Practical experiences from the implementation of extensive sensoring in a modern building

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Abstract. The extensive use of sensors is quickly becoming a standard feature of modern new buildings. Apart from the use of regular Building Management System (BMS) data, we see the addition of sensors that monitor in more detail the indoor environmental quality and the use and performance of innovative (and local) system solutions. This is also combined with integrated energy solutions at supra-building level. The assumption is that all these data are valuable to arrive at buildings that can optimize their operation towards indoor environmental and other sustainable performance indicators. In this research, data from a large modern building that combines office and educational rooms, features an innovative façade design and is connected to an aquifer thermal energy storage are considered. In order to perform detailed analyses, several sensor and data related issues had to be resolved first. In this paper we provide a procedure for structuring the data as was available for this specific building, originating from different sources. The outcomes provide a practical basis for other buildings to assess the correctness and quality of the sensor data and the analysis potential. An example of an analysis is presented. In addition, the paper demonstrates how the obtained measurement data can be used to calibrate a simulation model that is employed to analyse the ventilative cooling potential of the innovative façade in comparison to shading.

Keywords. Sensor data, Simulation, Model calibration, Ventilative cooling, Solar shading
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1. Introduction

According to literature, in most buildings 14-50% thermal energy and 9-13% electrical energy use reduction can be achieved by improving building controls [1]. Apart from energy, monitoring and optimization of Indoor Environmental Quality (IEQ) is increasingly in the focus of research, especially in office or educational buildings [2,3]. Health, comfort and productivity for its occupants are regarded as important performance aspects of buildings. From a cost-perspective, investing in good IEQ is beneficial: literature indicates an order of magnitude cost ratio of 1:5:200, where for every Euro spent on building construction cost, five are spent on maintenance and building operating and 200 on staffing and business operating costs [4]. Therefore, rates on return can be high in this case, but this should be supported by thorough performance evaluation and control of the IEQ [5].

There are several platforms available for building energy management and control. Some are control hardware-independent, such as Strukton PULSE platform, Cloud Energy Optimizer, Spectral Smart Building Platform, Entronics facility analysis platform, and bGrid. Others are optimized for the hardware developed by the same company, such as control solutions of Priva, Schneider Electric, Siemens, Johnson Controls, and SAIA. Websites for further information on these platforms are provided in the reference list.

These efforts and the scientific community could benefit from further application of sensory data for real world performance analysis of innovative solutions being applied in buildings. In this paper, an example is shown of how different sensory data can be combined and analysed. However, not every building parameter can be measured, and to explore future scenarios one cannot rely merely on measured historical data. Therefore, in this paper we also present an example of using a calibrated building energy simulation model to investigate the ventilative cooling potential of an innovative façade system, decreasing the cooling energy demand.

2. Context

2.1 Building information

To aid the efforts of conducting new research about building energy, occupant comfort and building control systems, the Eindhoven University of Technology (TU/e) started the Atlas Living Lab project. In this project, the recently renovated Atlas building serves as the source of measured building performance and occupant comfort data, thus providing input for new research. The Atlas building dates back to the 1960's. Since then, it served as the main building of the TU/e campus. A comprehensive renovation process started in 2016, when the building was equipped with a new façade with remotely openable windows, an automated shading system, new interior and building systems (see **Fig. 1**).

Fig. 1. Atlas building. Image source: TU/e.

As part of the renovation process, the building was equipped with sensors which can be categorized to three main sources of information about the building's performance and its boundary conditions:

Indoor environment: 474 air temperature, 460 occupancy and 126 CO_2 level sensors provide information about the indoor conditions in hourly resolution.
Energy: Heating, cooling and electric meter data with 5-minute resolution metered for each floor separately.
Weather: Ambient temperature, relative humidity, wind speed and solar irradiance components are measured on campus in minute resolution.

The sensor information from the three sources is stored in three different databases: the *indoor environment* data is extracted from the building management system (BMS), the *energy* data is extracted from the database of a campus-wide smart meter network, and the *weather* data for this study was extracted from a weather station on campus [6]. A new weather station on top of the Atlas building is operational now.

2.2 From data to information

To be able to assess the energy and IEQ performance of the building, and therefore retrieve more valuable information about a system, the three data sources need to be merged and cleaned. In order to do this, an automated process was developed in Python programming language with the following main steps:

Find the temporal overlap of the time series: The official opening of the Atlas building was on the 21st of March 2019, however, the commissioning process of certain data logging systems took longer, therefore all data sources are available simultaneously from 1st of November 2019.

Identify missing values: In case of a small gap (e.g. for metered heat < 1 hour) in one of the data sources the missing section can be replaced with linear interpolation. In case of a larger gap (e.g. > 1 h), the data for the same section is removed from the other data sources as well.

Identify erroneous values: Erroneous values can be negative or impossibly large metered values, which can occur due to clipping or resetting of heat meters. When detected, the erroneous values are removed and the process described for missing values is followed.

Enhance the dataset with derived parameters: Some useful parameters can be calculated from the measured ones. One such derived parameter is the total incident solar irradiation on the façade of the Atlas building, which is calculated from the façade areas and separately measured solar irradiance components (global horizontal, direct normal and diffuse horizontal irradiance).

Resample all time series to a common time resolution: The hourly, 5-minute and 1-minute datasets are resampled to hourly or daily resolution.

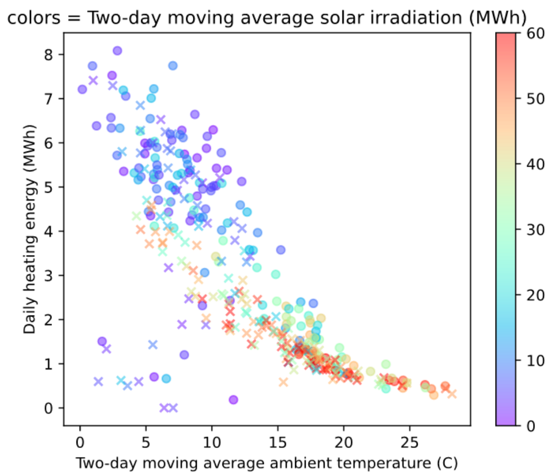

Fig. 2. Heating energy signature curve of the Atlas building for occupied (o) and unoccupied (x) periods and as function of the solar irradiation on the façade.

The cleaned and pre-processed time series are saved in a new database which is used for analysing the energy performance and IEQ of the building. One example (visualization) of the cleaned and merged sensor data is shown in **Fig. 2**. It presents the so-called heating energy signature curve. In this graph also information on the solar irradiation and occupancy is included.

With respect to the latter, the occupancy during the period shown was heavily influenced by the COVID restrictions that have been in place on and off during the last two years. Due to this situation, it was not possible to investigate the ventilative cooling potential of the façade from the available measured data. Therefore, building simulation was used to answer the research question. The available data was used for calibrating the model. The following part of the paper will address the modeling and the outcomes of that investigation.

3. Building energy modeling

In order to virtually investigate different (ventilative cooling) control strategies for the Atlas building, a building energy model has been developed that can serve as a testbed to try out new control strategies.

3.1 Model considerations and tested strategies

In order to reduce the modeling effort, only the 10th floor of the Atlas building was selected for modeling. This is a fairly generic floor of the building and we assume that the effect of the tested modeling strategies would act similarly on the entire building and therefore expect that the conclusions of the study are applicable for the entire building.

The simulations were conducted using EnergyPlus [7], DesignBuilder [8] and Python. The model geometry and the construction materials were built in DesignBuilder (see **Fig. 3.**), then the model was exported to EnergyPlus, to perform the model fitting using Python. The model parameters from the best fit then were used as an input in the initial DesignBuilder model to perform the simulations for the different case studies (see **Fig. 4**.). This modeling process takes advantage of the convenient geometry editor of DesignBuilder and the easy automation of large numbers of EnergyPlus simulation runs with Python.

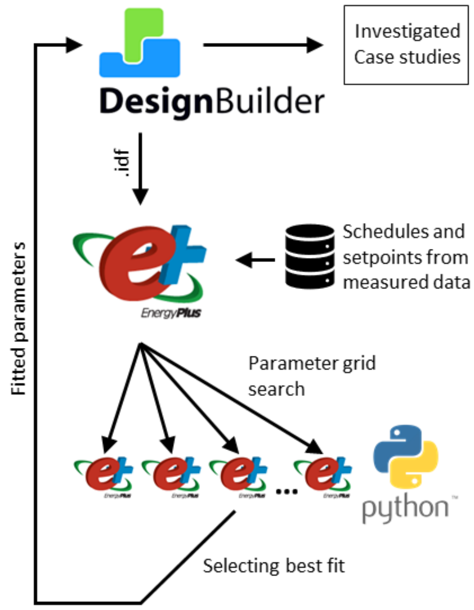

Fig. 4. Schema of the modeling process.

The tested cases investigate the effect of different control strategies for shading and natural ventilation (ventilative cooling). This is done by comparing the simulated heating and cooling demand of the following 7 cases to the measured heating and cooling demand of the 10th floor of the Atlas building:

1. A baseline case EnergyPlus model that was fitted to the measured data (*fitted_ep*).
2. A baseline case DesignBuilder model, that uses the fitted parameters from the EnergyPlus model (*baseline_db*).
3. A case without solar shading (*no_shade*).
4. A case with solar shading that is half-drawn every time it is activated (*half_shade*).
5. A case with temperature-controlled natural ventilation through the windows, with a control logic that turns of the HVAC systems in the zones while the windows are open (*nat_vent_opt*).
6. A case with temperature controlled natural ventilation, but without the above control logic (*nat_vent_unopt*).
7. A case that combines cases *nat_vent_opt* and *no_shade* (*nat_vent_opt_no_shade*).

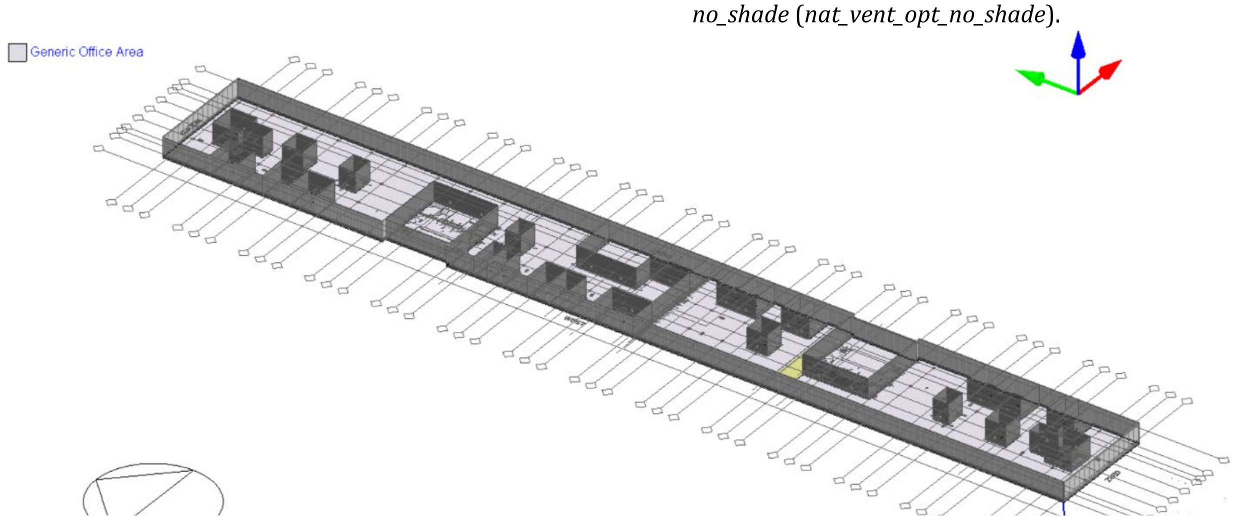

Fig. 3. DesignBuilder model geometry of the 10th floor of Atlas.

Table 1. contains the temperature setpoints that were used by the above listed cases.

Table 1. Temperature setpoints

Parameter	Value	Unit
Heating setpoint/setback	22/18	˚C
Cooling setpoint/setback	24/28	˚C
Ventilative cooling setpoint	23	˚C
Min/max outdoor temperature limit for ventilative cooling	14/23	˚C
Ventilative cooling setpoint	23	˚C
Solar transmittance of shading	0.1	-

3.2 Description of the fitting method

Though most building related information was available for the model, there is a need to fit (i.e. calibrate) the building energy model. In order to do that the following known model parameters are applied:

1. Actual weather in Eindhoven (prepared from measured weather data).
2. Floor electric energy use (historical measured electric energy use of the floor). The heat gain from this is evenly distributed in the building.
3. Hot and cold energy use of the floor from smart meter data export (this is used for checking goodness of the fit).
4. Zone temperatures (measured in every zone - the model has as many zones as measurement locations available).
5. Zone occupancy (measured in every zone).
6. Certain HVAC system parameters and schedules.

The HVAC system of the 10th floor of the Atlas building is modeled in EnergyPlus with two parallel systems that provide the fresh air and zone heating:

1. A Dedicated Outdoor Air System (DOAS) is providing constant air flow to the zones:
   - Inlet air temperature: 18 °C
   - Heat recovery sensible effectiveness: 70%
   - Outdoor air flow rate (this is a fitted variable)
   - Availability schedule: 07:00 h to 17:00 h on weekdays

2. A Packaged Terminal Air Conditioner (PTAC) for every zone, providing the local heating/cooling:
   - The heating/cooling availability schedule is prepared based on actual measured operation of the heating/cooling system of the building: when there was heating/cooling energy consumption on the floor, the heating/cooling system in the model is allowed to operate.
   - Heating/cooling setpoints are indicated in **Table 1.**

In the real building the zone heating/cooling is supplied with a heated/cooled ceiling. The lack of latency and heat storage in the PTAC system (as opposed to the heated/cooled ceiling system in the real building) is compensated by adding more internal thermal mass to the zones during model fitting.

Since not all building properties are known, the following building parameters are used as variable parameters during the model fitting:

- Minimum fresh airflow rate of the DOAS system
- Additional internal thermal mass in the building (mass and surface area)
- Infiltration
- Fraction of measured electric energy use dissipated as heat in the zones
- Global horizontal irradiance limit for activating the shading system.

Since it is difficult to implement the entire (unknown) control logic of the building systems, the aim is to achieve a thermal state of the building during the simulated year that is similar to the thermal state of the building in reality. This can be achieved by using measured weather data, and by giving the measured zone temperatures as heating/cooling setpoints for the model. This way, when the heating is on, the zone temperatures match closely in the model and in the real building. Via system availability schedules it is also enforced that the heating can only run in the model when it is running in the real world as well. Information for this is available from the collected smart meter data. Similarly to heating, the ventilation is also controlled with schedules and only running based on an availability schedule.

Thermal mass is added as a timber material in 4 cm sheets. The mass/floor area of the thermal mass is the fitted parameter, and the surface area is calculated from it. As mentioned above this thermal mass is added to compensate for the lack of latency of the PTAC air system used in the model.

The execution of the fitting is done with a grid search using Python. For each of the above listed fitted parameters there is a "multiplier" built in the EnergyPlus model, which at each simulation run changes the value of the corresponding parameter. The range of the tested multipliers is shown in **Table 2.**

Table 2. Model parameter multipliers

Parameter	Initial value	Multiplier range	Unit
Outdoor air	1	0.3 - 1.5	l/sm^2
Thermal mass	200	0.15 -2	kg/m^2
Infiltration	0.2	0.5 - 2	1/h
Electric equipment	3	0.15 - 1	W/m^2
Shading control	250	0.25 - 2	W/m^2

Choosing the best fit was done by first running 674 simulations while varying the above multipliers, then calculating the daily and hourly Mean Absolute Error (MAE) of the heating and cooling energy demands for each simulation run. **Fig. 5** and **Fig. 6** show the hourly and daily MAE of heating and cooling demand, respectively. The combination of parameters that resulted in a good agreement for both the heating and cooling energy demand and both on an hourly and daily level was searched for. Therefore, in **Fig. 5** and **Fig. 6** the simulation runs were ordered by the hourly and daily MAE of the zone heating and cooling demand, and a simulation run was selected that ranked low in all four MAE orders (indicated with a green marker in both figures).

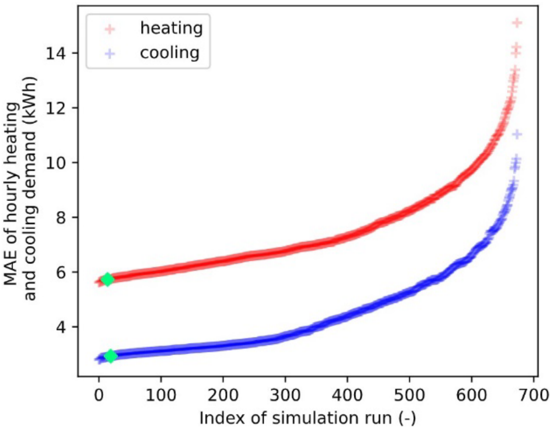

Fig. 5. MAE of hourly heating and cooling demand in ascending order with the best fit case marked in green.

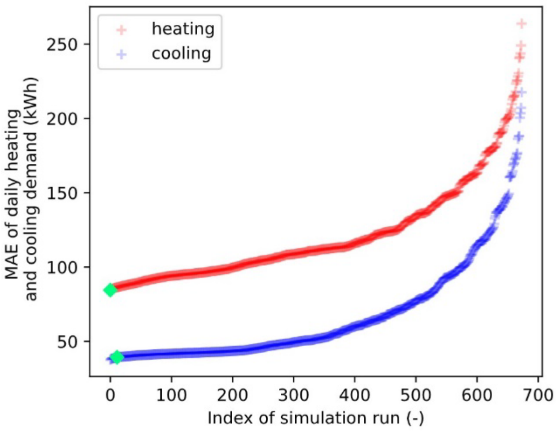

Fig. 6. MAE of daily heating and cooling demand in ascending order with the best fit case marked in green.

The multipliers of the best fit resulted in the simulation parameters as shown in **Table 3.**

With the above parameters the simulated mean zone temperatures were confirmed. **Fig. 7** shows the comparison between the measured and the simulated heating and cooling energy demands. The model fitting aimed to minimize the difference between the measured and simulated zone heating and cooling loads both on an hourly and daily level. Here we can observe that the fitting was fairly successful.

Table 3. Model parameter multipliers

Parameter	Value	Unit
Outdoor air	1 * 0.5 = 0.5	l/sm^2
Thermal mass	200 * 0.15 = 30	kg/m^2
Infiltration	0.2 * 0.75 = 0.15	1/h
Electric equipment	3 * 0.15 = 0.45	W/m^2
Shading control	250 * 0.25 = 65	W/m^2

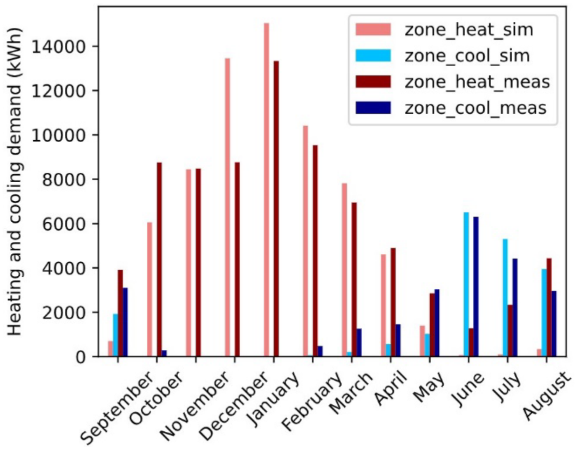

Fig. 7. Monthly measured heating and cooling demand of the 10th floor of Atlas.

The model fitting was done in EnergyPlus, by using a Python script to set the model parameters, run the simulations and interpret the results. However, we would also like to investigate the effect of natural ventilation on the building performance. In order to be able to conduct air flow network simulations conveniently, the above determined model parameters are used as an input for the DesignBuilder model that was used to create the initial model. This workflow facilitated a more convenient implementation of the air flow network with the control of openable windows in DesignBuilder as opposed to implementing it by hand in EnergyPlus.

4. Results and discussion

Fig. 8 shows the measured and simulated annual heating and cooling demand of the different cases (as defined in Section 3.1).

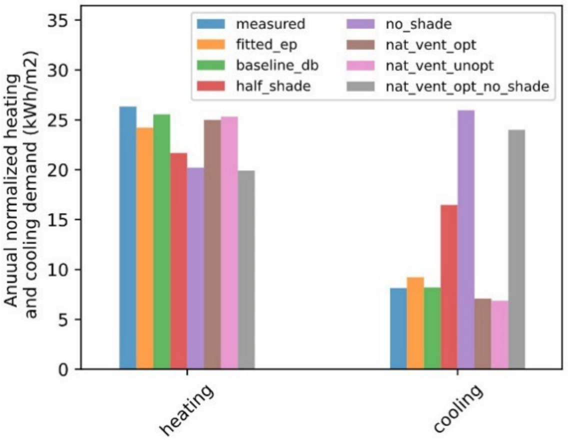

Fig. 8. Annual heating and cooling demand of the 10th floor of Atlas with different solar shading and natural ventilation controls.

The annual heating and cooling demand of the fitted EnergyPlus model (*fitted_ep*) deviates by 8% and 13% respectively from the measured heating and cooling demand. The DesignBuilder model (*baseline_db*) that is built using the fitted parameters deviates by 3% and 0.8% from the measured values. The difference between the best fit EnergyPlus model and the baseline DesignBuilder model is likely due to the slightly different way of setting model inputs in EnergyPlus and DesignBuilder and perhaps a difference between the EnergyPlus version used by DesignBuilder (8.9) and the version used for model fitting (9.5). Another source of difference is that in the DesignBuilder model it was not possible to take into account occupant interaction with the heating/cooling setpoints. It was assumed that the heating/cooling setpoint offset options of the room thermostats are not used by the occupants.

The *no_shade* case investigates the scenario when the shading system of the building is not active throughout the year. We learned that in the summer the automatic operation of the shading system was not active in the real building due to high cost of damage when various objects (e.g., backpacks) are left under the shade when it gets drawn. If this is the case throughout the year, then according to the simulation results, it would lead to a significant 24% decrease in heating demand. However, it also would lead to a more than three-fold increase in cooling energy demand. Therefore, it is recommended to strive for using shading in the summer months as much as possible.

If damage to the shading screens is a common problem, it could be considered to draw the shading only half way (if this is technically possible). This way the chance of damage to the shading screens would reduce, while still allowing for some protection from overheating. This hypothetical case is modeled with the *half_shade* scenario. In this case the cooling demand increase is only two-fold.

Another strategy is to use natural ventilation to reduce the cooling loads. With the *nat_vent_opt* model it is demonstrated that a 12 % reduction in cooling loads can be achieved, if the windows are opened when they can contribute to the cooling of the zones. In this model, the windows are opened if the outdoor temperature is between 12 °C and 23 °C and if the indoor temperature is higher than 23 °C. The mechanical cooling in this case turns on if the zone temperature increases over 24 °C and it never operates when the windows are open. Moreover, in this model the windows are closed in case of rain or high wind speeds. The *nat_vent_unopt* case, models a less sophisticated system that does not connect the operation of the HVAC systems to window opening, nor the wind speed or rain. In this case, contrary to the expectation the cooling savings are slightly higher. Perhaps this is due to the higher freedom in operation and the fact that simultaneous operation of natural ventilation and the HVAC system was not really an option in the *nat_vent_unopt* case either, as the setpoint for the HVAC cooling is higher than the cooling setpoint with natural ventilation.

When comparing the effect of natural ventilation and solar shading, it can be concluded, that for the Atlas building, solar shading seems to have higher potential to reduce cooling loads than natural ventilation. Therefore, restoring (at least partially) the functionality of automated solar shading would greatly reduce cooling loads, because the primary cause of overheating in the Dutch climate and in the case of such a highly glazed building is not the high outdoor temperatures, but the solar gains. The higher significance of shading can also be observed in the results of the last simulation case, *nat_vent_opt_no_shade*. This case clearly shows that natural ventilation cannot recover much from the increased cooling loads in the case of simultaneous application of no shading and openable windows.

The comparison between ventilative cooling and shading use, however, is not complete. In the model we did not yet include the possibility to apply night-time ventilation to precool the building during the cooling season. Moreover, one could experiment with further, different combinations of mechanical cooling and ventilative cooling setpoints in order to more efficiently utilize the potential in the latter. The results, nevertheless, clearly indicate that in daytime shading should be part of the strategy to reduce the cooling energy demand. Furthermore, in the analysis thus far we also did not include yet the connection to the large aquifer system that serves most buildings at the campus. For balancing reasons, the heating and cooling energy requirements may have different optimized values when only looking at the outcomes for the building instead of at the campus as a whole. The analysis does show that the availability of measured data adds to the quality of the analysis possible, as we now learn and are able to assess the building performance in reality.

5. Conclusions

The results show that availability of sensor data can support the performance evaluation of in-use buildings. In order to make full use of the data, for the case investigated, it required quite some effort to clean and combine the data. The assumption is that such effort is also needed in many other buildings where more extensive sensoring is applied. The added value of bringing all the data in one database is that it allows for much more detailed information than just performance indicator checking such as, e.g., temperature conditions.

For control strategy assessment the available data is also useful, as it can help in developing building simulation models that more closely resemble the building. In the example presented it is shown that the innovative façade does contribute to the daytime reduction in cooling energy demand, though a well operated shading system should be prioritized for the Dutch climate. The full potential of the façade, however, has not been exploited yet and is intended for further research.

6. Acknowledgement

This work was financed by OPZuid, province Noord-Brabant and Eindhoven University of Technology. The help of all those involved in the Atlas project to obtain all the necessary information is highly appreciated.

7. Data access statement

The datasets analyzed during the current study are not available, but the work performed is part of an effort to make the data (and databases) from the Atlas building usable for future researchers.

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- https://www.priva.com/solutions/building-automation/priva-bi-metrics
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