# SIMULATION OF SMART BUILDINGS HOMES PILOT SITES

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## ABSTRACT

Within the scope of the HOMES programme, five pilot sites (real buildings) were chosen to study the benefits of active energy efficiency on building energy performance. This article deals with using simulation to assess control functions impact on energy consumption and comfort. Model's data came from audit report, expert knowledge but also from the use of site monitoring. Main goal for this first step was to compare the actual building performance with a similar building equipped with HOMES control solution.

## INTRODUCTION

HOMES (Habitat Optimisé pour la Maitrise de l'Energie et des Services) is a French collaborative innovation programme (2008-2012) involving 13 major industrial and research actors. With a European perimeter of tertiary and residential buildings, both new & existing, the program ambition is to "make the most of each building's energy" thanks to advanced control embedded in largely deployable, affordable technical infrastructures.

An extensive validation protocol was defined based on detailed simulations, test benches and pilot sites (Beguery & al., 2010). Pilot sites are real buildings used by the program to:

- Learn about building actual energy performance measurement.
- Evaluate control functions potential energy gains through simulation analysis.
- Evaluate how monitoring functions may modify occupants' behaviour
- Get insights about simulation tools use for existing building.

This article describes simulations done to evaluate HOMES control solutions impact on five pilot sites.

## HOMES PILOT SITES DESCRIPTION

Five pilot sites were identified. They are all located in France but were chosen to cover, as much as possible, European climate and program targeted market segments.

**Office building**

This site is a part of an office building located near Chambery (mountain/continental climate). Studied zone is a floor including nine office rooms and one meeting room (462 m²). Heating/cooling is done by multi-splits units. Single flow ventilation with relative humidity dependant outlets provides new air.

*Figure 1 - Office building.*

**Primary school**

This one-floor building (900 m²) is located near Grenoble. It includes 5 classrooms, polyvalent space, lunch area and computer room. A gas boiler provides heat through various emitters (radiators, fan coil unit and air handling unit). There is no cooling device and very limited mechanical ventilation. The main challenges with this building are its complex geometry and a highly intermittent use.

*Figure 2 - Primary school building.*

### Hotel, XIX$^{th}$ century building

The third pilot site building is a 2700 m² hotel, built on French Riviera in 1896 (Mediterranean climate). This is a five stories high building, located downtown. The building includes a restaurant, a sauna, a meeting room and a garden with swimming pool. Heating and cooling devices include a gas boiler, cooling roof top unit and several reversible heat pumps. Kitchen and laundry are located in the basement.

*Figure 3 - Hotel building.*

### Residential, collective

The most recent site is a social housing (1500 m²), near Paris (oceanic climate), built in 2010. The building was built under the French regulation RT2005, with THPE EnR label (very high energy performance, with renewable energy production). Heating and cooling is provided through heating floor connected to a reversible heat pump. Domestic hot water is done through a mix of solar collector and electrical heater. There are also 200 m² of photovoltaic panels.

*Figure 4 - Social housing.*

### Hotel, modern building

The last pilot site is a 30 years old hotel, built in Mediterranean climate zone, southwest of France. The hotel is 900 m², with only electrical energy, including electrical zone heaters. Work for this building was postponed and no result will be available until mid 2011.

## BUILDING DATA SOURCES

### Energy audits

For each site, a detailed energy audit was performed in 2010 by CMDL[1]. These documents provide building layout, envelope hypothesis, systems description, invoices analysis and some data measurement achieved through portable measuring devices.

While including a lot of information, audits do not provide all required data. Typically missing data are:

- Building detailed layout,
- Infiltration rate & thermal bridges,
- Systems detailed parameters (only nominal power is available),
- Occupancy pattern and occupant behaviour.

### Preliminary simulations

For two buildings (the school and large hotel), the audits also include simulations performed using Design Builder. These simulations include the 3D model of the whole building, basic occupancy scenario and systems nominal power with scheduled usage to compute the buildings heating needs.

*Figure 5 - Hotel 3D model.*

Furthermore, the school building was used to study the principle of Building Information Model (BIM) for real building modelling (Marconot, 2010). A 3D model was built under Autodesk, then exported in IFC format (Industry Foundation Classes) and imported into IDA-ICE[2]. Several iterations were needed as not all the building elements were correctly exported/imported. Ultimately, we got a complete school model under IDA-ICE software. Comparing Design Builder and IDA-ICE heating needs results show a small error (about 3%), which is

[1] - CMDL SAS, France, http://www.cmdl.fr/
[2] - EQUA, Sweden, http://www.equa-solutions.co.uk/

acceptable knowing that the 3D models were not exactly the same.

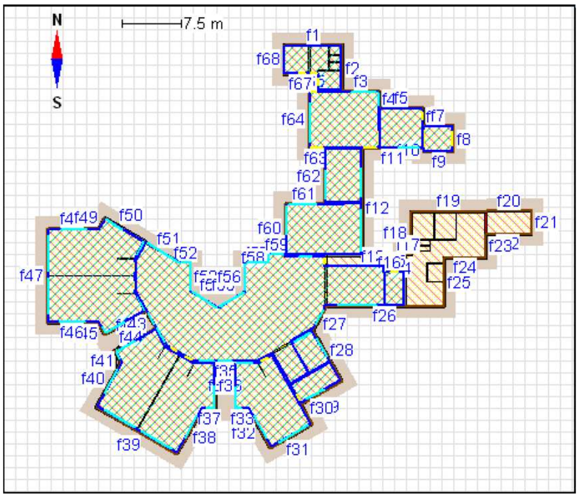


*Figure 6 - IDA-ICE school model.*

### Site Monitoring

Pilot sites were equipped with a complete set of sensors (about 90 to 100 variables measured on each site). These sensors provide energy measurement, occupancy and ambiance data. All data points are recorded with a 10 mn time step and transferred twice a day on a central server.

The instrumentation plan, built to measure the effective energy performance of a building, includes:

1 - Room level measurement:

- comfort data through 4 indicators: temperature, humidity, light and $CO_2$ ratio,
- energy consumed in the room, measured for heating/cooling, domestic hot water (DHW), energy flow lost by ventilation, lighting, Other Usages of Electricity (OUE) e.g. plugs and main other loads.
- occupancy by a presence detector.

2 - Energy used in systems data measurement: electricity, hot water energy for heating/cooling network, energy for DHW system.

3 - Weather station: temperature and humidity, speed and direction of wind, direct and indirect sunlight.

Figure 7 gives an example of water network temperature (°C) in the school building on a typical winter day. A three ways valve controls the water temperature to the classroom. The data clearly shows its daily behaviour, with setback temperature, pre-heating temperature, comfort temperature and frost protection temperature (activated on the last two hours of this given day).

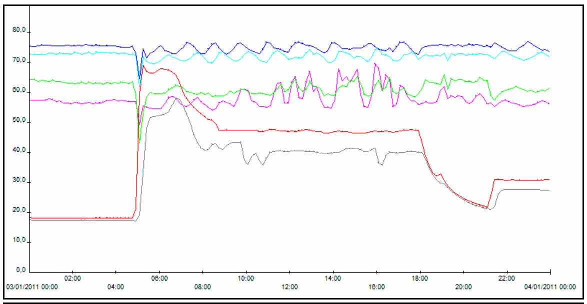

*Figure 7 – Monitoring example: school heating water network temperatures for a typical winter day: boiler input (green) and output (dark blue), common area air handling unit input (cian) and output (magenta), classroom input (red) and output (gray).*

## BUILDING SIMULATION MODELS

### Simulation tool

One of the HOMES targets is to evaluate a large number of control functions for energy efficiency and comfort control. The current project catalogue includes about 150 control functions, from very simple one (switching off the light on schedule) to much more complex one, like model predictive control approach (Lamoudi & al., 2011).

Being able to develop and test easily these control functions was one of the reasons that drove us to choose the Matlab/Simulink platform. The building and systems models are based on an updated version of the CSTB Simbad toolbox (Hussaundee & al., 1997) (Riederer & al., 2002).

Among the new features included in this version is the fact that most of the models are now C-coded. Also all models parameters are now recorded in a global XML file, which open the way to a Building Information Model (BIM) import feature.

### Building envelop and system design

A model of each building was developed based on information from the building audit. For computation reasons, the number of zones has to be kept around 20. Typically, this is done by merging some zones. However, to evaluate control at zone level, we need to consider each zone, especially to take into account real occupancy. So, for the most complex building, we decided to simulate only part of them. At the end, we made the following choices:

- Office: the studied area is one floor simulated with one room by zone.
- School: director tenement (yellow area in Figure 6) and temporary prefab classroom are not considered. Furthermore, some classrooms are merged two by two.
- Hotel: only two floors are simulated. The first floors mostly include desk hall and restaurant, while the second one include 14 bedrooms (one room by zone).

- Social housing: only two 4-rooms flats are simulated.

**System sizing**

In order to simulate heating needs, using site data is the preferred way for model parameters sizing. However, in the detailed building simulation approach used with Simbad, we found that using real data leads to two problems. First, we need many dimension parameters, and most of them are not available from site audit. Moreover, using wrong size might lead to false interpretation when comparing current situation and HOMES proposed control solution. Therefore, we decided to size the system parameters thanks to a sizing tool developed for the Simbad model. This tool tunes some of the systems parameters so that some classical/normative comfort target specifications are met. Tuned parameters typically include electrical power, size of heat exchanger, nominal mass flow …

**Weather data**

Each site has a weather station, but recordings start only at the end of 2010. We will use these data later, when one full year will be available. Meanwhile, we used the nearest Meteonorm weather station.

**Occupancy cycles**

Zone occupancy scenarios used for simulation are most often very simple (typically weekday/week-end pattern, repeated each week). Furthermore, the occupancy ratio model is frequently binary (only no occupancy and nominal occupancy cases are considered). This level of model might be sufficient for heating needs estimation. However, we would like to assess the benefit of automatic control able to take into account real occupancy, and so we need to use as realistic as possible occupancy cycles.
Possible solution for advanced occupancy modelling includes stochastic models like proposed in (Page, 2007). While powerful to generate realistic occupancy scenario, this method relies on a number of parameters that are difficult to set for real building, especially the ones with very different kind of usages.
To tackle this problem we use an alternative approach, taking into account:

- A basic day or week pattern based on occupant interview and monitoring data.
- Special days (typically holidays).
- Stochastic arrival/departure date in main zones.
- Fixed circulation pattern of people from main zone to main zone, based on the random time defined above.

This approach was used for the office and hotel buildings. In the later case, we also include an annual occupancy bedroom profile based on real site reservation book. For the school, a fixed schedule is used instead of stochastic behaviour. The more complex building in terms of occupancy is the social housing one. Work is ongoing to define a detailed stochastic scenario, but for the results presented here, we used a classical occupancy pattern.
Figure 8 analyses the full year occupancy ratio for each building. With a very high no occupancy ratio and no stochastic behaviour, the school building is well positioned for all the control function taking into account the building occupancy.

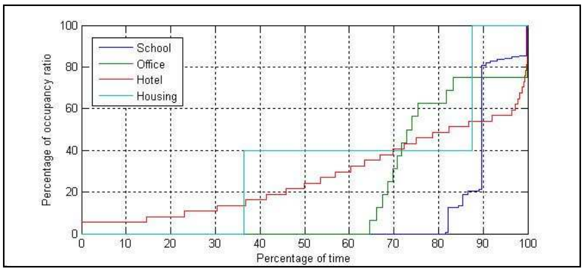


*Figure 8 – Occupancy scenario yearly analysis.*

**Other Usages of Electricity (OUE) cycles**

As for occupancy pattern, using a detailed OUE scenario (instead of a mean constant value) is critical to achieve a good evaluation of our control functions set. Not only OUE contribute to the building electrical and thermal balance, but we can achieve some savings by automatically switching off some electrical loads when not needed. Except in some cases, site monitoring did not give us a lot of information since sensor precision is not sufficient (they provide mean energy consumption, not power patterns). Using available data, we build the following OUE cycles:

- Office: typical computer pattern, and real printer/copier cycle (from measurement). Stand-by component are switched off when building is not occupied.
- School: real cycle (filtered mean weekly pattern) are used for classrooms. The main OUE are located in the kitchen but sensors accuracy is too low for cycle identification. So we use simple pattern built from user inquiry and tune this pattern to get the same mean consumption as measured on site.
- Hotel: OUE are limited in the simulated areas, so we decide not to model them.
- Housing: we use typical loads power cycle and mean energy consumption (most data were found at http://www.curbain.be). Tuning this data with detailed occupancy and site data will be part of the next step.

## CONTROL FUNCTION SIMULATION

In the early 2011 phase of the project, two simulations were performed for each building. The first one is representative of the actual building behaviour (we name it "Before HOMES") while the second one is performed with the control functions proposed by HOMES programme.

**Before HOMES control (actual building)**

Simulation of the existing building requires a mix of basic automatic control and manual behaviour models. Concerning the automatic control (typically for heating/cooling and ventilation systems), some data were available in the audit report. However, getting access to site data through sensors provides much more information and allows detecting a lot of things that were badly estimated during the audit. Examples of such additional information obtained by monitoring include (school building):

- The air handling unit setback controller does not work (constant temperature observed).
- For room equipped with thermostatic hot water radiators, audit mentioned no setback, while in the real building this setback behaviour is observed (achieve thanks to a 3-ways valve control).
- Reference comfort temperatures were considered, from 15 °C to 20 °C depending on the type of zone. Real data provides quite different values, with a 22 °C mean value in all zones.

Considering manual control of lighting and blind systems, we choose a basic human behaviour model:

- Light is switched on when needed (when zone is occupied and natural illumination is below comfort level minus 50 lux).
- Light is switched off when people exit the room.
- On some sites, no light seems to be forgotten for long period of time (school), while on others such behaviour is typical (for the office building, we detect 5% forgotten light, which contribute to made light the first energy consumption part for this site).
- For office and school, blinds are closed when glare is detected in an occupied room. They are opened every morning.
- For residential and hotel, blinds are opened every morning and closed every night.

**HOMES Control Functions**

For this first step of our study, we consider only simple control functions that can easily be embedded in commercial product. Also we do not consider any system changes, except in term of sensors and actuators (for example, we do not replace a boiler by a heat pump, but we consider that we can control emission at room level, even if the required actuators do not exist in the current building).

One exception for the "no system change" rule was made for the school building, for which a single flow ventilation system was added in classrooms.

Most important control features implemented are:

- Taking into account schedule to modify comfort set point and switch off equipment when not needed. For scheduling, we consider the following mode: expected occupancy (with or without occupation detected), short time vacancy (several hours), single day or multiple day vacancy, and a specific night mode for hotel and housing (reduced comfort during occupancy).
- Simple multi-applications zone control which defines, for each scheduled mode, what type of control and set points are used for each zone systems (heating/cooling emitters, blinds, light and ventilation).
- Adaptive optimal start time (control emitters to start heating/cooling zone-by-zone at the right time to achieve temperature target when scheduled occupancy start).
- Blinds are opened when a room is occupied, except in case of glare. When the room is not occupied, blinds position is chosen to optimize thermal contribution.
- The lighting system is controlled to provide just the right level of illumination.
- Ventilation is used to control the $CO_2$ level and provide free cooling in summer.

Schedule and comfort set points are defined by type of zone (we use 1 to 5 zone types per building). Comfort set points were defined as the ones used in the real building simulation. An important exception is the temperature setting: we consider that using a fine, local control with monitoring feedback will help the user accept a lower temperature in winter (respectively higher temperature in summer). Assessing the real impact of active control on comfort set points is not easy. We decided to use a 1°C set point variation between real building and HOMES controlled building, as suggested in chapter 7 of standard EN15232 (CEN, 2007).

## SIMULATION RESULTS

**Exploitation tools**

The simulation of one-year period with one-minute time step provides between 2 or 3 Go of raw data including ambiance, energy and control outputs. Manipulating such raw data is time consuming. Furthermore, it is necessary to enrich information with more explicit integrated criteria.

Performance evaluation and diagnosis were based on several criteria that can be classified into three categories:

1. First are comfort criteria that use ambiance data to provide an estimated level of comfort during occupied period. They are based on three classical perception fields, i.e. thermal, visual comfort and air quality. Comfort evaluation is computed from zone to building granularity.
2. Second are energy indicators that present the energy consumption impact. They evaluate total terminal and primary energy consumption, $CO_2$ equivalent emission and an estimation of financial cost. Energy rates are those from pilot sites bills. This information is available at global building level, but also by type of energy source, by zone and by type of device (see Figure 9).
3. Third set of indicators includes various more advanced post treatments that generate for example aggregated occupancy profiles building thermal signature, thermal balances, natural lighting contribution…

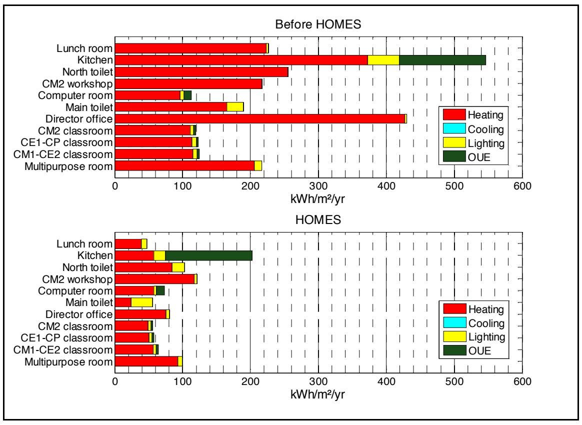

*Figure 9 – Zone-by-zone and appliance-by-appliance analysis of the before HOMES and HOMES simulations for the school building.*

According to each simulation frame and purpose some specific analysis and computation may be manually done. Nevertheless, most of the generic criteria mentioned above are automatically computed and stored at the end of simulation task. The automatic post treatment process is the following:

- Create low resolution data for quicker use.
- Create indicator base (Matlab/Excel).
- Store compressed raw data.

Other tools specifically developed on Matlab/Simulink were necessary to assist user on analysis of simulation results. Several automated graphical treatment were developed and parts of them are used to generate automated *Microsoft Word* reports for validation and/or capitalization.

**Energy efficiency control analysis**

Figure 10 presents a synthesis of results for the eight references simulations (2 types of control for the 4 building models). It is clearly visible that the chosen buildings are quite different, not only at global energy consumption level, but also on how their global consumption is split between the various applications.

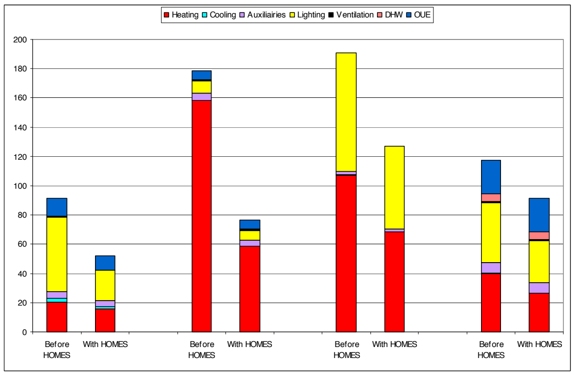

*Figure 10 - Terminal energy consumption, before and with HOMES solution. From left to right, office building (-43%), school building (-57%), hotel building (-33%) and social housing (-22%).*

More detailed analysis can be performed at zone level, to take into account the impact of the granularity of control. In the school case (the most heterogeneous building), energy savings range from 35% to 80%, depending on the room (see Figure 11).

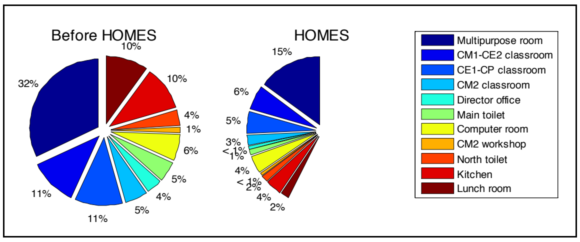

*Figure 11 - Consumption split by zones, for the school building, for the two simulations and the same scale (i.e. empty space on right pie graph represents the global savings).*

Specific site comments:

- Office: lighting consumption reduction allows 75% of the savings. This also explains why the heating savings are limited (as lighting contribution to heating has to be compensated).
- School: on this building, with large windows and nearly all occupancy during daytime, the lighting consumption is limited. On the other side, taking into account detailed schedule and better temperature control allow reducing the heating needs by more than 60%.
- Hotel: energy savings in this building are less important, mostly because the hotel is open all year round. Better results are expected when additional dynamic schedule functions will be implemented for bedroom (taking into account which rooms are not

rented to further reduce their energy consumption).

- Housing: this is the building with the less interesting results, which can also be explained by its high occupancy ratio. In addition, the heating floor reduces the capacity to tune finely thermal comfort to scheduled occupancy.

**Comfort analysis.**

About comfort, we use three instantaneous criteria:

- Thermal comfort: PPD < PPD_max,
- Lighting comfort: LuxLevel > Lux_min,
- Air quality: CO2Level < CO2_max,

with integral yearly criteria based on the percentage of time for which the instantaneous criteria are met, weighted by the number of occupant.

HOMES target was to keep the comfort as much as possible at the same level in both simulations (with or without advanced control). There were two mains exceptions:

- With the added VMC control in classroom, the air quality comfort is improved in the school building.
- Replacing the manual on/off thermal control by an automatic one in the office building allows the system to increase thermal comfort thanks to Optimal Start.

In both cases, improved comfort results in additional energy consumption.

Even if individual instantaneous criteria seems to follow our expectation, the global criteria does not always report this correctly. This is mostly because the comforts set points are define as a constant value for all the year and all building zones. We are currently working on improving this tool by introducing:

- Comfort target by zones.
- Various targets at different time of the day (it is not uncomfortable to have no light when occupant are sleeping).
- Variable level of clothes insulation (clo) depending on building and weather.
- Adaptive thermal comfort.

Other topics of interest might include taking into account the fact that discomfort level depend on the duration for which the discomfort take place.

**Energy costs.**

Yearly costs savings brought by energy consumption reduction were estimated based on site invoices prices parameters. They range from 2.3 €/m² for the social housing building to 4.5 €/m² for the school. These values will have to be compared with the estimated cost of HOMES solution.

## LESSONS LEARNED

After about six months of work on the pilot sites simulation, we got, among others, the following feedbacks.

**Need for BIM interface**

Creating the model of an existing building envelope is time consuming in most energy simulation tools. Furthermore, as most energy code does not have 3D viewer, identifying possible incoherence or error in the building envelope setting is difficult for the person who enters the data, and nearly impossible for other users. Benefits provided by a BIM interface will clearly reduce this pain point. The envelop model should be more easily defined, checked and modified. Furthermore, the CAD model might be used in parallel for other purpose like monitoring interfaces.

In the current version of Simbad, envelope data is entered manually. An IFC based interface will be developed between the CSTB Eve-BIM platform and Simbad.

**HVAC modelling, the right level of detail**

When trying to assess building control functions benefit, we faced the tricky problem of finding the right level of details for system models, and this is specifically true for HVAC simulation. Simbad tool was developed to allow the detailed dynamic simulation of HVAC components behaviour as illustrated in (Riederer, 2003). However, building the required HVAC model is complex (heavy manual design and setting) and the resulting model is delicate to control. Furthermore, we will no longer be able to provide yearly results in a reasonable time.

To speed up the simulation, we chose to simplify the model. The result is partially satisfactory. The simulation time is not so bad (3 to 6 hours for the pilot sites), but the model development complexity is still present without bringing anymore the capacity to evaluate all the HVAC distribution control functions.

In the future steps, we will consider working on a still more simplified HVAC model.

**Modular black-box modelling**

Parts of the building models are open Simulink model, but others are black-box dlls. While this choice might be relevant for commercial applications (simulation speed, robustness, and model confidentiality), it proves to be a constraint, especially as people in charge of the black box models were not in charge of control models development and integration. Using an open software environment is really a critical issue for research and development on simulation models.

**Use of sensor data**

One of the interesting outcomes of this study was the fact that a detailed monitoring based on site sensors is very useful to tune building simulation.

In classical existing building simulation, few parameters are directly available from site documentations and energy audit. A lot of parameters have to be estimated including infiltration, thermal bridges, comfort set points, occupancy cycle, user behaviour and control scheduling. Then, one parameter is used to tune the simulation results with the site energy invoice (for example, isolation thickness). The resulting model provides good global results, but the losses distribution might be misjudged.

Using sensors for site monitoring allows detailed tuning of the building simulation parameters. For example, real site measured infiltration rate seems to be much lower than the one estimated by expert.

Adding all the difference between expert simulation settings and real site data can lead to very different building performance results. For the school building, we started to set the simulation model with data from energy audit simulation (Design Builder model). Then we replaced expert data with available site data (both from sensors and from additional visits). Ultimately, we obtained a 30% reduction of the building heating needs. 5% can be attributed to modification of internal gains hypothesis, while the other 25% result from modification of infiltration rate, occupancy schedule, comfort set points and control scheduling.

So the current trend to add more and more mandatory metering and monitoring in building standard codes will be a great opportunity for more realistic building simulation models.

**Result analysis and diagnostic tools**

Within the timeframe of a research project, where both physical and control models evolved during the study, the need for automated post treatment has emerged. Indeed most of the simulations have to be done several times before complete validation of both control and physical models. Looking only at global integrated result, developer might miss some simulation errors. By giving more chance to detect abnormal model behaviors or erroneous settings, time invested for more detailed post treatment easily turned as a gain. A further step should be to integrate some diagnostic features in those post treatments to automatically point out strange results.

## FURTHER WORK

Making the proof of energy and comfort improvements is a major issue and task for HOMES program. Pilot sites are a great opportunity to combine the challenges of existing building simulation, use of sensors to feed simulators with real data, and evaluation of the benefits of advanced control functions.

Work will continue in the following months with:

- Use of sensor data from the monitoring system to analyse and improve the buildings models.
- Sensitivity analysis on buildings parameters.
- Addition of energy sources management and connection to the Smart Grid.
- Advanced control evaluation.
- 3D model and IDA-ICE simulations for all pilot sites.

## ACKNOWLEDGEMENT

This work is part of HOMES collaborative programme (http://www.homesprogramme.com) funded by OSEO (http://www.oseo.fr).

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