BUILDING ENERGY PERFORMANCE ASSESSMENT THROUGH SIMPLIFIED MODELS: APPLICATION OF THE ISO 13790 QUASI-STEADY STATE METHOD

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ABSTRACT

Following the issue of the European Directive on the "Energy performance of buildings" estensive international research activities have been carried out on the elaboration and adoption of standards containing common methodologies for building energy performance assessment.

One important item concerns the definition of a simplified method for the calculation of energy use for space heating and cooling (ISO/FDIS 13790). A simplified quasi-steady state calculation method is presented in this standard. A further validation is needed to apply this method to different building typologies and to different climatic conditions, and this should include comparison with detailed simulations as well as the analysis of different case studies.

The results of a research activity that has been concentrated on the validation of this simplified quasi-steady state method, is presented in this paper.

The analyses showed that the accuracy of the results is affected to a great extent by calculation assumptions, boundary conditions and input values, which should be carefully specified.

KEYWORDS

Space heating and cooling demand, Building energy assessment, Simplified methods, Dynamic parameters, Technical standards.

INTRODUCTION

Building energy performance assessment has become compulsory in Europe after the issue of the European Directive on the "Energy performance of buildings" (EPBD, European Union 2003). The EPBD sets energy performance requirements for new buildings and for existing buildings subject to major renovation and establishes that "when buildings are constructed, sold or rented out, an energy performance certificate has to be made available to the owner or to the tenant". The energy performance concerns the amount of energy consumed or estimated to satisfy all the needs of the building (heating, hot water heating, cooling, ventilation, lighting). As a consequence, extensive research activities, both at national and international levels, have been carried out to create a general framework for a calculation methodology of the building energy performance. Many problems have arisen, concerning the definition of energy ratings (based on metered energy – also called operational rating – or on the calculation using standard data – also called asset rating), the accuracy of the calculation methodology (simple or detailed), the discrepancies between an application to new or to existing buildings, the layout of the energy performance certificate, the mutual relation between energy performance and indoor environment quality (in terms of thermal and visual comfort and IAQ) and the opportunity of relating the energy certification to the indoor environment certification.

One of the main topics of interest is the assessment of the energy needs for heating and cooling which account, in Europe, for more than 56% of the end uses in both commercial buildings and dwellings. In order to assure a widespread diffusion of building energy certification (in Italy there are 13 million of buildings, most of which are residential - 86%) it is in fact very important to set up a simplified but sufficiently accurate calculation methodology.

BUILDING ENERGY ASSESSMENT THROUGH EUROPEAN STANDARDS

A series of standards aimed at defining a common calculation methodology, harmonized throughout different European countries (CEN 2005), is currently under development by CEN (European Committee for Standardization). Those standards can be grouped into three categories.

The first category deals with standards that define the different types of energy ratings of a building (design, asset, tailored, operational) and sets general criteria and validation procedures for the calculation models.

The second category includes standards that concentrate on the assessment of the thermal performance of the building and provides input data, material properties, boundary conditions and calculation procedures of the net energy needs for space heating and cooling.

The third category includes standards that provide the calculation procedures for system losses and efficiencies for the different energy systems (space heating/cooling, DHW, lighting, ventilation and air conditioning, use of renewables) and allow the annual energy use to be determined in terms of delivered energy-wares and primary energy from the energy needs for heating, cooling, DHW production, lighting.

The most important standard in the second category is ISO/FDIS 13790 (ISO 2007), which provides three building net energy calculation methods for space heating and cooling, common boundary conditions and input data. The first method is a quasi steady state method based on a monthly balance of heat losses and heat gains. The second method is an hourly calculation method based on a simplified analogous electric circuit. As a third choice, it is possible to use any detailed building energy simulation method.

All the models partition the buildings into thermal zones with different functions, set points and ventilation rates.

ISO/FDIS 13790 QUASI-STEADY STATE MODEL

This model, developed by Van Dijk and Spiekman (2003), is based on a monthly balance of heat gains and heat losses determined in steady state conditions. Dynamic effects are taken into account through the introduction of an internal temperature adjustment for heating and cooling intermittency and of an utilization factor for gain-loss mismatch. The basic formulations of the model (van Dijk et al. 2005) are:

$$Q_{NH} = Q_{L,H} - \eta_{G,H} \cdot Q_{G,H} \quad (1)$$

for the monthly energy need for heating Q_{NH}, and

$$Q_{NC} = Q_{G,C} - \eta_{L,C} \cdot Q_{L,C} \quad (2)$$

for the monthly energy need for cooling Q_{NC}, where:

$Q_{L,H}$: heat losses for the heating mode;

$Q_{L,C}$: heat losses for the cooling mode;

$Q_{G,H}$: heat gains for the heating mode;

$Q_{G,C}$: heat gains for the cooling mode;

$\eta_{G,H}$: gain utilization factor for the heating mode;

$\eta_{L,C}$: loss utilization factor for the cooling mode.

The utilization factors represent the portion of gains (during the heating season) or of losses (during the cooling season) that contribute to the reduction in the heating demand (during the heating season) or in the cooling demand (during the cooling season). The non utilized part of the gains (in winter) or of the losses (in summer) depends on the dynamic mismatch between the gains and losses, which may cause an overheating over the heating set point temperature in winter or an under-cooling below the cooling set point (e.g. during summer nights). For details on the quasi-steady state modeling assumptions and on the significance of the dynamic parameters, reference can be made to Corrado and Fabrizio (2007).

Even though Eqs. 1 and 2 can always be applied since it is always possible, from a theoretical point of view, to define correct utilization factors and intermittency adjustment factors that satisfy these equations, it is usually not simple to determine monthly (or seasonal) values of dynamic parameters by means of simplified correlations.

Application of this model to some reference cases and comparison with other simulation tools made by Corrado et al. (2007) for different climatic conditions as a part of a national research programme on building energy certification showed that the results are greatly affected by the determination of the numeric value that has to be assigned to the monthly utilization factor. The results are also affected by heat transfer nonlinearities.

The accuracy of this method, as regards the determination of the energy needs for heating, has been deeply investigated after a decade of applications of the standards that adopt this method (UNI 10344 in Italy, EN 832 in Europe) and of research activities (Sjösten et al. 2003, Jokisalo and Kurnitski 2007). The applicability of this calculation procedure to determine the energy needs for cooling still remains to be investigated.

CASE STUDIES AND VALIDATION PROCEDURE

The results of a research activity concentrated on the validation of the previously mentioned quasi-steady state method is presented in this paper. The following aspects were investigated:

- the influence of the zoning level on the accuracy of the results;
- the determination of heat losses
- the determination of the utilization factors
- the influence of intermittency

Three case studies were selected to validate the method through a comparison with a detailed building simulation tool. The first two case studies (a detached house and a block of flats) are representative of the Italian building stock and building construction technologies, while the third case study was based on international specifications drawn up for the EU SWIFT project.

Detached house

A 87 m², two-storey detached house of was adopted. The walls are made of two brick layers with an internal glass wool layer. The tilted roof is tiled and insulated. The floor is in contact with the ground and it is not insulated. The total window area is equal to 15.4 m². The ratio of the thermal envelope area (S_e) to the conditioned volume (V_c) is equal to 1.09 m^{-1}. The heat transfer coefficient of the building is equal to 301 W/K, and the internal heat capacity is equal to 27.3 MJ/K. Other constructions with higher thermal insulation and lower internal thermal capacitance were also simulated.

Block of flats

A 1230 m² five-storey block of flats was adopted. Like the detached house, the walls are made of two brick layers with an internal glass wool layer. The total window area is 177 m². The S_e/V_c ratio is equal to 0.41 m^{-1}. The heat transfer coefficient of the building is equal to 2370 W/K, and the internal heat capacity is equal to 404 MJ/K. Other constructions with higher thermal insulation and with lower internal thermal capacitance were also simulated.

Office building

The building is a medium-sized office building with office modules aligned on two facades, separated by a central corridor, with staircase/service spaces at both ends of the building (IEA 2002).

The external dimensions of the building are: length 67 m, width 15 m and height 26 m. The total window area corresponds to 34% of the front and the back façade. The S_e/V_c ratio is equal to 0.21 m^{-1} while the ratio of the thermal envelope area to the conditioned floor area (S_c) equals 0.65.

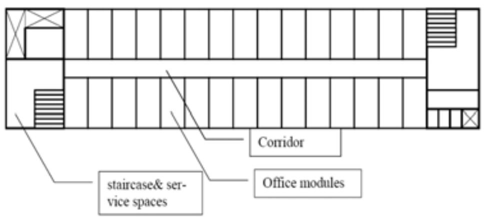


Figure 1 Top view of the office building

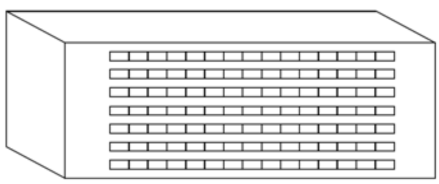


Figure 2 Front view of the office building

The validation procedure

The validation of the ISO 13790 quasi-steady state method was carried out through a comparison with the results of the dynamic building energy simulation obtained using the "EnergyPlus" software (Crawley et al. 2001). The net energy needs of the building, under ideal conditions, was determined by the software. An ideal system called "Purchased air with an infinite heating/cooling capacity" was adopted in order to make the results independent of the system features.

The necessity of having to determine the monthly heat gains and heat losses in steady state conditions to be used in Eqs. 1 and 2 led to a calculation procedure of the gains and losses through dynamic simulations. This procedure is fully described in Corrado and Fabrizio (2007).

THE INFLUENCE OF THE ZONING LEVEL ON THE ACCURACY OF THE RESULTS

Before the application of any thermal model, it is necessary to partition a building into different zones, in order to perform separate heat balance for each zone.
Standard ISO/FDIS 13790 defines criteria for the partitioning of a building into thermal zones. These criteria depend on the set point temperature difference between the spaces and on the coupling of the thermal zones with different heating/cooling systems.
The effect of the zoning level on the accuracy of the results has been analyzed in an office building case study. The zoning configurations selected are reported in Table 1.

The calculation of the building energy needs for heating and for cooling was performed through the ISO/FDIS 13790 quasi-steady state method for different locations (Tunis, Rome, Frankfurt and Stockholm), in order to ascertain the influence of different climatic conditions.

A comparison of heating and cooling energy needs for different zone configurations and for different cities is presented in figures 3 and 4. The relative energy needs are reported in these figures expressed as heating/cooling energy needs ratios for the current zoning configurations (Q_{NHC}) with reference to the heating/cooling energy needs (Q_{NHCref}) concerning the most detailed zone level (façade floor zone).

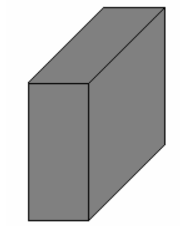
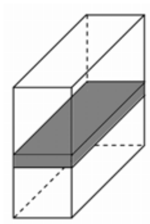
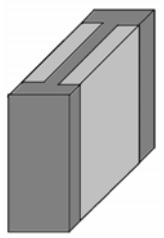
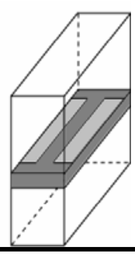
Some considerations can be deduced from the results reported in figures 3 and 4.

- The "single zone" and the "floor zone" configurations present the same energy needs. This is an obvious conclusion as the simplified method treats the floor zone configuration as an uncoupled zone (same indoor temperature for different floors), and therefore the total energy needs for the building are unaffected. However, the application of a floor zone configuration can be of interest since it gives important information about the heating/cooling power that has to be installed on each floor, if the calculations are also performed in design conditions.
- The "façade zone" and the "façade floor zone" configurations present the same energy needs for heating, but different energy needs for cooling.

This is caused by the vertical mixing of air in the "façade zone".

- The effect of a detailed zoning is important for extreme weather; in fact for Tunis, which is characterized by warm winters the relative error induced on the heating demand by an inadequate zoning is about 25%. On the other hand, for Stockholm, the relative error reaches 40% in cooling demand assessment.

Table 1 Zone configurations description

Zoning configuration	Configuration
Single zone Whole building as a single zone: all the building is conditioned. Mixing of temperatures and activities across the whole building; internal partitions/intermediate floor as internal mass	
Floor zone One floor as single zone: all the floors are conditioned. Mixing of temperatures and activities across the whole floor; top and bottom floors are different; internal walls as internal mass	
Façade zone Whole building as three zones: i. All office modules at one façade: Conditioned space ii. Corridor plus halls/service space : Unconditioned space iii. All office modules on second façade: Conditioned space Vertical mixing of temperatures, activities across on all floors on one facade; top and bottom floors are different; internal walls as internal mass	
Façade floor zone One floor and a set of office/corridor/ office as three zones. Office modules are conditioned. Mixing from façade to façade; no mixing between floors	

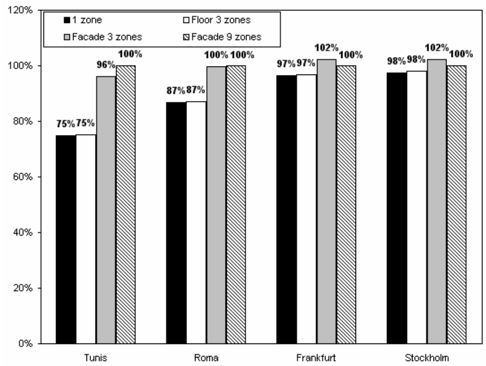


Figure 3 Energy needs for heating for different zonings

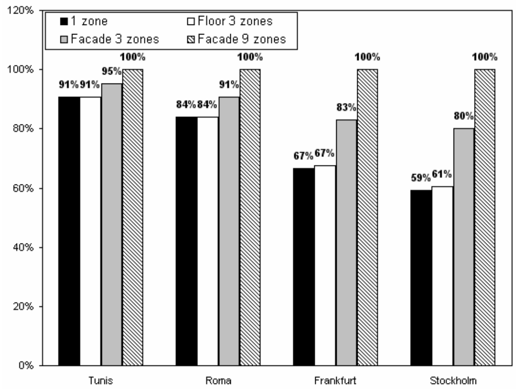


Figure 4 Energy needs for cooling for different zonings

THE DETERMINATION OF HEAT LOSSES

The validation of the simplified monthly quasi-steady state model has shown that attention should be paid to the determination of the heat losses. Although the driving force of the losses in the simplified model is generally considered to be the difference between the internal and the external air temperature, it should be pointed out that the heat transfer phenomenon is greatly affected by the sky vault temperature and by the heat transfer via the ground. The first phenomenon is taken into account in ISO/FDIS 13790 through a coefficient that reduces solar gains. The second phenomenon can be modeled according to the relevant normative standards that provide the calculation procedures to determine the heat transfer via the ground (EN ISO 13370).

THE DETERMINATION OF THE UTILIZATION FACTORS

The utilization factor depends on the thermal inertia of a building and on the ratio of the heat gains to the heat losses.

An equation in the form

$$\eta_{G,H} = \frac{1-\gamma_H^{a}}{1-\gamma_H^{a+1}} \qquad (3)$$

is usually adopted to determine the utilization factor, where γ_H represents the gain/loss ratio for heating. A similar correlation can be adopted in the case of the utilization factor for cooling

$$\eta_{L,C} = \frac{1-\lambda_C^{a_C}}{1-\lambda_C^{a_C+1}} \qquad (4)$$

where λ_C represents the loss/gain ratio for cooling. Values of the parameter *a* are usually determined using a correlation such as the one supplied by the ISO/FDIS 13790 standard

$$a = a_0 + \frac{\tau}{\tau_0} \qquad (5)$$

which provides the same numerical values of the parameters for both heating (subscript H) and for cooling (subscript C)

$$a_H = a_C = 1 + \frac{\tau}{15} \qquad (6)$$

In Eqs. 5 and 6, τ is the time constant of the building, expressed in hours, taking into account the thermal inertia of the building.

Application of the monthly method and a comparison with the results of detailed simulation software (Corrado and Fabrizio 2006) show that Eq. (4) proposed by CEN is correct in its general expression, even in the case of the determination of energy need for cooling, as reported in figure 5, but a better approximation of the numerical coefficient *a* is needed.

From the results of a large number of dynamic simulations performed on the detached house and on the block of flats (case studies tailored to the Italian building technologies and constructions) Corrado and Fabrizio (2006) determined the following correlation

$$a_C = 6 + \frac{\tau}{17} \qquad (7)$$

which shows a similar slope, but significantly higher values than the correlation of Eq. 6 proposed in ISO (2007). Jokisalo and Kurnitski (2007) also determined a much greater value of a_0 than 1, which is equal to 6 for space heating of apartment buildings and detached houses.

The building function has in fact a great influence on the correlation when determining the *a* coefficient. Another study by Corrado and Fabrizio (2007) showed that the differences between buildings (detached house, block of flat, offices) can be accounted for by adding a parameter to the correlation of Eq. 5 that depends on the glazed area of the envelope. This is due to the fact that highly glazed external envelopes yield a wide-ranging hourly profile of heat losses (leading to a decrease in the internal temperature below the cooling set point) and this effect is not duly taken into account through the building time constant. A new correlation was introduced for dwellings as well as for office buildings

$$a_C = 8 - 13\,\xi + \frac{\tau}{17} \qquad (8)$$

where ξ is the ratio between the glazed area of the envelope and conditioned floor area.

The above formulations are suitable for the Italian national building stock and climatic conditions.

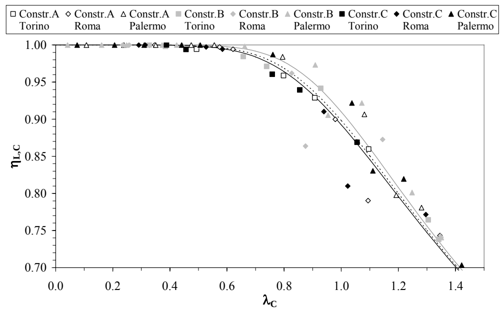


Figure 5 Values of the utilization factor for cooling vs. the loss/gain ratio for a block of flats

The need for dynamic parameters related to a national context and not fixed to those values proposed by ISO (2007) in the 13790 standard, also has been raised in other countries.

Similar studies have been carried out by Jokisalo and Kurnitski (2007) for modern Finnish buildings in a cold climate, showing that the monthly method is a reasonable choice for residential buildings if the new values of the determined dynamic parameters are adopted. On the other hand, they state that the same method is not suitable to model office buildings, and in this case they suggest the application of a simple hourly method or a detailed simulation method.

Salmeron Lissen et al. (2006) analyzed the relationship between the utilization factor for cooling and the cooling period, and came to the conclusion that the utilization factor for cooling varies as a function of the cooling period. This appears, however, to be consistent with the ISO/FDIS 13790 standard which accounts for this effect through the intermittency factor.

THE INFLUENCE OF INTERMITTENCY

Depending on the usage schedule of a building, the delivery of heating or cooling power to a conditioned space may be subject to intermittent modes, which depend on the occupancy time.

ISO/FDIS 13790 presents a method to assess the energy needs in intermittent mode by introducing an adjustment to the set point temperature or a reduction factor for heating and cooling energy needs. The reduction factor is a function of the building time constant τ and of the heat balance ratio γ.

An example of intermittent mode is presented in figure 6: before the start of the normal period (N), the conditioning system operates at its maximum power (φ_{hmax}) until it reaches the set point temperature (θ_i): this phase is called the boost phase (t_3); then the conditioning system begins to deliver energy to maintain the indoor temperature until the end of the normal period and the start of the reduced period (R).

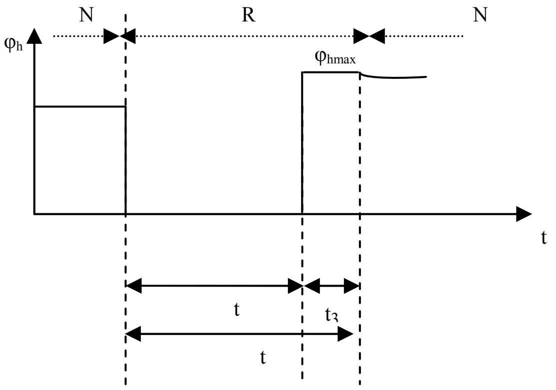


Figure 6 Intermittency mode

The effect of different intermittency patterns and different building technologies on the energy needs for heating and cooling has been analyzed in the previously described office case study. The building energy needs for heating and for cooling were first determined, considering the climate of Rome, by means of EnergyPlus software, in order to ascertain the influence of different heating/cooling patterns and of thermal inertia.

Structures varying from very light to very heavy weights were chosen (see table 2). The internal walls and internal floor constructions were changed to obtain the variation in the building inertia. U-values and internal specific heat capacity of the building were calculated in compliance with the ISO/DIS 13786 (2005) standard.

Table 2 Building inertia variations

Building inertia	Internal specific heat capacity [kJ/m^{2}K]	Time constant [h]
Very lightweight: VL	78	15
Lightweight: L	100	20
Medium weight: M	147	28
Heavyweight: H	260	50
Very heavyweight: VH	380	73

The following three heating/cooling patterns were adopted to study the heating/cooling energy needs:

- Continuous mode: the conditioning plants switched on every day and every hour.
- Intermittent night: the conditioning plants are only switched off during the nights (from 18 to 08 each day).
- Intermittent week end: the conditioning plants are switched off at week-ends.

Effect of heating/cooling patterns

The values of the heating/cooling energy needs resulting from simulations are reported in figures 7 and 8, where the percentage variations are calculated with reference to the continuous mode. The following considerations can be drawn.

- The effect of intermittency, as stated in the ISO/FDIS 13790 standard, is more important during the heating season than during the cooling season.
- An evening/night conditioning plant switch-off has only a limited effect on the energy needs for cooling.
- An evening/night heating plant switch-off has more effect on the energy needs for heating than a long period of cut-off.

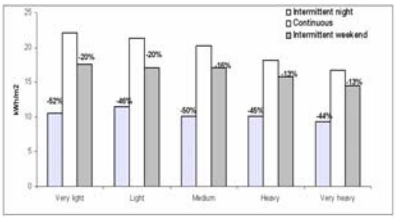


Figure 7 Effect of heating patterns on specific heating needs

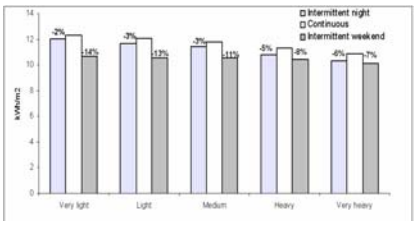


Figure 8 Effect of cooling patterns on specific cooling needs

Effect of thermal inertia

The same results shown in figures 7 and 8 are reported in figures 9 and 10 with reference to a medium-weight structure. The results show that the thermal inertia of the structures has an important effect on the total heat energy demand.

- The energy needs for heating increase with building thermal inertia during short intermittent periods while it decreases for long intermittent periods.
- The energy needs for cooling decrease with the building thermal inertia. This decrease is more significant for intermittent short time periods.

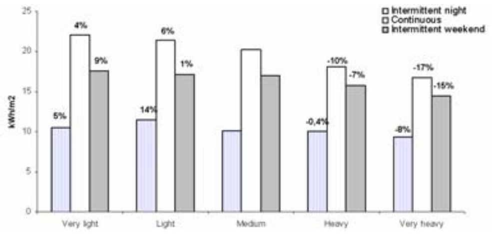


Figure 9 Effect of thermal inertia on specific heating needs

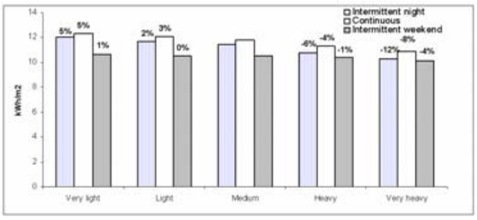


Figure 10 Effect of thermal inertia on specific cooling needs

Intermittent calculation for the simplified method

The simplified method proposed in ISO/FDIS 13790 was applied subsequent to the above detailed simulations, in order to correlate the dimensionless reduction factor for intermittent heating or cooling with the main building features.

According to ISO/FDIS 13790, an adjusted internal temperature is determined which:

- is a time average of the set point temperatures in the case where the set point temperature variations between the normal and reduced periods are less than 3 °C or the time constant of the building is less than 0.2 times the duration of the shortest reduced heating or cooling period;
- is equal to the set point temperature for the normal mode when the time constant of the building is greater than three times the duration of the longest reduced heating period.

In the case of intermittent heating (or cooling) which does not fulfill the conditions of adjusted temperature, the energy needs are assessed using a dimensionless reduction factor for intermittent heating or cooling $a_{H/C,red}$ applied to the energy needs calculated in continuous mode, and defined as follows:

$$a_{H,red} = 1 - b_{red}(\tau_{H/0}/\tau).\gamma_H.(1 - f_{H,hr}) \qquad (9)$$

$$a_{C,red} = 1 - b_{red}(\tau_{C/0}/\tau).\gamma_C.(1 - f_{C,day}) \qquad (10)$$

where:
$f_{H,hr}$: fraction of the number of hours in the week with a normal heating set point;
$f_{C,day}$: fraction of the number of days in the week with a normal cooling set point;
b_{red} : empirical correlation factor; value $b_{red} = 3$;
τ : time constant of the building zone;
$\tau_{H,0}$: reference time constant for the heating mode;
$\tau_{C,0}$: reference time constant for the cooling mode;
γ_H: gain/loss ratio for the heating mode;
γ_C: loss/gain ratio for the heating mode.

Due to the diurnal pattern of the weather and to the effect of the building thermal inertia, an evening/night thermostat setback or switch-off has in general a relatively much smaller effect on the energy needs for cooling than on the heating energy needs. This leads to slight differences between the two formulations ($f_{H,hr}$, $f_{C,day}$) of the reduction factor.

Figures 11 and 12 show that the reduction factor for heating is a linear function of the gain-loss ratio γ_H for long intermittence periods (week end), while for short intermittence periods the reduction factor tends to be independent of the gain loss ratio .

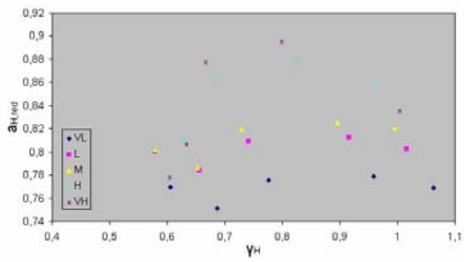


Figure 11 $a_{h,red}$ versus γ_h for different thermal masses – Night intermittency

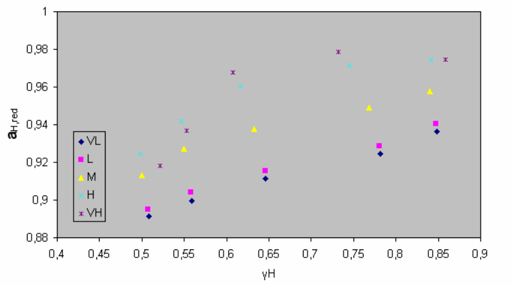


Figure 12 $a_{h,red}$ versus γ_h for different thermal masses – Long term intermittency

The reduction factor $a_{C,red}$ (fig. 13) is a linear function of the gain-loss ratio γ_C for the cooling mode and for long periods of intermittency (week end).

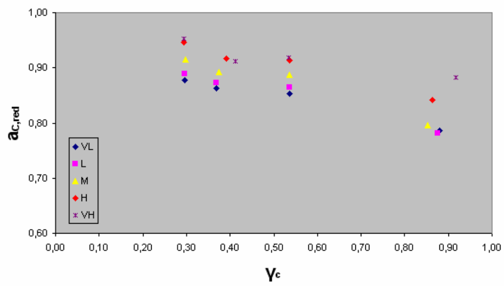


Figure 13 $a_{c,red}$ versus γ_c for different thermal mass – Week end intermittency

CONCLUSIONS

This paper analyzes the applicability of a monthly quasi-steady state method to calculate heating and cooling energy demands.

First, a need for dynamic parameters that are carefully determined and tailored to the building stock and the climate has to be satisfied. Attention should then be paid to other aspects, whose influence has here been addressed, such as the determination of heat transfer, and the zoning level of detail.

This method represents one of the few possibilities of responding to the need of a global building energy performance assessment for heating and cooling as stated in the EPBD.

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