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SEMI-AUTOMATED BUILDING PERFORMANCE EVALUATION
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Abstract

The paper describes an approach taken in the outPHit project to evaluate the performance of highly energy efficient buildings in the field. Efforts are made to streamline and automate most steps in order to make the process of building performance evaluation, with sound consideration of measuring uncertainty, accessible to a wider audience. A low-cost data acquisition system based on LoRa radio communication is outlined and tolerable measuring uncertainty of sensors discussed. Data collection, pre-processing and final evaluation are implemented within an on-line database. Measured data is used to update a detailed monthly energy balance calculation with actual boundary conditions and thus provide a yardstick to understand the metered energy consumption. Elementary comfort parameters are also part of the evaluation.

Introduction

The outPHit project aims to support building owners and housing companies in performing reliable, quicker and more cost-effective deep retrofits. It builds on the concepts for retrofit using Passive House components and technologies, called EnerPHit, outlined in Bastian (2021). A reduction of labour cost and probability of faults is sought with the use of prefabricated or preconfigured systems. Another element within this scope is a reliable and robust approach to quality assurance.

This quality assurance scheme makes use of existing programmes along the value chain, from certified designers, third-party design evaluation and certification, the use of certified products – the relevant properties of which were established by independent examination as well as certified tradespersons that have learned to understand the challenges in highly energy efficient construction. Airtightness testing for both pressurisation and depressurisation is a standard procedure for both Passive House and EnerPHit standards.

This scheme is extended within the outPHit project to include a standardised approach for performance verification in-situ. As a detailed monthly energy balance calculation is available for each Passive House or EnerPHit project from the design phase, that was subject to third-party evaluation in the design certification process, a good base exists for further study of building performance. The energy balancing with the Passive House Planning Package (PHPP) used in the process is largely based on the methodology of the EN 832/13790/52016 family of monthly balancing procedures.

The design stage calculations using standardised boundary conditions such as climate data and usage parameters can be updated in ex-post analysis with measured values and the results evaluated against metered energy consumption. A diagrammatic illustration of the process is given in figure 1.

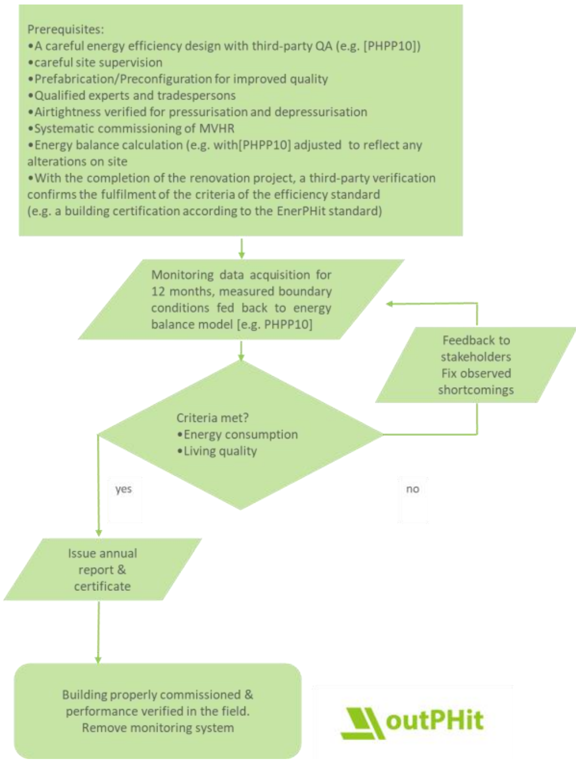

Figure 1: Flow chart of the proposed performance verification process

In the past building performance monitoring has largely been restricted to scientific evaluation programmes and demanded expert knowledge, experience and considerable budget- both for equipment and labour. As a result the numbers of methodically investigated buildings is very limited. Moreover the methodologies used tend to differ as each research campaign has a different focus.

Methodology

Any method seeking broadened application of building performance monitoring will have to face tight constraints in tolerable equipment cost as well as the availability of qualified staff for installation, maintenance, data handling and data evaluation.

Therefore, all components must be low-cost, mass produced items that still meet the quality requirements and processes must be formalised that use the experience from a significant number of building monitorings performed by the Passive House Institute over the last 25 years.

To make installation and the selection of suitable sensor locations possible by persons with little experiene in the field a range of training videos has been developed that will be transformed into a formal e-learning programme further down the project's time line. This way important knowledge is multiplied and experienced staff can remotely consult a large number or projects at the same time, focusing on quality assurance aspects.

Measuring uncertainty

As in any other measurement inherent uncertainties are an important characteristic also of in-situ evaluations of buildings. They range from uncertainties in the geometry of a real building (tolerances), to fluctuations in the properties of building materials, such as the themal conductivity of a specific batch of insulation material. The classic measuring uncertainty of sensors must be considered. Moreover, it must be kept in mind, that slight capacitve effects can have some effect in the context of a monthly balancing method. The latter are of limited magnitude though and on an annual scale altogether negligible.

Sensor-related uncertainty must meet comparatively high demands, much higher than are customary in typical building automation systems. For typical Passive House buildings the impact of temperature difference between inside and outside on the space heating demand is in the range of 15 %/K. The measuring uncertainties for both outdoor temperature and internal temperature apply in this case. It follows, that the practical limits for low cost sensors must be exploited and a tolerable uncertainty of less than ±0.3 K be met. Great advances have been made regarding inexpensive integrated sensors that provide a factory calibrated package of analog sensing and digitizing circuitry that can meet such demands for the time periods of interest here. While temperature measurements dominate, relative humidity can be important in the context of warm an humid climate with a need for active cooling and/or dehumidification; the typical uncertainty of good quality capacitive sensors is ±2 %rH which will be sufficient in most cases. Carbon dioxide concentration is recorded as an indicator of indoor air quality, ventilation system performance and a general occupancy signal. Inexpensive sensors do not provide better than ±60…80 ppm uncertainty, which is nonetheless suffcient for the purpose.

A usage factor that can, in principle, have great impact on the energy balance of a building is the user habits in terms of opening windows. From various monitoring campaigns in buildings with mechanical ventilation with heat recovery (MVHR) PHI concludes that opening windows for prolonged periods of time with high temperature differences between inside and outside and is not a serious concern in most instances. To measure it a complete suite of sensors for all openings were required that also distinguish tilt vs turn as well as the turn angle, and each sensor would present almost a single point of failure for the entire effort. A serious approach would multiply the cost for sensors as well as the complexity of the evaluation. Hence it is considered impractical, but also dispensable, in the vast majority of cases within the scope of the programme.

The measurements of weather parameters focus on outdoor temperature and relative humidity that follow the same specifications as the indoor sensors mentioned previously. Carbon dioxide concentration may be recorded as a reference to correctly interpret the indoor values but is hardly worthwhile due to the comtparatively large uncertainty of the low cost sensors that make the assumption of a constant outdoor concentration a competitive alternative and also due to the self-calibration implemented in the more recent sensors that automatically resets the lowest observed values within a week to a standardised outdoor concentration.

Irradiation measurement on the contrary is vitally important as the passive-solar yield constitutes a very important share of the heat losses in a Passive House building, typically in the range of 25 to 30 %. Finding low cost but still reliable solutions is challenging. The classic solution, a meteorologically qualified Pyranometer with calibrated amplifier and analog-to digital converter, is very costly at around 1500 € or more. Practical uncertainty is in the order of 3 % of daily integrals. A more cost-effective solution are calibrated PV cells in near-short circuit and combined with appropriate amplification and digitization of the signal. They also benefit from the fact that the voltage signal is about twice that of a thermopile pyranometer. Well made units achieve an uncertainty of about 5 % of daily integrals at a cost of around 150 € and are the preferred method for the given application.

The various effects of measuring uncertainty are discussed in Johnston (2020) in more detail. Lumped together it can be expected to calculate the *expected consumption* with an absolute uncertainty of about ±3 kWh/(m²a) with little dependence on the absolute magnitude. This can be considered a practical limit for comparisons of measured and calculated results. Therefore, the uncertainty is relatively higher in the case of a Passive House buidling at 10 kWh/(m²a) and decreases for EnerPHit refurbishments at around 25 kWh/(m²a) that are the primary concern within the outPHit project.

Finally, the metering of final energy consumed introduces its own uncertainties, if in a less complex way. For domestic electricity meters about ±2 % can be expected, less for commercial meters. Gas meters usually perform to a similar level of uncertainty while heat meters exhibit slightly larger margin of up to 5 % if sized adequately for the prevailing flow.

Data Acquisition

For temporary monitoring it is beneficial to use equipment that does not rely on fixed and expensive infrastructure, such as a wired network. Great advances have been made regarding reliable, low-power, medium range radio communication. From the available choices LoRa technology has been selected for its robust signal, good range and availablity of a great variety of inexpensive (50-100 €/quantity measured) sensors, counters and meters. The low power demand of the chosen radio makes battery powered operation possible for more than two years, at a data rate of four to six messages per hour. Hence no service is required within the typical duration of a monitoring campaign.

A stand-alone LoRa system is set up for each building under consideration, based on a low-power single board computer running the open-source software chirpstack. Data is automatically syncronised with a data base. This way no data is ever handled by third parties or their infrastructure. Combined with the two-level 128-bit encryption scheme incorporated in the LoRa protocol a reasonable level of data protection can be afforded.

Preprocessing

In the data base a building object can be attributed with zones, representing commercial units or flats, within them a number of rooms and an assortment of sensors in each room. All elements are also characterised by their area. Incoming data is first subject to graphing the history as well as simple statistical evaluation. This data is available from the very beginning and informs on the elementary comfort parameters and air quality indoors. As monitoring campaigns frequently also serve to assist the commissioning of buildings, eyeballing performance and the quality of the indoor environment is the first tangible benefit.

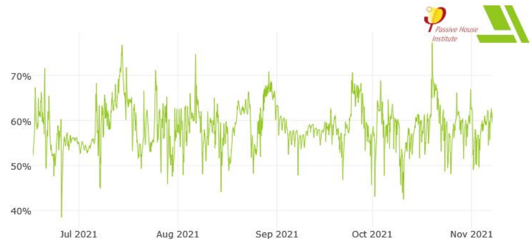

Figure 2: History of measured relative humidity

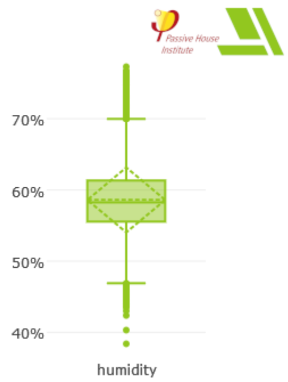

Figure 3: Elementary statistical values of measured relative humidity, given as quartiles, arithmetic mean with standard deviation and outliers

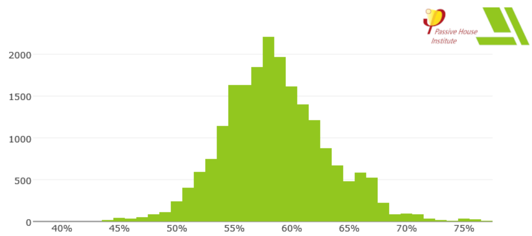

Figure 4: Histogram of measured relative humidity

Threshold	Hours	Fraction %
<5	0	0.0%
<10	0	0.0%
<15	0	0.0%
<20	0	0.0%
<25	0	0.0%
<30	0	0.0%
>70	41	0.47%
>75	7	0.08%
>80	0	0.0%
>85	0	0.0%
>90	0	0.0%
>95	0	0.0%

Figure 5: Cumulated hours of conditions outside defined comfortable range

The standard set of plots includes a history lines plot, a box plot with quartiles/min/max as well as mean and standard deviation, a histogram and a table of hours outside the comfortable range.

Once a sufficient observation time has passed, typically a few months to one year, data can be aggregated into monthly mean indoor conditions and internal heat gains, representating the usage, and weather data. Generally an area-weighted mean is used for indoor conditions, based on the areas of zones and rooms as defined in the data base setup. This has proven itself as a practical approximation of the real conditions. The typical measuring uncertainty for each sensor type is part of the data set.

Irradiation data is processed based on a sky model according to Perez (1990) in order to derive the global radiation on the vertical for the cardinal directions in addition to the original global horizontal irradiation. Data is then aggregated into monthly integrals.

The monthly data is handed out for further evaluation as a simple ASCII file.

Data Evaluation

As of its recent version 10 the PHPP contains a separate worksheet to compile, preprocess and evaluate measured data. It recalculates the monthly balances based on the measured values characterising usage and weather conditions for three cases: First the nominal values of all figures are used, disregarding the effects of measuring uncertainty. In the following two iterations limits of uncertainty are derived for cumulative effects of all individual measuring uncertainty values. As a result a plausible range of possible results is obtained. This serves to give further orientation, beyond the considerations outlined under the “Measuring uncertainty” paragraph.

Linked with the outPHit monitoring database the monitoring worksheet of the PHPP is automatically populated with preprocessed data. Results can either be studied using the plots and figures generated within this spreadsheet but are also fed back into the database for plotting and further evaluation. As a measure of quality assurance the completed calculations are crosschecked by human intervention and can then be cleared for display as an additional section in a public on-line building database. This database will, over time, present data of in-situ performance of a large number of buildings, all evaluated and normalised to the same yardstick, including sound estimates of uncertainty.

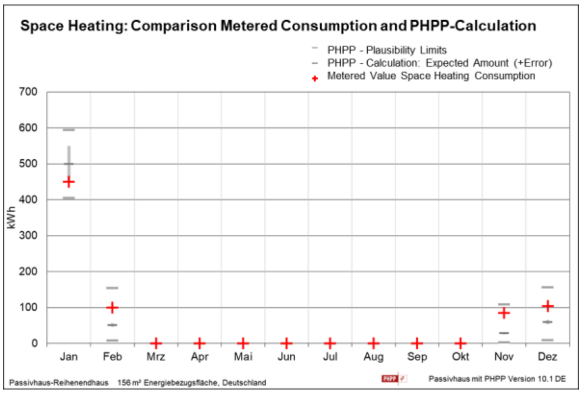

Figure 6: Expected monthly space heating consumption as per energy balance calculation [PHPP10] with uncertainty limits (dashes) against metered space heating consumption (crosses)

Moreover, the core of an individual report on the monitoring of any particular building can be exported to serve as a base for further manual editing. This will convey a compilation of all findings to the owner/user of a building for further reference and documentation. Clearly, the need for further improvement and/or the success of any action taken towards performance optimisation will be apparent.

Indoor conditions such as temperature, relative humidity and carbon dioxide concentration serve as indications of user comfort. The evaluation rates the measured data against the limits of a comfortable range for each quantity. Future work is aimed to rate all indoor conditions with regard to desired, seasonal target values. To this end the concept of the relative threshold deviation (RTD) method described in Rojas Kopeinig (2015) will be follwed, as it allows to merge the individual threshold deviations into a single figure characteristic for an entire building zone.

Results

The automated procedures have only started productive use but at the time of writing of this paper no results were automatically obtained yet. However, the implemented proccesses, in manual form, have been in use for many years at the Passive House Institute. A typical example shall be presented to further illustrate the nature of the method and the insights gained. While it can be presented here in abbreviated form and for energy demand only, an extensive discussion can be found in Peper (2008) and, in similar form, in Johnston (2020).

Subject of the evaluation is a residential building in Frankfurt/M./Germany with 19 flats, the treated floor area totals 1350 m². The building was completed in the early 1950ies and underwent deep retrofit with Passive House components and technologies, completed in 2006. Three years of complete monitoring data are available.

The space heating demand as calculated in the design phase with climate data for the location, derived from a 30-year period, amounted to 16.9 kWh/(m²a) at 20 °C indoor temperature. Updated for the prevailing weather conditions in 2009/2010, mainly milder outdoor temperature and differing global horizontal irradiation, this value is modified to 15.4 kWh/(m²a).

Indoor temperatures were continuously measured in one or two rooms in every apartment, depending on its floor area, and converted into an area-weighted mean value for the entire building. This effective indoor temperature was found as 22.4 °C for the heating season 2009/2010. As outlined previously it has a considerable impact on the space heating demand, and yields an adjusted figure of 20.5 kWh/(m²a). This value comprises the majour influences on the balance and is termed the *expected space heating consumption*. It disregards any effect of additional window openings as this cannot be measured in the field within the cost constraints imposed on the simplified monitoring discussed here.

In comparison to the *expected space heating consumption* the *metered space heating consumption* was observed as 23.6 kWh/(m²a), or 3.1 kWh/(m²a) higher than suggested by the calculation.

Discussion

The metered consuption falls just on the upper bound of the ±3 kWh/(m²a) uncertainty band, which could invite the assumption of some heat loss not reflected in the PHPP model, such as from window opening. However, this must largely remain a hypothesis as the measuring uncertainty is too large to provide a definitive answer.

The adjusted calculations and empirical observations do nonetheless agree within the expected uncertainty band and verify the performance of the building in the field under normal use conditions. There is no indication of any major shortcomings in terms of building fabric quality or MVHR performance or other systematic *performance gap*. The deviation from the initial design calculation results can be explained by the differing boundary conditions within the expected uncertainty range. The validity of the calculation methods of the PHPP is supported by the observation. A range of similar studies in new and refurbished buildings (see Johnston (2020) for an overview) with comparable match suggests further that user behaviour and internal heat gains, although not known in much detail beyond the indoor temperature preferences, are usually adequately reflected in the calculations.

The outPHit evaluation will attempt a slightly refined appraoch as it provides an estimate of actual internal heat gains, from occupancy and electrical energy use, diminished by estimates of evaporation and drain losses. Although such effects can be significant in the individual case, it is not expected that it will shift the perspective across a larger number of dwelling units and considered a precaution that may pay dividends in very small buildings with few dwelling units, where individual behaviour can indeed dominate the overall situation.

Conclusion

The outPHit project implements in largely automatted form a performance evaluation method that has been successfully applied at the Passive House Institute in manual form for many years.

Within its natural limitations, due to measuring uncertainty, it can verify the in-situ energy performance of buildings to a reasonable standard, despite using only low-cost equipment. Elementary comfort parameters are also part of the evaluation and are assessed against a comfortable range for each.

The use a of low-power wireless data transmission standard enables battery powered operation of all sensors for the duration of the monitoring campaign. This makes shipping a box of preconfigured equipment possible and reduces on-site activity to physically installing the sensors and plugging the data acquisition unit into power and data connections.

Data visualisation and statistical analysis within the monitoring platform provide a base for informed building commissioning and performance optimisation even before enough data for quantitative assessment has accumulated.

As data handling and data processing are automated and the installation of the low-cost field-level monitoring system is straightforward, performing a sound building monitoing becomes manageable for Architects & Engineers with some further training. This will help make post-occupancy monitoring become a standard procedure for quality assurance in highly energy efficient buildings.

While assistance and interpretation from highly qualified staff may still be necessary in some cases they can nonetheless oversee a large number of projects, overcoming a current bottleneck.

Further scientific work will eventually benefit from an increasing pool of measured data from lots of projects across wide geographic range/climates that includes both energy performance and comfort information, along with measuring uncertainty.

Acknowledgement

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