Effective Building Modelling for Energy Performance Contracting

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Abstract

Energy Performance Contracts (EPC) are contractual agreements between beneficiaries and energy service providers, where budgets are established in relation to a determined level of energy performance. Hence, the problem of forecasting the energy performance of buildings in the EPC tendering phase becomes relevant for the reliability of the overall contract. Unfortunately, fuzziness and incompleteness often characterize the technical information supporting EPC call for tenders. Furthermore, buildings that are the subjects of EPCs are normally quite complex public buildings (hospitals, schools, etc.) usually relatively old and not technically well known. Gathering information about such buildings is a time consuming and expensive process within the usually short time frame of EPC call for tenders. This paper investigates the application of Grey-Box modelling to the energy performance forecast of complex buildings, in perfectly and poorly informed operational cases. The proposed methodology offers a potential solution to the EPC operational requirements since it requires a substantially reduced parameter set. Results show that the proposed Grey-Box modelling can be used to arrange a calibration set-up with good forecasting performance. Furthermore, Grey-Box modelling allows an effective management of the information uncertainty usually present in the EPC context.

1. Introduction

An Energy Performance Contract (EPC) is a contractual agreement between a beneficiary and an energy service provider (usually an Energy Service Company - ESCO), where budgets are established in relation to a contractually bounded level of energy performance (Directive 2006/32/CE). According to the U.S. Department of Energy (DOE), there are several proven benefits from using EPCs, such as guaranteed improvements, cost savings, and enhanced performance (DOE, 2014). However, the results of the Transparense EPC survey (Garnier, 2013) shows that the application of the EPC concept in daily practice is somewhat difficult. Besides the financial and regulatory barriers witnessed by EU ESCOs, the application of the EPC concept has a technical implication that raises a fundamental issue in the building modelling research. In fact, the overall balance of EPCs substantially depends on the estimation of the building energy performance in real operating conditions. This is a totally new perspective for the procurement phase of an energy contract: the reliable forecast of the building energy performance during the tendering phase becomes essential for the reliability of the overall contract. Unfortunately, fuzziness and incompleteness often characterize the technical information supporting EPC call for tenders. Buildings that are the subjects of EPCs are usually quite complex public buildings (hospitals, schools, etc.) sometime relatively old. Gathering information about such buildings is time consuming and expensive. Furthermore, the time that is usually available from the call for tenders to the submission deadline is quite short; hence, onsite surveys are necessarily limited. Within this scenario, ESCOs can formulate reliable offers, minimizing the risks of a mismatch between forecasted and real costs, only if they are able to model the energy behaviour of the building, thoroughly exploiting the information available in the tendering phase, despite its fuzziness and uncertainty.

New modelling approaches are necessary for this task. Standard detailed building energy models are not suitable. They require a large amount of details, (wall geometry and section details, layouts, etc.), and a lot of human resources. Furthermore, their calibration is a time consuming and brittle process.

To overcome these barriers, this paper investigates the application of the Grey-Box modelling technique, a recent advance in the building energy modelling technology (Bacher and Madsen, 2011; Reynders et al., 2014), to the EPC tendering phase. Grey-box is a reduced-order building modelling technology that estimates the parameters of a reduced-order model of the building thermal behaviour, from sets of measured data. Despite the reduced set of parameters Grey-Box modelling has been proven effective in predicting the building energy performance with good accuracy. This paper proposes an adaptation of the Grey-Box modelling procedure to the EPC context. Since no extended monitoring data sets are usually available in the EPC tendering phases, the Grey-Box model has been configured so that the parameters can be estimated by means of a manual calibration process. The proposed Grey-Box modelling approach has a number of key features that fit well in the EPC framework. First, the reduced model structure is fixed and shared among a wide range of buildings. Second, the detailed building geometry is missing, causing a relevant speed-up of the modelling phase. Third, the building is represented by a reduced set of parameters that can be quite easily estimated in time-limited surveys. Fourth, the remaining modelling uncertainty is concentrated on a very limited set of parameters, and can be reduced thorough a quite simple calibration procedure, based on data set that are usually available to the building managers (e.g., monthly energy bills). Finally, the model size is extremely limited even for large buildings, and the simulation time is consequently negligible.

This paper exemplifies the application of the Grey-Box modelling approach in two case studies, characterized by different levels of knowledge about geometry, technology and systems: a university library located in Terrassa (Spain) and a multi-use building (offices and laboratories) located in Plymouth (England). Details about information processing and the reliability of the forecasted performances are discussed. Section 2 details the case studies. Section 3 discusses the Grey-Box model used in both cases. Section 4 reports about the calibration process and the reliability of the achieved results in the EPC context. A conclusion section summarises the paper achievements and introduces future works.

2. The Case Studies

Two case studies with different information background have been considered in this research.

2.1 The UPC Terrassa Library

The UPC Terrassa library (Fig. 1) is a three-storey building. The ground floor contains shops and the library entrance. The main reading rooms are located in the second and third floor, which contains also some offices and small meeting rooms. The UPC Terrassa Library building is rather well known, since it is regulated by a BEMS system. Detailed energy consumption, monitored occupancy rates and local weather files provide reliable information about external gains and energy consumptions.

Fig. 1 – The south east façade of the UPC Terrassa library building

The building and the systems' main features have been collected through the analysis of technical project drawings. The net floor area is about 754 m^2 and the floor to ceiling height is about 2.70 m. The external walls are made of bricks plus two layers of insulation separated by an air gap. All the external façades have windows and those facing south have aluminum louvre solar shadings. The currently heating and cooling system is the result of renovation works carried out in 2012: it consists of five heat pumps that serve fan coil units. At the second floor, air exchange is supplied by a mechanical ventilation system. Detailed energy consumption and occupancy rate are available through BEMS monitoring.

2.2 The Smeaton Building in Plymouth

The second case study is the Smeaton Building of the Plymouth University Campus located in Plymouth, UK (Fig. 2). In this case we have encountered the typical modelling conditions of a not well-known building.

Fig. 2 – The Smeaton Building in Plymouth, UK

The Smeaton Building is a four-storey building. The net floor area is about 2484 m² and the floor to ceiling height is about 2.90 m. The boundary walls' outside is made of sandwich panels, while the interior surface has concrete blocks with air gap and bricks, finished with plaster. On the ground floor, the sandwich panels of the outside face are missing. The building has single glazing system on the south side, and double-glazing on the north side. Every window has internal shades. Information about the Smeaton building systems was collected by visual inspection. The occupation profile is not monitored and it is different for each room since a lot of teaching rooms are present. Information about the maximum number of people and the teaching hours is available for every teaching room. The energy consumption was estimated from monthly bills that include other two nearby buildings.

2.3 Summary of the Case Studies

Table 1 summarises the main features of the two case studies.

Table 1 – Summary of the case studies' parameter

UPC Terrassa Library	Smeaton Building
Floor area: 797 m² Volume: 9325 m³	Floor area: 2484 m² Volume: 29808 m³
Envelope: brick (0.14 m), expanded polystyrene (0.04 m), air gap, expanded polystyrene (0.04 m), plasterboard (0.025 m) Floor: reinforced concrete, hollow slab (0.4 m) Windows: single and double glazing (U-value 5.6 W/m²K - 2.5 W/(m²K)) with solar shadings	Envelope: aluminium sheet (0.0015 m), mineral wool (0.09 m), aluminium sheet (0.0015 m), concreate blocks (0.3 m), air gap (0.18 m), brick (0.105 m), plaster (0.013 m) Floor: cast concrete (0.1 m), cement screed (0.1 m), linoleum (0.05 m) Windows: single and double glazing
Heating/Cooling: Heat pumps with fan-coil units	Heating: Boiler
Lighting: 17868 W	Lighting: N.A.
Operation: Monday to Friday: 9:00 am – 9:00 pm	Operation: Monday to Friday: 9:00 am – 18:00 pm
Setpoint temperature: winter 21 °C – summer 25 °C	Setpoint temperature: winter 20 °C
Annual electrical energy: 159674.85 kWh (year 2014)	Annual electrical energy: N.A.

Table 2 summarises the knowledge level reached for each class of information. A high knowledge level means reliable information and low uncertainty.

Table 2 – Knowledge level reached for each information class

Information	UPC Terrassa	Smeaton
Climate	High	High
Geometry	High	High
Envelope	Medium	Medium
Systems	Medium	Low
Operation	High	Low
Consumption	High	Low

3. The Grey-Box Model

The same Grey-Box model was used to simulate both buildings. It is made of four main blocks: the building envelope, internal walls and floors; the weather; the heating/cooling system and the internal gains block (see Fig. 3 and Table 3).

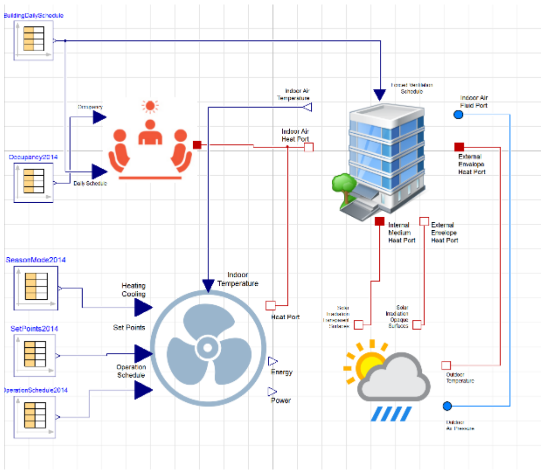

Fig. 3 – The Grey-Box model used to simulate both case studies

A single zone, third order model was used for the envelope and the internal walls and floors (Reynders, 2014). The indoor air volume is represented as a single volume. The building envelope and internal partitions and slabs are represented by means of a couple of lumped thermal resistances and capacities. The model was implemented using the basic thermal and fluid components of the Modelica Standard Library (Fritzson, 2004) in the Dymola simulation environment. No detailed representation of the building geometry is required. Only the overall geometric and physical parameters, like areas, thermal resistance and capacities are necessary. They can be easily and, quite reliably, estimated from design data, if available, or by a brief on-site survey. The weather block calculates the solar gains through the windows and the envelope, and provides the external temperature. Weather data are usually available from the web, and the consequent solar gains can be calculated by standard physics equations. More specifically, the following physics were implemented using the Modelica Buildings Library components (Wetter et al., 2011).

Distribution of room's solar gain - The solar gains per unit area for the room surfaces is calculated by assuming that all solar radiation that enters the room first hits the floor, and that the floor diffusely reflects the radiation to all other surfaces. Multiple reflections are neglected. Area-weighted solar distribution factors are used, instead of view factors between the floor and the other surfaces.

Solar irradiation - Both the direct solar irradiation on a tilted surface and the hemispherical diffuse irradiation are computed using an anisotropic sky model (Perez et al., 1990).

G-value - The reduction of the total solar energy transmittance caused by the external solar protection device is taken into account with a parameter (G-value) calculated according to UNI EN 13363-1.

Heat gain due to air infiltration through windows is represented by a single resistance. This parameter depends on the user behaviour and may significantly affect the overall building thermal performance. Data concerning the infiltration and air exchange rates are available from the regulation (e.g., UNI TS 11300-1:2014). However, to get a reliable figure for the specific case study, this parameter should be estimated indirectly through a calibration process. The thermal gains due to the occupancy are simply modelled by two components multiplied by an occupancy schedule: a fixed thermal source (default 130 W for each person) and a thermal source that corresponds to the fixed equipment gains.

Table 3 – The Grey-Box Model parameter set

Parameter	Availability
Building Volume	Project data and/or surveying
Opaque envelope area divided as per orientation	Project data and/or surveying
Window area divided as per orientation	Project data and/or surveying
Average monthly occupancy level	Monitored or estimated
System operation schedule	Monitored or defined indirectly by interviews or opening data
Indoor temperature set-points	Monitored or defined indirectly by interviews

Outdoor air - envelope coupling resistance	Regulation
Averaged resistance of the opaque envelope	Project data, estimated
Averaged heat capacity of the opaque envelope	Project data, estimated
Thermal resistance between the interior and the interior air	Regulation
Heat capacity for the interior walls and furniture	Project data and surveying
Internal air volume	Project data and surveying
Air infiltration resistance	Regulation
Mass flow rate through forced ventilation	Project data
Weather data file	Available through the web
Solar shading coefficient	Project data and survey
Heat gain per person	Regulation
Heat gain due to fixed equipment and systems	Survey
Thermal resistance between the HVAC system and the interior	Technical data-sheets
Heat capacity for the HVAC system	Technical data-sheets
Efficiency of the HVAC system	Technical data-sheets
Installed heating/cooling power	Technical data-sheets

Monthly occupancy data can be available, as in the Terrassa Library case, or not, as in the Smeaton Building case. If not, they can be quite reliably estimated by interviews, or extrapolated from observation.

Finally, the heating/cooling system is modelled by a simple thermal source, with positive/negative flux respectively, that performs at a given efficiency rate. The indoor temperature setpoint is controlled by a PID. Setpoints are generally known, as in our case studies, since they are explicitly stated in the system operation schedules. The non-linear closed loop control of the fluid temperature is regulated by a second internal PID. The heating/cooling system coupling with the indoor environment is modelled by a resistance and a capacity. These parameters can be estimated from standard technical data, but since they are subject to change during the lifetime of the system they should be fine-tuned through calibration.

Summarising, the proposed Grey-Box building energy model is described by 22 parameters. Among them, 14 parameters can be quite reliably estimated by analysing technical data or through on-site survey, the remaining 8 can be only roughly estimated, hence they should be fine-tuned, starting from standardised values, through calibration.

4. The Calibration Process

The calibration phase is a critical step in standard modelling since it is usually a complex and time-consuming process, dealing with hundreds or even thousands of variables (Coakley et al., 2014). The small number of parameters in the proposed Grey-Box modelling approach makes the calibration phase a manageable process. This is indeed an essential factor for the effective implementation of modelling procedures in the EPC context. When the knowledge level about the building is high, like in the UPC Terrassa Library case, some simple guidelines can be used to converge rapidly to a calibrated solution. When the knowledge level is low, the modeller should assume a paradigm shift. In these cases the standard modelling approach, aimed at building a detailed and trustworthy description of the portion of the reality under investigation, is not feasible. Rather, a new epistemic approach aimed at exploiting the available knowledge and minimizing the negative effects of the uncertainty on the final results should be assumed. In other words, instead of building a detailed picture of the reality, modelling should be aimed at constructing the best possible explanation of the building energy behaviour on the basis of the available data. In this perspective, the calibration process is essentially an explanation forming process, or, from a logical viewpoint, and abductive inference. Initially, information is ranked according to its reliability. Then, since the knowledge is incomplete, some assumptions must necessarily be formulated in order to compensate for the uncertainty. Consequently, the calibration process can be used to verify the plausibility of the assumptions made, within the context of the set of constraints imposed by the known parameters and by the implemented physics. We will exemplify this modelling perspective in the following section.

4.1 The calibration of the UPC Terrassa Library

The UPC Terrassa library is a rather well known building. Uncertainty is low and no critical assumptions must be made to start the calibration process. In this case it is possible to speed up the calibration procedure further by applying simple heuristics to prioritize the selection of the parameters.

The first step of the calibration process is the construction of the baseline. Energy consumption data are usually available through the energy bills. Collected consumption data must be analysed and eventually purged if some deviation from the standard operation schedule occurred (e.g., system breakdown period, malfunctioning, maintenance, etc.). The second step involves ranking the model parameters according to their uncertainty degree. Since the number of parameters is low, the standard ranking based on sensitivity analysis is less strategic than the uncertainty control that is consequent from the uncertainty based ranking. Despite, in principle, the uncertainty degree about a model parameter varies from case to case; usually data concerning the passive surfaces, walls transmittances, air masses and capacities can be estimated rather reliably. Hence, they usually score low uncertainty values. Weather data and solar gains are usually quite reliable as well. On the contrary, occupancy gains, ventilation and some system parameters affected by variation due to ageing, like system efficiency and coupling resistance, are quite fuzzy. Hence they should be adjusted first in the calibration process. All in all, as a general assumption we can use an Occam razor like principle, fixing reliable parameters and limiting the variable parameter sets to the most uncertain.

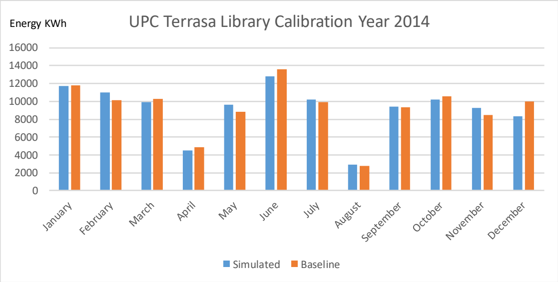

Fig. 4 – The baseline and the calibrated simulation of the UPC Terrassa Library - Year 2014 data set

In the UPC Terrassa Library case, this procedure rapidly converges to a satisfying calibration condition just after two iterations: initially the system efficiency was adjusted to compensate an offset occurring in both seasons; secondly, the ventilation rate was slightly increased to minimize the varying monthly offset. ASHRAE provides NMBE and CV(RMSE) indexes for assessing the model calibration (ASHRAE, 2002). For the UPC Terrassa library case NMBE= -0.65 % and CV-RMSE = 8.00 % was achieved using the 2014 data set. Fig. 4 shows the baseline and the calibrated model simulation of energy consumption for the year 2014.

4.2 The Calibration of the Plymouth Smeaton Building

The knowledge about the Smeaton building was affected by severe uncertainty about the system parameters, the operation, and the energy consumption. Since the building’s heating energy is supplied by a boiler shared with other buildings, very strong assumptions were made to extrapolate the energy baseline and the supplied heating power. No direct metering was available; hence the energy consumption extrapolation was made assuming a proportion between supplied energy and floor surfaces. The occupancy assumption was even weaker, since no monitoring data was available, an average daily occupancy rate, based on observation, was used. Under these uncertainty conditions, the calibration process was used to find a credible parameter arrangement based on the evidences provided by the simulated internal energy dynamic.

Initially, the same heuristic procedure of the previous case was used. Hence, the first iteration involved the set-up of the supplied power and of the system efficiency. The supplied power parameter was increased until the system was able to drive the indoor temperature to the setpoint of 20 °C. Then, in a second iteration, the system efficiency was adjusted to minimize the overall energy consumption offset. These two initial iterations mostly affected the NMBE factor. A third iteration involved the ventilation rate, that was adjusted to compensate mismatches between cold and mid-season months, and occupancy rate. After three iterations, promising NMBE= -1.03% and CV-RMSE = 17.86% were reached. Fig. 5 shows the baseline and the simulated energy consumption for the heating months. Nevertheless, according to (ASHRAE, 2002) the model was not yet calibrated. This is essentially due to the prediction mismatch in May, which amounts to -46 %. There may be multiple reasons of this mismatch. It could have been caused by unknown operational conditions, system maintenance or other totally occasional and unknown factors. But it is unlikely that the mismatch could be the result of a simulation fault. According to the simulation, the low consumption in May was due to favourable climatic conditions. The outdoor temperature rose to about 19 °C for about a couple of weeks. Hence, the indoor temperature was kept close to the setpoint by wall inertia and by solar and occupancy gains, and the system didn't switch on.

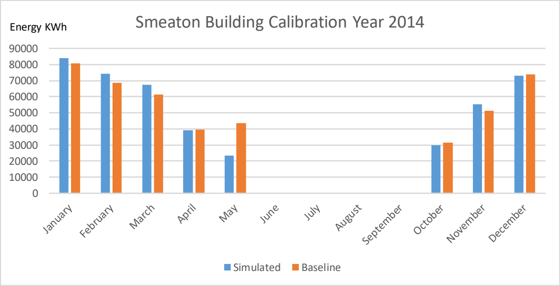

Fig. 5 – The baseline and the simulated energy consumption of the Smeaton Building in Plymouth - Year 2014 data set

Sensitivity analysis shows that neither wall inertia nor solar and occupancy gains can be reasonably adjusted to compensate the energy consumption mismatch registered in May, without corrupting the results of other months. Therefore, the most likely explanation that can be given in this context of uncertainty is that May can be considered an anomaly. If May is cancelled from the calibration data set, the model can be considered calibrated, scoring NMBE= 3.40% and CV-RMSE = 7.06%. Of course the validity of this calibration is bounded by the limits imposed by the discussed assumptions. However, this is the best explanation of the Smeaton building energy dynamics that can be given with the available information. These insights provide the ESCO decision maker an information background that can be used to drive his/her contractual strategies in the EPC contexts, because they combine the estimation of the energy dynamics and of the saving potentials with the analysis of the accompanying uncertainty.

5. Conclusion

A Grey-Box modelling methodology to forecast building energy performance, has been proposed. The paper shows how it can be effectively used to provide decisional support in the EPC tendering phase, when modelling time and costs must be minimised, and when the uncertainty significantly affects the technical and operational knowledge. It has been shown how the proposed method allows the exploitation of all available knowledge by increasing the confidence level on simulation outcomes that are based on uncertain assumptions.

A number of improvements and extensions are still necessary to implement the proposed procedure at an industrial level. The modelling is limited to energy consumption and does not include comfort. Cost benefit analysis concerning multiple zoning has not been carried out. Finally, the overall conceptualization and guidelines must be refined, as well as the uncertainty management approach that is still in its initial formulation stage.

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