



ENSURING DESIRED NATURAL VENTILATION RATE BY MEANS OF OPTIMIZED OPENINGS

Louis STEPHAN^{1*}, Alain BASTIDE², Etienne WURTZ¹, and Bernard SOUYRI¹

¹Université de Savoie, 27, rue Marcoz, 73011 CHAMBERY, France

²Université de La Réunion, 117, Avenue du Général Ailleret, 97430 Le Tampon, France

*Corresponding author. Tel.: +33 4 79 44 46 18 E-mail address: louis.stephan@univ-savoie.fr

ABSTRACT

Since naturally ventilated buildings respond to site conditions and microclimate, there is no "one set of specific criteria" for every naturally ventilated building. So natural ventilation should be optimized to deal with thermal comfort in passive buildings during hot season. For this aim, we will propose a new method to reduce the number of independent parameters based on an analogy with a mechanically ventilated building, then we will apply an adapted optimization approach to produce an optimized ventilation sequence, and finally we will perform an inverse calculation to determine a series of opening heights corresponding to the optimized ventilation sequence.

Keywords: Natural ventilation, GenOpt, SimSPARK, Inverse, Optimization(8/10)

INTRODUCTION

Natural ventilation can replace some or all of a building's mechanical cooling systems requirements and leads to important advantages such as an attenuation of the environmental impact of dwellings, a reduction of energy costs of operating air conditioning systems and a restriction of the first cost of unnecessary mechanical equipments. However, external climate (temperature, wind, humidity...) has a great influence on natural ventilation performances and an appropriate design of naturally ventilated buildings has to adjust to site-specific conditions and microclimate on a daily basis to maximize occupant comfort. This is why there is no "one set of determined criteria" applicable to every naturally ventilated building. A correct simulation analysis can constitute a valuable approach for solving this problem. During the last decade, several models with different levels of precision have been developed. Detailed techniques like Computational Fluid Dynamics models (CFD) can provide an extensive description of flows around and inside buildings but they are usually limited to steady state conditions, need high computational time and can not be used for annual energy simulation. This is why "reduced models" based on a network approach have been developed to predict bulk flows through external and internal openings. There are a lot of programs using multizone airflow models but the most established

ones are : COMIS¹, CONTAM² and Modelica (Wetter, 2006). In this study we will develop a model based on this macroscopic approach and we will try to optimize natural ventilation flow rates by varying the dimensions of building openings. This means that opening's height will be calculated at each time step in order to optimize both air flow rate and occupant's thermal comfort. For this purpose, we will first treat our building as a mechanically ventilated building in order to reduce the number of independent variables. Then we will apply an adapted optimization method to produce an "optimized ventilation sequence". The "objective function" for optimization is based on the adaptive comfort criteria relative to the climate of the site. Finally we will perform an inverse calculation to determine opening heights corresponding to the optimized ventilation sequence.

PHYSICAL MODEL DESCRIPTION

Governing equations

The method that we will use is based on the one proposed by Yuguo Li (Li et al., 2000), where a neutral plane (z^*) is evaluated for each opening and at each time step. In this formulation we assume a uniform distribution of temperature and wind velocity acting on the opening. These simplifications yields to the fact that for an opening, we can have at most one neutral plane given by:

$$z^* = \frac{p_{ext}(0) - p_1}{(\rho_0 - \rho_1)g} \quad (1)$$

where $p_{ext}(0)$ is the external pressure at floor level given by $p_{ext}(0) = \frac{1}{2}\rho C_p v^2 + (\rho_0 - \rho_1)gH_1$

Depending on the position of z^* relative to a vertical opening $[z_1 z_2]$ we could have, one or a combination, of the following situations :

for $(z_1, z_2) \subset (0, z^*)$

$$q = K_t b [\rho_0 \vee \rho_1] \int_{z_1}^{z_2} |P_{ext}(0) - P_1|^n \times \left(1 - \frac{z}{z^*}\right)^n \times Sgn(P_{ext}(0) - P_1) dz \quad (2)$$

¹developed by the National Institute of Standards and Technology (NIST)

²developed within IEA Annex 23 at the Lawrence Berkeley National Laboratory (LBNL)

for $(z_1, z_2) \subset (z^*, R_1)$

$$q = K_t b [\rho_0 \vee \rho_1] \int_{z_1}^{z_2} |P_{ext}(R_1) - P_1|^n \times \left(\frac{z - z^*}{R_1 - z^*} \right)^n \times Sgn(P_{ext}(R_1) - P_1) dz \quad (3)$$

where $[\rho_0 \vee \rho_1]$ means that either ρ_0 or ρ_1 is selected depending on the sign of $(P_{ext}(R_1) - P_1)$, q is the mass flow rate, b is the width of opening $[z_1 z_2]$ and K_t is the opening's flow coefficient. As a convention, a positive pressure difference denotes an inflow to the considered zone whereas both subscripts 0 and 1 stand for the outdoor and indoor zones respectively. Following the same approach, $p_{ext}(R_1)$ is the external pressure at ceiling level given by: $p_{ext}(R_1) = \frac{1}{2} \rho C_p v^2 - (\rho_0 - \rho_1) g H_1$

Solution method

At the level of a "zone i", mass flow rate balance yields to the following equation:

$$\sum_{j=1}^{N_i} q_{j,i} = 0 \quad (4)$$

where $q_{j,i}$ is the net mass flow rate through opening j and N_i is the number of openings in "zone i". However, in their published work, Li et al. (2000) considered volumetric flow rates and therefore, equation 4 denoted a volumetric flow rate balance, an assumption which could lead to significant errors with big temperature differences between "zone i" and "zone j". This is why we introduced, in eq.2 and 3, the quantity $[\rho_0 \vee \rho_1]$ to obtain mass flow rates. Equation 4 is then applied for every room of the simulated building.

The resulting set of non-linear equations is solved using SPARK (Simulation Problem Analysis and Research Kernel), an object-oriented software system that solves mathematical models composed of differential and/or algebraic equations (LBNL, 2003). The advantage of this environment is that the solution sequence is non-oriented. In fact, graphs are used to represent the problem at a level of equations and variables rather than procedural multi-equation blocks (Edward F. Sowell, 2004). So in this environment, it is not necessary to order the equations or to express them as assignment statements in opposition to conventional modular environments such as matlab/Simulink or TRNSYS (Wurtz et al., 2006). This means that inverting a problem doesn't need a reprogramming of the entire model because we don't have predefined input and output sets. Moreover, SPARK uses the graph algorithms to decompose the problem into strong and weak component thus reducing the computational time. Finally, the robustness of SPARK's solver allows it to solve highly non-linear problems with minimal convergence problems.

Following this approach one obtains a system of equations that is completely reversible. Every variable can be chosen to be an INPUT or a REPORT and no system linearisation is needed. This will later help us to impose a user desired mass flow rate "q" as an INPUT into

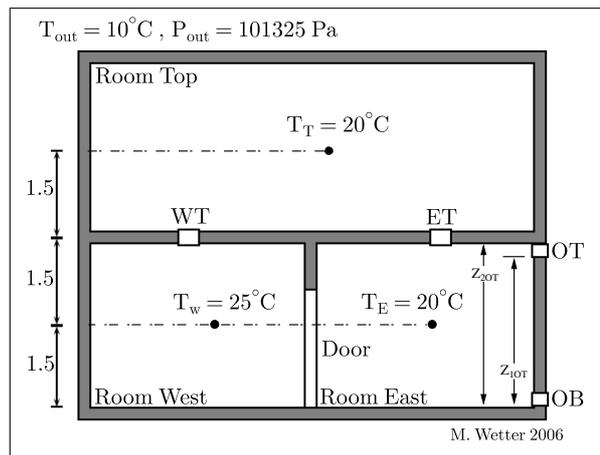


Fig. 1: Side view of the three interconnected rooms

Table 1: Parameters of the flow elements

	ORIFICE	DOOR
Discharge coefficient C_D	0.65	0.78
Flow coefficient n	0.5	0.5
Area A in m^2	0.1	2.2
Width w in m	-	1
height h in m	-	2.2
Transition to linear pressure law ^a		
$\Delta P_{0,\epsilon}$ in Pa	0.1	0.1
Number of compartments ^a n_{com}	-	10
Minimum velocity ^a v_ϵ in m/s	-	0.001

^aSpecific parameters for Modelica

our model and have, as a result, the necessary height of openings.

Inter-Model validation

The next step is to determine a test case and compare our results to those computed in CONTAMW2.1 and Modelica. We decided to base our validation on the example proposed by Michael Wetter (Wetter, 2006). It consists on evaluating the buoyancy driven air flow rate through orifices (room/room, room/outside) and through an open door separating the western and the eastern room (Fig.1).

Table.1 lists all the parameters that were used to describe the flow elements whereas fig.1 shows the applied temperature profile and building geometry. Simulation results are listed in table 2 where we can see a dissimilarity between these softwares that appears at *the door* where a bidirectional flow exists. This is probably due to the difference in the discretization method along the door height. However we can notice that the discordance in mass flow rates between SimSPARK and CONTAM is 1.7% and is less than 0.2% between SimSPARK and Modelica. This deviation is significantly smaller than the uncertainties that one can have when choosing problem parameters like : discharge coefficient, flow exponent...(Wetter, 2006).

Advantage of this model

The advantage of this model is that we will couple it to building envelope models with no time lag where as

Table 2: Comparison results (kg/s)

FLOW ELEMENT	CONTAM ^a	MODELICA ^a	SIMSPARK ^b
Door W → E	0.4103	0.4184	0.4173
Door E → W	0.4146	0.4228	0.4218
Orifice WT	0.0044	0.0044	0.0044
Orifice ET	0.0044	0.0044	0.0044
Orifice OB	0.0080	0.0080	0.0080
Orifice OT	0.0080	0.0080	0.0080

^aref. M.Wetter

^bSimulation plateforme based on SPARK

Table 3: Cases and results for model inverse tests

Flow element	Var.(H) (case 1)	Var.W/H ($W = 2.5 \times H$) (case 2)
Width [m]	0.15 (fixed)	0.19
Z_{2OT} [m]	3.0 (fixed)	3.0 (fixed)
Z_{1OT} [m]	2.9	2.92

EnergyPlus uses airflow rates that were computed using COMIS in the previous time step (ping-pong approach) which can cause instability if time step become large (Sahlin, 2003). Besides, some flow models in COMIS and CONTAM can give non-repeatable results. For example, the crack model used in COMIS evaluates the density of the air at the crack using the flow that was found in the previous evaluation step (Lorenzetti, 2001). This can cause converging problems. Additionally, as mentioned earlier, the model here proposed is completely reversible i.e any variable could be chosen to be an INPUT or a REPORT. Lets consider the previous case study, and suppose that we need a certain mass flow rate "Q" in kg/s flowing through orifice OB. What should then be the dimensions of opening OT in order to satisfy this condition? Table 3 presents the cases that we considered. In case 1, opening OT has a fixed width equal to 0.15m and a variable height whereas in case 2, opening OT has a variable width (w) and height(h) with $W = 2.5 \times H$. For both cases, a mass flow rate of 0.015 kg/s should enter the Eastern room through orifice OB.

CASE STUDY: CARGÈSE (FRANCE)

The developed model was used, in this study, to optimize the natural ventilation potential for a residential building in Cargèse (FRANCE), a village located at 50 km to the north of Ajaccio, on the west coast of Corsica. In fact, we will try to minimize the number of hours when thermal comfort is not achieved and therefore reduce the percentage of dissatisfaction. Building envelope is modeled using the SimSPARK platform and coupled to the air flow model (described in the previous section). From now on, we will be referring to as "the natural ventilation model".

Meteorological and technical considerations

Following are the basic climatic and technical data that will be used as fixed input for all upcoming simulations :

- Climatic conditions: for this optimization study, we will use external temperatures and solar radiation

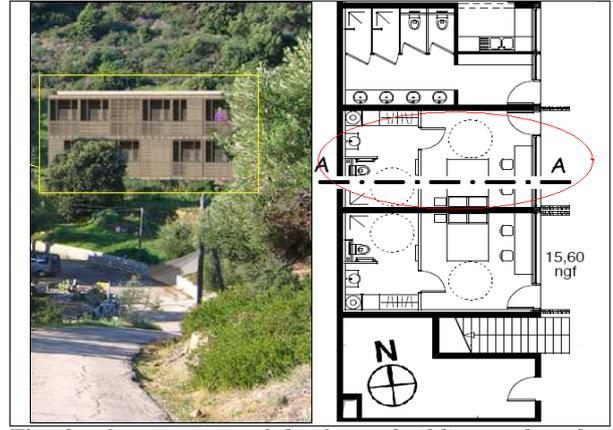


Fig. 2: On site view of the future building and a plan view of a typical floor

measured during 15 days of a relatively hot year (year 2005).

- Geometrical room dimensions ($W \times L \times H$): 4m x 7m x 3m,
- Eastern and western glazing: Low emissivity double glazing ($U = 2.73W/m^2K$)
- Walls: 15 cm heavy weight concrete ($\rho_{concrete} = 2500kg/m^3$, $\lambda_{concrete} = 1.75W/m.K$), 15 cm of external insulation ($\lambda = 0.038W/m.K$)
- Two openings: on the eastern and on the western wall (width and height to be evaluated)

Comfort analysis

Comfort criteria: The way people react with the thermal indoor environment is very complicated and depends on several conditions. A number of these parameters are included in the thermal comfort concept defined as the condition of mind which expresses satisfaction with the thermal environment (ISO7730, 1994). The method that we will use is called "the adaptive model" where comfort temperature is considered to be closely related to the prevailing outdoor temperature, and could be expressed by the following equation (McCartney, 2002):

$$T_C = aT_{RM} + b \quad (5)$$

Where T_C is the comfort temperature (°C), T_{RM} is the running mean temperature (°C) and a, b are constants to be determined experimentally. In a EU-funded research project, Smart Controls and Thermal Comfort (SCATs) (Nicol, 2001), an adaptive control algorithm was developed and data were provided for the evaluation of constants "a" and "b" and it was found out that for France (McCartney, 2002):

$$T_C = 0.049T_{RM} + 22.58 \quad T_{RM} \leq 10^\circ C \quad (6)$$

$$T_C = 0.206T_{RM} + 21.42 \quad T_{RM} > 10^\circ C \quad (7)$$

where T_{RM} is given by the following equation :
 $T_{RM_n} = 0.8T_{RM_{n-1}} + 0.2T_{DM_{n-1}}$ and T_{DM} is the daily mean temperature on day n-1 ($^{\circ}C$).

Comfort evaluation: There are two methods suggested in the EN15251 for evaluating thermal comfort conditions (EN15251, 2006):

- **Percentage outside range:** the percentage of the occupied hours during which the temperature falls outside the acceptable zone.
- **Degree hours criterion:** The time during which the actual operative temperature exceeds a specified range of comfort is multiplied by the corresponding exceeding degrees.

we decided to use, throughout this study, the degree hours criterion defined as:

$$ddh = \sum (T_{int} - T_C) \frac{dt}{3600} \quad \text{if } T_{int} > T_C \quad (8)$$

Where ddh is the discomfort degree hours ($^{\circ}Ch$), T_{int} is the simulated room temperature ($^{\circ}C$) and dt is the simulation time step (s).

OPTIMIZATION METHOD

The goal of our natural ventilation optimization analysis is to be able to achieve a minimal volumetric flow rate of 0.5 ACH during the day and a convenient high ventilation rate during the night in order to activate the thermal mass and hence reduce thermal discomfort during the following day. Due to the fact that a parametric study is a time consuming process and impractical for our application, we decided to couple the building model to an optimization software : GenOpt 2.1.0 (Wetter, 2008). GenOpt is a generic optimization program that has been developed to find, with less labor time, the independent variables that yield the best performance of complex systems involving many independent variables and where the cost function is computationally expensive and its derivatives are not available (Wetter, 2000). Genopt can be coupled to any simulation program that reads and writes its input/output to text files. It is divided into a kernel part that reads the input files, calls the simulation program, stores the results ... and an optimization part that contains the optimization algorithms (Wetter, 2008). Figure 3 shows the details of the connection of GenOpt with a simulation program.

Even if the maximum number of independent variables is not restricted in GenOpt, it is preferable not to exceed 10 variables. This condition will quickly constitute a handicap to achieving our goal. It is due to the fact that natural ventilation is intrinsically related to "inside/outside" air temperature and wind speed. This means that if at instant "t" and under given external/internal conditions β , an opening with height "h" produces a natural flow rate of 0.5 ACH, at instant "t+1" with new conditions β' we will need an opening having a height "h'" to reproduce the same ventilation rate (i.e 1 variable for every time steps and for each opening). Lets

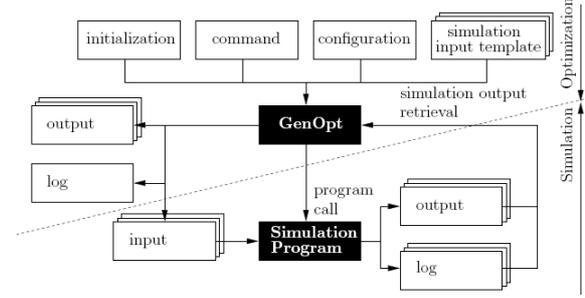


Fig. 3: Interface between GenOpt and the simulation program (Wetter, 2008)

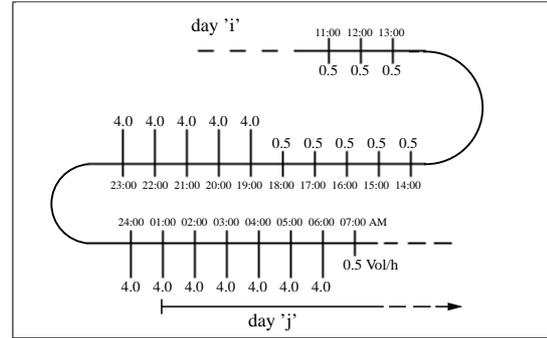


Fig. 4: Fictive control sequence

now consider a sequence of "n" simulation days and focus our attention, for example, on the transition from "day i" to "day j". If we suppose that the represented ACH sequence (fig.4) is the one that is optimized and allows on day "j" a certain level of thermal comfort, attaining this sequence with GenOpt would have required the use of $2 \times 24h = 48$ variables (if we consider two openings). Due to the fact that the external conditions on "day j+1" could be completely different from "day j", a 15 days simulation would have required $48 \times 15 = 720$ variables.

Obviously we need to reduce the number of independent variables in order to carry on with the optimization process. Consequently, we decided to treat the building as a mechanically ventilated one. This will help us to bypass the need of 1 variable for every time steps and for each opening. In fact if we want to reproduce (under mechanical ventilation conditions) the ventilation sequence shown in figure 4 all we need to know is the rate of night ventilation (1 variable) and when to start and stop it (2 variables), i.e a total of 3 variables per day instead of 48.

Nevertheless, if we consider a 15 days simulation time, we will have the equivalent of $15 \times 3 = 45$ variables. So we still need to further reduce the number of independent variables. This is why we decided to subdivide the simulated days into groups according to the following criteria : $T_{ext} > 24^{\circ}C$. As we can see in figure 5, three patterns were identified:

- Pattern A: Reference case
- Pattern B: Temperature stays lower than $24^{\circ}C$ till

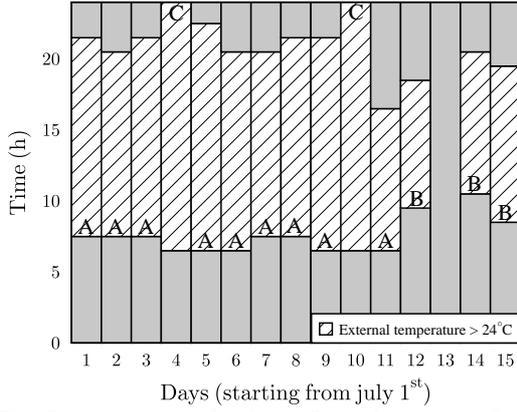


Fig. 5: Regrouping the days of simulation into 3 patterns (A, B, C)

Table 4: List of independent parameters

PARAMETER NAME	MIN	INITIAL	MAX	STEP
TLL_A	6	8	10	1
TLL_B	8	10	12	1
TLL_C	6	8	10	1
$TLLr_A$	19	20	22	1
$TLLr_B$	17	18	20	1
$TLLr_C$	21	22	23	1
Vn_A	2	3	5	1
Vn_B	1	2	4	1
Vn_C	3	4	6	1

late in the morning

- Pattern C: Temperature stays higher than 24°C till late in the evening

As a conclusion we now have $2 \times 3 = 6$ variables for starting/ending time and $1 \times 3 = 3$ variables for the rate of mechanical night ventilation i.e a total of 9 independent variables. Now, we can start our optimization process using GenOpt and the result will be a sequence of hourly ventilation rates equivalent to a 15 days simulation period. This sequence will then be used, in the next section, as an INPUT for the natural ventilation model and hourly opening heights will be calculated.

Design variables

In table 4 we have a list of design variables with specifications about their initial values, as well as their lower and upper bound. TLL is the time when we shift from a night ventilation rate (NVR) to a constant daytime ventilation rate of 0.5 ACH, TLLr is the time when night ventilation is activated, Vn is the night ventilation rate whereas suffixes A, B, C stands for patterns A, B, and C respectively.

The algorithm used is the Hybrid Generalized Pattern Search Algorithm with Particle Swarm Optimization Algorithm (GPSPOCCHJ) (Wetter, 2008). It starts by performing the Particle Swarm Optimization (PSO), a stochastic population-based algorithm, for the *continuous and discrete variables*. Afterwards, it initializes

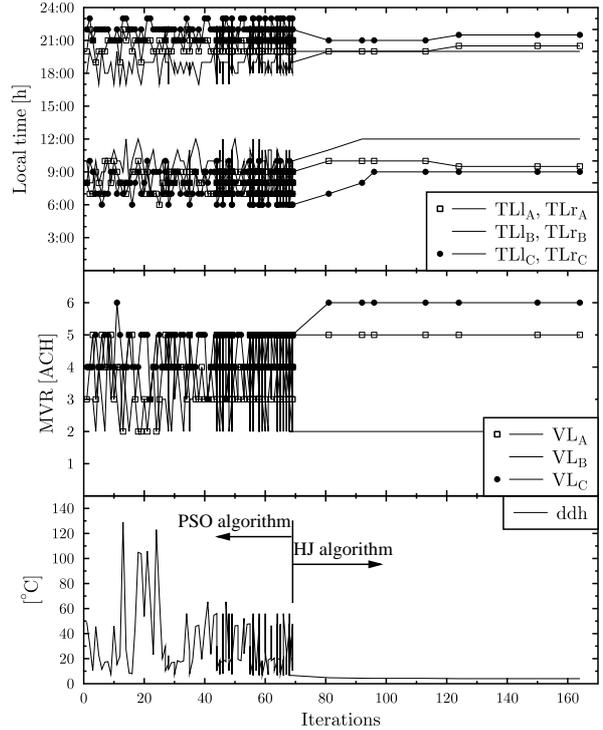


Fig. 6: Iteration run for the minimization of "ddh"

the HookeJeeves Generalized Pattern Search algorithm (GPS) using the *continuous* independent variable of the particle with the lowest cost function value. The advantage of this hybrid algorithm is that "PSO algorithm" increases the chances of getting close to the global minimum, and then "HJ algorithm" refines the search locally. The step size indicated in table 4 is further reduced by "HJ algorithm" during the search procedure.

Optimization results

The search performed for minimizing the discomfort degree-hour is shown in figure 6. Each iteration is equivalent to a fifteen days simulation time³. Furthermore, a constant step size integration method is selected when solving the equations with SPARK, so that the integration mesh won't change from one simulation to the next⁴. Therefore, a change in "ddh" value between different points is not caused by a change of the integration mesh. We can notice, from (Fig.6), that the particle having the minimum cost function, obtained using the PSO algorithm, is used to initialize the direct search HJ algorithm. In our case 200 iterations were needed to reach the required accuracy.

Using this algorithm, discomfort degree hours was reduced by 92% compared to the initial values ($ddh = 49 \rightarrow 4[^\circ\text{C}.h]$). As shown in figure 6, a minimum discomfort degree-hour (ddh) is attained when we de-

³A simulation equivalent to a 6 month period preceding *july 1st* is done and final snapshot data are used to initialize the 15 days simulation period.

⁴A variable step size integration can cause a discontinuity in the cost function *ddh* and optimization algorithms might terminate at points that are non-optimal.

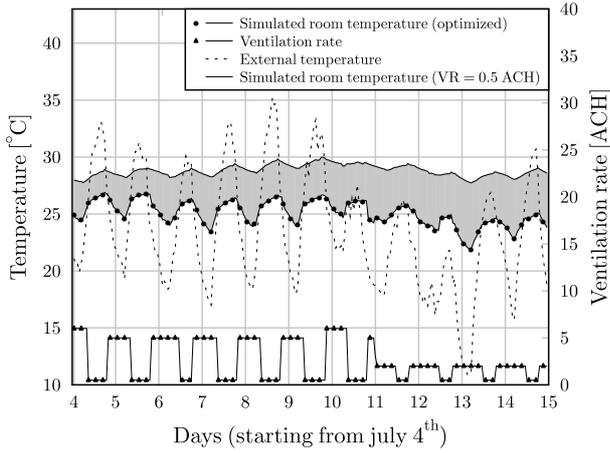


Fig. 7: Comparison between a **constant** ventilation rate and an **optimized** one

lay the activation of mechanical night ventilation system (MNV) for pattern C (21:30 h) and retard to terminate it for pattern B (12:00 h). Moreover, we observe that for pattern B a ventilation rate of 2ACH is sufficient to optimize thermal comfort. This could be explained by favorable climatic conditions between days 12 and 15 as shown in figure 7. In fact we experience low temperatures at night ($10 \sim 17^{\circ}\text{C}$) and moderate maximum temperatures during daytime.

Using higher rates for pattern B (6 ACH, case 3 in fig.8) would have yield to lower internal room temperatures. However, a mechanical ventilation rate of 2 ACH is enough to attain internal temperatures lower than the comfort temperature T_C as evaluated by equation 5 and hence doesn't have an influence on the value of "ddh" (fig.8).

Results verification

In order to be sure that the optimization algorithm converged to a global minimum, we conducted a parametric run on 5832 possible parameter configurations using the EquMesh⁵ algorithm available in GenOPT (Wetter, 2008). It turned out that this exhaustive search did not reveal any independent parameter combination resulting in a lower discomfort degree hours ("ddh"). Besides, all "ddh" values that were calculated are greater than the ones obtained using the optimization algorithm. Consequently, we can say that GenOpt has probably converged to a global minimizer for cost function "ddh".

DETERMINING TIME DEPENDENT OPENINGS HEIGHTS

As a result of our previous optimization, we now have a suitable sequence of mechanical ventilation rates and starting/ending hours for night ventilation mode that ensure convenient thermal conditions. The objective now

⁵The EquMesh algorithm allows making parametric runs on an orthogonal, equidistant grid that is spanned in the space of the independent parameters.

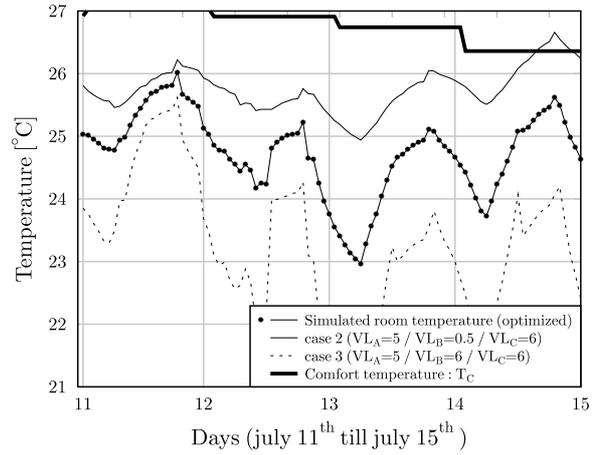


Fig. 8: Results for $V_{LC} = 0.5, 2$ and 6 ACH

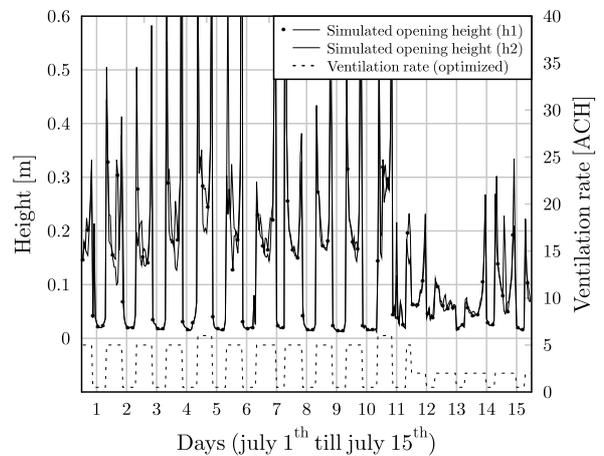


Fig. 9: Variable openings heights

is to try to reproduce this sequence under natural ventilation conditions by determining the adequate opening's heights at each time step.

Preliminary results

We used the optimized ventilation sequence as an INPUT for our natural ventilation model, and resulting opening's heights are evaluated assuming a "zero wind velocity" condition so that openings will insure, as much as possible, the desired ventilation rate without needing any wind assistance. We can notice that the results shown in figure 9 reveal some peaks in openings heights. This is due to a small temperature difference between inside and outside zones and to the "zero wind" condition. However, we can say that a maximum opening height of 30 cm seems to satisfy the largest number of situations.

Effect of limiting opening height

Due to the fact that for over 92% of the time, opening height is smaller than 30 cm, we decided to limit openings dimension to $1.5 \times 0.3\text{m}^2$. This manoeuvre will probably have an effect on thermal performance of the building and on ventilation rates. In order to assess this impact, we limited the maximum values shown in figure

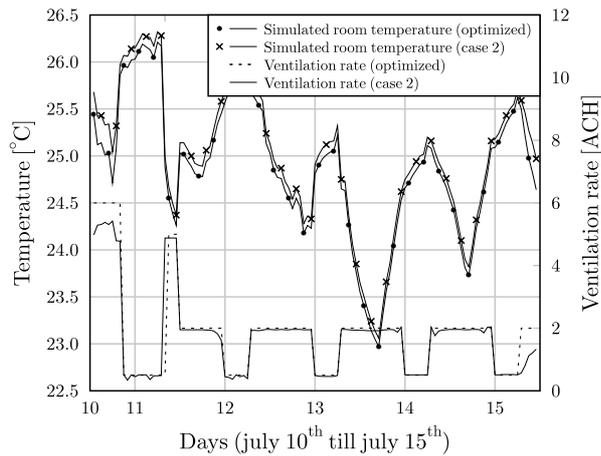


Fig. 10: Effect of limiting opening height

9 to 0.3m and obtained a new profile of opening heights. Figure 10 shows a comparison between two different cases: the optimized result (reference fig.7) and the one obtained using the new profile (case 2). As we can clearly see, there are some conditions where the needed night natural ventilation rate could not be achieved. The same phenomenon occurs, on day 11 and day 12 but this time regarding the minimal hygienical flow rate where sometime, an air change rate of 0.5 Vol/h could not be reached. This is a direct result of a lower natural air change rate attained during the previous night which lowered building's thermal mass activation. Besides, we can notice a small raise in internal temperatures with no significant effect on the value of the discomfort degree hours (ddh) because even with these disturbances, internal temperature does not exceed the estimated comfort temperature T_C . However we can say that in the real application, the possible presence of external wind could help overcome this lack in buoyancy driven flow rate.

CONCLUSION

This work is an example showing the advantage of performing an optimization study in order to get the most advantage of natural ventilation potential. The method here presented has the benefit of drastically reducing the number of independent variables. This was done by treating the problem as a mechanically ventilated one and optimizing it using GenOpt. The resulting ventilation sequence is used as an INPUT for natural ventilation model and needed opening dimensions are evaluated at each time step. We can say that this work is a basic step and a first approach and still needs improvements especially regarding the natural ventilation model. In fact the model needs to be modified in order to enhance the accuracy of the simulations particularly regarding the wind effect in case of cross ventilation conditions where kinetic energy of wind is dominant. Finally, based on the presented results, it is possible to develop a new control system able to vary the section of openings to obtain the necessary air flow rate specially

for buildings with high thermal inertia.

References

- Edward F. Sowell, Michael A. Moshier, P. H. D. C., April 2004. Graph-theoretic methods in simulation using spark. In: High Performance Computing Symposium of the Advanced Simulation Technologies Conference (Society for Modeling Simulation International). Arlington.
- EN15251, 2006. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.
- ISO7730, 1994. Moderate thermal environments- determination of the pmv and ppd indices and specification of the conditions for thermal comfort. Geneva.
- LBLN, 2003. SPARK 2.0 reference manual. Lawrence Berkeley National Laboratory and Ayres Sowell Associates Inc.
- Li, Y., Delsante, A., Symons, J., 2000. Prediction of natural ventilation in buildings with large openings. *Building and Environment* 35 (3), 191 – 206.
- Lorenzetti, D. M., 2001. Assessing multizone airflow software. Lawrence Berkeley National Laboratory.
- McCartney, Kathryn J., F. N., 2002. Developing an adaptive control algorithm for europe. *Energy and Buildings* 34, 623 – 635.
- Nicol, M., 2001. Scats: Final report – public. Oxford Brookes University.
- Sahlin, P., 2003. On the effects of decoupling airflow and heat balance in building simulation models. *ASHRAE Transaction*.
- Wetter, M., 2000. Design optimisation with genopt. *Building Energy Simulation User News* 21.
- Wetter, M., 2006. Multizone airflow model in modelica. The modelica association.
- Wetter, M., 2008. GenOpt, Generic Optimisation Program. Lawrence Berkeley National Laboratory, Berkeley, CA 94720.
- Wurtz, E., Mora, L., Inard, C., 2006. An equation-based simulation environment to investigate fast building simulation. *Building and Environment* 41 (11), 1571 – 1583.