OPTIMIZATION OF BUILDING CONTROL STRATEGIES USING DYNAMIC PROGRAMMING
FOR BUILDING SIMULATION 2013 CONFERENCE

ABSTRACT

Being increasingly insulated, new buildings are more and more sensitive to variations of solar and internal gains. Controlling mechanical or natural ventilation often constitutes an efficient solution to maintain indoor comfort during hot periods. The proposed energy management is a predictive set of optimal commands issued from a dynamic programming optimization knowing in advance the weather, occupancy and internal gains for the next 14 days. This method is tested on a bioclimatic house situated in Chambery, France with an annual heating demand of 26 kWh/m². The results issued from the mechanical and natural ventilation controllers are compared.

INTRODUCTION

The main objectives for control systems in buildings are to save energy and increase comfort. During a cold winter period, control systems can be used to decrease the energy consumption of the heating system (Escriva-Escriva, 2010) or to reduce peak demand (Malisani et al. 2011). During a summer period, control systems are also used to reduce the energy consumption of air conditioning or to maintain comfort using passive cooling. Previous studies concerned the control of solar protections (e.g. Nielsen et al. 2011), (Lollini et al. 2010), (Favre et al. 2012), ventilation (Chahwane et al. 2011), and active cooling, (Mathews et al. 2000), (Le et al. 2008). Night ventilation can be used to cool the building structure. The higher the thermal mass, the more the temperature elevation during the day is reduced, corresponding to a passive storage (Braun et al. 2001). The storage and discharge of heat at the right time benefits from a predictive controller able to anticipate the variation of ambient temperature, solar irradiance and internal loads. Many advanced control systems are reviewed in (Dounis et al. 2009). For predictive controllers, a thermal model of the building is required (Oldewurtel et al. 2010), (Morel et al. 2001), (Freire et al. 2008). Due to the time step of this model, a combinatorial optimization is required. Among these methods, the A* (Hart et al. 1968), and the Branch and Bound algorithms (Narendra et al. 1977), need an assumption of the lower or upper bound not available here. Dynamic programming is then chosen because of its exact optimization character. It has served in a building context mainly for winter operation of the heating system (Morel et al. 2001), (Nygard Ferguson 1990). In this publication, a dynamic programming optimization is used to set up a predictive controller knowing in advance ambient temperature, solar gains and internal loads. This controller serves to maintain comfort in the building by controlling mechanical or natural ventilation during two weeks. The first week corresponds to a strong heat wave, the second week is a typical summer week. It is then possible to study the efficiency of natural ventilative cooling compared mechanical ventilation.

MODELS

In this paper, a predictive controller using natural or mechanical ventilation is sudied to maintain thermal comfort in a building. Therefore, we define what kind of comfort is considered, then present the thermal model of the building, the model used to integrate natural ventilation in this thermal model and finally the optimization method.

Adaptive comfort

Comfort is a complex notion. It depends on the direct thermal environment of inhabitants but also on their bodies' metabolism. It is usually defined as the state of mind which expresses satisfaction with a given thermal environment. Among the many parameters influencing thermal comfort, the adaptive approach states that the indoor comfort temperature T_C (°C) depends on the ambient temperature (Humphreys 1995), or its variation over a week (Mc Cartney et al. 2002):

$$T_C = a\ T_{RM} + b \quad (1)$$

with T_{RM} the running mean temperature over a week (°C) and a, b are constants determined experimentally in the Smart Controls and Thermal Comfort project.

For France, the relation is (Mc Cartney et al. 2002):

$$T_C = 0{,}049\, T_{RM} + 22{,}58 \text{ if } T_{RM} \le 10°C \quad (2)$$
$$T_C = 0{,}206\, T_{RM} + 21{,}42 \text{ if } T_{RM} > 10°C$$

with $T_{RMn} = 0{,}8\ T_{RMn-1} + 0{,}2\ T_{MOYn-1}$, T_{MOYn-1} being the daily mean temperature of day n-1 (°C). This definition of thermal comfort assumes that in the

French context air velocity and humidity level have less influence. This comfort temperature is re-calculated every 24 hours so the set point changes each day. The indoor temperature cannot be maintained at this exact value at all time. The Predicted Mean Vote (PMV) (Fanger 1967) approach is partially used, and we consider that the comfort is maintained if:

$$T_C - 2°C < T_{in} < T_C + 2°C \quad (3)$$

T_{in} corresponds to an operative temperature, accounting for air but also wall surfaces because convective and radiative transfer influence comfort.

Thermal model of the building

The building is modeled as zones of homogenous temperature. For each zone, each wall is divided in meshes small enough to also have a homogeneous temperature. There is one more mesh for the air and furniture of the zone. A thermal balance is done on each mesh within the building:

$$C_{mesh}\,\dot{T}_{mesh} = Gains - Losses \quad (4)$$

C_{mesh} being the thermal capacity of the mesh, T_{mesh} its temperature, Gains and Losses including heat transfer by conduction, radiation and convection but also possible internal heating and cooling from equipment and/or appliances, and solar gains.

For each zone, repeating equation (4) for each mesh and adding an output equation leads to the following continuous linear time-invariant system (Peuportier et al. 1990):

$$C\,\dot{T}(t) = A\,T(t) + E\,U(t) \quad (5)$$
$$Y(t) = J\,T(t) + G\,U(t)$$

with

- T mesh temperature vector
- U driving forces vector (climate parameters, heating, etc)
- Y outputs vector (indoor temperatures accounting for air and wall surfaces)
- C diagonal thermal capacity matrix
- A, E, J, G matrices relating temperatures and driving forces vectors

In order to perform simulation, it is important to know the occupancy of the building, which defines the emission of heat by inhabitants and appliances, the thermostat set point influencing the heating/cooling equipment, and possible actions regarding ventilation and solar protection. Another important aspect is the weather model, influencing heat losses and solar gains. All the data of the occupancy and weather models are contained in the driving forces vector U.

A high order linear model is thus constituted. But its state dimension is too large to allow a fast convergence of an optimization algorithm. A modal reduction is then applied in order to lower the state dimension and to make the algorithm faster.

Natural ventilation model

There are many different ways to model airflows in a building depending on the precision required. A nodal model is described in Axley 2001. We choose to use a similar model developed by Trocme 2009, which takes into account stack effect and wind.

The effect of wind on a point at a height z is calculated according to the wind speed v and direction θ. For each wind direction and each façade and roof, a pressure coefficient Cp is defined as follow :

$$Cp_k(z,\theta) = \frac{P_k - P_0(z)}{P_{dyn}} \quad (6)$$

With

$$P_{dyn} = \frac{\rho_0 v^2}{2} \quad (7)$$

- P_k the external pressure at point k
- $P_0(z)$ static external pressure at point k
- v the freestream velocity of the fluid

The calculation of these C_p coefficients is very difficult because boundary conditions data needed to perform CFD calculations are generally not available. An other way to evaluate Cp coefficients is to use a software developed by TNO Building Research (TNO Webapplications). The building is described with its environment and Cp coefficients are provided for each defined point and for different wind directions. For example, the Cp coefficient on a south façade is shown in Figure 1.

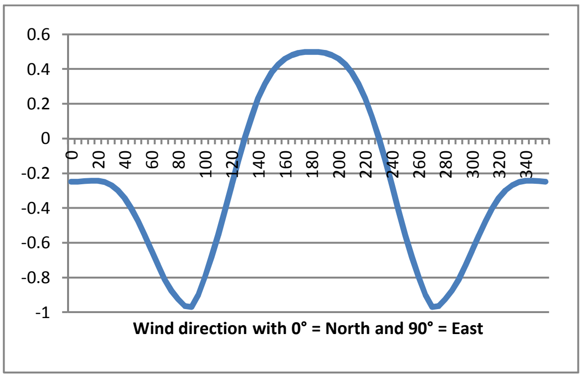

Figure 1 : Cp on the South Facade in terms of wind direction

One can see that for a south façade, the maximum value of the Cp coefficient is for a wind coming from south, and the minimum values are for wind directions perpendicular to the façade.

The effect of wind on the pressure at a height z ($P_w(z)$) is calculated as follows :

$$P_w(z) = C_p(z,\theta)\frac{\rho_0 v^2(z)}{2} \quad (8)$$

The impact of the stack effect on the pressure for an opening at a height *z* is :

$$P_i(z) = P_{i,0} - \rho_i \, g \, z \qquad (9)$$

with

- $P_i(z)$the static pressure in zone *i* at the level *z*
- $P_{i,0}$ reference pressure for zone *i*
- ρ_i the density of air in zone *i*

Air flows are derived using a power law for each opening:

$$\dot{m}_{i\rightarrow j} = C \, \Delta P^n \qquad (10)$$

with

- $\dot{m}_{i\rightarrow j}$ the air flow from zone i to zone j
- *ΔP* the pressure difference between the two sides of an opening
- *C* ,*n* coefficients characterizing the opening (accounting for geometry and area of the opening)

Conservation of mass is then applied in each zone of the building, which leads to the following mass balance:

$$\sum_j \dot{m}_{i\rightarrow j} = 0 \qquad (11)$$

The problem is now reduced to *n* non-linear equations, the variable to calculate being the indoor pressure vector P = {P_1, P_2, …, P_n}, with *n* the number of zones. A Newton-Raphson method is applied using the external pressures around the envelope of the building as boundary conditions.

Once all airflows are calculated, the corresponding heat transfer over a timestep is calculated for each zone.

Therefore, the data needed for this model are the ambient temperature, the wind speed and direction at each timestep, the pressure coefficients C_p and the characteristics of the openings *C* and *n*.

Optimization algorithm

The dynamic programming algorithm is a sequential optimization method which provides an optimal set of commands over a period. A state variable describing as well as possible the system is discretised temporally:

$$x(t) = x_t \in X_t , X_t \subset R^{Ne} \qquad (12)$$

with X_t the set of possible states, *Ne* the dimension of X_t. There is also a control vector with *Nc* dimension:

$$u(t) = u_t \in U_t , U_t \subset R^{Nc} \qquad (13)$$

with *Ut* the set of possible controls. The state equation at each time step *t* is then:

$$x(t) = x_t , x(t+1) = f(x(t), u(t), t) \qquad (14)$$

We now define a value function v_t which is the cost to go from *x(t)* to *x(t+1)* :

$$v_t(x_t, x_{t+1}), x_{t+1} \in \mathrm{T}_t(x_t) \qquad (15)$$

T_t being the set of possible state variables at time *t*. The cost function is then the sum of all value functions at each time step:

$$V_0^t = \sum_{j=0}^{t-1} v_j(x_j, x_{j+1}) \qquad (16)$$

The optimization seeks to maximize the following objective function over *N* time steps corresponding to the period from 0 to t:

$$J = Max[V_0^N] \qquad (17)$$

This equation gives us a set of controls to go from x_0 to x_t. Bellman's principle of optimality is applied to accelerate this optimization by breaking this decision problem into smaller sub-problems (Bellman 1957):

"An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

Equation (17) becomes then:

$$J = Max[V_0^N] = Max[v_0(x_0, x_1) + Max[V_1^N]] \qquad (18)$$

To summarize, we have to find a set of commands U_N = (u_0, u_1, … , u_N) maximizing (18) for a system described by (14) with constraints on state variables (12) and on controls (13).

CASE STUDY

In this part, the building studied is described as well as the optimization parameters used for this study.

Building description

The building under study is a French single-family house, similar to an experimental passive house part of INCAS platform built in Bourget du Lac, France. The envelope and systems of the house correspond to a standard house according to the last French thermal regulation. The house has two storeys and a total living floor area of 89 m². 34% of its south facade area is glazed while the north facade has only two small windows. All windows are double glazed except on the north façade equipped with triple glazing. The south facade also includes solar protection for the summer period. The external walls are made of a 30 cm-thick layer of concrete blocks and the floor is composed of 20 cm reinforced concrete. The insulation is composed of 30 cm of glass-wool in the attic, 15 cm in external walls and 20 cm of polystyrene in the floor. According to thermal simulation results using the thermal model described in the Models part, the heating load is 26 kWh/(m².year) which is typical for new houses.

Figure 2 : view of the house(west and south facade)

Optimization parameters

The chosen state variable is the total energy *E* stored in the building calculated as follows:

$$E = \sum_{i=1}^{nbr\_meshes} E_i = \sum_{i=1}^{nbr\_meshes} C_i\, T_i \tag{19}$$

with E_i the energy stored in mesh i, C_i the thermal capacity of the mesh *i*, and T_i the temperature of the mesh *i*. An upper and lower bound of this state variable is defined according to its initial value. Then it is discretised in 200 parts.

The model of the building is mono-zonal, there is only one control for the whole building. It entails that in the case of natural ventilation, the percentage of opening is the same for all windows.

The optimization is done over 14 days: a very hot week (Figure 3) for a worst case scenario and a typical summer week (Figure 4). Wind speed and direction data corresponding to Greater Paris Area are also used. The simulation includes also a two weeks initialization period.

The occupancy of the building corresponds to a typical four people family. The building is non-occupied only during the working days from 8.00 a.m. to 17.00 p.m.. Each occupant emits 80 W due to his metabolism, there are also internal gains from appliances during occupied hours.

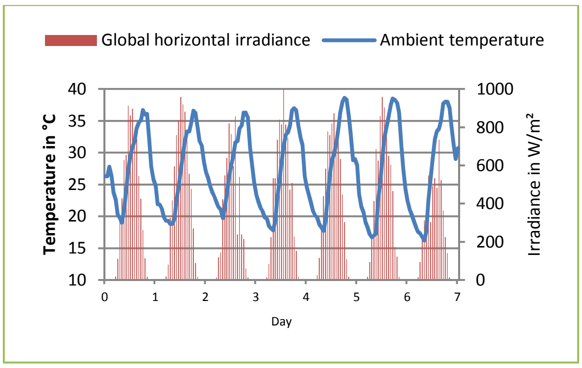

Figure 3 : hot summer week weather

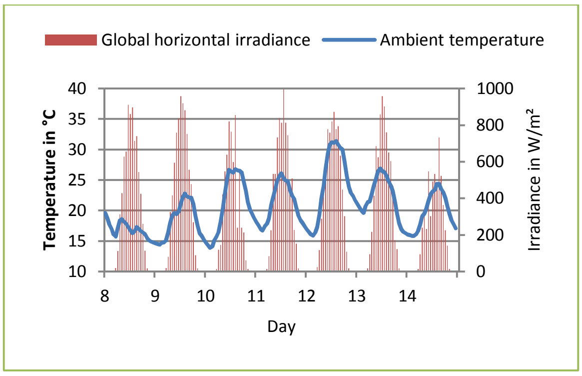

Figure 4 : typical summer week weather

The time steps of the simulation and the optimisation are both of 30 min.

The cost function to be minimized in this study is the sum of the differences between the indoor temperature and the comfort temperature calculated in equation (2) at each time step.

RESULT ANALYSIS

Mechanical ventilation control

The mechanical ventilation control is first optimized, the roller blinds being open at all times during the two weeks. The air flow rate can vary between 0.3 and 6 ach (air change per hour) with no heat recovery in summer. The minimum value of 0.3 ach is only authorized when nobody is in the building. Otherwise the minimum value is of 0.6 ach in order to guaranty sufficent air change for the health of the inhabitants. The maximum value of 6 ach is quite high but this value was chosen in order to see the maximum effect of the mechanical ventilation. The value function (see equation (15)) is :

$$v_t(E_t, E_{t+1}) = abs(T_{in} - T_C) \tag{20}$$

with T_c the comfort temperature and T_{in} the indoor temperature.

The results of the dynamic programming optimization are shown on *Figure 5*.

At the beginning of the very warm week, the indoor temperature is over the value of the comfort temperature, then the mechanical ventilation is operating at its maximum value during the night to decrease the indoor temperature. From the fourth day, the night ventilative cooling is not used at its maximum potential in order not to decrease too much the indoor temperature.

The comfort condition (3) is not maintained during this very warm week, especially during one day when the indoor temperature is sometimes 3°C higher than the comfort temperature. The average difference between indoor and comfort temperature is 1.7°C over the week. It reflects that the comfort level during the night is rather good.

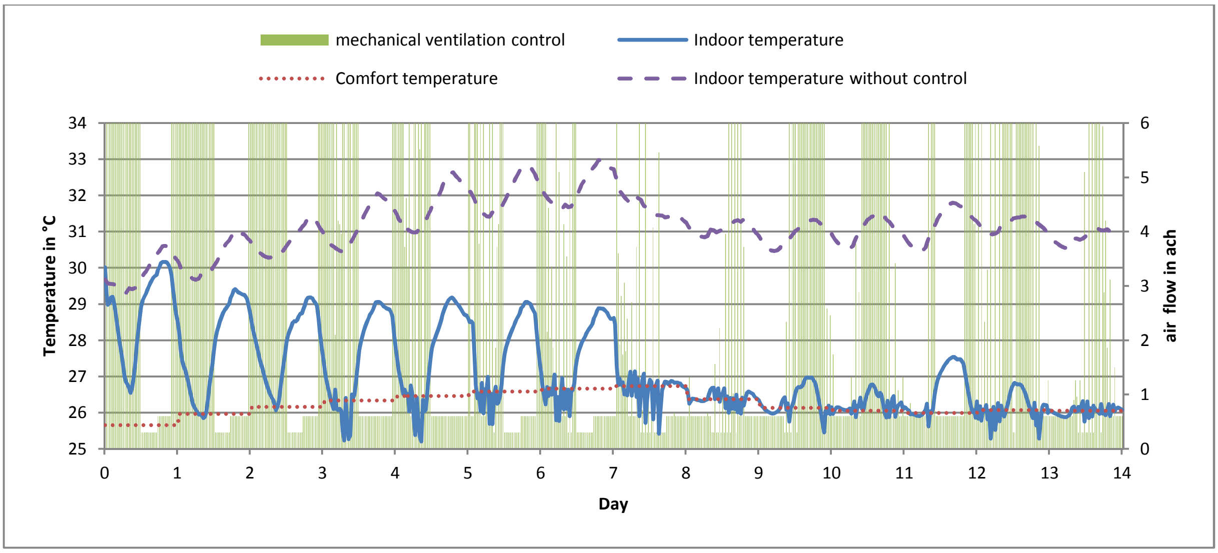

Figure 5: Variation of indoor temperature and mechanical ventilation control over the two considered weeks

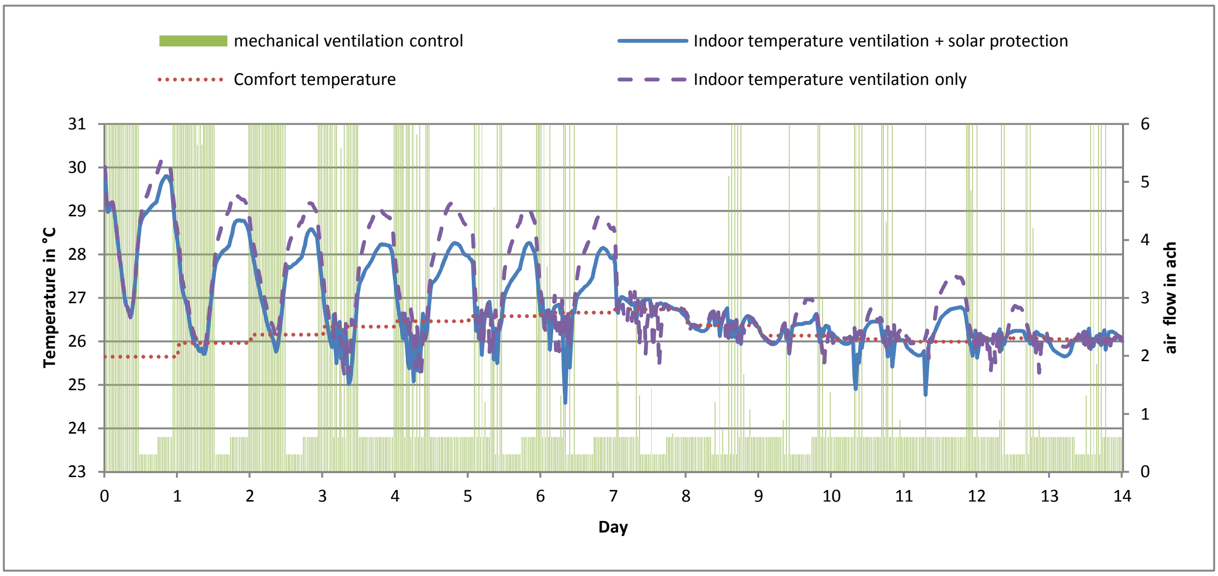

Figure 6 : Optimization with mechanical ventilation and solar protection controls

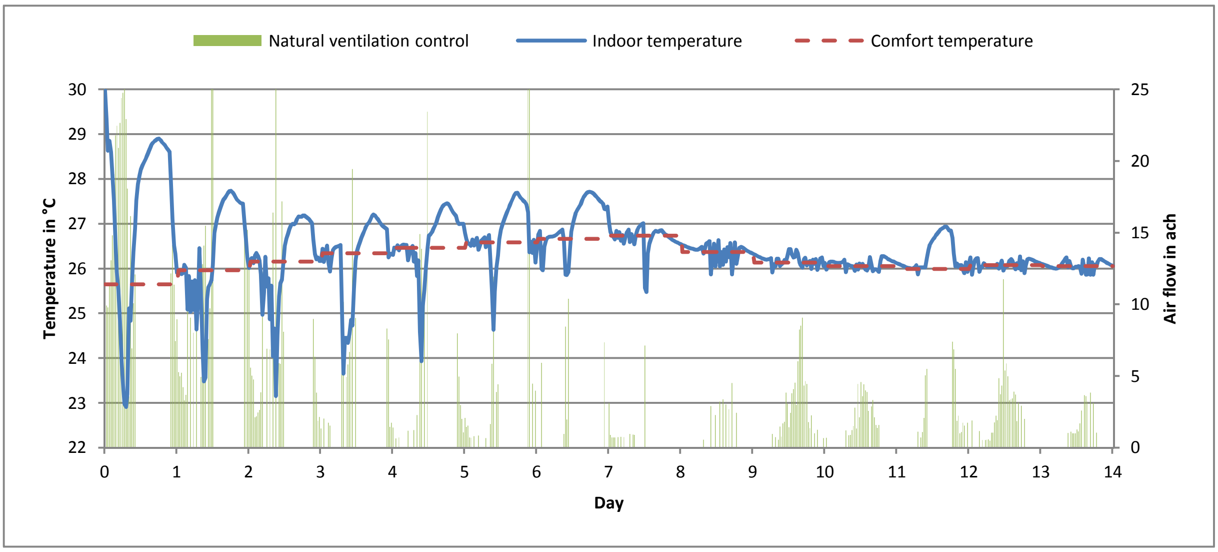

Figure 7 : optimization with natural ventilation control

During the two first days of the second week, almost no night free cooling is necessary to follow the decrease of the comfort temperature. Then night ventilation allows cooling the thermal mass of the building in order to maintain comfort during daytime. One can see that the mechanical ventilation control is sometimes used and the indoor temperature increases above the comfort temperature. This case happens when during the day the ambient temperature is lower than the indoor temperature, so the mechanical ventilation is on but is not effective enough to maintain the temperature due to high solar gains. During the second week, the thermal comfort is maintained at each time in the building, and the difference between indoor and comfort temperature is 0.3°C.

The temperature inside the building without any controller would be much higher, around 5°C more than the comfort temperature. Even in a building with high thermal mass and a very good insulation, it is necessary to have a controller (or equivalent occupant's action) to maintain comfort during a strong heat wave.

Controlling solar protection during the day and mechanical ventilation during the night

In this second optimization, a second command is operated for solar protection. Roller blinds are closed when the ambient temperature is higher than the indoor temperature, and when the global horizontal irradiance is over 200 W/m², basically when using mechanical ventilation is not efficient. Mechanical ventilation is on during the rest of the period. The value function is the same than previously, see equation (20).

The results of this optimization is presented in *Figure 6*. Only the mechanical ventilation control is presented, the roller blinds are always closed during the first week and most part of the second week.

Even if the indoor temperature increases less than in *Figure 5* during the first days, the two controllers combined can hardly do any better than uniquely with mechanical ventilation control. The average difference between comfort temperature and indoor temperature during the first week is 1.3°C (1.7°C previously). During the second week, reducing the solar gains allows to decrease the use of mechanical ventilation and thus the consumption of electricity.

Natural ventilation control

Four openings are considered for the natural ventilation control: 1 m² oriented east on the ground floor 1.8 m above the ground, and one in each of the three bedrooms at the first floor, two oriented south and one west. These three openings have a size of 2.25 m² and are 4 m above the ground. The coefficients *C* and *n* (see equation (10)) are standard values; 0.5 for *n* and *C* is calculated as follows:

$$C = C_d A \left(2/\rho\right)^n \qquad (21)$$

with

- C_d at a standard value of 0.5
- *A* the area of the opening
- ρ the density of air

The pressure coefficients *Cp* are calculated using (TNO webapplications) assuming a flat terrain roughness and no obstacles around the building.

In this case, the optimization algorithm is operating differently. The control is fixed; there are only four different possibilities:

- opened at 100 %
- opened at 50 %
- opened at 23 %
- closed

There is still only one control, which means that every window (opening) is opened the same way (same percent value).

Figure 7 shows the results with the natural ventilation control. Only one night is needed to decrease the indoor temperature by 7°C. The heat stored in the thermal mass of the building is rapidly discharged so that the following days the windows are opened less often. During the first week with the heat wave, the temperature inside the building is sometimes outside of the comfort zone (equation (3)) but this time under the low limit. This is the consequence of the only three possibilities of percentage opening and the high air flows that are achieved by ventilative cooling. The average difference between indoor and comfort temperature is 0.9°C (1.7°C and 1.3°C previously) during this first week. Using a natural ventilation control, the strong heat wave has almost no impact on the indoor temperature.

During the second week, the controller is particularly efficient: the indoor temperature is most of the time within 0.5°C near the comfort temperature.

DISCUSSION

The maximum value of ventilation from the mechanical ventilation control is *6 ach* whereas for the natural ventilation control it can theoretically go up to *65 ach*. This is the main difference between these two controls; it explains why the natural ventilation cooling is more effective. This effect is also shown on *Figure 8*, where the total energy stored in the building as calculated in equation (19) decreases for both controls but faster with the natural ventilation control. The high level of energy at the beginning of the simulation is the result of a non-controlled period during a heat wave (initialization period). After two or three days of operation, the total energy is around 900 kWh for the mechanical ventilation control and 870 kWh for the natural ventilation control. The mechanical ventilation control is limited to its free cooling possibility with a maximum value of *6 ach*, it can not discharge as much heat as the natural ventilation control, that is why the indoor temperature is often well over the comfort temperature in *Figure 5*. This control has difficulties to maintain thermal comfort with both heat wave and an initial high total energy stored in the building. If the control was applied continuously, so with less initial energy, the mechanical ventilation control could have better results.

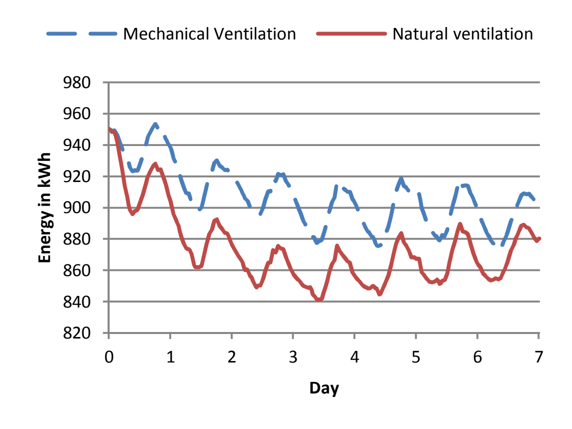

Figure 8 : Evolution of total energy stored in the building during the heat wave week

Overall, even during a strong heat wave, the comfort is maintained in the building, the total energy is decreased meaning that the building is discharging heat. Thus using an appropriate control, this building could face on even stronger heat wave. This is possible because even if the ambient temperature is very high during the day, it decreases to 20°C or less during the night. If the ambient temperature stays at a very high level all day long, no ventilative cooling is possible, the use of air conditionning is then necessary.

The number of hours when the comfort condition of equation (3) is not respected is shown in the following figure:

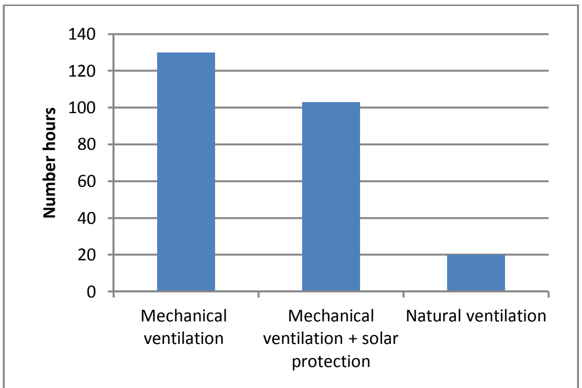

Figure 9 : Number of hours where comfort conditions are not respected during the heat wave week

One can see that natural ventilation is very efficient using this simple indicator of thermal comfort. But during the first hours when natural ventilation occurs, the indoor temperature decreases by 7°C in 7 hours (*Figure 7*). This could be a too fast decrease particularly during a sleeping time when the possibility of adaptation to the thermal comfort is reduced. This is due to the very high air flow achieved with natural ventilation. Such air flow could also be a problem for comfort with a too fast air speed within the building. This is a limit for taking into account only thermal comfort. In the same way, controlling solar protection is interesting in regard of thermal comfort, but there are limits related to visual comfort.

There are also other limits regarding the natural ventilation control. It may be more efficient than the mechanical ventilation control, but it needs more data to know or predict: wind speed and wind direction. Thus the natural ventilation control is more sensitive to the precision of weather forecasts. It also depends more on the occupancy because the air flows inside the building are currently calculated with open doors between the different rooms: this is the result of the mono-zone thermal model. A multizone model accounting for closed doors is more precise but assumptions are needed regarding occupants' behavior. In the same way the opening of windows is dependent on others parameters like rain or security of neighborhood.

To conclude, a natural ventilation control seems more efficient than a mechanical ventilation or a solar protection control, but its performance is more difficult to assess and even more to guarantee.

CONCLUSION

Dynamic programming optimization has been used to study the control of ventilation and solar protection in a low energy building. A control strategy can be identified to optimize comfort during a strong heat wave week and a typical summer week. Natural and mechanical ventilation controls are compared, showing that in this case study natural ventilation is more efficient during a heat wave to maintain comfort in the building. Further studies will address multizone building models.

NOMENCLATURE

T_c = comfort temperature
T_{in}= indoor temperature
E = state variable, total energy stored in the building

ACKNOWLEDGEMENT

This work has been supported by the chair ParisTech-VINCI "Ecodesign of building and infrastructure" and by the ANR project SIMINTHEC.

REFERENCES

Axley, J.M. 2001. Residential passive ventilation systems : Evaluation and design. Technical Note n° 54, Air Infiltration and Ventilation Center, Coventry, 158 p, 2001

Bellman, R. 1957. Dynamic Programming. Princeton University Press.

Braun. J.E., Montgomery, K.W, Chaturvedi, N. : Evaluating the Performance of Building Thermal Mass Control Strategies. HVAC&R Research. 7, 403-428 (2001).

Chahwane L., Stephan, L., Wurtz, E., Zuber, B. : On a novel approach to control natural and mechanical night ventilation. 12th Conference of International Building Performance Simulation Association (2011).

Dounis, A.I., Caraiscos, C. : Advanced control systems engineering for energy management in a building environnement – A review. Renewable and Sustainable Energy Reviews. 13, 1246-1261 (2009).

Escriva-Escriva, G., Segura-Heras I., Alcazar-Ortega M., 2010. Application of an energy management and control system to assess the potential of different control strategies in HVAC systems. Energy and Buildings, vol. 42, 2010, p. 2258-2257.

Fanger, P.O. 1967. Calculation of thermal comfort: Introduction of a basic comfort equation. ASHRAE Transactions (1967)

Favre, B., Peuportier, B., 2012, Using dynamic programming optimization to maintain comfort in building during summer periods, International Conference on Sustainability in Eneergy and Buildings 2012, Stockholm, Sweden.

Freire, R.Z., Oliveira, G.H.C., Mendes, N. 2008: Predictive controllers for thermal comfort optimization and energy savings. Energy and Buildings. 40, 1353-1365, 2008.

Hart, P. E., Nilsson, N. J., Raphael, B. 1968. A Formal Basis for the Heuristic Determination of Minimum Cost Paths. IEEE Transactions of Systems Science and Cybernetics, 4, 100-107, 1968

Humphreys, M.A 1995. Standards for thermal comfort : indoor air temperature standards for the 21st century

Le, K., Tran-Quoc, T., Sabonnadière, J.C., Kieny, C., Hadjsaid, N. : Peak load reduction by using air-conditioning regulators. Electrotechnical Conference, the 14th IEEE Mediterranean (2008).

Lollini, R, Danza, L., Meroni, M. : Energy efficiency of a dynamic glazing system. Solar Energy. 84, 526-537, (2010).

Malisani, P., Favre, B., Thiers, S., Peuportier, B., Chaplais, F., Petit, N., 2011. Investigating the ability of various buildings in handling load shiftings, 2011 IEEE Power Engineering and Automation Conference (PEAM), Wuhan : China.

Mathews, E.H., Arndt, D.C, Piani, C.B, van Heerden, E., 2000. Developing cost efficient control strategies to ensure optimal energy use and sufficient indoor comfort. Applied Energy. 66, 135-159 (2000).

Mc Cartney, K.J., Nicol, J.F. 2002. Developing an adaptive control algorithm for Europe. Energy and Buildings, 34, 623-635, 2002

Morel, N., Bauer, M., El-Khoury, M., Krauss, J. 2001, Neurobat, a predictive and adaptive heating control system using artificial networks. International Journal of Solar Energy. 21, 161-201 (2001).

Narendra, P.M., Fukunaga, K. 1977. A Branch and Bound Algorithm for Feature Subset Selection. IEEE Transactions on Computers, 6, 917-922, 1977

Nielsen, M.V., Svendsen, S., Jensen, L.B. : Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy daylight. Solar Energy. 85, 757-768 (2011). American Control Conference (2010).

Nygard Ferguson, A.M. 1990. Predictive thermal control of building systems. Thesis from Ecole Polytechnique Federale de Lausanne.

Oldewurtel, F., et al. 2010. Energy Efficient Building Climate Control using Stochastic Model Predictive Control and Weather Predictions. 2010 American Control Conference (ACC).

Peuportier, B., Sommereux, .I.B. 1990. Simulation tool with its expert interface for the thermal design of multizone buildings. International Journal of Sustainable Energy. 8, 109-120, 1990.

TNO webapplications. http://cpgen.bouw.tno.nl

Trocme, M., Peuportier, B. 2009. Studying innovative concepts by coupling simplified Simulation and multizone airflow model. CISBAT 2009 - Renewables in a changing climate : from nano to urban scale, Lausanne, Switzerland.