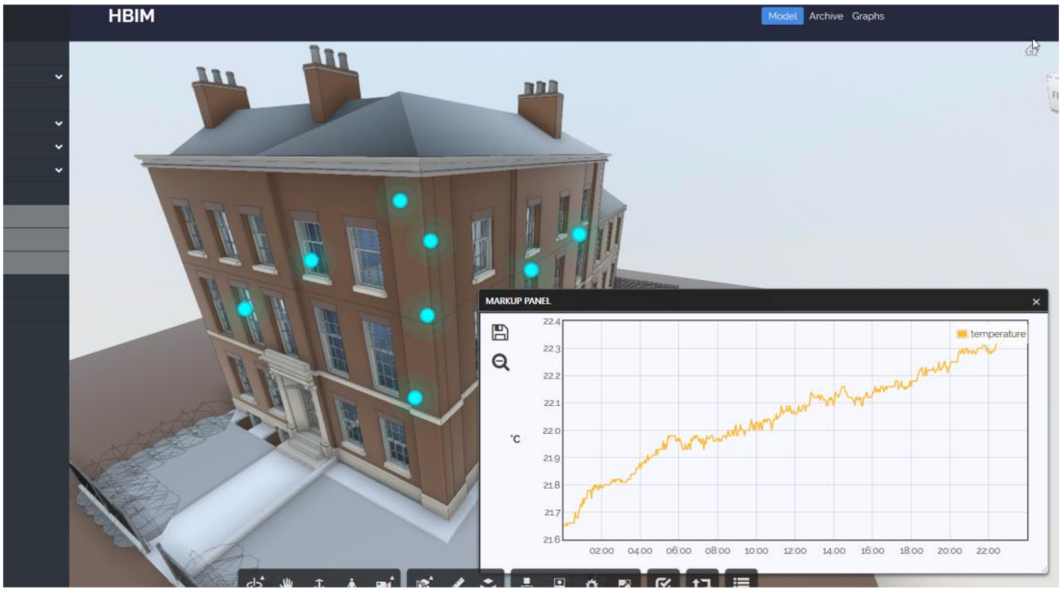


Figure 30 Real time data view in the HBIM platform

The real-time view shows the location of sensors installed in the building using labelled markups, stating the latest reading, or “off” where the sensor is not reporting. Clicking each sensor brings up a panel with a graph of the value during the last 24 hours, and a link to the data navigator for more options.

Data Navigator

The data navigator is displayed outside the main viewer window. It contains various options for browsing, graphing, and exporting data from all installed sensors, weather stations, and other data sources. The generated graphs are interactive, allowing panning, zooming, and exporting selections, and can be embedded in another web page using a generated url.

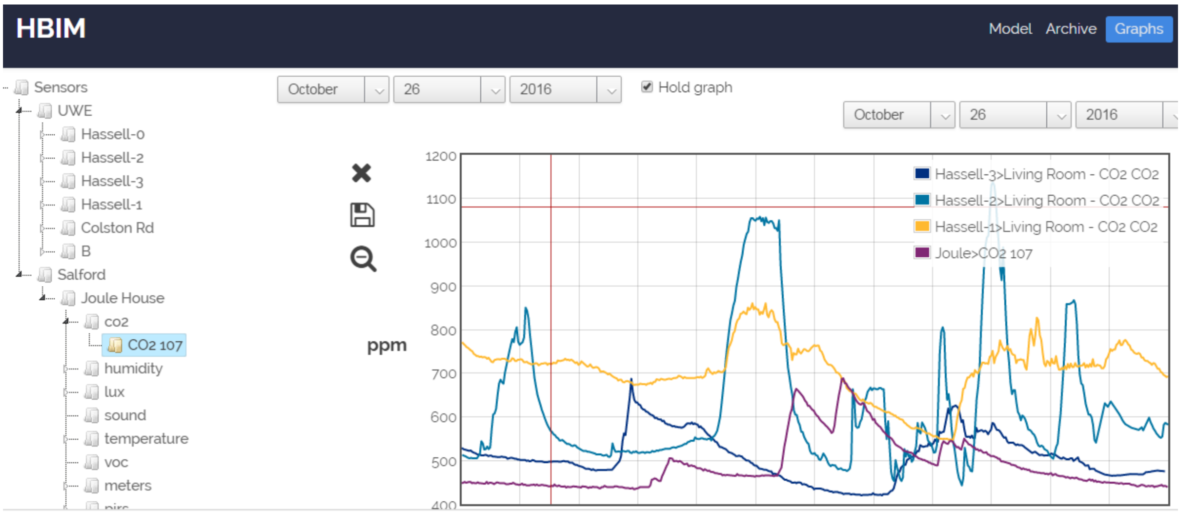
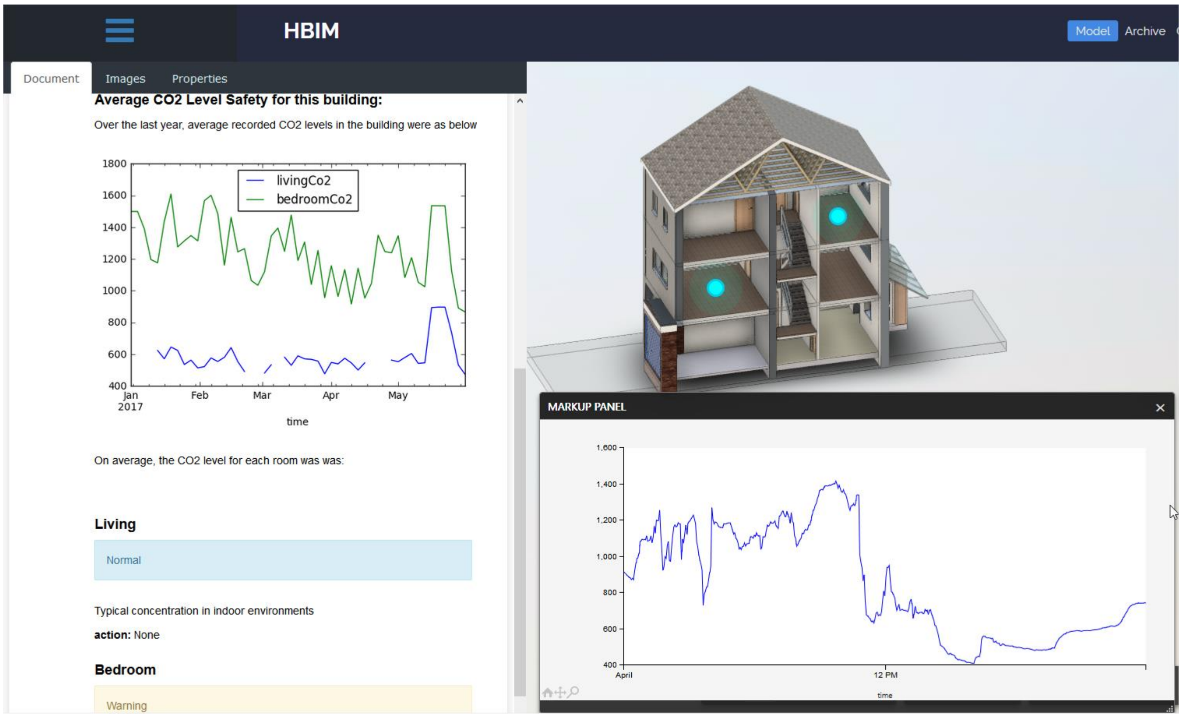


Figure 31 Data visualisation in the HBIM platform

Analysis Modules

Analysis modules are a set of external executables that make use of model information and stored environmental data to analyse a certain facet of the performance of the building, outputting an automatically generated report not unlike those that were manually created, including a document, a viewer state, and properties. Each analysis module defines a set of configuration inputs, and can be run on demand or scheduled to run periodically.



Average CO2 Level Safety for this building:

Over the last year, average recorded CO2 levels in the building were as below

On average, the CO2 level for each room was was:

Living

Normal

Typical concentration in indoor environments

action: None

Bedroom

Warning

Figure 32 Analysis report output

As an example, a simple analysis module can be used to evaluate CO2 levels in several rooms of the building. The input configuration, accessible through the gear icon on the module link, defines the time resolution to work with and the tolerance. Once the configuration is submitted, the module is ran, marked by a progress indicator next to its name, until outputs are generated. The automatically generated report consists of a text document with a static introduction to the calculation methods used and the results of the analysis, and a viewer state with color-coded graphic markups. The color of the markup indicates risk level, and clicking it shows the graph of CO2 levels over the analysis period.

Summary and Conclusion

Low-cost remote environmental sensing has the potential to significantly change the practice of managing and conserving heritage buildings, and the installation of such solutions is now possible without technical help. Nonetheless, no solution is perfect, and technical knowhow is often required. This guide provided details on the benefits of sensory data capture, the problems to be expected, and when different solutions are more appropriate; which can be consulted in choosing a sensor solution for a certain building.

References

[1] L. Atzori, A. Iera and G. Morabito, “The internet of things: A survey,” *Computer networks,* vol. 54, pp. 2787-2805, 2010.

[2] J. Kleissl and Y. Agarwal, “Cyber-physical energy systems: Focus on smart buildings,” in *Proceedings of the 47th Design Automation Conference*, 2010.

[3] A. Rabl, “Parameter estimation in buildings: Methods for dynamic analysis of measured energy use,” *J. Sol. Energy Eng.;(United States),* vol. 110, 1988.

[4] R. Everett, “Rapid thermal calibration of houses report ERG055,” *Science and Engineering Research Council Report. London,* 1985.

[5] J. Berger, H. R. B. Orlande, N. Mendes and S. Guernouti, “Bayesian inference for estimating thermal properties of a historic building wall,” *Building and Environment,* vol. 106, pp. 327-339, 2016.

[6] M. Killian and M. Kozek, “Ten questions concerning model predictive control for energy efficient buildings,” *Building and Environment,* vol. 105, pp. 403-412, 2016.

[7] J. K. Kissock, J. S. Haberl and D. E. Claridge, “Inverse modeling toolkit: numerical algorithms (RP-1050),” *Transactions-American society of heating refrigerating and air conditioning engineers,* vol. 109, pp. 425-434, 2003.

[8] L. Mahdjoubi, S. Hawas, R. Fitton, K. Dewidar, G. Nagy, A. Marshall, A. Alzaatreh and E. Abdelhady, “A guide for monitoring the effects of climate change on heritage building materials and elements,” 2017.

[9] C. Sabbioni, P. Brimblecombe and M. Cassar, The atlas of climate change impact on European cultural heritage: scientific analysis and management strategies, Anthem Press, 2010.

[10] M. Mirsadeghi, D. C{\'o}stola, B. Blocken and J. L. M. Hensen, “Review of external convective heat transfer coefficient models in building energy simulation programs: implementation and uncertainty,” *Applied Thermal Engineering,* vol. 56, pp. 134-151, 2013.

[11] R. F. Rupp, N. G. Vásquez and R. Lamberts, “A review of human thermal comfort in the built environment,” *Energy and Buildings,* vol. 105, pp. 178-205, 2015.

[12] Y. Cheng, J. Niu and N. Gao, “Thermal comfort models: A review and numerical investigation,” *Building and Environment,* vol. 47, pp. 13-22, 2012.

[13] A. Martínez-Molina, I. Tort-Ausina, S. Cho and J.-L. Vivancos, “Energy efficiency and thermal comfort in historic buildings: A review,” *Renewable and Sustainable Energy Reviews,* vol. 61, pp. 70-85, 2016.

[14] I. Requena-Ruiz, “Thermal comfort in twentieth-century architectural heritage: Two houses of Le Corbusier and André Wogenscky,” *Frontiers of Architectural Research,* vol. 5, pp. 157-170, 2016.

[15] G. Böhme, “Atmosphere as mindful physical presence in space [Sfeer als bewuste fysieke aanwezigheid in de ruimte],” *Oase,* vol. 91, pp. 21-32, 2013.

[16] J. M. Daisey, W. J. Angell and M. G. Apte, “Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information,” *Indoor air,* vol. 13, pp. 53-64, 2003.

[17] R. Archacki and J. Moore, *Routine and urgent remote notifications from multiple home comfort systems,* Google Patents, 2006.

[18] S.-H. Choi, “Development of the Prediction System of Condensation Based on Wireless Communications,” *International Journal of Distributed Sensor Networks,* vol. 9, p. 564869, 2013.

[19] R. Gupta and S. Chandiwala, “Understanding occupants: feedback techniques for large-scale low-carbon domestic refurbishments,” *Building Research \& Information,* vol. 38, pp. 530-548, 2010.

[20] P. Merello, F.-J. García-Diego and M. Zarzo, “Diagnosis of abnormal patterns in multivariate microclimate monitoring: A case study of an open-air archaeological site in Pompeii (Italy),” *Science of The Total Environment,* Vols. 488-489, pp. 14-25, 2014.

[21] M. Zarzo, A. Fern{\'a}ndez-Navajas and F.-J. Garc{\'\i}a-Diego, “Long-term monitoring of fresco paintings in the Cathedral of Valencia (Spain) through humidity and temperature sensors in various locations for preventive conservation,” *Sensors,* vol. 11, pp. 8685-8710, 2011.

[22] A. Zoha, A. Gluhak, M. A. Imran and S. Rajasegarar, “Non-intrusive load monitoring approaches for disaggregated energy sensing: A survey,” *Sensors,* vol. 12, pp. 16838-16866, 2012.

[23] A. L. Webb, “Energy retrofits in historic and traditional buildings: A review of problems and methods,” *Renewable and Sustainable Energy Reviews,* vol. 77, pp. 748-759, 2017.

[24] S. Wang, J. Burnett and H. Chong, “Experimental validation of CO2-based occupancy detection for demand-controlled ventilation,” *Indoor and Built Environment,* vol. 8, pp. 377-391, 1999.

[25] M. Jin, N. Bekiaris-Liberis, K. Weekly, C. Spanos and A. Bayen, “Sensing by proxy: Occupancy detection based on indoor CO2 concentration,” *UBICOMM 2015,* vol. 14, 2015.

[26] R. Claude-Alain and F. Foradini, “Simple and cheap air change rate measurement using CO2 concentration decays,” *International Journal of Ventilation,* vol. 1, pp. 39-44, 2002.

[27] H. Xin, H. Li, R. S. Gates, D. G. Overhults and J. W. Earnest Jr, “Use of CO2 concentration difference or CO2 balance to assess ventilation rate of broiler houses,” *Transactions of the ASABE,* vol. 52, p. 1353, 2009.

[28] S. Darby, “Why, what, when, how, where and who? Developing UK policy on metering, billing and energy display devices,” 2008.

[29] I. E. Commission, *IEC 62056: Data Exchange for Meter Reading, Tariff and Load Control,* 2014.

[30] M. Pullinger, H. Lovell and J. Webb, “Influencing household energy practices: a critical review of UK smart metering standards and commercial feedback devices,” *Technology Analysis \& Strategic Management,* vol. 26, pp. 1144-1162, 2014.

[31] E. Commision, “Equipment and Protective Systems intended for use in Potentially Explosive Atmospheres (ATEX) Directive 94/9/EC,” 2008.

[32] I. MacLeay, Digest of United Kingdom energy statistics 2010, The Stationery Office, 2010.

[33] J. Froehlich, E. Larson, S. Gupta, G. Cohn, M. Reynolds and S. Patel, “Disaggregated End-Use Energy Sensing for the Smart Grid,” *IEEE Pervasive Computing,* vol. 10, pp. 28-39, 1 2011.

[34] S. R. Vitullo, R. H. Brown, G. F. Corliss and B. M. Marx, “Mathematical models for natural gas forecasting,” *Canadian applied mathematics quarterly,* vol. 17, pp. 807-827, 2009.

[35] S. R. Shaw, S. B. Leeb, L. K. Norford and R. W. Cox, “Nonintrusive Load Monitoring and Diagnostics in Power Systems,” *IEEE Transactions on Instrumentation and Measurement,* vol. 57, pp. 1445-1454, 7 2008.

[36] B. Ray, “ZigBee Vs. Bluetooth: A Use Case With Range Calculations,” 2018. [Online]. Available: https://www.link-labs.com/blog/zigbee-vs-bluetooth.

[37] SmartThingsUK, “Z-Wave and ZigBee FAQ,” 2018. [Online]. Available: https://support.smartthings.com/hc/en-gb/articles/208672926-Z-Wave-and-ZigBee-FAQ.

[38] W. Swan, R. Fitton and P. Brown, “A UK practitioner view of domestic energy performance measurement,” *Proceedings of the Institution of Civil Engineers - Engineering Sustainability,* vol. 168, pp. 140-147, 2015.

[39] CEN, “EN 13757 - Communication Systems for Meters and Remote Reading of Meters-Part,” *European Commision Standards,* vol. 4, 2005.

[40] I. D. A. Modbus, “Modbus application protocol specification v1. 1a,” *North Grafton, Massachusetts (www. modbus. org/specs. php),* 2004.