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TOWARDS DATA-DRIVEN BUILDING RETROFIT

Mario Frei, Zoltán Nagy and Arno Schlueter

Architecture and Buildings Systems, Institute for Technology in Architecture, ETH Zürich, John-von-Neumann-Weg 9, CH-8093 Zürich

ABSTRACT

Due to the relatively low construction rate of new buildings in Europe, the energetic performance of the building stock can mainly be improved by retrofitting existing buildings. Current methods to derive and assess retrofit measures require either on-site inspection by an expert consultant and code based approaches, or numerical simulations using a building energy model that needs to be first developed. Since the former is rather inaccurate and prone to overestimating the retrofit measures (prebound effect), and the latter is time and cost intensive, in this work we propose a data-driven-retrofit (DDR) approach to derive optimal retrofit measures. The approach uses wireless sensor networks (WSN) for the determination of building characteristics, energy consumption and occupancy patterns. Building models in the broadest sense can be extracted from the collected data. Retrofit scenarios can be incorporated in these buildings models in order to estimate the future energy consumption of the building, and to choose the optimal measures. The approach is presented as a chain-like framework. The deployed WSN can remain installed to verify the retrofit execution, and to perform continuous long term monitoring for fault-detection and optimal performance of the installed building systems. This work extends our previous research in this area, and presents the DDR framework, and results from a case study on a listed building in Zurich, Switzerland.

Keywords: data-driven retrofit, in-situ measurement, system identification, building modelling, zero-emission retrofit

INTRODUCTION

Energy related carbon dioxide emissions in building account for 25% of the total global carbon dioxide emissions. Therefore, optimizing building performance offers a big leverage to face the challenges of climate change [1]. Due to the relatively low construction rate of new buildings in Europe, the performance of the building stock can mainly be improved by retrofitting existing buildings. Typically, to decide what measures to apply, first the current building performance has to be assessed. This is usually done by experts performing code-based calculations, e.g., the SIA 380/1 for heating demand in Switzerland. However, results from such code-based calculations may differ significantly from measurements, as the pre-retrofit performance of buildings tends to be underestimated (pre-bound), and the post-retrofit performance tends to be overestimated (rebound) [2]. This results in an overestimation of the effect of the retrofit measures. Another method to assess the performance of a building is by simulation. However, building simulations require a lot of effort to accurately reproduce the thermal behaviour of the building. Also, detailed information about the properties of an existing building is often difficult to obtain.

Therefore, in this work, we propose the data-driven retrofit (DDR) approach as a non-intrusive and cost-effective method to determine actual buildings parameters and energy performance. Based on this data, better assessment of the current state of the building can be made, and more effective retrofit measures can be determined. Finally, the same techniques can be applied as a quality control measure, to validate the performance after retrofit.

The paper is structured as follows. In the next Section, we detail related research. Then, the proposed data-driven retrofit approach will be outlined in the "Methods" Section. In the "Results" section, we will show examples of a verification case study in terms of the DDR approach. Finally, we conclude the paper by discussing our results.

RELATED RESEARCH

In this Section, we briefly review current building performance assessment methods, building modelling approaches and data acquisition methods.

Typical procedures for the energy performance assessment of a building require on-site inspection by an expert. Recently, decision aid tools for retrofits have been proposed [5, 6]. The current deterioration of building elements is based on visual inspection and comparison. Based on the assessment cost and energy performance of a retrofit a refurbishment is assessed. A survey may include visual inspection of the building, gathering energy bills, occupant questionnaires, and individual measurements [7]. The end result is usually a heat loss coefficient (in W/K) or normalized energy consumption in a standard year. However, only the performance of the whole building can be assessed, and compared against each other. There is no insight on individual components of the building and their respective performance.

The energy consumption of future buildings can be estimated by performing a building energy simulation (BES). Usually BES is not available for existing buildings facing a retrofit. In this case the BES would need to be developed from scratch, which is cost and time intensive, prone to errors and requires validation with real data to be useful for retrofit predictions.

Papafragkou et al. presented a simple and inexpensive method for building performance assessment, without the need of on-site inspection [3]. A small USB-temperature logger is sent to the customer, who places is near the thermostat. Based on the measured data, the building in question can be qualitatively classified into four categories. However, no quantitative data is obtained, and the method is only applicable for specific cases, where the heating system has a night setback mechanism.

Thermal RC models for buildings have been used since the 1970s [8], and are often applied for model predictive control of building systems [9]. The verification, i.e. parameter fits, of such models is often based on the error of predicted temperature and not on comparisons of the physical entity represented by the RC-components. This does not ensure the physical meaningfulness of these models, and therefore sub-components of the models cannot be altered, such as needed for the prediction of retrofit measures. Other models, e.g., neural networks, ARMA models or statistical models are difficult to physically interpret as they may even completely ignore the internal physics of a building. This is acceptable for control tasks. However, it is virtually impossible to predict changes in building performance due to retrofit measures.

All these assessment methods have in common, that, because lack of data, they rely on a variety of assumptions. There are a lot of applications of building models, mainly in building control and energy performance estimation of planned buildings. Techniques from this fields applied to building retrofits are not satisfying, as they lack the possibility to appropriately reproduce the physical details of the thermal behaviour of a building, or they lack the possibility to project changes to the building.

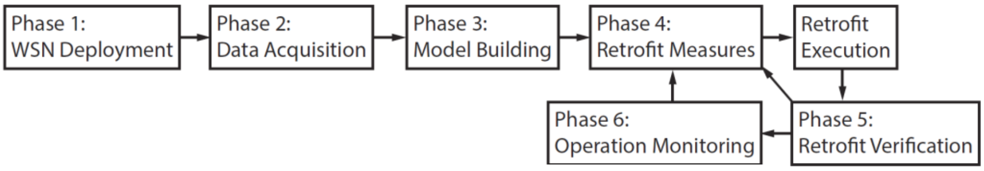

Figure 1: Data Driven Retrofit approach

METHOD

In this section we introduce the Data-Driven-Retrofit (DDR) approach shown in Figure 1. In brief, in phase 1 a wireless sensor network (WSN) is deployed as a necessary basis to gather data on the thermal behaviour of the building in phase 2. Then, in phase 3, the data is fused into a building model. This model can be used to derive and analyse retrofit measures in phase 4. After refurbishment, the effect of the implemented retrofit measures can be verified with another measurement period in phase 5, which can potentially be extended to a permanent operation monitoring in phase 6. In the following, we detail each of these phases:

Phase 1 is dedicated to improving the available data on the building by in-situ measurements. First, building plans can be completed by in-situ U-value, and energy consumption measurements, such as electricity, oil or gas. Energy consumption measurements yield high-resolution data, and also allows for an insight on energy usage patterns, and building dynamics. Secondly, a reference baseline for the temperature set points and comfort of the occupant can be established by measuring the room temperature, air humidity and outdoor temperature. Monitoring the outdoor conditions allows for normalization of the energy consumption using the actual local data rather than measurements from a potentially far away weather station. This normalization in turn allows for comparisons, especially before and after the retrofit.

The main key for success of DDR is a quickly deployable, modular, online wireless sensor network (WSN) for building performance assessment, which is not available up to this date. Quick deployment requires a full wireless operation for both energy supply of the WSN, as well as data transmission to a central server for further analysis. Modularity is needed because each building is individual, and the installed building systems and energy meters do not have a unified read port. In brief, the process of data gathering must be as fast as possible, saving both time and money.

Phase 2 incorporates, online data acquisition, i.e., the data is sent to a central server via the mobile network, which is key for a fast assessment. This centralized data acquisition allows to constantly monitor the quality of the data, and, thus, perform the measurements just as long as needed for the required data quality. This minimizes the duration of the measurement installation. Further, online monitoring allows for fault detection and correction. This is not possible with offline data loggers, which are typically used [2,3].

In phase 3, a building model is built. This model shall be able to incorporate the measured building characteristics and it should be able to incorporate retrofit measures, in order to predict the performance of the building after the retrofit. Most probably, simple RC models which reflect the physical properties well can be employed successfully, as we have shown in an earlier example [4]. In addition to the building, models for the behaviour of the occupant can be extracted from the data as well, which is important as occupancy patterns are significant for the energy consumption of a building [10]. Our approach is more time efficient than a traditional BEM simulation, and preserves the ability to determine the thermal behaviour of the building.

In phase 4, possible retrofit measures are incorporated into the previously established building model. This allows to analyse and choose the optimal combination of retrofit measures for the desired result. This phase is followed by the execution of the selected retrofit measures.

For the verification of the retrofit procedure, the WSN is deployed again in phase 5. This enables quality management of the newly installed measures. Re-measuring energy consumption indoor and outdoor conditions allows for consideration of multiple effects, such as possibly altered occupancy patterns, outdoor conditions and occupants behaviour. A data based verification allows for an objective confirmation that the performance goals of the building were reached or allows, if necessary, for further improvement.

In a potential phase 6, the verification can be extended to a continuous operation monitoring by simply leaving the WSN in place. This enables fault detection in operation, which ensures that the building systems operate as designed.

We note that the DDR process chain does need do to be applied completely from beginning to end. For example only phases 1 through 3 could be applied, improving the data quality. Then a traditional retrofit process could follow. Also, phase 5 could be applied on its own, verifying the result of a performed retrofit. The sensing hardware could further be used for single applications such as U-value measurement or energy-metering, without the surrounding framework. The versatility of the framework allows for an application tailored to the need and resources.

RESULTS

In this section we present results from a DDR for phases 1,2 and 5 focusing on retrofit verification. The employed WSN, shown in Figure 2, is a further development of our previous work [4], and is able to measure, temperatures, air humidity, heat-fluxes, electric pulses, solar radiation, luminosity and mains-current. The input for electric pulses was used to read out an oil flow meter of a heating system and an electricity meter. The main focus during the development of this version of the WSN was modularity and fast deployment. For robustness reasons, we choose to have wired power for each sensor node; data transmission between the nodes and to the central server was done wirelessly.

The WSN was installed in a listed building in Zürich. It is the same building as in [4]. The measurements performed with the current iteration of the WSN took place after the refurbishment, which consisted of replacing the windows and the application of insulating plaster. This case study is an example for a retrofit verification (phases 1,2 and 5). We measured the U-value of one office wall, air temperature and humidity of the same office, as well as oil consumption and electricity consumption of the building. It took about 45 minutes in average for each sensor node to install. The measurements started on October 16, 2014 and ended partially on the January 22, 2015.

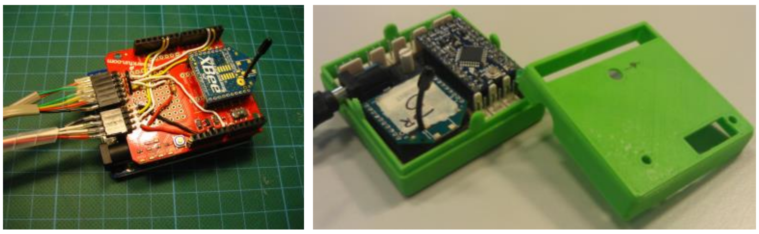

Figure 2: Wireless Sensor Node, left v1 [4], right: v2 (this work)

The heating energy demand was calculated for the building before as well as after the refurbishment, according to SIA 380/1. These calculations included estimations of U-values according to SIA 279.

As shown in Table 1, the measured U-value after the retrofit agrees well with the predicted value. Thus, we can conclude that the retrofit measure of the insulating plaster has been performed adequately.

Method	**U-Value (**W/m^2K**)**
Calculation pre-retrofit	1.43
Calculation (prediction) post-retrofit	0.71
Measurement post-retrofit	0.67

Table 1: Comparison U-Value Calculations vs Measurements

The heating system was monitored by an oil-meter, connected to the WSN. This allowed for a monitoring of the oil-consumption of the heating system, with high temporal resolution (5min data). Further, the supply temperature and return temperature of the heating system was monitored. Paired with the indoor and outdoor temperature measurements already taken with the U-value setup the following detailed analysis was performed.

We calculate the total thermal loss per heating degree day as 14.1 kWh/(K·d) for 2014 after the retrofit. This is an improvement compared to 16.8 kWh/(K·d) before the retrofit [4]. Next, as shown in Table 2, we find the annual energy consumption to be 172 MJ/m^2a, a clear improvement to the 204 MJ/m^2a from before the retrofit. While a clear improvement of the retrofit measures can be seen, it is also clear, that the code-based calculation overestimates the improvement effect of the retrofit by over a factor 2. This is a strong pre-bound effect and is mostly likely due to the fact that retrofit measures are financially incentivised for a predicted improvement rather than actual improvement.

Method	**Pre-Retrofit (MJ/m^2a)**	**Post-Retrofit (MJ/m^2a)**	**Improvement (%)**
SIA 380/1	408	251	38
Oil Consumption Measurement	204	172	16

Table 2: Overview Heating Demand Calculations and Measurements

Finally, Figure 3 shows the time series of air temperature and humidity of the monitored office after the refurbishment. The set-point room temperature after the retrofit is on average 23.01°C, in comparison of 22.89 °C during the same time a year earlier. Thus, we can not identify a rebound effect. However, the gathered data clearly shows that the air conditions in the room are always out of the comfort zone. While this may be typical for the heating season (especially the low humidity levels), it is also an indication that the retrofit did not yield any improvement for the comfort of the occupant.

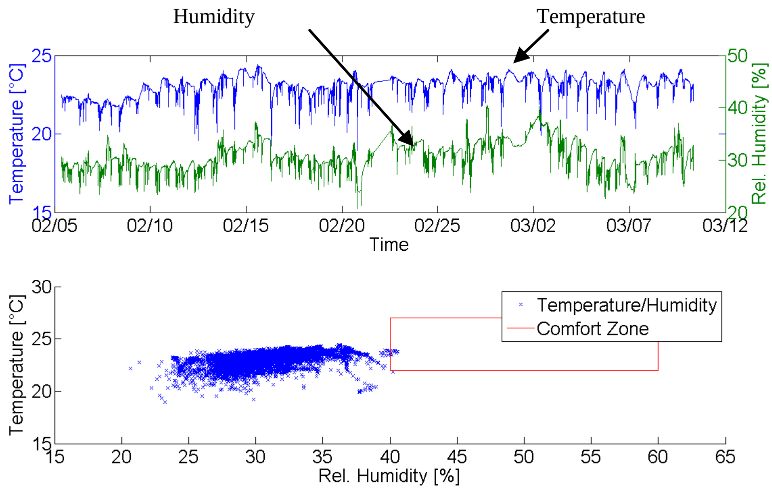

Figure 3: Comfort Measurement Data

Conclusion

We have presented an overall scheme for data driven retrofits (DDR), and we have shown practical application of a wireless sensor network. In our case study, the sensor network was deployed quickly, and delivered robust online monitoring. DDR can improve the current best practice of building performance determination by eliminating assumptions through measurements and parameter estimation, without the effort of elaborate building simulations. More entities can be measured for an elaborate data driven retrofit framework, which in combination yield a precise representation of the current thermal performance of a building. DDR is a powerful tool for a cost effective and efficient retrofit of the building stock.

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