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GENERATING GLOBAL ENERGY MANAGEMENT STRATEGIES: APPLICATION TO THE CANOPEA BUILDING

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ABSTRACT In this paper, the energy management system that has been developed for the CANOPEA building is detailed. It is based on a virtual representation of the building system including envelope, domestic appliances and technical appliances. The paper presents a core high level language to model building systems and a projection mechanism to generate mixed integer linear programming problems used for the generation of energy management strategies. It has been applied to the generation of energy management strategies for the CANOPEA building system.

INTRODUCTION

The building sector is going to face two main upcoming issues. Firstly, the increasing weight of renewable energies in the power resources requires means to adjust the consumption of the power resources, which are becoming less controllable i.e. it requires means to directly manage or to support occupants and managers during decision making processes. Secondly, decreasing the energy impact of buildings requires on the one hand, more efficient appliances and building envelope, but also, on the other hand, to adjust the configuration of a dwelling system, including configuration of shutters, windows, HVAC system and of other appliances, to the current context related to weather conditions, energy availability and occupant preferences and demands. Therefore, energy management may help to solve the two main upcoming issues.

In the literature, energy management concerns generally specific systems but not a whole dwelling with all the appliances. (John and Smith, 1995) and (Guo and Moncef., tion) propose an optimization strategy for HVAC system based on appliance consumption shifting out of peak consumption periods. It is carried out by exploiting the thermal inertia of buildings. (Guo and Moncef., tion) shows that 10% savings are possible with such a strategy. (Linda et al., 2008) and (Christian and Ion, 2010) propose a temperature control set-point based on a model predictive control algorithm (MPC) but it does not take into account the overall energy efficiency problem. (Eynard, 2010) (Guillaume, 2009) (Gregor and Dodier, 2003) focused on consumption management based on local production capacity. A global model based energy management approach has been proposed in (Ha et al., 2012) but practical validation is still missing.

In (Ha et al., 2012), the management system uses mixed integer linear programming solvers to find best solutions for energy consumption in a dwelling. The input of solver is a problem description in a low level language MILP (for Mixed Integer Linear Programming) according to virtual representation of thermal phenomena and appliance responses to possible controls.

Indeed, from a practical point of view, new issues arise such as how to easily tune model parameters that fit an actual building and how to estimate variables that are difficult to measure. Another issue is to manage the composition of mathematical representations of a complex dwelling that can be used with mixed integer linear programming algorithm for optimization. This paper focuses on the latter point considering the CANOPEA prototype building proposed for the Solar Decathlon Europe 2012 contest by the French Rhône-Alpes team.

Figure 1: Canopea nano-tower principle

The Solar Decathlon Europe 2012 contest is an international competition where 18 teams participate. They have to develop futuristic visions of buildings that integrates new technologies. This paper presents a part of the Rhône-alpes team vision the winner of the contest. It consists on nano-towers bars that can be handled by architects to compose urban islands. Each nano-tower is composed of maximum of ten houses with one house per floor. It mixes between advantages of individual dwellings and collective housing. Houses offers 360 °Cpanoramic vision around, privative space and individual air conditioning system. The nano-towers mutualizes services like common area, washing machine,boiler of central heating system, hybrid and PV panels installed on the roof, electric and thermal storage.For the SDE 2012 contest, only the two last floors corresponding to one dwelling and one common area of the nano-towers built. The resulting prototype named CANOPEA includes individual appliances and common to building appliances. BEMS was developed to manage the appliances and to inform occupant about the interesting actions to be more efficient for the energy usage.

PROBLEM STATEMENT

Model development yields compatibility problems with solver capabilities. Solvers used for simulation are not necessarily the same than the one used for energy management and for parameters identification. Actually, the system needs a high level model description that describes physical phenomena without integrating solver constraints. High level flexible language description is the keystone for the generality.

LANGUAGE REQUIREMENTS

A core high level modeling language is an interface between the model programmer and different applications. The requirements for this core language follow.

non causal language, The first requirement is an a-causal language. This requirement is related to the MILP solver used to generate energy management strategies. Problem formulation is quite simple. It consists in a set of variables and a set of inequality and equality constraints with a given objective. For instance, Matlab/Simulink models cannot be used because they require variables to be either inputs or outputs i.e. causality.

High level language modeling, To model simple dwelling, the formulation can takes over then 15000 constraints. Somme of these constraints are due to mathematical manipulations and temporal projections. The modeler should write only the mathematical equations.

multi-application modeling core language, When designing a model, there is a validation and a tuning process to set up the building system model. The component models are finally used to compute energy management strategies in buildings. A core modeling language has to make it possible to transform core models into application model. These core models should lead to simulatie model for validation by setting up a set of variables as parameters and keeping others as variables to be computed by the solvers. Then, core models should also be reformulated for parameter identification application whose objective is to minimize error between simulated values and actual measurements. For this application, some variables used for simulation have to be considered as parameters and some variables have to be considered as inputs coming from sensors. Another application using models is the preliminary design. It helps designers to evaluate main choices at the beginning of the project design (Chenailler et al., 2010). Transformation into application languages or models should also be possible.

composition mechanism, Most languages offer the possibility of composing basic modeling elements through graphical user interface. This facility should be available for a core multi-application language.

transformation patterns, Transforming a core model into a model for energy management that can be solved by a MILP solver requires some transformations that basically consist in applying linearization patterns. Usual linearization patterns are given in (Ha et al., 2012). They are applied recursively:

- product of n binary variables
- semi-continuous product of a binary variable and a continuous one
- logical implication or equivalence
- minimum or maximum
- linearization of nonlinear function by a stepwise function
- linearization of ordinary differential equations

Therefore, the core language should allow symbolic handling to detect and transform nonlinear expressions.

A prototype of core language has been developed according to the previous requirements. Then, a projector implementing the linearization patterns has been built in order to translate the core models into MILP models. Then, CPLEX or GLPK solvers can be used.

PROBLEM GENERATION AND SOLVING

The scheme presented in figure 2 explains the transformation of a core model written in Algebraic Modeling Language into a mixed integer linear programming problem starting from model composition and ending at the proposition of optimal values for variables. The core model is composed by a set of files: an *AML problem description* that contains model elements with the connections between variables. Each model element is described by a class file *AML component class description* whose parameters are specified in the *AML problem description*. Then, the AML core model is linearized using the linearization patterns (within the linearizer module) and then majorants and minorants in the patterns are reduced to facilitate the problem resolution.

Indeed, linearization may cause problems during the solving process when minorants and majorants are too large: it uses to increase considerably the computational time. The solution for this problem is to tighten the acceptable domain as much as possible.

Finally the problem may be transformed into a mixed integer linear problem. Regarding the contest, the solver was hosted in a datacenter.

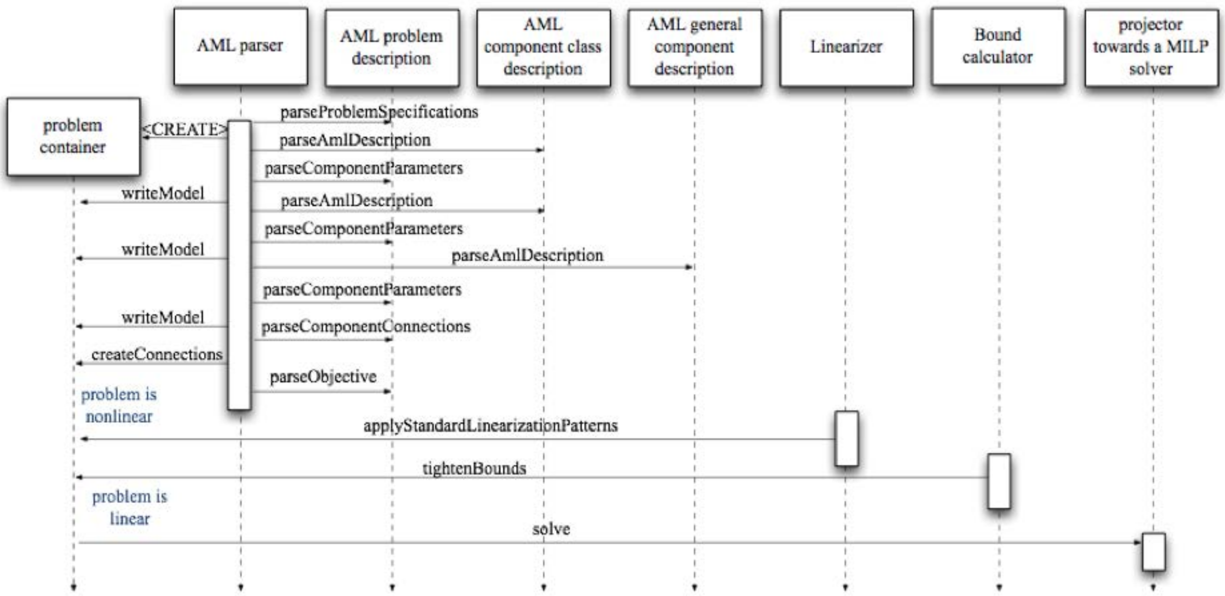

Figure 2: Mechanism of problem generation and resolution

CANOPEA MODEL

Canopea integrates a lot of technical systems. The walls of the envelop are composed of different materials. There are double glass windows and doors. Windows can be obstructed by shutters equipped with electrical actuators but also by blinds made of fabric. Canopea project integrates buffer space around the house. Over architectural considerations, this buffer space creates and maintains fresh temperature, thanks to wind. Buffer isolates home walls from sun radiation by adding another transparent and/or semi-opaque membrane made of glass. In cold periods, this space limits thermal losses if the membrane is completely closed.

Figure 3: Global view of the envelop

Thermal modeling is done considering the whole dwelling as a single thermal zone. The single zone is modeled as a first order differential equation. This representation is not very precise but sufficient for the problem to solve. Indeed, errors related to the prediction of external conditions make precise models not meaningful.

$$T_w(k+1) = F.T_w(k) + G_oT_o(k) + G_i\phi_i(k) + ...$$

$$...G_w\phi_w(k) + G_aT_a$$

$$T_i(k) = H_wT_w(k) + H_oT_o(k) + H_i\phi_i(k)$$

with

$$F = e^{\frac{-\Delta}{\tau}}$$

$$G_o = K_o\tau\,(1-F)$$

$$G_i = K_i\tau\,(1F)$$

$$G_w = K_w\tau\,(1-F)$$

$$G_a = K_a\tau\,(1-F)$$

$$H_w = \frac{R_v}{R_v + R_i}$$

$$H_o = \frac{R_i}{R_v + R_i}$$

$$H_i = \frac{R_iR_v}{R_v + R_i}$$

with : T_o : outdoor temperature
T_i: indoor temperature for the considered thermal zone.
T_w: average temperature of the walls around the room.
T_a: average temperature of the adjacent thermal zones.
ϕ_i: power provided directly inside the thermal zone .
ϕ_w: power provided directly inside the wall.
$R_o; R_i$: equivalent thermal resistances.

R_v : Thermal resistance (deduced from Heat exchanger).
C_w : equivalent wall thermal capacity.
R_a : equivalent thermal resistance defining the power flow exchanged with adjacent rooms.

Appliances Domestic appliances like washing machine are modeled as temporary service (see (Ha et al., 2012)), i.e. a average power consumed during a given time period for which ending time is used to evaluate occupant satisfaction.

Let $\mathbb{K} \equiv [floor(F_{in} - D), ceil(F_{max})]$. In the next, $\forall k$ means $\forall k \in \mathbb{K}$. Let $\forall k, f$ be the ending time of the service with $dom(f) = [F_{min}, F_{max}]$. Let $\forall k, \delta_1(k) \in \{0, 1\}$ satisfying: $\delta_1(k) = 1 \leftrightarrow f \leq k\Delta$. The ending time is before $k\Delta$. Let $\forall k, \delta_2(k) \in \{0, 1\}$ satisfying: $\delta_2(k) = 1 \leftrightarrow f - D \leq k\Delta$.

The starting time is before $k\Delta$.

Let $\forall k, d(k)$ be the service duration during the period k(only if $d(k) \geq 0$).

It can be stated that:

$$\forall k, d(k) = min(f, (k+1)\Delta) - max(f - D, k\Delta)$$

with

$$min(f, (k+1)\Delta) = (k+1)\Delta - ...$$

$$...(k+1)\Delta\delta_1(k+1) + \delta_1(k+1)f$$

and

$$max(f - D, k\Delta) = -D + D\delta_2(k) + ...$$

$$...k\Delta\delta_2(k) + f - \delta_2(k)f$$

Therefore,

$$\forall k, d(k) = D + (k+1)\Delta - (k+1)\Delta\delta_1(k+1)...$$

$$... - D\delta_2(k) - k\Delta\delta_2(k) - f + \delta_1(k+1)f + \delta_2(k)f$$

Energy computation: Let

$$\forall k, \delta_3(k) \in \{0, 1\}$$

satisfying:

$$\delta_3(k) = 1 \leftrightarrow d(k) \geq 0$$

Let $\forall k, E(k) \in [0, P\Delta]$ be the energy consumed during the period k. It can be stated that:

$$E(k) = P\delta_3(k)d(k)$$

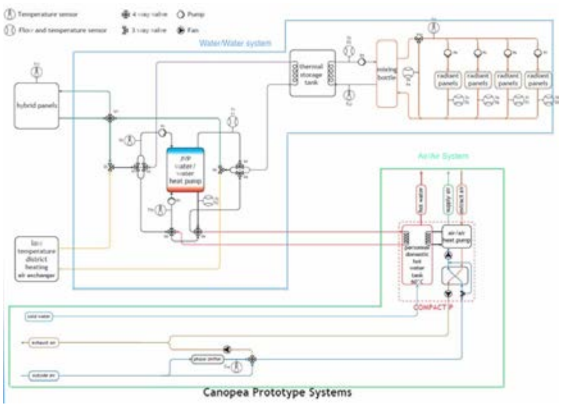

Figure 4: Heating system

Air conditioning system The air conditioning system is composed of a series of fans installed along a network of air transmission. This network begins with a phase-shifter which allows constant air flow to shift the temperature with a 12 hour time delay. This system saves energy when the night is cold and the day is hot. However, in other cases, the system can consume more energy then what is saved. To get delayed temperature when the system needs it, there is a powerful air fan permanently on.

After the phase shifter, there is a three-way valve that allows to the internal system to choose between air coming through phase shifter or external air. After the three-way air valve, the air flow is directed to an air/air heat pump coupled to a static exchanger. The system contributes to recycle the internal ambience while renewing the air. One part of the heat recovered by the air/air heat pump is injected to the domestic hot water tank and the other part is injected in the air of the thermal zone. The system is managed by selecting an operational mode, there are two free-cooling modes, active and passive heating mode and active and passive cooling mode. Model of the system is divided into two parts: the first one concerns heat transfers and the second CO2 concentration.

The thermo-dynamical heat pump is presented to show the approach:

$$\phi_h = \dot{m}_h C_p (T_{out}^{cond} - T_{in}^{cond})$$

$$\phi_c = \dot{m}_c C_p (T_{out}^{evap} - T_{in}^{evap})$$

$$\phi_{elec} = \phi_h + \phi_c$$

$$COP = \frac{\phi_h}{\phi_{elec}}$$

$$\phi_{elec} = \delta * P_{elec}^{compressor}$$

$$T_{in}^{cond} = T_{in}^{outdoor} * HeatMode + T_{in}^{indoor} * CoolMode$$

$$T_{in}^{evap} = T_{in}^{outdoor} * HeatMode + T_{in}^{indoor} * CoolMode$$

$$T_{out}^{evap} = T_{out}^{outdoor} * HeatMode + T_{out}^{indoor} * CoolMode$$

$$T_{out}^{cond} = T_{out}^{outdoor} HeatMode + T_{out}^{indoor} * CoolMode$$

$$HeatMode + CoolMode + OffMode = 1$$

Water circuit The water circuit is an alternative way for temperature adjustment, it is a casing system, bringing water from an external hot water loop, or from hybrid panels. The water loop recovers heat from plants near the building and provides it to the inhabitants. The hybrid panels are located on the roof of the building to pick up the heat from sun or freshness of heaven vault by water casing and photovoltaic cells. The electric energy produced is directly used or sent to the grid or stored into batteries. The thermal energy coming from panels is transferred to an internal circuit of casings embedded into walls, floors and ceilings or to a thermal storage tank. The water coming from outdoor is not the same as the water flowing in the internal circuits. Indeed, there is an isolation done by a water/water heat pump that increase efficiency of the system and control the internal water temperature in the loops. Water/water heat pump send energy to the internal loops through thermal storage tank that yields inertia to the system and the capacity to delay the energy usage from the moment of production. Exchange is carried out by a mixing bottle.
The equations of water/water heat pump are similar to air/air heat pump, only the connections are different but it will be developed in the composition section. The modeling of the system is done through components that describe different parts that compose the system, these parts are: hot water loop, hybrid panel, water/water heat pump, thermal storage, mixing bottle, water casings and three-way valves.

Solar irradiance For modeling purpose, solar irradiance has been modeled according to the geographical localization of the building and the direction of each facade of Canopea. The model takes into account the four seasons of the year where the sun is more or less far from the earth, which influences the thermal and photovoltaic gains. The model takes into account predicted nebulosity over the region were the building is situated and is able to compute direct and diffuse radiation around the building. The predictions concerning radiation are used by other elements, for example, the energy that can be captured by photovoltaic panels, windows or shutters.

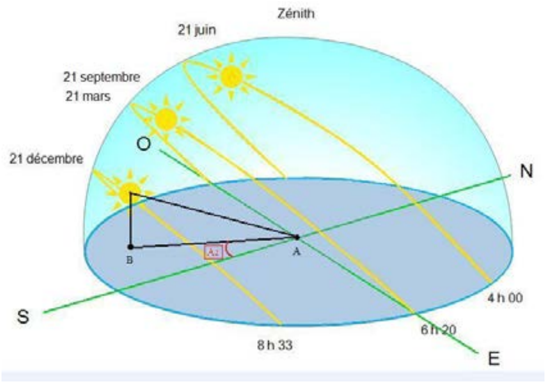

Figure 5: Solar trajectory

Comfort Comfort models quantify services provided by appliance according to the criteria given by occupants. For the ambient temperature,for example, there are a preferred, minimum and maximum acceptable temperatures. Between the preferred and min/-max temperatures, the dissatisfaction increase linearly. When the predicted temperature matches exactly the preferred temperature, the dissatisfaction is equal to zero and when the predicted temperature is extreme the dissatisfaction is maximal and equals to one. It is modeled by:

$$\varsigma(k) = \frac{T_{pref}}{T_{pref} - T_{max}} + \frac{T_{pref}(T_{max} - T_{min})}{(T_{pref} - T_{min})(T_{max} - T_{pref})} * \dots$$

$$\dots * \delta_a(k) + \frac{1}{T_{max} - T_{pref}} T^{felt}(k) + \dots$$

$$+ \dots \frac{T_{max} - T_{min}}{(T_{max} - T_{pref})(T_{min} - T_{pref})} z_a(k)$$

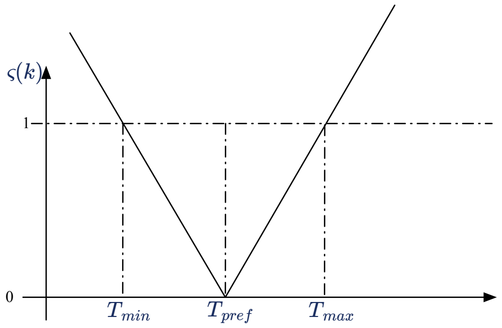

Figure 6: Disatisfaction

Another dissatisfaction model is used for the so-called temporary services. The dissatisfaction is modeled by a rectangular curve. It models the fact that there is no preference regarding the ending time except that it has to belong to a acceptable time interval.

Composition and specifications

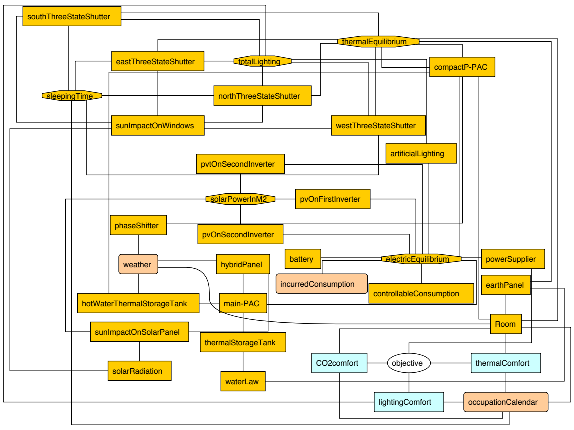

Figure 7: Composition scheme

The composition as shown in figure 7 corresponds to the connections of variables related to different elements modeling the system.

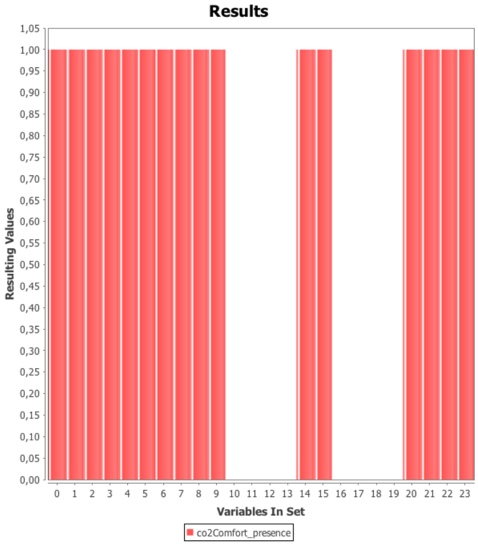

Figure 8: presence

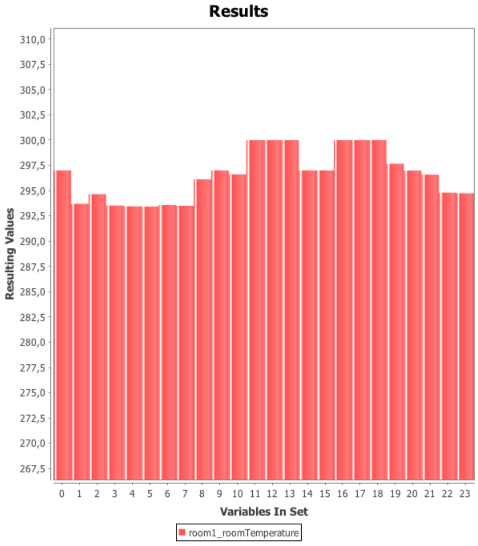

Figure 9: room temperature

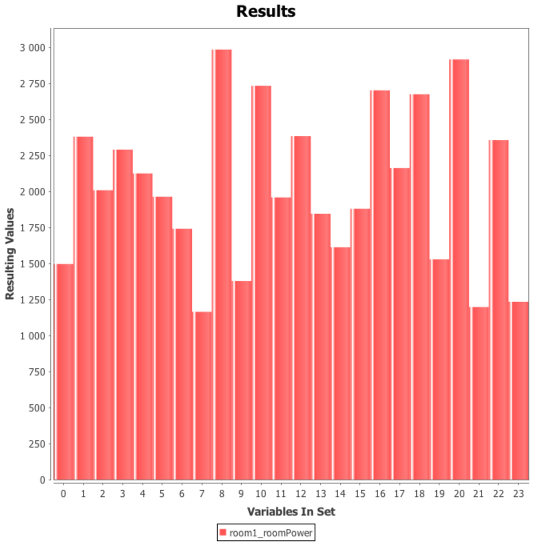

Figure 10: room power absorbed

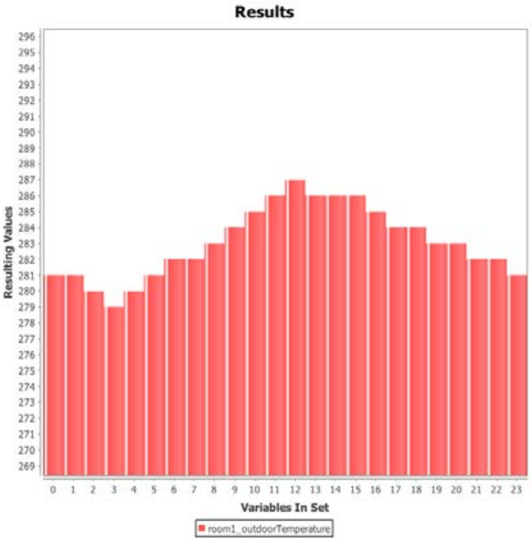

Figure 11: outdoor temperature

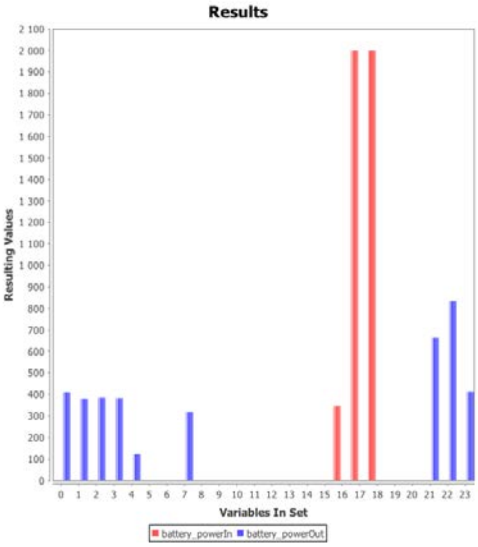

Figure 12: battery charge and discharge

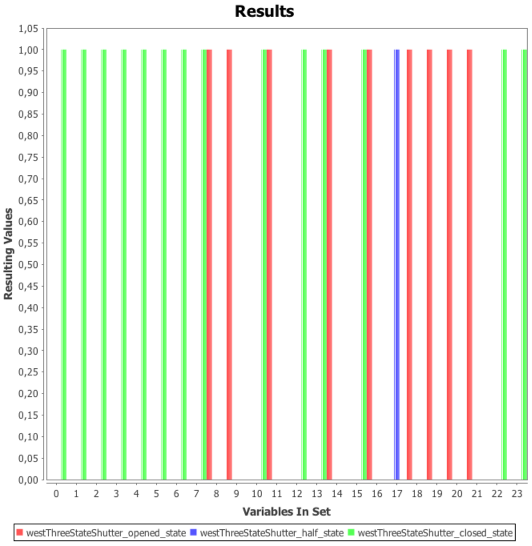

Figure 13: west shutter

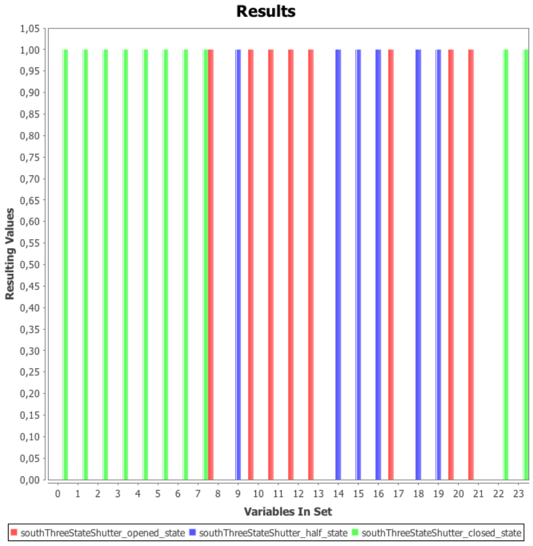

Figure 14: south shutter

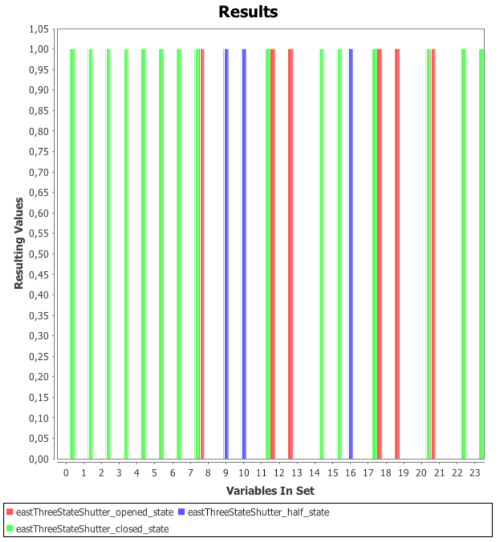

Figure 15: east shutter

The case studied to generate results concerns a sunny and cold day. The external temperature is shown in figure 9. Figure 8 shows the presence in the house during the studied day. Sample time is 1 hour and time horizon for energy strategies is 24 hours. The results presented above are non exhaustive because there is more than 500 variables that are monitored. We focus only on indoor and outdoor temperatures with required heating energy and preferred temperature: 297K. Shutter positions contribute to manage the total heat power provided in the house. A difference between average outdoor temperature and preferred temperature can be observed. This difference induces heating needs. Figures 13, 14, 15 point out the management of the shutters, the behavior of the heating system according to occupancy and external temperature. Thanks to the model developed for Canopea, globally consistent results have been obtained and demonstrate to the jury of the contest. It illustrates that with the proposed approach very complex buildings can be managed. During the contest, a tablet application shows that this management system can be handled easily by people.

CONCLUSION

This paper describes the core mechanisms used to manage the energy within the Canopea building, that got the pole position of the Solar Decathlon Europe 2012 contest. The core modeling prototype language that has been developed is strongly inspired from existing ones but it is extended to multi-application context. For the contest, this language has been projected to mixed integer linear problems according to a proposed process: parsing of the core language, composition of modeling elements, transformation into an application language using linearization patterns and bound calculations. The proposed approach proved to be able to manage very complex buildings because it has been able to handle the global model of the Canopea building, written with the core modeling language.

Some improvements regarding the multi-application modeling language are under study. Indeed, the language proposed for CANOPEA is certainly able to handle simulation and computation of global energy management strategies but it is actually not able to handle parameter estimation problem, which leads to nonlinear optimization problems. New principles are under development: they rely on formal symbolic manipulations of constraints. It will increase the capability of model transformations.

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