VENTILATION CONTROL BASED ON INDOOR AIR QUALITY USING SIMBAD BUILDING AND HVAC TOOLBOX

David JREIJIRY[1], Ahmad HUSAUNNDEE[2] ,Christian INARD[3], Jean Georges VILLENAVE[4]

ABSTRACT

The control industry integrates more and more complex control strategies of ventilation systems (hybrid systems, mechanical systems, etc) to satisfy energy and environmental issues.

A number of models have been developed to calculate air flows in both single and multizone buildings. There is a need to have an appropriate simulation tools to integrate more complex control strategies (fuzzy logic, finite state machines…).

SIMBAD Toolbox (SIMulator of Buildings And Devices), developed in the Simulink graphical environment is a library of models of HVAC components. It has been used in the field of control of HVAC systems, mainly for heating/cooling systems. In order to extend the capabilities of the toolbox for ventilation control, it is necessary to introduce models of air flow components and pollutants in SIMBAD Toolbox.

The paper gives a description of the library of air flow components and the macroscopic pollutants models to simulate demand controlled ventilation based on indoor pollutant concentrations. Moreover this paper shows the implementation of a ventilation control strategies based on occupancy and indoor air quality using the Stateflow environment for description of finite state machines and the models developed in Simulink environment.

[1]PhD student, Building Automation and Energy Management Group, Sustainable Development Department, Centre Scientifique et Technique du Bâtiment, 84 avenue Jean Jaurès, BP 02, F-77421 Marne-la-Vallée, France.
[2] Energy Engineer, PhD, Building Automation and Energy Management Group, Sustainable Development Department, Centre Scientifique et Technique du Bâtiment, 84 avenue Jean Jaurès, BP 02, F-77421 Marne-la-Vallée, France.
[3] Professor, Department of Civil Engineering, Université de La Rochelle, Avenue Michel Crépeau, 17042 La Rochelle, France.
[4] Senior Scientist, Air Conditioning, Ventilation and Indoor Air group, Sustainable Development Department, Centre Scientifique et Technique du Bâtiment, 84 avenue Jean Jaurès, BP 02, F-77421 Marne-la-Vallée, France.

INTRODUCTION

The quality of indoor air has an immediate impact on the occupant health and productivity. The main pollutants sources are the occupants metabolism, the occupants activities (cooking, washing,…) the furniture and the building materials. Ventilation is used to dilute the pollutants to an acceptable concentration and to remove moisture in dwellings. The main steps to define the magnitude of the required supply airflow are as follow (Trepte, 1989): (1) identification of pollutant of prime concern in the situation of interest; (2) specification of limiting, maximum acceptable indoor concentration; (3) estimation the factors other than the dilution effect that influence the concentration (source strengths, sink strengths,…).

Since the pollutants could be related to occupant presence, the use of constant ventilation rate lead to over ventilation during reduced occupancy periods and cause energy loss in terms of both the thermally conditioned air and the energy use of the fan. With demand controlled ventilation based on indoor air pollutants concentrations or occupancy detection sensors, the ventilation is modulated below the design supply airflow while still maintaining adequate ventilation rate for an acceptable indoor air quality level. DCV offers two potential advantages (Fisk et al 1998): (1) better control of indoor air pollutant concentration; (2) lower energy use and peak energy demand. The main pollutants driving DCV systems are (Mansson et al 1992): (1) moisture; (2) carbon dioxide (CO_2); (3) volatile organic compounds (VOCs).

Nowadays, innovative airflow components include electronic drives that support more complex control strategies using a combination of the above-mentioned pollutants. In addition to usual ventilation evaluation criteria with respect to energy consumption and indoor air quality, manufacturers are interested in methods and tools to evaluate the stability of such control strategies. There is a need to know the components states (position of grilles, detection level of one sensor, fan speed,…) at different times.

Our aim in this paper is to implement dynamic model of the main DCV driving pollutants in SIMBAD toolbox which is adapted for the design, test and evaluation of ventilation control strategies.

SIMBAD BUILDING AND HVAC TOOLBOX

SIMBAD Building and HVAC Toolbox is a library of models of HVAC components (Husaunndee et al 1997) developed in the Matlab/Simulink environment (Simulink 2001) for test and design of control systems. The toolbox shown in Figure 1 consists of building zone models, models of heating ventilating and air conditioning components, controllers of such equipment and various utilities (weather data files, occupancy profiles, data acquisition interfaces…) that are necessary to build up virtual systems to study the behaviour of HVAC plants. The models available in this toolbox are structured using a methodology of modelling in a graphical simulation environment (Husaunndee et al., 1997).

The toolbox benefits from the user friendliness of the Simulink graphical environment and uses the "drag and drop" method of the graphical environment to select the components required. The latter are linked together to build the systems.

One main characteristic of the toolbox is the definition of connection vectors to transfer data from one block to another: air vector, water vector, information network, weather vector… To facilitate the use of the toolbox, several systems are provided. The building thermal zone model ranges from a detailed zonal model (Riederer 2001) requiring a full description of walls to predefined R-C models representative of high/low inertia, high/low insulation, residential/non-residential buildings. In fact, for several control studies, the user need to verify that the control strategies are suitable to a class of buildings instead of one particular building.

SIMULINK uses hierarchical top-down and bottom-up modelling approaches (SIMULINK, 1998). Block is composed from several levels of model detail. We simulate a model by implementing the algorithms of the physical concepts describing the models. For each block, SIMULINK allows creating a dialog box, called Mask, which will appear by clicking over the block. The Mask editor enables user to specify initial conditions and model parameters. Therefore, the models in the library are structured in order to allow experienced users the access to all parameters and source code while the beginner can use the models even without a particular knowledge of modelling. The models are developed in a way that the necessary parameters are easily available or can be obtained from manufacturer data or rating points.

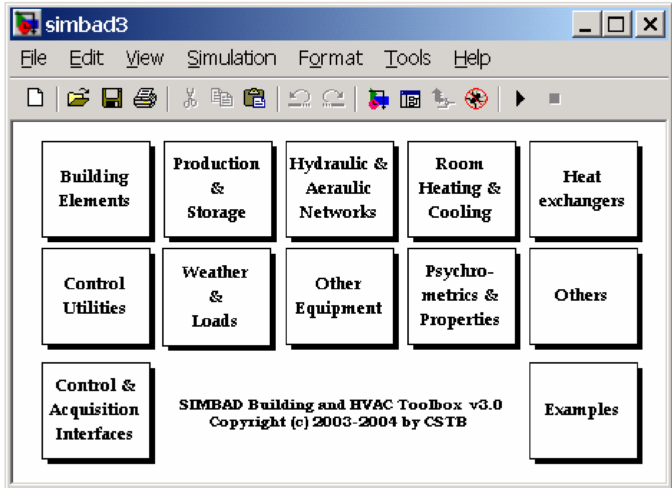


Figure 1: SIMBAD Toolbox in Simulink graphical environment

Integrating Airflow models

The simulation of airflow zone model is based on “Pressure Airflow Network” from Orme (1999). This model is used to calculate air flow rates into and out the zone and between adjacent zones. In this network, each zone is represented by one node and is connected to other zones by flow paths. The permeability model described in Millet et al (1995) calculates the air infiltration rates.

Several types of air inlets (De Gids 1997; Jardinier et al 1990) are integrated in SIMBAD. Inlets can be active or passive. Active inlets can be connected to building management system. For passive inlets, it could be either uncontrolled, like crack, where the airflow rate through the inlet is variable and depends on external and internal air conditions (wind pressure, air temperature…) or self-controlled, like pressure controlled inlets where the airflow would be constant. The plant components implemented (Figure 2) are ducts, variable speed fan, static extractor, extract opening, T- joint.

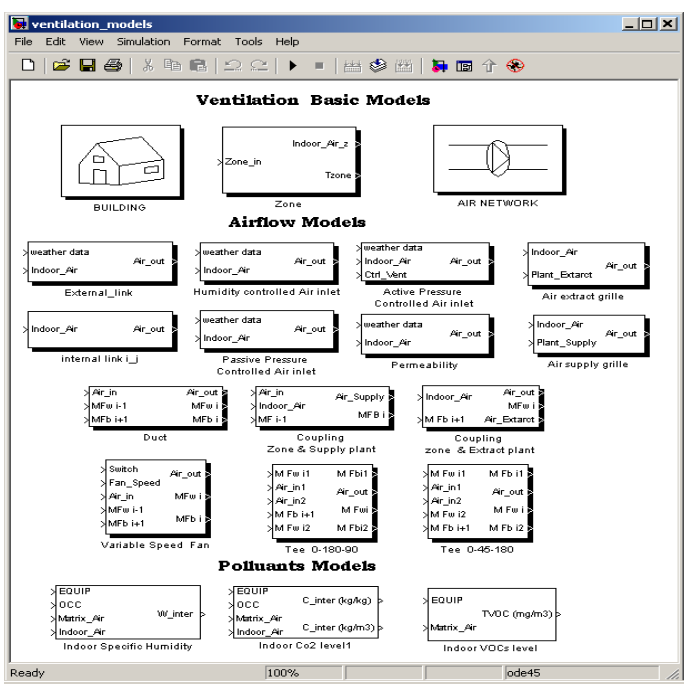


Figure 2: Airflow zone modelling and components

The Simulink loop solver uses Newton's method with weak line search to solve algebraic equations. This method is very robust and avoid convergence problem due the choice of the initial condition. For the plant simulation, the equation loop or the inverse solver technique is used. The models developed are detailed and validated in Jreijiry et al (2003).

The plant is simulated based on the fact that the algebraic sum of the pressure drops in any closed loop should be zero and in any junctions the air-mass balance should be maintained.

Indoor air quality model

Two types of models for indoor air quality that are currently used are (Axley 1988), (Knoespel et al. 1991): (1) microscopic models, which uses a two- or three-dimensional fluid mechanics code to describe airflow and pollutant distribution in a ventilated room; (2) macroscopic models, which describe pollutants transport through a multiple zone ventilation system. In SIMBAD, the macroscopic model will be implemented. SIMBAD airflow model is base upon the network technique where each building zone is representing by one node at uniform pressure, temperature, and pollutant concentration, and nodes are connected by airflow paths.

The pollutant transport model assumes no chemical reactions between pollutants, no adsorption with building materials and is based on a mass balance pollutant in each zone as given in Equation (1) (Knoespel et al. 1991). In the following equations, the subscript p, in and out indicates the pollutant, into the zone and out of the zone respectively:

$$\frac{dm_p}{dt} = \dot{m}_{p,in} - \dot{m}_{p,out} \quad (1)$$

where

m_p	mass of pollutants p	[kg]
$\dot{m}$	mass flow rate	[kg/s]

By replacing the mass flow rate by the volume flow rate, the final form of the general pollutant balance equation for a zone is :

$$\frac{dC_p}{dt} = \frac{Q_{in}}{V_a} C_{p,in} - \frac{Q_{out}}{V_a} C_{p,out} \qquad (2)$$

where

C_p	concentration of pollutant p	[kg/m^3]
Q	volume flow rate of air	[m^3/s]
V_a	air volume in the zone	[m^3]

By including all possible airflow paths into or out of the zone i, Equation 2 is now written as:

$$\frac{dC_{p,i}}{dt} = \frac{S_{p,i}}{V_{a,i}} + \frac{Q_{in,i}}{V_{a,i}} C_{p,oa} - \frac{Q_{out,i}}{V_{a,i}} C_{p,i} + \frac{\sum_{j=1, j\neq i}^{N} Q_{j,i} C_{p,j}}{V_{a,i}} - \frac{\sum_{j=1, j\neq i}^{N} Q_{i,j} . C_{p,i}}{V_{a,i}} \qquad (3)$$

where

C_p	concentration of pollutant p	[kg/m^3]
S_p	pollutant volume source	[kg$_p$/s]
V_a	air volume in the zone	[m^3]
Q	air infiltration volume flow rate	[m^3/s]
$Q_{i,j}$	airflow from zone i to zone j	[m^3/s]
$Q_{j,i}$	airflow from zone j to zone i	[m^3/s]

The first term on the right hand side of Equation 3 is the pollutants volume source located in zone i. Equation 3 is implemented in SIMBAD and the transient solution of this equation requires a small simulation time step when there is a change of source levels or of airflow rates.

Relative humidity model

Indoor water vapour level depends on ventilation rates, on the outdoor specific humidity, indoor water vapour sources, surface condensation and water vapour sorption process due to the indoor furnishings and building materials. Experimental studies showed that more than one third of the airborne moisture can be absorbed by indoor surfaces. (Duforestel et al. 1994), (Kusuda 1981), (Monchoux et al. 1989). To simulate the sorption processes, a hygroscopic model proposed by Duforestel et al. (1994) is now implemented in SIMBAD. One buffer represents all hygroscopic materials in one room. It is composed of two volumes: (1) buffer's surface, with variable moisture density, exchanging vapour with the ambient air and buffer's heart; (2) buffer's heart, with constant moisture density.

Each zone is assigned a buffer model. Global room hygroscopic coefficients are fixed to represent "low absorption" furniture for the bathroom and for the corridors and "high absorption" for all the other rooms.

DEVELOPMENT OF A CONTROL STRATEGY

In this section, a single family dwelling is simulated with a strategy basic on logic programming controllers for the heating season (see Figure 3). As an application for the developed tool, a single dwelling with two floors is simulated.

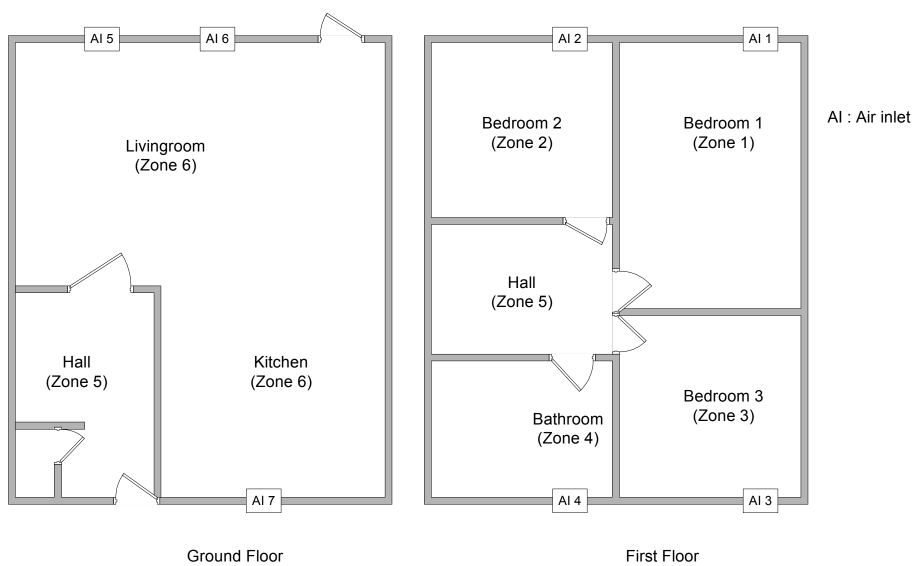


Figure 3: the simulated single family dwelling

The occupancy schedule is defined in Table 1.

Table 1.
Occupancy Schedule

Time (Hours)	Occupants Locations	Number or occupants
23:00-7:00	Bedroom 1	2
	Bedroom 2	1
	Bedroom 3	1
7:00 -8:00	Living room	3
17:00-21h00	Living room	4
21:00-23:00	Living room Bedroom 2	3 1

A schedule of water production for shower and cooking activities in the dwellings is used based on the Annex 27 (Millet et al. 1998). Showering is assumed to take place according to the schedule given in

Table 2 .Water vapour production is assumed to be 300 g per shower. The water vapour production due to the cooking activities is given in Table 3.

Table 2.
Showering schedules

Person	Hours
Man	6.00 - 6.10
Woman	6.30 - 6.40
Child 13	7.15 - 7.25
Child 10	7.30 - 7.40

Table 3.
Water vapour production due to the cooking activities

	Water production [g]	Schedule
Breakfast	100 100	6.30 - 7.00 7.00 - 8.00
Dinner	1200	17.00 - 18.00

The ventilation system is mechanical exhaust system with natural supply inlets. The air is extracted from the services rooms (kitchen, bathroom and toilet). The air inlets are controlled and defined by their reference airflow for reference pressure difference of 20 Pa across the opening.
The air inlets are controlled with several positions of the grilles (see Table 1). The air inlets types and locations are described in Table 4 and Table 5.

Table 4.
Air inlets characteristics

Air inlets			
Position	Reference airflow rate (m^3/h)@20 Pa		
	Type 1	Type 2	Type 3
1	5 m^3/h	5 m^3/h	0 m^3/h
2	30 m^3/h	60 m^3/h	15 m^3/h
3	x	x	30 m^3/h
4	x	x	45 m^3/h

Table 5.
Air inlets types and locations

Air inlet	Location	Type
AI 1	Bedroom 1	2
AI 2	Bedroom 2	1
AI 3	Bedroom 3	1
AI 4	Bathroom	2
AI 5	Living room	3
AI 6	Living room	3
AI 7	Kitchen	2

The mechanical exhaust flow is divided as follows:
- 1/2 part in kitchen,
- 1/3 part in bathroom,
- 1/6 part in toilet.

The fan has three output levels:
- High (level 3) 50l/s
- Middle (level 2) 40l/s
- Low (level 1) 10l/s

The air-tightness of the building is taken as 1 ACH at 50 Pa. Leakage is distributed according to the room areas as defined in Millet et al. (1998). The floor is assumed airtight. The leakage is simulated as a crack. In this case, half of the cracks are located at 0.625 m from the floor and the other half at 1.875 from the floor.

Control strategies

The main idea of this strategies is supply air where and when there is a need of the fresh air.
First control strategy: The ventilation control strategy is based on:
- Presence detectors in the bedrooms
- Relative humidity sensor in the extract system
- CO_2 sensors in the living room

The presence detectors is an infra-red detector which provides a Boolean signal (0/1), according to the presence or not of people in the room. When there is human presence detection, the air inlet in the room is fully opened (position 2) and the fan controller has target airflow as mentioned in the Table 6.

Table 6.
Fan target levels in the bedrooms

Presence detection	Fan target level (-)		
	Bedroom 1	Bedroom 2	Bedroom 3
0	low	low	low
1	medium	medium	medium

The grille positions of the air inlets in the living room (AI 5 and AI 6) are based on CO_2 level as described in figure 4.

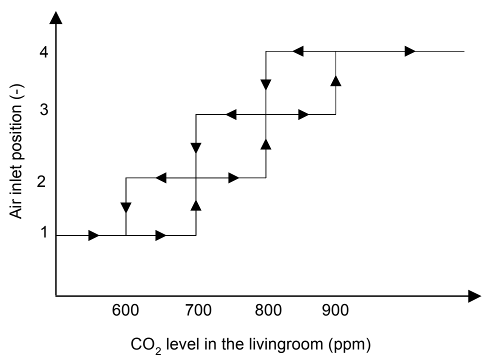


Figure 4 : Inlets control signals in the living room

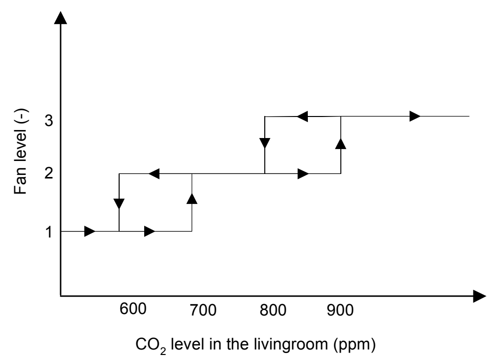


Figure 5 : the living room fan target level

For the kitchen and the bathroom, the air inlets are fully opened when the humidity is higher then a fixed set point of 50% and the fan is set on the high level (see Figure 6 and Figure 7).

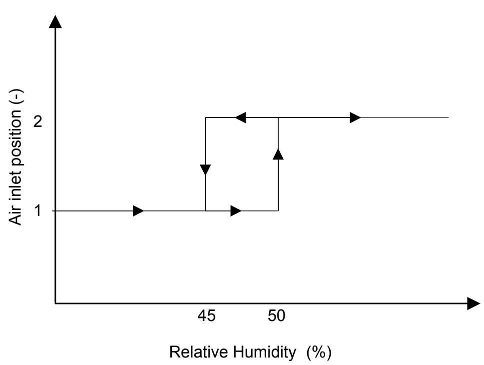


Figure 6 : Inlets control signals in Kitchen and the bathroom

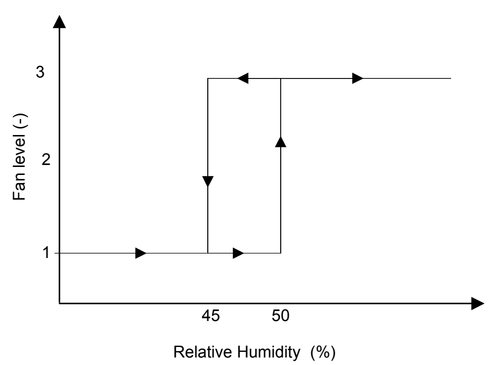
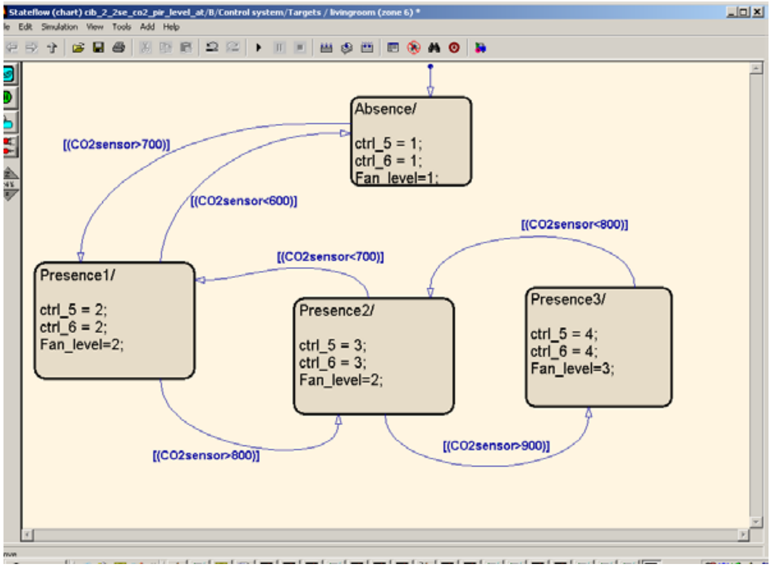


Figure 7: Fan target level based upon the relative humidity of the exhaust airflow

The fan level will be the highest one from the different rooms target levels.

The control strategies are implemented in the Stateflow environment which is dedicated to the description of finite state machines in the Simulink graphical environment. The implementation of such sequential logic is straight forward in this environment and it enables direct visualisation of states during the simulation. Figure 8 shows the control algorithm described in Figure 4 and Figure 5 implemented in Stateflow.



Ctrl_5: control signal to the air inlet 5

Ctrl_6: control signal to the air inlet 6

Fan_level : the fan target level

CO2_sensor: the CO_2 sensor detection

Figure 8: Living room control algorithm implemented in Stateflow.

Second control strategy: The ventilation control strategy is based on:

- CO_2 sensors in the living room and the bedrooms
- Relative humidity sensor in the extract system

The grille positions of the air inlets in the bedrooms (AI 1, AI 2 and AI 3) are based on CO_2 level as described in Figure 9. Also, based in the CO_2 detection in the bedrooms the fan target speed is defined (see Figure 10).

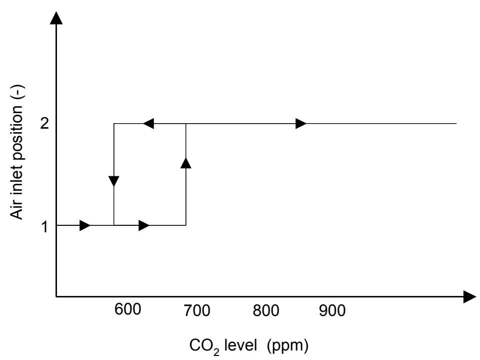


Figure 9 : Inlets control signals in the bedrooms

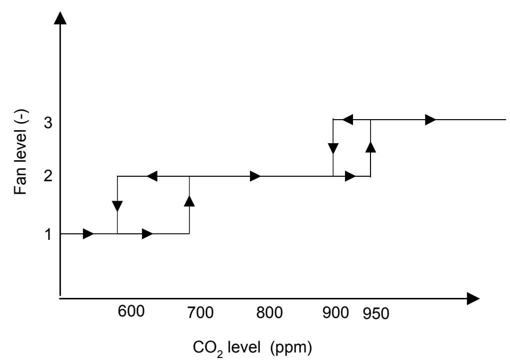


Figure 10: Fan target level in the bedrooms

The same strategy as the first strategy is used for the grilles in the living room, the bathroom and the kitchen.

EXAMPLE SIMULATION RESULTS

To show the usefulness of the tool, a simulation run of one winter day has been performed with one minute simulation time step. Table 7, Table 8 and Table 9 show some results of the fan regimes, the CO_2 concentration, and the states of the inlet grilles.

Table 7.
Fan level during a winter day

Control strategy	Number of level change	Fan level in % of time		
		low (level 1)	middle (level 2)	High (level3)
1	4	35%	31%	34%
2	6	36%	32%	32%

Table 8.
Carbon Dioxide concentrations in the habitable rooms

	Zone 1		Zone2		Zone 3		Zone6	
Startegy number	1	2	1	2	1	2	1	2
Mean CO_2 concentration (ppm)	650	600	605	580	660	630	560	605
Maximum CO2 concentrations (ppm)	930	910	835	840	850	840	915	910

Table 9.
Number of grilles position changes during a winter day

Air inlet	Location	Number of grilles position changes	
		Strategy 1	Strategy 2
AI 1	Bedroom 1 (Zone 1)	2	2
AI 2	Bedroom 2 (Zone2)	2	2
AI 3	Bedroom 3 (Zone 3)	2	2
AI 4	Bathroom (Zone 4)	4	4
AI 5	Living room (Zone 6)	8	10
AI 6	Living room (Zone 6)	8	10
AI 7	Kitchen (Zone 6)	4	4

The two developed strategies are able to maintain an acceptable indoor CO_2 level in the occupied zones (see Table 8). In both cases, the condensation occurs in the bathroom when showering take place (see Figure 11) and there is no condensation in the other zones.

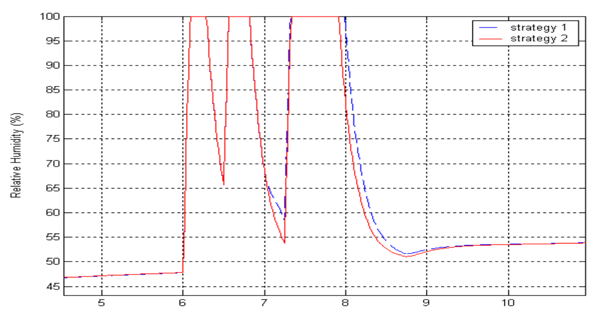


Figure 11: Relative humidity in the bathroom when showers are taken

For the air inlets in the bedrooms, the number of position changes is the same for the two strategies since the number of occupant per bedroom is not variable during the occupancy period. Hence, the strategy based on presence detection sensor in bedrooms is efficient to maintain acceptable indoor air quality in these rooms. The main difference between the two strategies is the number of times of the fan changes speed (see Table 7). Criteria will be developed to assess the life cycle of components.

CONCLUSION

This paper gives an overview of the enhancement of SIMBAD toolbox for design and test of ventilation control strategies. The SIMBAD Toolbox has been completed with pollutants models and airflow models so that whole building simulation with short time step can be achieved. It will thus be possible to test more and more sophisticated ventilation control strategies, in particular to simulate the dynamics of the system and to evaluate control loops.
Besides, two control strategies based on indoor air quality and presence detection and using controlled air inlets have been proposed and implemented using Stateflow. The comparisons between the two strategies showed the capability of such strategies to maintain an acceptable indoor quality. These results illustrates how this tools could be use to check the advantages and the disadvantages of different ventilation control strategies with respect to their stability and impact on the components. A more traditional overall performance assessment would take only into account discomfort in the zones, the pollutants concentrations exposure and the influence of the air tightness of the buildings on the control strategies.

REFERENCES

Axely, J. 1988. Integrating Microscopic and Macroscopic Air Movement and contaminant Dispersal in Buildings, Proceedings of NSF/ASHRAE Symposium: Buildings systems: Room Air and Air Contaminant Distribution. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

De Gids,W.F.1997. Controlled Air inlets, NATVENT work package 3, Activity 2, http://projects.bre.co.uk/natvent/

Dols, W.S., Walton,G.N., Denton,K.R. 2000. CONTAMW 1.0 User Manual, National Institute of Standards and Technology, 2000, p. 133.

Duforestel, T., Dalicieux, P.1994. A model of hygroscopic buffer to simulate the indoor air humidity behaviour in transient conditions, Proceedings of European Conference on Energy Performance and Indoor Climate in buildings. Lyon, France, pp 791-797.

Fisk, W.J., De Almeida, A. T. (1998). Sensor-based demand-controlled ventilation: a review, Energy and Buildings, Vol 29, Issue 1, pp. 35-45.

Husaunndee, A., Lahrech, R., Vaézi-Néjad, H., Visier, J.C. 1997. SIMBAD: A simulation toolbox for the design and test of HVAC control systems. Proceedings of the 5th international IBPSA conference, Prague, Czech Republic, Vol. 2, pp. 269-276.

Jardinier, P., Simonnot, J. (1990). Principle and Aim of a Natural Huimidity-Controlled Ventilation System. International CIB W67 Symposium, “Energy Moisture and Climate in Buildings”, Rotterdam, Netherlands.

Jreijiry, D., Husaunndee, A., Inard, C.and Villenave J.G. (2003). Control of ventilation in buildings using SIMBAD Building and HVAC Toolbox. Proceedings of Building Simulation 03, Eindhoven, The Netherlands.Vol2, pp. 591 – 598.

Knoespel P.D., Mitchell J.W., Beckman W.A. 1989. Macroscopic model of indoor air quality and automatic control of ventilation, ASHRAE Trans, Vol 97, part 2 pp. 1020-1030.

Kusuda T, Indoor Humidity calculations, ASHRAE Transactions, 81, part 2, 1983.

Manson L.G., Svennberg S. A. (1992). Demand Controlled Ventilating Systems, International Energy Agency Annex 18, Source Book, p.195.

Millet J.R., Villenave J.G., Manson L.G., De Gids W. (1998). Evaluation and Demonstration of Domestic Ventilation Systems- Volume 2: Indoor Air Quality. International Energy Agency Annex 27, Vol 2, p. 55.

Monchoux, F., Serin, G., Thellier F, Gestion de l’air d’un local, Modélisation des échanges d’humidité internes air-habitant-mobilier, Revue générale de la thermique, n°335-336, décembre 1989.

Orme, M. (1999). Applicable Models for Air Infiltration and Ventilation Calculations, AIVC Technical Reports, UK. p. 76.

Riederer, P., Marchio, D., Visier, J.C., Husaunndee, A., Lahrech, R., (2001). Influence of sensor position in building thermal control: Development and validation of an adapted zone model, Proceedings of Building Simulation 01, Rio de Janeiro, Brazil, pp 449-456.

SIMBAD, Building and HVAC toolbox, Version 3.1.0. 2001. Centre Scientifique et Technique du Bâtiment, France.

SIMULINK dynamic System Simulation for MATLAB. 2001. Mathworks Inc., Ma., USA. Version 3.0.

Stateflow and Stateflow Coder for Complex Logic and State Diagram Modeling for MATLAB. 2002. Mathworks Inc, Ma, USA, Version 5.0.