COMPUTER-AIDED ENERGY USE ESTIMATION IN SUPERMARKETS

M. Orphelin & D. Marchio
Centre d'Energétique de l'Ecole des Mines de Paris
60, boulevard Saint-Michel
75272 Paris Cedex 06, France

ABSTRACT

A simulation software focused on HVAC energy consumption in large supermarkets, called Clim Top, has been recently developed in France. The first originality of this tool is to have a friendly interface, especially designed for supermarkets, which makes it really available for various users involved in energy savings in supermarkets (architects, maintenance managers, technical store managers, energy consulting engineers, ...), as well in terms of HVAC design as in terms of energy audit. The second originality of this tool is to propose a new methodology to consider coupling between air conditioning and refrigeration display cases leading to a global energy analysis.

INTRODUCTION

Electricity consumption in large supermarkets represents a substantial share of about 4% of the national electric energy use, either in the United States than in France. A large part of it, varying from 50 to 70 %, is due to air conditioning and refrigeration cases. Corresponding electric consumption is about 400 kWh/(m².year), which plants it as a real challenge for energy savings.

Thermal behaviour of supermarkets is specific, especially because of interactions between HVAC system and display cases (experienced by the consumer as the 'cold aisle' feeling, due to air vertical stratification near display cases).

This paper reports work performed for the development of Clim Top, a simulation tool focused on HVAC energy consumption in large supermarkets. This software has been developed for the A.M.E.C., a French association promoting energy management in supermarkets.

In the first part of this paper, a review of bibliography of some previous energy consumption studies in supermarkets is proposed. This underlines two separate issues particularly investigated by the authors, which are detailed in the next two sections. The first one is that such a new tool has to be really adapted to users needs. The second one is that interaction between air conditioning system and display cases must be modelled. In the last part of the paper, a short sensitivity analysis of energy consumption to main parameters allows to expose some of the possibilities of Clim Top.

WHY DEVELOPING A NEW SIMULATION SOFTWARE FOCUSED ON SUPERMARKETS ?

The use of simulation in practice

During a workshop which followed Building Simulation ‘95, reported in [3], simulation developers and expert users have discussed on the future of building energy simulation tools. One considerable aim concerning proposed methods and structures was the improvement of pre and post processing methods. More particularly, two points were underlined. First, considered as the priority, the interest of an adaptable interface regarding user and stage in the design process. The second point concerned a knowledge-based front end with intelligent default parameters.

These considerations are a reality concerning building energy simulation tools use applied to energy management in supermarkets. Various users could be interested in a software tool especially adapted for design and audit of HVAC systems , such as:

- the architect, who wants to choose the most suitable HVAC system at the beginning of a project;
- the maintenance manager, who monitors consumption evolution and seeks malfunctions;
- the technical store manager, who wants to evaluate the consumption and be able to take decisions regarding objective considerations;
- the energy consulting engineer, who wants to introduce some reliable innovative technical improvements.

Existing research pieces of software are badly adapted to these users, because they are very complex to use, and not specifically designed for supermarkets. Consequently, our predominant aim was to elaborate a consistent but easy-to-use tool software, in order to promote the use of simulation in practice. Interfaces and functionality of Clim Top have been defined in close relationship with future users, as it will be exposed in the next section.

HVAC and refrigeration equipment coupling

Interactions between refrigerated display cases and air conditioning system are often unknown or misunderstood, as underlined in [1]. Traditional separation of industries of air conditioning and refrigeration has limited design information exchange. Anyway, since the early 80's, some progress has been done, as with the development of efficient desiccant cooling implementation, described in [7].

Energy analysis of a whole supermarket has been already developed in [6], using TRNSYS as a building simulation model. However, this study is mostly based on a detailed modelling of various refrigeration components and on possible improvements of refrigeration system. It gives no idea of the interaction between air conditioning and refrigerated cases.

A significant work on influence of ambient humidity on refrigerated display case consumption has been presented in [4]. The results are validated on experimental data. In [5], regressive equations are given to evaluate, for typical cases, heat and moisture transfers under any ambient relative humidity. A building simulation has been used to see the influence of the relative humidity control on air conditioning energy consumption. However, ambient temperature setpoint influence is not studied in this paper.

No modelling of the 'cold aisle phenomenon', which is essential in the considered coupling, has been found. Considering all display cases operating at ambient conditions equal to those experimented in the rest of the sales area could lead to large mistakes in global energy consumption evaluation.

PRACTICAL ASPECTS OF CLIM TOP

The project has been developed in three stages. The first phase associated software developers and future users in order to describe thoroughly the specifications of software inputs and outputs. The second stage of the project consisted in software making up and also in the writing of three user manuals (user guide, support to decision making guide, algorithms and programs folder). The last phase consisted in checking software results face to real measurements. Simulation results have been confronted with a metered-supermarket, giving good accuracy with monthly measured consumption. This phase has also been turned to check the practical aspect of interfaces.

Excel 5 has been chosen by the users as the most convenient interface. Inputs are organised in four items -Location, Building, Occupation and Equipment- and are presented under forms easily interpretable and largely accessible. As an example, supermarket managers often control the number of cash desk tickets per hour. This is a very useful information on hourly occupation of the supermarket, as the average number of person per ticket could be easily estimated.

For each required information, the user chooses between two levels of detail according to his available level of knowledge. When using simplified inputs, typical default values are always proposed as an help. A detailed data acquisition is also possible. As a first example, concerning walls description, one can choose between two pre-determinate compositions in simplified acquisition, or, in detailed mode, choose to define each wall as a composition of up to three materials in a given list. Another example is lighting, which can be described with only the installed electric power or with the installed electric power and daily profile (for example, to take into account lighting before store opening due to products restocking, midday lighting reduction, ...).

A special attention has been paid to display cases description, which is essential due to their large part in the global energy balance. In a conception stage, some default average values of level of equipment are proposed to the user. In other stages of a project, one can use pre-selected typical display cases configurations and only enter corresponding cases lengths. In a more detailed acquisition, if information is available from equipment manufacturers, one can enter lengths, freezing energy rates, induction rate, auxiliaries (lighting, fans, heating pipes, defrosting).

Outputs are also presented on Excel 5. Various tables and charts allow to compare simulation results with real consumption, and also to compare simulations between them. Three examples of output spreadsheets are given in figures 1, 2 and 3., respectively concerning visualisation of temperatures evolution and use of heating for a given winter week, monthly values of HVAC system running hours and annual energy balance split by end-uses.

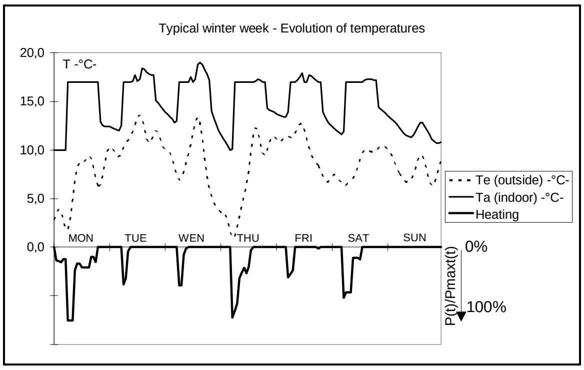

Figure 1: visualisation of parameters

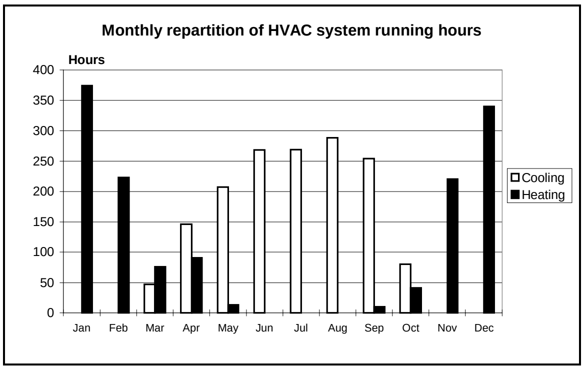

Figure 2: monthly values of running hours

Energy consumption by end-use Annual Balance		kWh/year	price (FF)
HVAC		**182075**	**72830**
with:	Sales area	164492	65797
	Storeroom	13288	5315
	Office	4295	1718
Lighting		**276222**	**110489**
with:	Sales area	245622	98249
	Storeroom	25500	10200
	Office	5100	2040
Display cases		**408299**	**163320**
with :	positive cases	265238	106095
	auxiliaries cases +	78362	31345
	negative cases	54652	21861
	auxiliaries cases -	10046	4019
Bakery		**13832**	**5533**
Others (carpark lighting)		**50000**	**20000**
Others (estimated)		**50000**	**20000**
Estimated total		**980428**	**392171**
Effective total		**1050452**	**420181**

Figure 3: annual energy balance

MODELLING OF COUPLING HVAC AND DISPLAY CASES

Before studying the interaction between air conditioning and display cases, we propose models for each of them.

Roof-top air conditioner modelling

Air conditioning systems are sized to face a maximal thermal load, corresponding to the nominal operation. However, the system always works under different conditions, mostly in partial load. The proposed model is explained in more details in [13]. If Pe is the compressor electrical power and Pc is the cooling energy rate, the ratio (Pe/Pc)/(Pe,nom/Pc,nom) is approximated as a second degree polynomial of ΔT=(Te/Ts)-(Te,nom/Ts,nom), where Te and Ts are respectively the outdoor and the supply air temperatures, and nom is an index related to nominal characteristics. Another similar equation gives the cooling energy rate. With these two equations, real running-time and performance of the system can be calculated. Testing these equations on various manufacturers data sets relative to characteristics of roof-top leads to an average quadratic error of less than 4 %. The main advantage for using such model is the small number of required data.

Supply air conditions are a result of supply air flow rate m_S and loads of the building Φ -total load, in [W]- and W -moisture load, in [kg/s]-, which are calculated using an already validated dynamic multi-zones building simulation model (COMFIE, details about validation can be found in reference [11]). Simulation are performed on a whole year using a one-hour step-time. As roof-top air conditioners are running with a constant air flow, knowing the fresh air flow rate and the return air flow rate , one can calculate (at each time step) the supplied conditions (Ts, ws), the cooling energy rate and the compressor electrical power. Air handling cycles in the psychometric chart, and finally energy consumption of roof-tops including auxiliaries (fans) are calculated, as described in [2]. For each step, information on occupation and in-occupation, occurrence, month, electric tariff period is kept in order to be able to do a costs analysis. Validation of this equipment modelling is presented in [13].

Display cases modelling

The heat balance of a display case is influenced by different heat gains and losses, those due to exchanges between the ambience outside the case and inside conditions (transmission through insulated surfaces of the furniture, induction due to air curtains or openings of the furniture, radiation from surrounding surfaces), and those due to equipment implemented in the furniture (lighting, fans, heating pipes, defrosting system, restocking of food into the case). The moisture balance of the display case has also to be calculated, due to moisture exchanges (by induction) and finally corresponding defrosting power can be known.

The relative weight of each term in the global balance, under nominal conditions (25°C, eps = 60 %), is the results of laboratory tests. Values according to display cases typical configurations (multishelf, reach-in, positive, negative, ...) are given in [12].

Display cases continuously operate as heat and moisture trap. During summer period, uncontrollable ambience cooling by display cases is very consuming, because display cases evaporator temperature could be near -35°C, versus about 4°C for a roof-top air conditioner. Furthermore, dehumidification in display cases is also consuming, due to the additional energy required for defrosting and re-cooling cycles.

Coupling between HVAC system and display cases

The proposed methodology is described in details in [10].

Display cases are conventionally tested under specified conditions (25°C, 60% RH), which are very different from those met in real operation. In a typical supermarket, display cases are concentrated in about 20 % of the total sales area. Vertical cases are generally facing each other, creating aisles. The typical height of those types of equipment is about 2 meters. In this area, the nominal cooling rate is near 200W/m². Heat and moisture exchanges depend on immediate surrounding air. The cold air remains in the cold aisle. A vertical stratification is then experienced : this is what is called the cold aisle phenomenon.

Our methodology is based on the study of induction through the air curtain.

If we consider as an example a vertical display case, the discharge jet is blown from the top to the bottom. Induction of air occurs between the discharge jet and the ambient air and between the discharge jet and the air inside the display case. Near the supply nozzle, there is little mixing due to the high velocity of the jet. Induction increases continuously to be maximum near the extraction, as the jet decreases in velocity and widens.

Discretising the air curtain in horizontal layers, the exchange coefficient for each layer depends on evolution of turbulence across the jet. Results of [4] on turbulence calculations show that the initial flow and diameter of the curtain air are the two parameters influencing the exchange coefficient. From these results, our model considers a constant exchange rate in each layer, called r_J. Results presented in [8], based on a Navier-Stockes 2D modelling of the air curtain under standardised conditions show that r_J increases nearly linearly from the top to the bottom. A linearly regression is chosen in our model.

If the conditions $h_{AJ} = h\,(T_{A,J}, w_{A,J})$ of the ambient air in the layer j of the cold aisle are known, enthalpy exchanges in the layer can be extrapolated by:

$$\frac{Q_{2,J}}{Q_{2,nom,J}} = r_J \cdot \frac{h_{a,J} - h_{i,J}}{h_{a,nom} - h_{i,J}}$$

where :

$h_{A,NOM}$ corresponds to nominal conditions, as described previously -h (25°C,60% RH)-

$h_{i,J}$ describes the conditions (T_I, eps_I) inside the display case

$Q_{2,J}$ is the enthalpic exchange due to induction through the Jth layer of the air curtain

In the upper layer, the conditions T_A and w_A are the boundary conditions imposed by the rest of the sales area. Once, one can calculate the vertical profile of temperature in the cold aisle and T_C, the mean temperature in the cold aisle can then be computed.

The ratio between actual load and nominal load (corresponding to 25 °C and 60 % all around the case) is then calculated at each time step. A example of actual load for a typical vertical multi-shelf display case is shown on figure 4. This kind of results is not a standard output of Clim Top but needs expert use and adaptations.

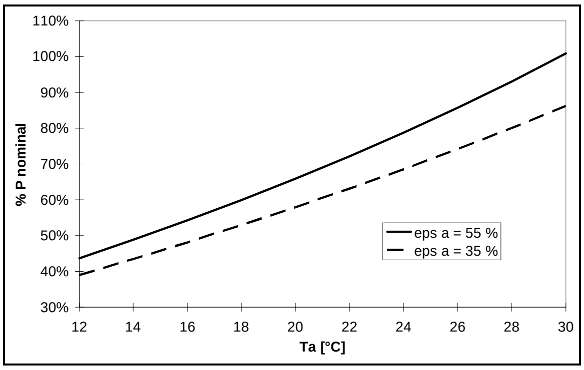

figure 4: real loads of display cases in the cold aisle

At each step time, all terms of the balance of display cases (operating in cold aisle) varying with ambient conditions are calculated. Real loads of heat and moisture created by display cases are then updated in the building global balance as to obtain Φ and W.

On figure 5, hourly average loads due to cooling, defrosting and display cases operation (separated in positive cases -which operate around 2°C, 80%- and negative cases -which operate around -18°C, 90 %-) are shown for a given day of May.

As we can see, display cases actual loads variations due to changes in indoor temperature and humidity ratio are far from negligible. Energy consumption due to electric defrosting is also increasing during store occupation, due to high moisture loads coming from air infiltration and people.

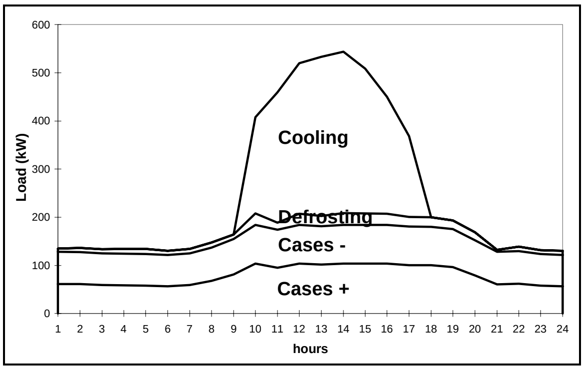

figure 5: cumulated load curve

SENSITIVITY ANALYSIS

Different uses of Clim Top have been already performed on real supermarkets. Here are some examples of these first applications (the sales area of each supermarket is indicated in brackets) :

- estimate the influence of excessive air infiltration in the building (1300 m²).
- estimate interest of heat recovery on condensers of display cases (2000 m²)
- replacement of existing unit heaters by heat pumps (1500 m²)
- design of air conditioning system (2500 m²)
- comparison with metered monthly values of energy consumption by-end use (10000 m²)

Instead of describing one of those particular studies, which are relatively confidential, we develop here below a short sensitivity analysis realised on the basis of a real supermarket located in Paris. Its main characteristics are as following:

The sales area is around 2500 m^2 (4m height - 10000 m^3).

Light structure.
Exterior walls : 15 cm concrete.
Floor : 20 cm concrete.
Roof : 6 cm cellular concrete, 50 cm glass wool, tiles.
Glazing : Simple glass, 16 m^2 East orientation.

The ground plan of the supermarket is shown on figure 6.

For more information on other parameters (location, occupation, equipment, ...), one can refer to [9].

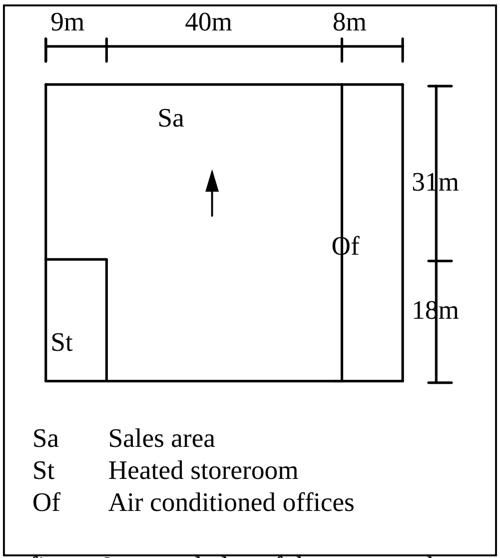

figure 6: ground plan of the supermarket

Results for reference case

The following analysis mainly concerns air conditioning consumption. Of course, as explained before, energy analysis or energy audit must be global in supermarkets by taking into account all uses : lighting, display cases air conditioning, ...
HVAC energy consumption is one element in the global energy invoice. Some global energy balances are presented in [10].

The required energy rate of HVAC system depends on outdoor temperature and humidity ratio, solar gains, internal gains and setpoints (temperature and even humidity). For each outdoor temperature, the different values of heat loads are calculated and then sorted out. The aim of sorting values is to reduce the 8760 hourly loads to about an hundred of average conditions (outdoor temperature, load) before calculations of the system (this methodology is described in more details in [2]). For each situation, other parameters are averaged (i.e.: indoor temperature, outdoor and indoor humidity ratios, moisture loads). When sorting the loads, they must be split into:

- Loads during occupancy periods;
- Loads during non occupancy periods.

Information on number or number of hours of occurrence and electric tariff periods is kept in order to be able to make a complete economical analysis.

Figure 7 illustrates the values of sorted loads (Cooling is negative and Heating positive) versus outdoor temperature. Due to the fact that there is no setpoint during non occupancy periods, cooling operates only during occupancy. Heating is mostly concentrated during non occupancy when internal gains are low.

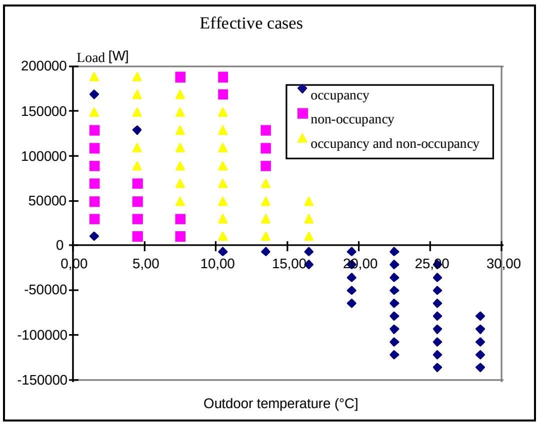

figure 7

Heating occurs during 1203 h, cooling during 3747h. During the remaining 3786 h, the building is in free evolution.

The annual consumption for all needs is 1 220 000 kWh for 2500 m^2, i.e. 500 kWh/m^2. Relative shares of consumption by end-use are as follow:

Sales area	heating	15%
	cooling	4%
Storage area	heating	5%
Offices	cool.+heat.	1%
Lighting		16%
Display cases		43%
Others		16%

A sensitivity analysis of the HVAC energy consumption to various parameters is developed hereafter. HVAC energy consumption in sales area is compared to the basis case - i.e. 232 000 kWh (93 kWh/m^2), defined as a basis 100-. Only a part of the simulations given in [9] is reported in this paper. Influence of following parameters is studied :

- Air infiltration due to occupancy (AI),
- HVAC system characteristics(H),
- Setpoints (S).

Air infiltration

Majority of air infiltration is due to the apertures of the doors, increasing with number of clients in the supermarket. In the base case, air infiltration is 3 vol/h, we simulated the influence of 1 ACH (vol/h) (AI1) and 5 ACH (AI2). HVAC energy consumption is very sensitive to air infiltration as shown in the table. It is highly advised to set up an airlock at the entrance of the supermarket and to prevent infiltration from storerooms.

	Cooling basis 100	Heating basis 100	Total basis 100
AI1	134	37	58
AI2	86	149	135

HVAC system characteristics

During operation, fouling of coils makes the efficiency of the system decrease. A test has been processed to evaluate the importance of this phenomenon on energy consumption with diminution of 20 % of the coefficient of performance of the Roof Top (H1). Then, heat recovery on condensers of display cases is investigated : 20 kW recovered (H2), 40 kW recovered (H3). Influence of fouling shows the interest of good maintenance of equipment to save energy. As one can observe in the table, it is also a very good energy investment to have recovery on display cases ; it becomes more and more usual to find it in supermarkets.

	Cooling basis 100	Heating basis 100	Total basis 100
H1	111	116	115
H2	100	83	86
H3	100	70	77

Setpoint influence

Supermarkets technical managers are interested in knowing how changes in the setpoints are influent on the energy invoice. Some tests are proposed hereafter. The basis case conditions are 17°C for heating, 25°C for cooling and 12°C during non occupancy periods.

	Set Points	Sales area
S1	heating. occ. [°C]	20
	cooling. occ. [°C]	25
	heating. non-occ [°C]	15
S2	heating. occ. [°C]	18
	cooling. occ. [°C]	23
	heating. non-occ [°C]	9
S3	heating. occ. [°C]	19
	cooling. occ. [°C]	24
	heating. non-occ [°C]	9
S4	heating. occ. [°C]	21
	cooling. occ. [°C]	26
	heating. non-occ [°C]	11

For these different setpoints the HVAC energy consumption varies as shown below. It is clear that setpoints are very influent but the technical manager must take care of comfort considerations which react on sales amount, even if it is hardly quantifiable.

	Cooling basis 100	Heating basis 100	Total basis 100
S1	100	152	140
S2	134	139	138
S3	118	146	140
S4	83	142	128

Figure 8 shows the influence of 1°C on daytime setpoint on cooling consumption (between 11 and 12% in the considered range). The basis 100 % corresponds to a setpoint of 22 °C.

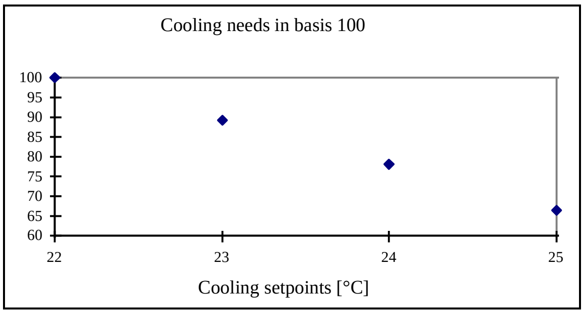

figure 8

Figure 9 shows the influence of 1°C on a daytime setpoint on heating consumption (around 5 % in the considered range). The basis of 100 % corresponds to a setpoint of 17 °C.

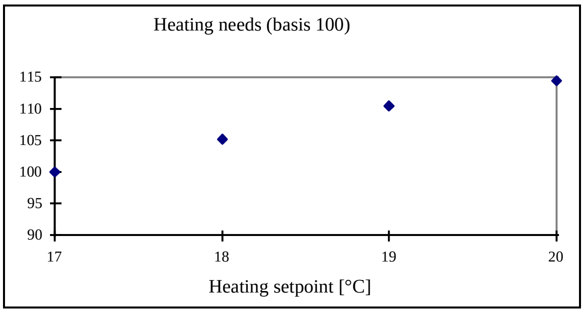

figure 9

It is obvious that these results are only valid for the studied supermarket.

CONCLUSIONS

This work demonstrates the feasibility of a simulation tool adapted to users who are not familiar with the use of simulation in practice. The close relationship between developers and users has allowed to create a easy-to-use interface. Taking into account the specifications of supermarket thermal behaviour (for example: description of display cases) has also been important. A first version of Clim Top has been distributed to store managers. Future exchanges will enable to see in more details and on a longer period the users interests in using this tool.

A major issue coming from the sensitivity analysis is that ambience conditions have a large influence on HVAC energy consumption. However, it is clear that energy balance must also include refrigeration equipment. The proposed modelling methodology of coupling between HVAC and display cases could be useful in order to consider such a global balance.

As a research tool, this software is going to be improved and is going to be used to test improved technologies applied to air conditioning system, such as desiccant cooling or night cooling storage.

REFERENCES

[1] Adams P., 'Intereffects in supermarkets', ASHRAE Journal, p.38-40, October 1985

[2] Casari R., Marchio D., Stan S., Dumitru R., 'Air conditioning energy consumption estimation', Proceedings of Clima 2000, 1992

[3] Crawley D. B., Lawrie L. K., Winkelmann F. C., Pedersen C., 'Next-Generation Building Energy Simulation Tools - A Vision of the Future', Proceedings of the 1996 ACEEE summer Study, Vol. 4, 1996

[4] Howell R. H., 'Effects of store relative humidity on refrigerated display case performance", ASHRAE Transactions Vol. 99, 1993

[5] Howell R. H., 'Calculation of humidity effects on energy requirements of refrigerated display cases', ASHRAE Transactions Vol. 99, 1993

[6] Khattar M.K., Morton H.B., Walker D.H., 'Modeling supermarket refrigeration energy use and demand', ASHRAE Journal, July 1991

[7] Meckler G., 'Efficient integration of desiccant cooling in commercial HVAC systems', Desiccant cooling and dehumidification, ASHRAE Special Publication, 1992

[8] Morillon C., 'Aéraulique des M.F.V.', proceedings of Journées Froid et distribution commerciale, Juin 1996

[9] Orphelin M., Marchio D., Casari R., Tassone A., 'Clim Top: logiciel pour la conception et l'audit de la climatisation des grandes surfaces de vente', December 1996

[10] Orphelin M., Marchio D., 'Influent parameters on energy consumptions in frozen food area of large

supermarkets', to appear in the Proceedings of Clima 2000, 1997

[11] B. Peuportier, I. Blanc, 'Comfie - Passive solar design tool for multizone buildings', User guide Centre d'Energétique, Ecole des Mines de Paris, January 1992

[12] Rigot G., 'Meubles et vitrines frigorifiques", Pyc Editions, 1990

[13] Stan S., 'Maîtrise et calcul des consommations des installations de climatisation dans le secteur tertiaire', S. Stan, Thèse de doctorat, Centre d'Energétique, Ecole des Mines de Paris, January 1995

NOMENCLATURE

T	temperature [K]
eps	relative humidity [%]
P_E	compressor electrical power [W]
P_C	cooling energy rate [W]
h	specific enthalpy [J/kg dry air]
w	humidity ratio [kg water/kg dry air]
F	building enthalpic loads [W]
W	building moisture load [kg/s]
Q	heat rate or cold rate [W]
r	induction exchange rate coefficient

Indices

A	indoor conditions
E	outdoor conditions
S	supply air conditions
C	cold aisle conditions
I	conditions inside cold display case