Proceedings of BS2013:
13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28

A BUILDING CONTROL ORIENTED SIMULATION ARCHITECTURE

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ABSTRACT

Poorly functioning and tuned control systems are a frequent source of building underperformance. Simulation can be an excellent method to study building controls, but a number of practical obstacles often interfere. The mapping of control functions—from a physical control system to a simulation model—is often error prone and contains gross simplifications. A major reason for this is that many simulation tools simply do not support modeling of realistic controls. However, even with a simulator that does allow complex controls, the practical mapping of actual to simulator supported control mechanisms is non-trivial, especially when addressing building or zone level supervisory controls typically embedded in building management systems (BMS) or room controllers.

This paper proposes a simulation architecture that will help overcome some of these problems. It attempts to standardize some trivial choices, so that at least these will not lead to unnecessary complications and misunderstandings in this critical and error prone issue. The control concepts are collected from real building controls, and a simulation model that incorporates these is developed to prove the applicability in a whole-building, full-year simulator context.

INTRODUCTION

In a setting of ever increasing building energy efficiency targets, recent studies have shown that the potential of "active," (i.e. control oriented, energy efficiency) solutions on the building stock might be as high as 50%. This is similar to an estimated potential of "passive solutions," i.e. replacement of physical devices or elements of construction (Cottet, 2012). However, to achieve these savings, control will need to be more integrated and complex, which is a trend that will be pushed even further by the future connection of buildings to so called "smart grids.[1]"

Today, standalone equipment controls are the most common. Furthermore, most control strategies are very simple, aiming at keeping constant or scheduled comfort set points. In the near future, control solutions are likely to be more cooperative, sharing information and targets. They will have some learning capacity and apply a predictive strategy (i.e. use available forecasts on price, occupancy and weather to define an optimal strategy over a given time horizon) and/or a reactive strategy (i.e. adapt the predefined strategy to unexpected events) to make the best of building energy storage capacity (Lamoudi, 2012). These advanced control solutions already exist (Dounis, 2009), but their exploitation is prevented by lack of controller interoperability, tools, and expertise of design and implementation teams.

What will be the role of simulation in this evolution? Whole building simulations are increasingly used for design optimization and building certification, but most existing tools are seriously wanting in the area of controls. They consider only standalone equipment control, i.e. each piece of equipment has its private control logic without connection to others, and it is often highly simplified.

This paper proposes development of more realistic control functions in whole-building simulation. In the first part, a general control architecture is proposed, with different supervision layers at the building and zone levels. The second part will describe some typical problems in simulation of multi-applicative supervisory control. The third part will present the implementation of the architecture in a simulation tool, and the fourth part will give examples of its benefit.

BUILDING CONTROL ARCHITECTURE

Some typical building control architectures include:

- All equipment controlled separately (a very common approach in old or small buildings).
- Large buildings with some supervision control embedded in their Building Management System (BMS).

[1] Energy distribution networks that sell energy to the building but also buy locally produced energy, and exchange dynamic information with the building, e.g., demand response signals, production/consumption forecasts, varying energy prices etc.

- Some level of cooperation between equipment in a zone (blinds, heating, cooling, ventilation, lighting). This zone level control can be purely local, or it can be connected to the building level control.
- Finally, in the context of a smart grid connection, the building control is linked to the outside world, exchanging demand and response signals, energy consumption and price profiles.

The French HOMES research program proposed a generic four layer control architecture that merged all of the above (http://www.homesprogramme.com):

- The Service layer is responsible for connecting the building energy management with the outside world (energy providers, weather forecast, cooperative district control, etc.).
- The Building layer manages the global building energy balance (i.e. exchange with the energy provider, transformation and distribution through HVAC systems, and storage), planned occupancy schedules and global set points.
- The Zone layer manages the cooperation of zone equipment to achieve the local comfort requirements, taking into account planned as well as actual occupancy.
- The Equipment layer carries out the local control within each piece of equipment applying the strategy defined by higher layers. The Zone equipment layer will receive targets from the Zone layer, while central HVAC systems equipment will communicate directly with the Building layer.

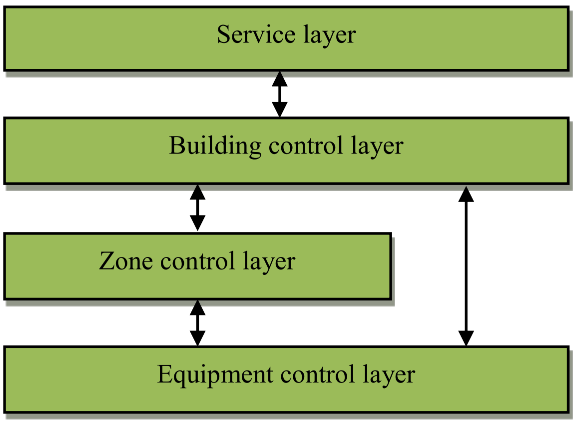

Figure 1 - HOMES control layer architecture.

A similar architecture has been proposed in the recently published German standards on zone control (VDI 3813, 2011) and on building control (VDI 3814, 2008).

Having defined these layers, the next step is to identify which part of the control belongs to which layer and determining the interfaces between the different layers.

Examples of functions that belong to the Building layer are: thermal season management, global comfort set point variation (to adapt to weather), peak load shifting strategies and planned occupancy pattern.

The Zone layer, on the other hand, will manage local planned schedules, occupancy sensors and multi-device optimization (e.g. how the various zone devices work together to achieve the desired comfort level).

The Equipment layer only includes the algorithms needed to apply the strategy and obtain the set points defined by the previous layers.

One of the benefits of this architecture is to separate the supervision layers which reflect a more or less advanced strategy that should, as much as possible, be independent from the choice of equipment. For example, deciding when to apply anti-glare protection can be decided at the Zone layer, independently of the blind type. Then, at the Equipment layer, this functioning mode will be applied in a different way depending on the blind type, e.g. lowering a drape blind based on sun position, darkening electro chromic windows based on façade luminance or positioning the slate of a venetian blind to protect from glare while keeping maximum daylight.

In addition to the proposal of a layered architecture, some of the signals passed between the different layers can also be standardized. Figure 2 shows a selection of such signals, with a proposal for their names. Given the standardized signal names and definitions, a large variation of control properties can be achieved with a minimum number of standard controllers. A user may also define ad hoc controllers and signals. The rule then is that it is an error if a downstream controller requires a signal that the upstream controller does not provide, while a downstream controller may choose to ignore any signal sent to it.

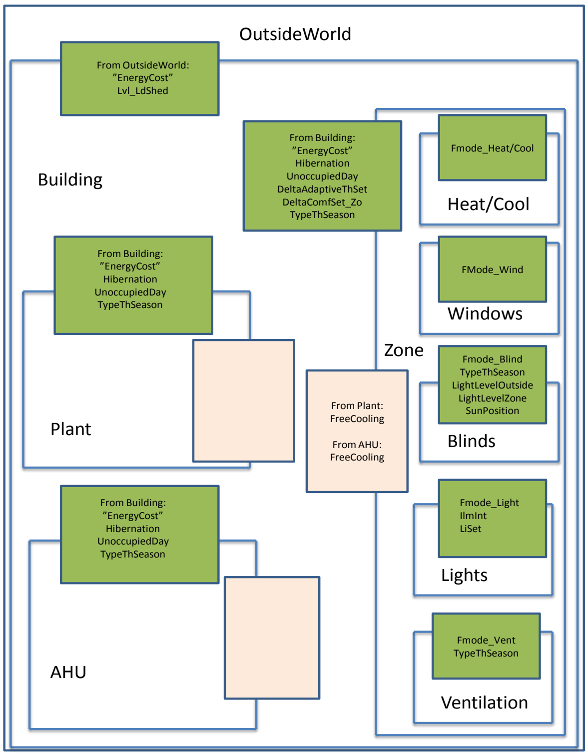

Figure 2 - Standard controller roles and signals.

The following example will illustrate the cooperation between the different control layers. Consider a blind controller that has to achieve the following:

- Blinds are closed when the zone is not supposed to be occupied.
- When the zone is supposed to be occupied but no occupant is detected, the blinds are used to optimize heating/cooling needs.
- Blinds are used for anti-glare protection when occupancy is detected.

Figure 3 describes how this strategy is implemented in a typical autonomous blind controller. The planned occupancy schedule and comfort set points are available to the blind control, and every needed sensor (temperature, illumination, occupancy) is directly connected to the function. The blind controller includes all three functioning modes (heat/cool optimization, closed, glare protection).

On the other hand, in the proposed supervisory control architecture, part of the control will be moved to the Building and Zone layers. Figure 4 shows the resulting architecture. The equipment controller is left applying a given functioning mode with specific set points. The Zone layer multi-appliance management relies on the planned occupancy schedule and occupancy sensor signal to define the functioning mode (for all equipment) and adapted comfort set points. The Zone layer receives additional information from the building layer, like the thermal season (is the building generally being heated and/or cooled?), possible offsets in global comfort set points, or information about a specific day during which the building is closed.

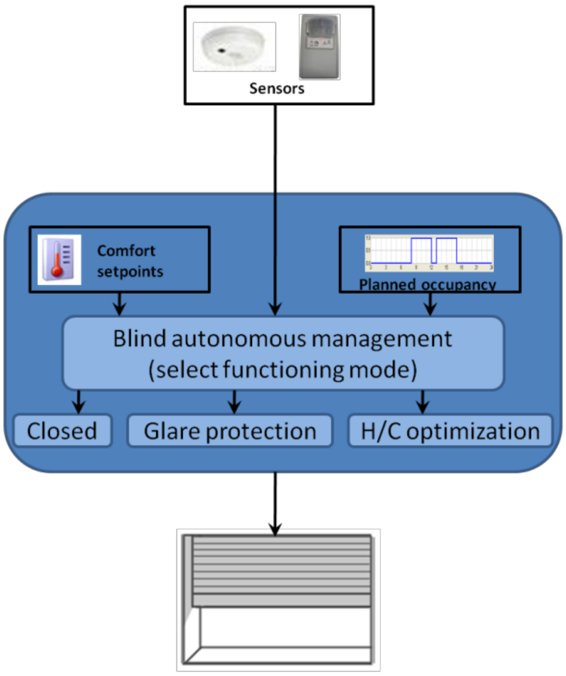

Figure 3 - Typical autonomous blind control.

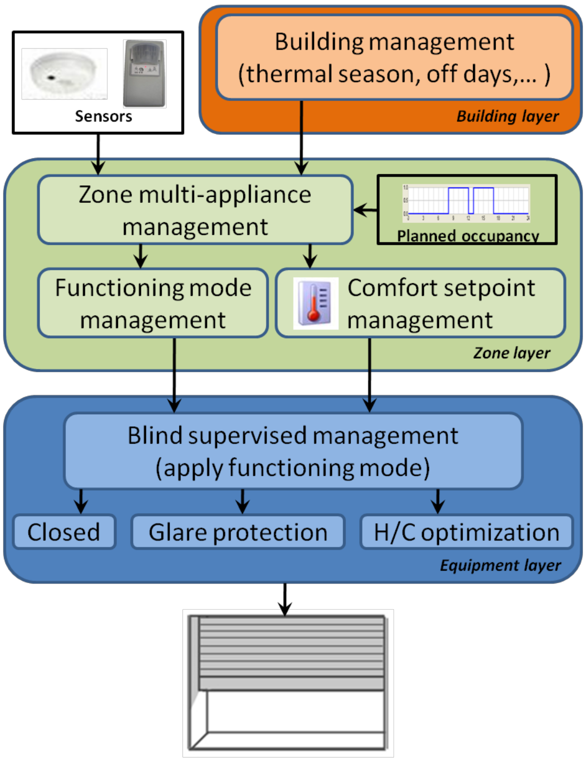

Figure 4 - Supervised blind control.

In the following sections, we will illustrate the proposed methods in more detail. However, first we will discuss some of the needed simulation capabilities.

MODELING WHOLE BUILDING SUPERVISED CONTROL

Tool Selection

We pose two requirements on the selected simulation approach: (1) there must be no limitations on the complexity of applied control schemes, arbitrary multiple input, multiple output (MIMO) controllers must be within scope, and (2) simulation of fully complex buildings, with potentially thousands of zones, must be possible within the time frames (and competence) available in typical design situations.

Traditional building simulators provide some capabilities for HVAC system simulation, often allowing the user to combine a fixed library of component models in the most common configurations. However, since the solution algorithms applied are tailored to specific component configurations, it is not possible to apply general control functions where essentially any control signal may depend on any measurable quantity in the building. Co-simulation, where two or more separate simulators sequentially exchange information during the solution process, is offered with some simulators as an option for the study of more complex systems and controls (Pang, 2012). While co-simulation can be efficient for weakly coupled systems, it is equally inefficient and fragile if the systems indeed depend heavily on each other—which often is the case for a controller and its controlled system.

Research-oriented tools such as TRNSYS, SIMBAD, HVACSIM+ and bare Modelica development environments (www.modelica.org) will fulfill the first criteria but fail the second.

IDA Indoor Climate and Energy (IDA ICE) (www.equa.se/ice) is built on a general equation-based method. It supports NMF as well as Modelica component models and therefore provides the required level of generality. It has proven to be applicable in mainstream projects. However, air-flow network equations are always applied in IDA ICE models, and this poses a practical restriction to about two hundred zones. Currently (version 4.5.1), this prevents very large-scale models from being simulated in IDA ICE.

However, a new method of parallelization is able to overcome these limitations, and in-house simulations of very large-scale models (>2500 zones) have been performed within an acceptable execution time (<4h). Development is currently underway to deploy these methods in a commercial release, which should also fulfill the second criterion.

The Need for an Improved Control GUI

While in a fundamental sense IDA ICE soon will fulfill the requirements, constructing arbitrarily complex control systems has previously required the user to operate on the mathematical level of the user interface. To some degree, this corresponds to the same level of abstraction as work in SimuLink or in a Modelica development tool where individual mathematical modules are interconnected. While sufficient for proof-of-concept work, this is not practical for a very large-scale building model in a real design situation.

To allow a more efficient application of the proposed control architecture, IDA ICE has been extended in a number of ways:

- All equipment (except ideal units) can optionally be controlled by user-defined controllers that are defined on the standard level[2].
- The possibility of adding zone and building level supervisory controllers on the standard level has been added.
- Such controllers may be named and stored in portable libraries.
- A "bus" concept has been developed to send signals from supervisory to downstream controllers and to collect sensor signals from the building.
- The concept of planned occupancy (in contrast to actual occupancy) has been added. A common simplification in building simulation is to omit the separation of planned from actual occupancy. In many real situations the distinction is essential. For example, a corridor may not have any significant occupancy but must still be conditioned.
- A signal from a zone about the time to the next planned occupancy has been added. This is primarily used by optimal start functions that strive to condition the building just in time for planned occupancy.

TEST IMPLEMENTATION

In order to test the proposed control architecture on full-scale projects, part of the list of control functions proposed in the HOMES program has been implemented in IDA ICE as a separate customization add-in. Some details are presented here.

Equipment control layer

A management block has been developed for each type of zone equipment. This handles all functioning modes of the device, including some manual control modes. The following functioning modes have been developed:

- Heating/Cooling emitters: "On" and "Off."

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[2] The GUI where a building is normally described by users that are not immediately concerned with the mathematical details of a model.

- Lighting: "On," "Off," "Manual on," "Forget," and "Constant lighting."
- Ventilation: "On," "Off," "CO_2 control," "Free cooling."
- Blinds: "Closed," "Open," "Glare protection," "H/C optimization," "Manual Residential," "Manual Office," "Standby," and "Anti Light Pollution."

Zone control layer

The most important control mechanism at the Zone layer is to manage the different categories of zone usage, and for each of them to define the comfort set points and equipment functioning modes. The categories (called in the HOMES framework "zone functioning modes") considered are:

- Three functioning modes corresponding to the typical usage of the zone (e.g. corresponding to the planned occupancy schedule):
  - No planned occupancy.
  - Planned occupancy, occupied.
  - Planned occupancy, unoccupied.
- Two functioning modes corresponding to specific days during which the building is not occupied at all. The difference between the two modes is the duration of the closing period:
  - Off days (single or a few days).
  - Hibernate (closed for longer periods).
- A specific functioning mode that will be dynamically defined to restart the building after unoccupied time:
  - Optimal start

Other functioning modes that have not be considered in this first prototype might be added later ("Sleep" for example, a specific occupancy mode for dwellings and hotels).

Except for the "Optimal start" mode (which will be described in more detail in the following section of this paper), all zone functioning modes are simply derived from the planned occupancy schedule, the Hibernate schedule, and the occupancy sensor.

Having defined the zone functioning modes, the equipment functioning modes and the set points for heating and cooling, CO_2 level and illumination are then mapped. This mapping is displayed in the table presented in Figure 7, which allows fast setting of different zone control types. The table is called a Control Strategy Matrix.

Building layer

The Building layer consists of several blocks that govern the behavior of the building as a whole. In the HOMES framework, the following mechanisms are available:

- Heating and cooling set points as a function of outdoor temperature and load shedding level.
- Hibernation mode and signal for thermal season (Heating season, Cooling season, Mid season).
- Building level Optimal start model (which decides, based on building occupancy and set points, whether the whole building should be put in Optimal start mode).
- Controls and set points for air handling units and the plant.

From the Building layer, signals are sent to the building plant/AHU (set points and operation signals), and to the zones (Hibernation, change of heating/cooling/lighting/CO_2 levels as a function of load shedding and outdoor temperature, thermal season information, and building Optimal start information).

The building level Optimal start receives its needed information from the zones by the help of zone sensors which retrieve signals such as: time until next planned occupancy, air temperatures, etc.

ADVANCED CONTROL FUNCTIONS - APPLICATION EXAMPLES

The new facilities can be useful for development and testing of advanced supervisory control functions. In the HOMES framework, a single Control Strategy Matrix prescribes the set points and equipment behavior of different zones. This matrix is then replicated to all zones (or can be set separately for each one), but since the planned occupancy/occupancy/optimal start mode might be different for all zones, the resulting control behavior can be quite complex. As an illustration, consider the example of the implemented zone level optimal start function.

There are many different ways to achieve optimal start. Basically, this block computes the time needed to increase the zone temperature from the setback level to the targeted comfort set point at the time of next occupancy. To achieve this, the function will use:

- The time of the next planned occupancy.
- The heating/cooling set point at next planned occupancy.
- The zone temperature.
- The outdoor temperature.
- The type of thermal season: heating and/or cooling allowed.

The block relies on a few parameters which depend on the building shell quality and on the available heating and cooling capacity. It does the following:

- It checks whether the zone is in No planned occupancy mode. If so, it calculates the heating/cooling set points from the Control Strategy Matrix for the appropriate mode and adjusts these to the Building level control shifts with respect to outdoor temperature and load shedding (calculated at present time; a simplification, but a small one).

- Next, the block calculates if heating or cooling is needed and the time needed to reach this set point from the present time, and compares this with the time remaining to the next planned occupancy. If the time needed is larger than the time to planned occupancy, a signal is sent to the zone controller which will put the zone functioning mode into Optimal start mode. This will create new set points and equipment functioning modes, specifically turning the Heating/Cooling functioning mode On.

Control packages

A first application goal of the new architecture and the HOMES framework has been to develop several typical control packages. For residential and office buildings, three levels of control have been implemented:

- Basic control, meaning constant temperature and manual control of other equipment.
- Building control, representing a typical BMS control strategy with global occupancy schedules used for temperature setback, lighting and ventilation airflow.
- Zone control, demonstrating the most advanced strategy, compliant with the HOMES' recommendations. At this level, each zone relies on local planned occupancy schedules and sensors.

For testing and demonstration purposes, a specific interface was developed (see Figure 8). In this interface, the user can populate a whole building by the default Building and Zone layers macro and default settings of the Control Strategy Matrix for that control package. Only the building dependent parameters will have to be defined by the user (in this case, the planned occupancy schedule, list of holidays and the two parameters of the Optimal start functions).

The zone functioning mode in action

As a small example of the zone level control, one can see the results below in Figure 5 and Figure 6. The simulation case is here a poorly insulated single zone building, run for January. One simulation is run with ventilation and heater always on, blinds always open, and with a constant heating set point of 21 degrees.

In Figure 5, the zone functioning mode is shown for the zone for the date, the 16th of January.

The zone starts out with No planned occupancy (zone functioning mode 3), detects a coming planned occupancy at 06.00, and enters the Optimal start functioning mode (zone functioning mode 4) a short while before the planned occupancy at 06.00.

There is no actual occupancy until 07.00, so the zone enters the Planned occupancy/no occupancy functioning mode (zone functioning mode 2) for an hour, before entering Planned occupancy/Occupied (zone functioning mode 1) at 07.00 when people arrive. At 17.00, people leave and the zone is again in No planned occupancy mode.

Looking at the zone temperatures during this day in Figure 6, one can see that the zone drops down in temperature towards 17 degrees during the night (set point for No planned occupancy mode). The Optimal start pushes it up to 21 degrees (set point for Planned occupancy), which is kept for the whole Planned occupancy, after which it again drops during the night. It would be possible to have a different heating set point for the Planned occupied/Not occupied functioning mode if one wishes, but this is not the case here.

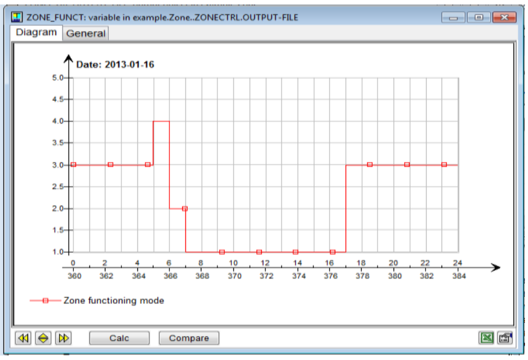

Figure 5 - Zone functioning mode.

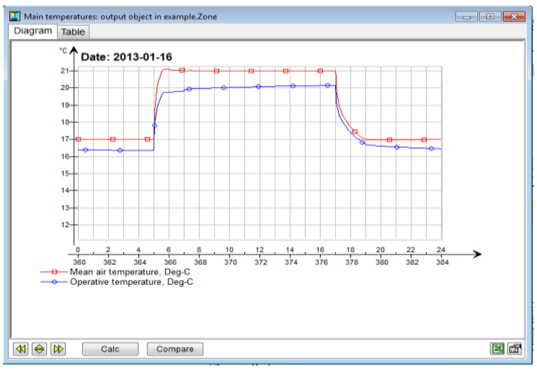

Figure 6 - Zone air temperature.

In a second case, the zone control strategy is set with variable heating set point, ventilation control and blind management. The ventilation is turned off when there is no planned occupancy, and the blinds are closed during the night to preserve heat (at which point, the Heating/Cooling optimization mode is used), leading to much lower energy costs compared to a zone keeping the same 21 degrees throughout the whole day and night (with ventilation on and blinds in the raised position). The heating energy consumption for the zone level control strategy is 32% lower than the non-controlled building in January. Lights and ventilation energy also decrease. This large number is due to the constant ventilation chilling of the room in the reference case to some extent, but even with very little ventilation, there are clear heating energy gains to be had.

CONCLUSIONS AND FURTHER WORK

A control architecture that is applicable both to simulated and physical buildings has been defined and a range of controllers has been implemented to test its practical application. In addition to the examples presented above, practical testing has been done in some full scale cases, and the methods seem to work well.

In addition to the fundamental advantage of being able to experiment off-line with various control solutions, the approach opens up some exciting opportunities:

- Automatic controller deployment. If an automatic translation mechanism is developed, the same source code for simulated and actual controllers could be used. This is likely to increase the quality of deployed control solutions and they may better represent the intentions of the HVAC designer. Such automatic code generation is frequently done for industrial controllers, so the basic technology is already proven and available.
- Reusable libraries of building, zone and device controllers. Both open-source and commercial controllers could be shared and traded, enabling more proficient controls at lower cost.
- Fewer problems with overly "creative" coding. Today, individual control programmers in the field perhaps have too much freedom to solve typical problems in un-standardized and un-tested ways. An approach that is based on proven components on a higher level of abstraction is likely to result in better quality results and easier debugging.

To meet the conservation challenges that inevitably lie ahead, energy conservation measures in existing buildings will be extremely important. Control oriented solutions are often the most attractive, and in many situations they may be the only ones available. In poorly insulated buildings, setback strategies can be very beneficial.

The HOMES control framework has a strong focus on room control; clearly, much more can also be done on the building level. The next steps in this work involve an increased focus on plant and air handling systems.

The authors welcome collaboration with researchers as well as developers in the further work and deployment of this technology.

ACKNOWLEDGEMENT

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

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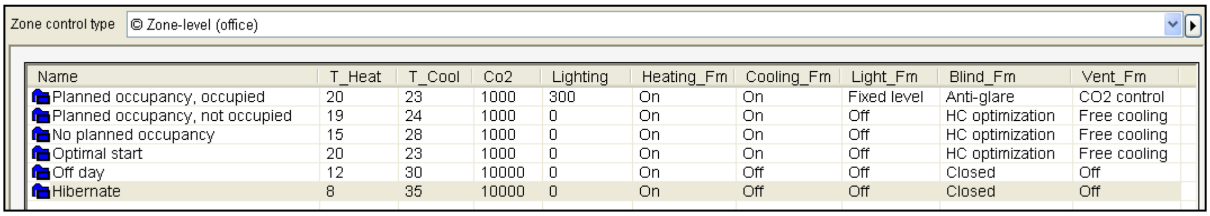
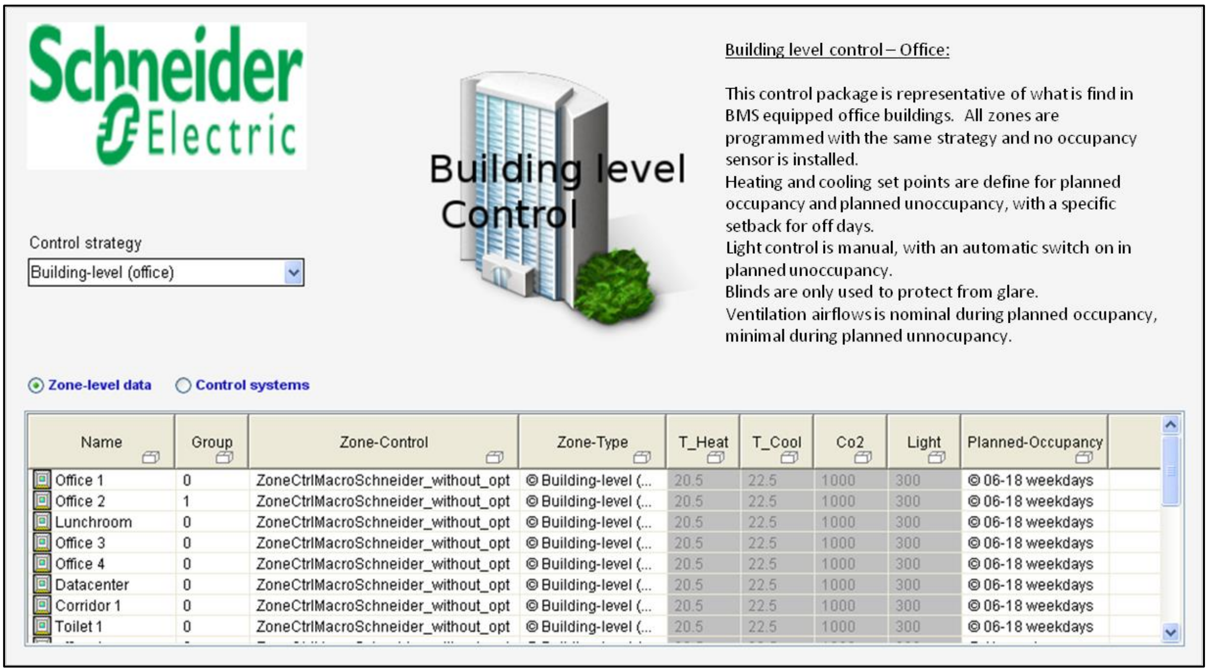


Name	T_Heat	T_Cool	Co2	Lighting	Heating_Fm	Cooling_Fm	Light_Fm	Blind_Fm	Vent_Fm
Planned occupancy, occupied	20	23	1000	300	On	On	Fixed level	Anti-glare	CO2 control
Planned occupancy, not occupied	19	24	1000	0	On	On	Off	HC optimization	Free cooling
No planned occupancy	15	28	1000	0	On	On	Off	HC optimization	Free cooling
Optimal start	20	23	1000	0	On	On	Off	HC optimization	Free cooling
Off day	12	30	10000	0	On	Off	Off	Closed	Off
Hibernate	8	35	10000	0	On	Off	Off	Closed	Off

Figure 7 - Comfort set points and zone equipment functioning mode matrix.



Name	Group	Zone-Control	Zone-Type	T_Heat	T_Cool	Co2	Light	Planned-Occupancy
Office 1	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Office 2	1	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Lunchroom	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Office 3	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Office 4	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Datacenter	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Corridor 1	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays
Toilet 1	0	ZoneCtrlMacroSchneider_without_opt	© Building-level (...	20.5	22.5	1000	300	© 06-18 weekdays

Figure 8 - GUI for quick setting of whole building control strategy.