Performance Validation of a Positive Energy Building in France using Advanced Data Analytics and Calibrated Simulation
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Abstract
As very efficient buildings are more and more common, there is a growing concern about the real performance achieved by these buildings once in operation. Indeed, it is often observed that supposedly green buildings consume much more than the original estimation: this is the so-called “performance gap”. It is thus of prime importance to compare the real behavior of the building with the expectations and to be able to correct the defaults and gain experience for future projects. This article presents such a “real vs estimation” comparison for the “Woopa” building, a recent positive-energy large office building near Lyon in France. The study relies strongly on the concept of simulation calibration, which consists in adjusting the building model used in the design phase so that the simulation matches well the actual behavior of the building. The calibrated simulation reached a satisfying precision with a relative Mean Bias Error of -1% and a monthly CV RMSE of 5%. The precision on temperature is also excellent. The study showed that the building actual consumption for 2013 was relatively close to the target one. Most of the difference was due to the target model underestimation of the electric equipment consumption. The analysis also showed that AHUs were often not functioning properly. The article eventually draws conclusions on the best practices for using building management system data and energy simulation for closing the performance gap and improving building day-to-day operations.

Keywords – Energy performance of buildings, performance gap, simulation, calibration, data analytics

1. Introduction
The European Union spends over €1 Billion [1] every day on energy imports representing over 53% of Europe’s energy needs. By contrast, the United States reached a peak of 30% in 2006 and are now below 10%. As a result, the European Commission (EC) aims to reduce this risk through a series of coercive measures including the enhancement of energy efficiency
in buildings. Final energy consumption in Europe increased by 10% in absolute terms between 1990 and 2006, when it peaked at 1 190 Mtoe [2]. Over this period, the proportion accounted by residential and non-residential buildings rose from 35% to 38%, making buildings the largest single energy consumer in Europe. This situation, in particular when linked to climate change mitigation emergency, makes the buildings sector one of the pillars of energy union and a highly strategic sector [3], [4].

The major steps in this direction were made with the publication of two main laws: the Energy Performance of Buildings Directive (2010) and the Energy Efficiency Directive (2012). They both state clear targets in terms of new buildings performance guarantee and other buildings refurbishment. Although efforts are consequent at the national level, there are still significant discrepancies between the targets defined at the design stage of a building and the actual performance over the operation phase both in terms of energy efficiency and users’ comfort.

The PERFORMER project addresses those issues by developing an innovative integrated concept for monitoring and evaluating building energy performance which will help reduce the gap between predicted and actual performance in a performance guarantee perspective. The greatest added-value of the project is not only embedded in the technology but also in the recommendation generator addressed to the Building and Facility Managers.

This paper aims at providing its contribution to the development of the PERFORMER project’s integrated concept for evaluating building energy performance. This contribution is built around the modeling, simulation and calibration of one of the project’s pilot building. Hereafter are the main sections of this paper: section 2 and 3 briefly describes the building and explains how the building and its components are modeled; section 4 focuses on the instrumental data collected in situ; Section 5 provides the calibration methodology; Section 6 shows the results of the case study.

2. Building description

General description of the building

The Woopa building is a recent building located in Vaulx-en-Velin, near Lyon. The building project was launched in 2008, and finalized at the end of 2011. The total floor area is 11 000 m², mainly dedicated to office spaces. Common areas, including break rooms, a restaurant and meetings rooms, are located in the last two floors. The ground floor is dedicated to commercial spaces. Excluding the ground floor, the building was designed to be a Positive Energy building. The performance is reached thanks to a good thermal envelope and efficiency HVAC systems associated with a cogeneration, biomass and photovoltaic plants. The building is organized in 3 sub-building: the Q+ building, the NEF building and the Agrafe at the top.

After more than 2 years of occupation, it is of high interest to study the real performance of the building.
Consumption targets
As mentioned above, the Woopa building is supposed to produce more energy than it consumes. The produced heat through the cogeneration plant is shared with a nearby housing building. According to the engineering company responsible for the building energy design, Etamine, the simulated energy consumption balance is +3.9 kWh Primary Energy Source (PES)/m². More details on the consumption target can be found in the Table 2 at the end of this article.

3. Modeling the building

This section presents the building model used as baseline for the calibration procedure. As the initial TRNSYS model wasn’t available, the following describes the model that was created in order to closely match the building target model.

Modeling tools
Building geometry, shadings and characteristics such as architectural details, walls, windows, material types, or infiltrations have been designed using Design Builder software. The whole building simulation program EnergyPlus has been used for the simulation. In addition, the open source python package “oplus” (an object-oriented language dedicated to building simulation management specially developed by Openergy) is used to programmatically modify the building model description file (.idf), launch the EnergyPlus’s simulation and manage the calibration process.

Envelope
The airtightness of the envelope is excellent (q4 coefficient equal to 0,59m³/(h.m²)). The walls show also excellent performances: their heat transfer coefficient is between 0,75 W/(m².K) and 0,85 W/(m².K). The roofs (made of steel) have a heat transfer coefficient of 0,13 W/(m².K) and the floor has a heat transfer coefficient of 0,31 W/(m².K). The shadings and masks were based on Google Maps and some pictures.
Zoning

The full model of the building contains 71 elementary thermal zones, 14 of these zones corresponding to circulation or restrooms, the other zones are mostly office and meeting rooms.

In order to assign specific parameters and characteristics to all zones efficiently, the concept of “metazone” has been developed and implemented. A metazone regroups together zones with the same usage (identical characteristics: people occupancy ratio, lighting rate, etc…). In the case of Woopa, 6 metazone types were defined: office, inner circulation, meeting room, kitchen, break rooms, restrooms and circulations areas.

![Building model and zoning example](image)

**HVAC systems**

To satisfy the comfort, the building is mainly heated and cooled through an active floor system, i.e. a floor that can be heated in winter and cooled in summer. Each floor heats or cools both the zones above and below it. The energy production is provided by heating and cooling plant with a cold ground source associated to a direct exchanger, a rapeseed oil cogeneration system and a biomass boiler production plant. A gas boiler provides the necessary backup for the biomass boiler. Due to the lack of availability data on control and real behavior of the system, the heating plant has not been included in the simulation model. The modeling is based on the energy requirements of the building and the French legal rates for the boilers.

The renewal air is performed by 3 Air Handling Unit (AHU). In terms of operation, AHUs units 1&2 are used for indoor air renewal only, while AHU3 has a role in maintaining thermal comfort in the Agrafe.

**Comparison to target model**

A French thermal regulatory study (RT2005) was carried out for the Woopa building before construction. We compared our simulation results to this study and also to the Etamine’s simulation results. Excellent agreement (4% discrepancy) was observed when comparing the thermal losses and infiltration rates. As well, the comparison of the consumption of the different items showed good agreement with Etamine’s simulation (6% discrepancy).
4. Measured data

This section is an overview of the data treatment applied to the building data collected in 2013. It presents a standardized data processing and a description of the data that were selected to calibrate the simulation. This process consists of the following steps: selection, nomenclature, correction and gap filling.

Data process and difficulties

The Building Management System (BMS) provides data from 732 acquisition points, recorded at various time steps depending on the point (1-minute, 15-minutes, 1-hour, 1-day). The sensors are classified by categories and types. There are 8 categories (‘Zone’, ‘AHU’, etc…) and 11 types (‘Temperature’, Relative Humidity’, etc…).

Generally, the measured data quality is reasonable with workable time periods combined with large gaps and a nomenclature not designed to link missing values to sensor types or categories. In order to understand the missing values and make comparisons with the simulation easier, a new nomenclature was developed and missing data estimated.

Estimation of the missing data

For the processed data, 3 steps lead to an estimation of missing data, in order to fill the data gaps. If the gap duration is smaller than or equal to 2 hours, missing data are estimated with a linear interpolation. If the gap duration is greater than 2 hours and smaller than or equal to 2 months, missing data are estimated with a rolling mean on the equivalent time on the previous 3 weeks and next 3 weeks. If the gap duration is greater than 2 months, missing data are set to the mean value for temperature and humidity sensors and to 0 for other sensors. The data treatments are specific for each data type (temperature, meter, incremental meter, etc.).

In addition, a correction factor of the sum of the thermal energy was computed for the thermal energy sensor data as it was not equal to the total thermal energy measured independently. A data quality example, after processing, is showed in Fig. 1 below.

![Fig. 1 Data quality for 1-day data point, after processing](image)
5. Calibration of the building energy simulation model

The principle of the calibration is to adjust all important simulation aspects in order to obtain the best fit to the real building behavior. There is a growing interest in the community for such methods due to the increasing importance of building simulation and better availability of energy data [5, 6]. The main value of the calibration process is to get a full understanding of the real building behavior and identify the causes behind any discrepancy between the real and the target consumptions.

The calibration follows 3 major steps. The first step is to set up the schedules: if measured data are available, these data are used; otherwise, the best estimate is used (e.g. occupation schedule). Step 2 handles the systems: analyze system operation and consumption in order to check planning, set points and sizing. Step 3 calibrates the building construction parameters.

The weather data used for simulation come from the ENTPE whether station, close to the Woopa’s building. The data have been casted to match with EnergyPlus data file. The lights, electric equipment and AHU schedules were fed with the real consumptions, in order to focus on parameters that cannot be easily measured (e.g. infiltration rate).

Calibration criteria

In order to quantitatively evaluate the precision of the calibration, the study followed the recommendations of the ASHRAE Guideline 14 and IPMVP protocol. Accordingly, the following quantities were computed on energy consumptions:

- Relative mean bias error
- Coefficient of variation of the root mean square error

In addition to these official criteria, similar quantities for indoor temperature calibration are used: Mean bias error and Root mean square error.

For the schedules of the lights, the electric equipment, and the AHUs, real consumptions have been transformed into simulation inputs. Occupation schedules have been kept similar to the target ones, except for holidays that have been detected through electric equipment loads.

Systems calibration

The systems that were calibrated are the AHUs and the heat production plant. The AHU3 unit (associated to the Agrafe zones) results are different from the design ones. This may come from the fact that it has undergone some modifications. Also, all the operating schedules are not in agreement with expectations. As no standard operating modes were found, the real ones were adopted for the calibration. The calibrated thermal consumption plant shows good agreement with the expectations.
Construction parameters calibrated

Two construction parameters were calibrated: the thermal losses and the internal mass. The thermal losses are specific to zone type. The calibration has thus been done for each metazone. The results are very close to the Etamine’s hypotheses. To take into account internal inertia inside a zone, internal mass has been added to each zone. The results are systematically higher than the regulatory values. It is explained by the fact that, in addition to model the internal furniture, the internal mass also represents zones’ dividing walls and water inertia, not included in the EnergyPlus model.

Calibration precision assessment

All the equipment’s consumptions are very close the real ones thanks to the use of the real schedules. The calibrated thermal consumption behavior is also very close to the real one, with MBE=0,13°C over the whole period and RMSE=0,21°C, monthly.

![Weighted average office temperatures](image)

Fig. 4: Office metazone hourly calibrated simulation model building temperatures 2013

Thanks to data processing, accurate analysis of building behavior and calibration tools, the simulation model reaches the temperature and energy calibration target. Table 1 summarizes the global consumption indicators (including all the equipment, the lights and the systems consumptions).

<table>
<thead>
<tr>
<th>Acceptable precision</th>
<th>Total energy consumption</th>
<th>Average building temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBE</td>
<td>CVRMSE</td>
</tr>
<tr>
<td></td>
<td>All Period</td>
<td>Monthly</td>
</tr>
<tr>
<td>Acceptable precision</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>Calibrated model</td>
<td>-1%</td>
<td>5%</td>
</tr>
</tbody>
</table>
6. Results

Consumption vs production balance

One may want to know whether Woopa is a positive energy building or not. To do so, simulation is not necessary and one can just compare consumption and production over the year. For 2013, we get:

- consumption: 113 kWh PES/m² for thermal power and electrical equipments
- production: 67 kWh PES/m² for cogeneration and PV, which is below the expected production due to difficulties encountered with the cogeneration plant.

Therefore, the building did not reach a positive energy balance for the 2013 year.

Understanding the differences between target and measured consumptions

During the calibration process, we’ve noted significant discrepancies between target and measured consumptions. In order to understand these differences in a more detailed way, we made use of the calibrated simulation developed in the previous section. More precisely, starting from the target model, we transformed this model step by step up to the calibrated model. Figure 6 summarizes the obtained results.

Fig. 6: Origin of the differences between target and real energy consumption

AHU 3 shows a significant higher consumption in comparison with the target. AHU 3 handles the Agrafe building which had infiltration problems during the first two years of operation: the AHU had to function more than
designed, in order to counterbalance the infiltration heat loss of this zone. Note also that AHU 1 and 2 show better than expected consumption, but this is in fact due to wrong scheduling: the AHUs were functioning at a lower air flow than they should have for several month, failing to provide enough fresh air to the building occupants. This exemplifies that, when interpreting the energy consumption of systems, one has to keep in mind that consuming less than expected is not necessarily desirable.

3 years results

From the very beginning of the project, important efforts were made to integrate the best practices in building monitoring in order close the performance gap and improve building day-to-day operations. These efforts (for example: active floor system and pumps control, lighting system control) made by the Building and Facility Managers were supported by modeling and simulation work and measure data analysis. Table 2 shows the evolution of building energy consumption during 3 year of operation and a comparison with the developed models.

One can see that the consumption decreases year after year, getting very close to the target set during the design phase. The PV production is in line with the target; however, the cogeneration plant operated less than expected, leading to a negative energy balance for the building.

Table 2: Three year of operation and comparison with simulation

<table>
<thead>
<tr>
<th>kWh PES/m²</th>
<th>Item</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating Aux.</td>
<td>2,3</td>
<td>10</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Cooling Aux.</td>
<td>2</td>
<td>11</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Target Simulation for the office building</td>
<td>Heating</td>
<td>15,6</td>
<td>29</td>
<td>18</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Ventilation</td>
<td>11</td>
<td>14</td>
<td>6</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Office Lighting</td>
<td>12,6</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Office Electric Equipment</td>
<td>41,3</td>
<td>44</td>
<td>53</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Elevators</td>
<td>3,8</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Common Equipment</td>
<td>9,2</td>
<td>21</td>
<td>18</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Suppressors</td>
<td>1,2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>98,9</td>
<td>139</td>
<td>113</td>
<td>108</td>
<td>112</td>
</tr>
</tbody>
</table>

Production

<table>
<thead>
<tr>
<th>kWh PES/m²</th>
<th>Item</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photovoltaic</td>
<td>61,8</td>
<td>0</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Cogenerated electricity</td>
<td>41,8</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Cogenerated heat</td>
<td>14,4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total production</td>
<td></td>
<td>118</td>
<td>0</td>
<td>67</td>
</tr>
</tbody>
</table>

(1) Etamine’s simulation at the design phase; (2) 2012 measured data; (3) 2013 measured data; (4) 2014 measured data; (5) Openergy/ENGIE model for typical year;
7. Conclusions and outlook

The aim of this paper was to describe the methodology used to validate the energy performance of the Woopa’s building. The process relied on modeling, simulation and calibration, and resulted in the quantitative analysis of the differences between the real and target energy consumption. Such an analysis gives powerful insights for the Building owner and the Facility manager to close the building performance gap.

On a longer term, this work will also contribute in embedding the calibrated and targets simulations in an online platform. This platform will provide the Facility manager a new kind of tools for real time data-driven decision making.

Finally, this work will contribute to the development of a comprehensive energy performance assessment framework. In particular, the main findings of this simulation and calibration work were used to adjust the accuracy of the expert rules developed simultaneously in the PERFORMER project. These expert rules were included in the PERFORMER energy performance assessment methodology in a first instance to provide functional requirements and specifications for the toolkit and the user interface developed to manage energy consumption and ensure the continuity of the performance all over the life cycle of the building.

Acknowledgment

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References