Automated commissioning of buildings heating systems by numerical model calibration

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Abstract

This paper presents a commissioning method of building HVAC systems. The method has a sequential and bottom-up approach based on the calibration of white-box models. It is applicable to all buildings and systems and is automated in its realization. In addition, tools are presented: a database for instrumentation plan design and a Modelica library for fast building modelling. Then a case study is presented, which focuses on a hydraulic heating system and makes it possible to locate the components and settings incriminated in the malfunction of the system.

Introduction

According to (Neumannn et al. 2010), a major barrier to market penetration of the commissioning phase is the lack of methods and tools to ensure that advanced HVAC components and systems operate energy-efficiently.

Existing regulations consist in the visual inspection of equipment and their comparison with technical documentation (GSA 2005). Developed methods include the comparison of indicators from simulations with indicators derived from the measurements or fault detection diagnosis. But none of these methods were developed for a full-scale building and a wide range of HVAC systems with the use of white-box models simulation (Katipamula and Brambley 2005).

Moreover, the time allocated for building commissioning is often too short and on-going commissioning is rare. However, the potential economic impact on the energy bill justifies it realization (Mills 2010).

To improve this phase, we propose a new methodology for whole building commissioning based on a bottom-up approach and four nested levels of indicators.

The originality of our approach is to use sensitivity analysis and evolution algorithms for the realization of the commissioning phase and the development of tools for its automatization.

This paper focuses in its first part on the general methodology description: the definition of energy performance indicators. Then we will move on to the overall description of the Modelica library developed for the fast modelling of buildings and of associated systems. Finally, we will discuss sensitivity analysis and evolutionary algorithms, used for calibration. Then a case study performed to validate and illustrate the accuracy of our strategy is presented.

Methodology

Hierarchical structure

A building and its systems can be described as a hierarchical structure of 4 levels, as illustrated in Figure 1. The *components* are at the lowest level: from components of production to components of emission. Between these two types of components, the components of transmission, transformation, storage, monitoring and control, …, are inserted. A *system* is then a set of components. Systems with same goals can be gathered into a *service*, corresponding to the third level. The *building* is at the highest level, including service and envelope. This bottom-up approach is the most used in the commissioning phase because this phase is today mainly focused on components' performance assessment and on initial commissioning.

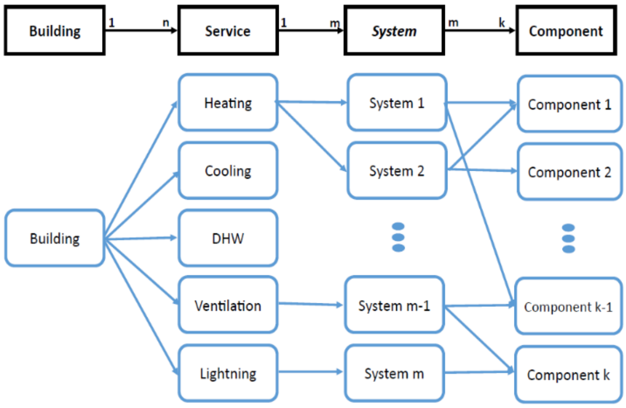

Figure 1. Building's hierarchical structure

The performance assessment of an isolated component is relatively easy to achieve even for a new technology. For the overall commissioning, more attention must be given to the dynamic operation and the interaction between systems and services, because buildings become increasingly integrated. Moreover, when a fault is observed on a component, its seriousness in terms of whole building performance is still difficult to estimate.

It is therefore necessary to carry out the commissioning at all levels of the building's hierarchical structure. To achieve this, a metric was developed in this paper with 4 levels of nested performance indicators, from components indicators for the lowest level, to building indicators level at the highest level.

The nesting of our indicator levels (see the top line of the Figure 1) accounts for the possibility for one component (among "*k*" components) to be shared by "*m*" systems, or

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for *"m"* systems by one service. The relation between component and system indicators is of type *many-to-many* because a component can be part of several systems (a boiler can provide heat for hydraulic heating system and for an air conditioning system) and a system is generally composed of many components. The relation between systems and services is of *type many-to-one* because several systems can be installed for the same application in a building. The relationship *many-to-one* is also applied between service and building.

Each time a component or a system is shared, a coefficient is applied to the upper level of indicators. These coefficients allow the nesting of our different levels and calculating to what extent a component dedicates itself to a system or to what extent a system is dedicated to a service. This structure of indicators allows an easy commissioning phase after the substitution of components or systems. Indeed, it is enough to replace the *Performance* and *Energy* indicators of the substituted parts by the new indicators related to the new components

The bottom-up methodology was retained for this ability to be applied on a low energy building. Indeed, with the opposite "top-down" approach, the impact of a fault on the whole building performance can often vanish due to the large thermal inertia.

Performance indicators

Each level of these indicators allows different lessons to be learned about the operating HVAC installation. The *component indicators* replace the conventional commissioning phase by ensuring energy performance at the lowest level and by the calculation of indicators specific for diagnosis of fault or malfunction (for example, a fan fault detection if outlet air temperature is too high in comparison with the inlet air temperature), as shown in equation 1.

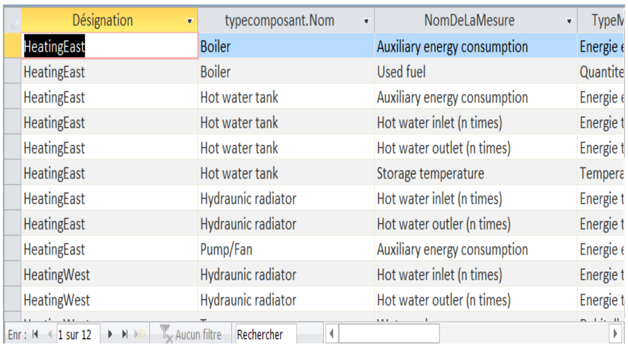
$$P_c = \sum_{k=1}^{n} \dot{m}_{air}^{k}[1.006(T_s - T_r^k) + w_s(2501.6 + 1.805 * T_s)] \quad (1)$$

This *Energy indicator* calculates the heat exchanged by a heating coil with n the number of air inlet, $\dot{m}_{air}^{k}$ the air mass flow rate of each inlet, T_s the supply air temperature, T_r the return air temperature and w_s the absolute humidity of the supply air. These component indicators allow comparison with the documentation as in the current commissioning methods. At system level, the gathered information makes it possible to know the energy performance of each system and to compare it with the regulations. It is also possible to check set-points and Monitoring & command settings. This level of indicator also allows to know the impact of a retrofit action or of a replacement of a system. It also indicates where the improvements must be carried out as a priority.

The *service indicators* present the overall performance of a service and the distribution of different systems. They also make it possible to consider interactions between services, in particular in the event of a fault. The *building indicators* allow to know the interactions between the envelope and the systems and the impact of a fault on the whole performance of the building. Indicators at this level are essentially regulatory indicators and energy performance indicators.

To assist users in carrying out a commissioning phase, a database has been created ,referencing all measurement points required for the assessment of each indicator (Thomare, Rouchier, and Woloszyn 2016). The database is based on the description of the building composition from the component level to the building level as a whole. Once the building is described, the database returns a list of indicators to the user for each hierarchical level in accordance with the building description.

The user is free to select indicators of interest for the commissioning phase, its objectives and budget. Finally, the database interface returns an instrumentation plan in accordance with our method and its goals. The instrumentation plan provides uniform standards of measurement points based on European guidelines (EN15239 2007) (EN15240 2007) (EN15378 2007) without redundancy if different indicators call the same measurement point, as well as formulas for the computation of indicators.



Désignation	typecomposant.Nom	NomDeLaMesure	TypeM
HeatingEast	Boiler	Auxiliary energy consumption	Energie e
HeatingEast	Boiler	Used fuel	Quantite
HeatingEast	Hot water tank	Auxiliary energy consumption	Energie e
HeatingEast	Hot water tank	Hot water inlet (n times)	Energie t
HeatingEast	Hot water tank	Hot water outlet (n times)	Energie t
HeatingEast	Hot water tank	Storage temperature	Tempera
HeatingEast	Hydraulic radiator	Hot water inlet (n times)	Energie t
HeatingEast	Hydraulic radiator	Hot water outler (n times)	Energie t
HeatingEast	Pump/Fan	Auxiliary energy consumption	Energie e
HeatingWest	Hydraulic radiator	Hot water inlet (n times)	Energie t
HeatingWest	Hydraulic radiator	Hot water outler (n times)	Energie t

Enr : 1 sur 12 Aucun filtre Rechercher

Figure 2. Screenshot of an instrumentation plan from the database

Formulas can be used to directly calculate and evaluate energy performances and interactions of HVAC systems present in the building without further downstream approach if the user has the necessary knowledge to assess the relevance of measurement results.

Modelling and calibration

However, a user is not necessarily a specialist of HVAC systems performance and should be further assisted. To automate the commissioning process without using a prior knowledge, a method based on sensitivity analysis and calibration algorithms coupled with white-box models has been developed in the present work. The goal is to automate the detection of performance drops, to characterize interactions and to carry out the commissioning phase on each level.

The process uses the library of components and systems described in the following part to assemble models with the value of parameters following the as-built documentation (boiler nominal powers, exchangers efficiency, characteristic curves of pumps / fans, …). The building *is modelled* including sub-models for services and systems. Each sub-model of component or system can be isolated from the rest of the building for its calibration in order to calculate the interactions between hierarchical levels.

When the modeling of the different components and systems is done, *sensitivity analyses* are carried out to identify the most influential parameters as described in the dedicated part of this paper. For each level of the hierarchical structure of a building, a calibration process is carried out based on our indicators as output. The principle of calibration is to reduce the gap between indicators derived from building measurements and those calculated using models and simulation. This is achieved by finding the optimal value of the set of parameters extracted following the sensitivity analysis. This process enables calculating the deviation of the influential parameters supposed to represent the correct behaviour of the model.

The results of this process can lead to different cases:

- If the gap between the indicators from the models and those measured remains large after calibration, it is either because of a discrepancy in the modelling of the building, or because the envelope and the systems operate at very suboptimal conditions (faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures, ...)
- If the gaps between the indicators have been reduced satisfactorily but the input parameters have varied greatly, it means that the implied components, systems, or services have been poorly commissioned or sized. Thanks to the granularity of our indicators, the location in the building of this dysfunction can be easily localized and its impact measured over the whole building. To know precisely the reason for this malfunction, a targeted inspection on the incriminated part can then be carried out.
- Finally, the most positive case is when the calibration is satisfactory without causing significant variation of the input parameters. This means that the building has been designed and executed with the right set of systems and components and that it operates at near optimal conditions.

The semi-automated Modelica library

(Pang et al. 2012) present the interest of a dynamic and equation-based simulation environment such as Modelica for the whole building performance assessment compared to static simulation environments. As of today, the time of implementation of such models is however still unrealistic to be spread in the industry. To limit this time, our library is a systems-based library that groups together the most common HVAC equipment in buildings.

Our library of systems is dedicated to the commissioning phase and fast building modelling. It was developed using the Modelica *Buildings* library (Wetter, Zuo, and Stephane 2011) and *IDEAS* library (Baetens et al. 2016) as a basis for components and control systems. We named it FBM (Fast Building Modelling) and is freely available on GitHub (https://github.com/locie/comis). The Buildings and Ideas libraries are prerequisites for its operation. Work is in progress so that our library can be used with only prerequisite the Annex 60 library developed within the IEA EBC program (https://github.com/iea-annex60/modelica-annex60).

In our FBM library, systems are grouped in categories of services, according to our hierarchical description of buildings. Within the same service (heating, ventilation, etc.), the different models proposed differ by the number of components for production (Input) and for emission (Output). For a heating system, this would correspond to several component types producing the necessary heat (boiler, solar panel, heat pump, ...) and to the number of emitter types (floor heating, radiators, ...). The number of each type of components is declared independently (several radiators don't have to be declared several times – their number can simply be indicated in a dialog box).

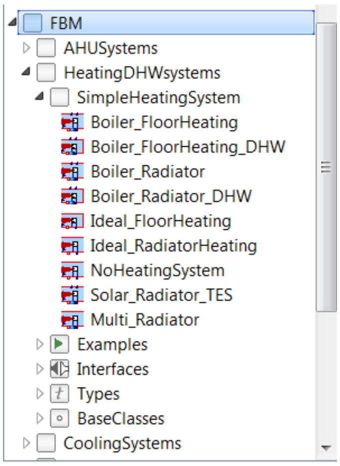


Figure 3. Package structure of the FBM library

The systems can only be composed of active components (for example, a boiler, pumps, valves, and radiators for a heating system) or be detailed with all the distribution networks modelled if the user wishes so. The completeness of the desired model is a dialog box to be filled in. The detailed model allows accounting for all the pressure and heat losses. The choice depends on the modelling aim, but also on the complexity of the system and the available computation power.

The user can also specify the number of thermal zones served by the system. The distribution network will automatically adapt accordingly. For a heating system, this may be several secondary pipes, for a ventilation system, the number of openings.

An example of automatically generated model is shown in Figure 4, where a two-storey building (modelled by two thermal zones) includes two floor heating systems (one by floor) powered by a condensing boiler and a ventilation system with heat recovery. Only the envelope and the exchanges between the thermal zones and the systems need to be added. The only part requiring implementation time is therefore the building envelope. The examples that can currently be consulted in the FBM library use components of the *Buildings* libraries for thermal zone modelling (Buildings.Rooms.MixedAir) but the use of a reduced order model can be considered to further reduce the modelling and simulation time.

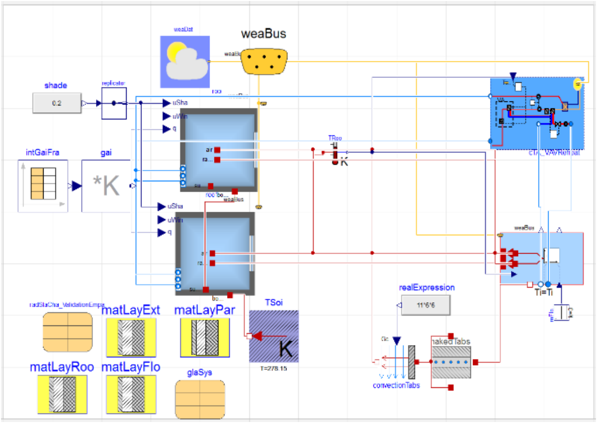


Figure 4. Screenshot from Modelica of a model with floor heating and AHU system

If an equipment is not yet implemented in the library, the templates allowing the creation of a new model and detailed help for their handling are available. Moreover, within the Elementary Blocks sub-package, a collection of the most common hydraulic and air element circuit patterns allows the fast modelling of complex networks.

Moreover, because this library was developed to be used with our commissioning method, the implementation of all sensors and meters necessary for the assessment of each indicator is automatically proposed for the component and system levels.

Calibration process

As previously mentioned, one originality of our approach lies in the coupling of sensitivity algorithms with evolution algorithms for model calibration. It enables calculations of the deviation of influential parameters supposed to represent the correct behaviour of the building.

The large number of parameters needed for a whole building model make the calibration process impossible to carry out in terms of simulation time without upstream work. But thanks to the hierarchical structure defined for our indicators, it is possible to calibrate the hierarchical sub-levels before considering the whole building. Consequently, as a first step, only the parameters of the sub-system need to be calibrated, reducing the number of parameters from several hundreds to a dozen for each level. It is then possible to carry out a sensitivity analysis for each sub-model, and to keep only parameters with a significant contribution to the output for the next steps.

In this aim, after the sensitivity analysis we classify the parameters in decreasing order of their contribution. The number of parameters required to keep at least 80% of the total influence on our indicators is selected. Once the initial set of influential parameters is selected, the calibration process is initiated with values from the 'as-built' documentation. The calibration follows the work-flow shown in Figure 5.

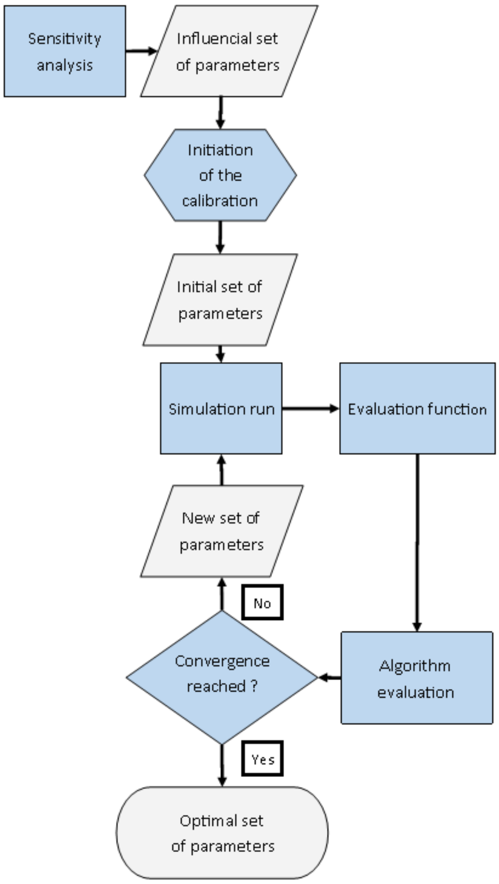


Figure 5. Full calibration process

Algorithms description

First, our method searches for influential parameters using *sensitivity analyses*. Sensitivity analyses quantify the contribution of inputs of a model to the variation of its outputs. (Mara and Tarantola 2008) and (Saltelli 2008) give a broad overview of available methods. One of these methods – the Morris method - particularly caught our attention as it is well adapted for searching influential parameters within large model framework with many parameters.

The Morris method is adapted to models with quantitative inputs and outputs. It is a statistical analysis of the empirical estimates of the partial derivatives (or variations) of model output with respect to each factor. In the case of a computationally expensive model, or model with many factors (several dozens), the method is a simple way of making a first sorting among the factors per their influence. This method is generally only a first step in the sensitivity analysis of a model, but it proves to be sufficient in our approach.

The next step of our method is the *calibration*. The HVAC systems in use within buildings are governed by thermodynamics laws but are possibly highly non-continuous, due to control-induced discontinuities. We therefore had to choose an evolution algorithm able to work in this constraining mathematical environment as discussed in (Coakley, Raftery, and Keane 2014).

CMA-ES (Covariance Matrix Adaptation Evolution Strategy) was chosen as algorithm for calibration. The CMA-ES is an evolutionary algorithm for difficult non-linear non-convex optimization problems in continuous domain (Hansen and Ostermeier 2001). The CMA-ES is considered as state-of-the-art in evolutionary computation and has been adopted as one of the standard tools for continuous optimization in different fields, including building performance simulation (Rouchier et al. 2016).

The CMA-ES is typically applied to unconstrained or bounded constraint optimization problems, and search space dimensions between three and a hundred. The method should be applied, if derivative based methods, e.g. quasi-Newton BFGS or conjugate gradient, fail due to a rugged search landscape (e.g. discontinuities, sharp bends or ridges, noise, local optima, outliers).

The Morris and CMA-ES algorithm are already implemented in *Python* in the *SALib* (Usher and Herman 2016) and *DEAP* (Fortin et al. 2012) packages. Therefore, this scripting language was used as the implementation platform for our method. The call of the simulation software (Dymola) was realized through to the *Buildingspy* package (Wetter 2016), also developed in *Python*. The fitness function of the CMA-ES algorithm is the quadratic deviation between measurements and predictions for each time step of the measurements (in the following example 10 minutes) as presented in Eq 2. A penalty coefficient, as presented in Eq 3. is applied if parameters exceed the parameter definition interval as defined in (Rouchier et al. 2016).

$$fit = \left(\sum_{i=1}^{M} \sum_{j=1}^{N} \frac{(Y(i,j)_{measured} - Y(i,j)_{calculated})^2}{N} \right) + (a * \chi) \quad (2)$$

$$\chi = \left(\frac{\sum_{i=1}^{P} (\rho_i - \rho_0)}{P} \right) \quad (3)$$

With M, the number of indicators, N the number of time steps, Y an indicator, P the number of parameters, “a” the penalty coefficient, ρ the parameter value at the iteration and ρ_0 the centre of the definition interval of the parameter.

Case study

Building and system description

The HELIOS building, located on the Technolac campus, at Le Bourget-du-Lac in Savoy, France, was used as a case study (see figure 6). With a heated area of approximately 6000 m², this building is built on three levels, including offices, meeting and training rooms and several chemical laboratories. The offices, meeting rooms and laboratories are spread over the three main wings East, South and West. These wings with the North wall build the enclosure of the atrium, vast interior space protected by a canopy but unheated.

Figure 6. West facade of the Helios building

The offices overlook the exterior facade of the building while the laboratories are all oriented towards the atrium. The northern facade is dominated by a monumental scoop which supports the solar thermal panels and participates in the natural ventilation of the building. HELIOS building is an energy efficient construction, with implemented several innovative systems (solar heating and cooling, natural ventilation for summer comfort, etc.). An extensive monitoring system is installed as well.

Component and system calibration

The calibrated system detailed in this example is a heating network composed of 38 radiators serving the west and south wings for a total nominal power of 43.5 kW. Coupled with this system is a 3-way valve with a heating curve regulating the inlet temperature of the circuit, a variable-flow pump, and thermostatic valves for each radiator. This system is powered by a solar installation coupled to two wood-fueled boilers. The volumetric flow rate and temperature delivered by these energy sources as well as the weather conditions and indoor temperature were defined as boundary conditions. This allows us to focus on the emitting part of the circuit. The system being quite simple and the calculations time reasonable, the model with high level of completeness was chosen.

Calibration of performance indicators at the component level was only possible for one radiator. Since all the radiators are of the same brand and range, we have assumed that the parameters obtained for one radiator were valid for all the radiators.

The boundary conditions of the radiator are the temperature in the office and the temperature of inlet and outlet of the heating network. We calibrated the set of parameters reported in Table 11 by reducing the difference between the consumption indicator resulting from our model and measurements over a period one month (January 2016).

Table 1. Results of component indicator calibration

Name of parameters	Initial value	Calibrated value
Exponent of heat transfert	1.240	1.280
Nominal heating power (W)	1070	1704
Water inlet temperature at nominal condition (°C)	45.00	52.30
Water oulet temperature at nominal condition (°C)	35.00	44.60
Water volume of a radiator (Liter)	6.200	6.150

Before the calibration, our model under-estimated greatly the energy use. The new set of parameters enabled the error on the energy use to be reduced by a factor of 3, bringing the relative error under 5%. This situation allows us to conclude that the calibration process is effective but that the component or the system operates far from nominal values and is thus badly commissioned.

The parameters of the radiators are interrelated and highly dependent on the system. Thus, calibration of the system level was carried out as the next step, with energy use as performance indicator. Once again, the parameters selection process was carried out, then calibration algorithm was run. Results are shown in Table 2.

Table 2. Results of system indicator calibration

Name of parameters	Initial value	Calibrated value
Nominal supply temperature of the water logic (°C)	45.00	54.91
Nominal return temperature of the water logic (°C)	35.00	35.45
Nominal outdoor temperature of the water logic (°C)	-11.00	-9,73
Water inlet temperature at nominal condition (°C)	45.00	52,11
Set point temperature of the day (°C)	19.00	24.07
Set point temperature of the night (°C)	16.00	18.61
KV of the 3-way valve	80.00	95.49
KV of the thermostatic valves	35.00	48.13

The automated commissioning process for this relatively complex system took two days in total (on a standard computer), without parallel simulations. Similar processes on different case studies have shown that the parallelization of 4 simulations enabled to reduce the computational time by 60%. However, computing time remains significant, especially for applications in on-going commissioning.

Figure 7 shows the energy use in January. It can be seen that the calibration process enabled better representation of measured data (real consumption over the month of 21.7 MWh, consumption of the initial model of 13.1 MWh and consumption of the calibrated model of 18.1 MWh, i.e. a 57% decrease of the difference between simulation and measurement). However, the behavior is quite different over the month. During the first 3 days, both models predict some energy use while there is no measured energy use. Then, during the next 9 days, the measurements are considerably superior to the models. This unpredictable behavior is due to a failure of all heating systems during the first days of the year, causing a sharp fall in the indoor temperature, next compensated by a sudden restart of the systems. The models do not represent the failure: in the predictions the systems operate correctly, maintaining the indoor temperature at adequate level all the time.

During the second half of the month (day 16 to 30) the predictions of the calibrated model are relatively close to the measurement.

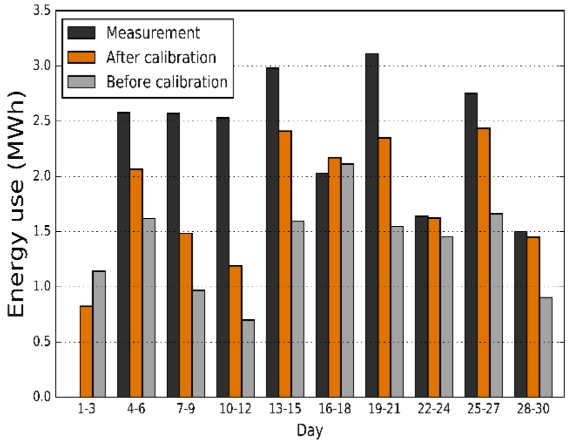


Figure 7. Energy use of the system in January

In order to validate the calibration process, a comparison of the indicator values was carried out during three weeks of February following the calibration phase. The results are shown in Figure 8. Again, over this period, the calibrated model is closer to the measured values (real consumption over the three weeks of 12.69 MWh, consumption of the initial model of 6.79 MWh and consumption of the calibrated model of 12.11 MWh, i.e. calibration process enables a 79% decrease of the error between simulation and measurement). This proves that an isolated failure of the real system (first days of January here) does not necessary invalidate the values obtained during the calibration phase. However, it can degrade the accuracy of the results. Indeed, there is still some discrepancy between the measurements and the simulations reported in Figure 8.

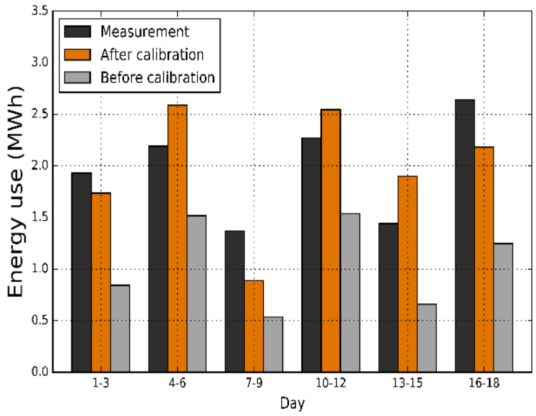


Figure 8. Energy use of the system in February

It is very interesting to compare the 'a priori' parameter values with the values obtained through the calibration process. Some differences between initial values and calibrated values concern the nominal supply temperature of the heating curve (54.9°C instead of 45°C) as well as the nominal outside temperature (-9.7°C instead of -11°C). After verification of the water supply curve on the Energy Management System (EMS), visible in Figure 9, the values (pointed out in Figure 9 by respectively the green dots 1 and 2) found by the calibration process are very close to the actually implemented values (55°C and -10°C). Similar trend is observed for the set-point temperatures (number 3 and 4 in Figure 9). The values found by the calibration process are also confirmed by EMS. However, some residual gap remains (day-time: 24°C for the calibration instead of 23°C implemented and night-time: 18.6°C instead of 19°C).

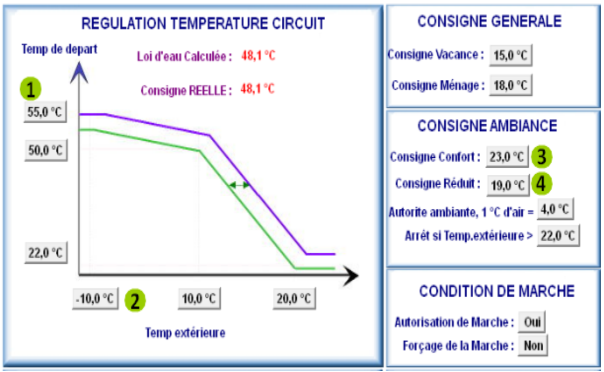


Figure 9. Screen-shot of the EMS soft: Implemented heating curve (in French)

After discussion with the building operator, it was found that these parameters were modified by the building manager because the initial temperature set points were not reached in the building and the occupants discomfort was too high.

Figure 10 shows the water outlet temperature. Even the calibrated model still shows some discrepancies with the measurements. Moreover, the differences are the most important during weekends (days 6, 7, 13 and 14). Indeed, the model cannot somehow translate the behaviour of the building. Some weekends (days 6 and 7) the building seems to be heated and others weekends not (days 13 and 14). After inspection, it turns out that the behaviour of the building is abnormal at the weekend and that neither the as-built documentation nor the operator could explain the current rules of the control during these periods. Consequently, this application of our method allowed us to detect a contradiction between measurement and simulation. Nevertheless, neither the calibration result nor the expertise of the operators has made it possible to provide a reasonable explanation. A possible interpretation of these results is that the system was badly sized and/or the losses were sub-estimated during the design phase. To remove this doubt, future investigations at the service level will allows us to know which system does not produce the expected service share. In addition, calibration at the building level will also teach us if the losses of our envelope are undervalued.

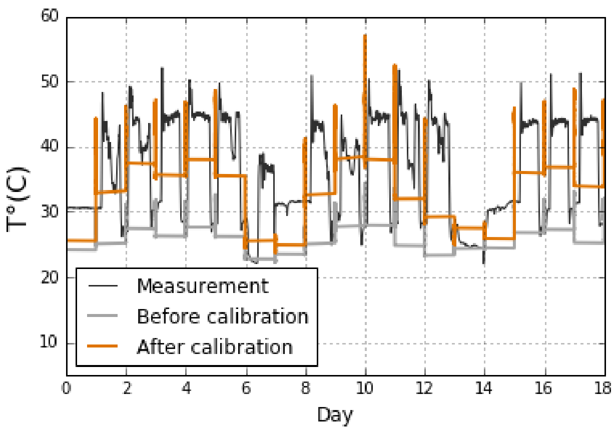


Figure 10. Outlet temperature of the system during 15th first days of February

We can conclude that divergences of parameters found at the component level for the radiators are explained by the modification of the temperature set points at the system levels. Indeed, an increase of the temperature regime in the heating circuit induces an increase of the nominal power of the component.

The difference in temperature between the supply temperature (54.6°C) and the inlet temperature in the radiator (52.6°C) show that the heat losses in the distribution network are about 2°C. The divergence of the K_V coefficient of the three-way and thermostatic valves suggests that pressure losses and the hydraulic resistance of these valves are probably sub-estimated by our model of network. The balancing and thermal insulation of the distribution network are in consequence probably perfectible.

To conclude this case study, all these learnings allowed us to validate our method. It was indeed possible to detect the incorrect commissioning of some systems and the modification of other elements during the building's operation.

Conclusion

A methodology for the commissioning of HVAC systems has been developed. This method aims at being semi-automated, adaptable to different buildings and accounting for interactions between systems.

Two tools were created to support this method. The first one is a database for the automated generation of an instrumentation plan. The second one is a Modelica library for a faster and easier modelling of large energy systems in buildings.

The proposed methodology associates measurements and simulations. In the simulation phase two steps are performed: first step consists in sensitivity analyses enabling determination of the most influential parameters. The second step is the calibration step where an evolutionary algorithm is used to find the adapted values of parameters. It is a comprehensive methodology, which can be performed at four hierarchical levels: component / system / service / building.

A case study was performed on a hydraulic heating system on two levels: component (radiator) and system. The calibration of the influential parameters allowed to determine the new water supply temperature curve implemented a year after the initial commissioning of the building. The determination of the influential parameters and their calibration confirmed to be an appropriate approach to reduce the differences between white-box models and the data obtained from the energy management system. The association of two levels of calibration proved to be particularly useful.

However, some differences remain between measurements and the calibrated model (failure of all HVAC systems at the beginning of year 2016, weekend's behaviour …). In future, complementary investigations will be performed on other hierarchical levels (service and building).

The practical application of the method required thousands of white-box model simulations and raised the issue of computational time. As a solution, a rapid fault detection method is under study. It should be able to highlight the energy performance drifts of the HVAC systems and to limit the number of processes carried out to strict minimum. Error propagation techniques are being studied to solve this problem and will be developed in upcoming work.

Acknowledgements

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References

Baetens, R, R De Coninck, J Van Roy, B Verbruggen, J Driesen, L Helsen, and D Saelens. 2016. IDEAS v0.3.0. https://github.com/open-ideas/IDEAS.

Coakley, D., Raftery P., and Keane M. 2014. A Review of Methods to Match Building Energy Simulation Models to Measured Data. *Renewable and Sustainable Energy Reviews* 37: 123–41. doi:10.1016/j.rser.2014.05.007.

EN15239. 2007. Ventilation for Buildings -Energy Performance of Buildings -Guidelines for Inspection of Ventilation Systems.

EN15240. 2007. CEN - EN 15240 - Ventilation for Buildings - Energy Performance of Buildings - Guidelines for Inspection of Air-Conditioning Systems | Engineering360. *TC* 156.

EN15378. 2007. Heating System in Buildings, Inspection of Boilers and Heating Systems. Bruxelles. https://www.boutique.afnor.org/norme/nf-en-15378/systemes-de-chauffage-dans-les-batiments-inspection-des-chaudieres-et-des-systemes-de-chauffage/article/712564/fa140991.

Fortin, F-A., De Rainville F-M., Gardner M-A., Parizeau M., and Gagné C. 2012. Evolutionary Algorithms Made Easy. *Journal of Machine Learning Research* 13: 2171–75.

GSA. 2005. The Building Commissioning Guide. https://www.wbdg.org/ccb/GSAMAN/buildingcommissioningguide.pdf.

Hansen, N., and Ostermeier A. 2001. Completely Derandomized Self-Adaptation in Evolution Strategies. *In Evolutionary Computation* 9 (2): 159–95.

Katipamula, S., and Brambley M. R. 2005. Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems— A Review, Part II 11 (1).

Mara, T. A., and Tarantola S. 2008. Application of Global Sensitivity Analysis of Model Output to Building Thermal Simulations. *Building Simulation* 1 (4): 290–302. doi:10.1007/s12273-008-8129-5.

Mills, E. 2010. A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions. Lawrence Berkeley National Laboratory. http://cx.lbl.gov/2009-assessment.html.

Neumannn, C, H Yoshida, D Choinière, and N Feretti Milesi. 2010. Annex 47 : Commissioning Tools for Existing and Low Energy Buildings.

Pang, X., Wetter M., Bhattacharya P., and Haves P. 2012. A Framework for Simulation-Based Real-Time Whole Building Performance Assessment. *Building and Environment* 54: 100–108. doi:10.1016/j.buildenv.2012.02.003.

Rouchier, S., Woloszyn M., Kedowide Y., and Béjat. T. 2016. Identification of the Hygrothermal Properties of a Building Envelope Material by the Covariance Matrix Adaptation Evolution Strategy. *Journal of Building Performance Simulation* 9 (1): 101–14.

Saltelli, A. 2008. *Global Sensitivity Analysis : The Primer*. John Wiley.

Thomare, W., Rouchier S., and Woloszyn M. 2016. Génération automatisée de plans d'instrumentation pour le commissionnement des bâtiments. In *IBPSA France*, 1–8. Marne la vallé.

Usher, W, and J. Herman. 2016. SALib -Sensitivity Analysis Library in Python. https://github.com /SALib/SALib.

Wetter, M. 2016. BuildingSpy. http:// simulationresearch.lbl.gov/modelica/buildingspy/.

Wetter, M., Wangda Zuo, and Thierry Stephane. 2011. "Modeling of Heat Transfer in Rooms in the Modelica ' Buildings ' Library." *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney*, 14–16.