SIMPLIFIED MODELS FOR BUILDING COOLING ENERGY REQUIREMENT

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ABSTRACT

This work regards the development and the validation a simplified model for building cooling energy requirement. It aims to be as similar as possible to the procedure adopted for calculating the winter heating energy demand of the UNI-CEN standards. The latter, a procedure based on a steady-state model, including one or more corrective numerical-experimental correlations, that take into account in a simplified way – and thus approximately – the effects of thermal capacities on the phenomena under examination. The critical evaluation of the first results suggested changing the approach, in the model correlations developing process, from a physical parameters based to a building typology based. Nevertheless, following such approach, a good agreement has been achieved between the results of a detailed hourly simulation and the values predicted by the simplified model. Indeed there is evidence that acceptable results can only be obtained by providing a correlation by building archetype. To avoid such massive work in developing building archetype based correlations, it was developed and validated a more complex simplified dynamical model, using an average monthly day, and based on the approach followed by the prEN 13792 [3] standard for the free-floating summer room temperature profile evaluation. The results show that the use of such model did not increase the quality of the results, due to too strong simplifying assumption even if more physically based, especially if compared to the full hourly dynamical simulation (i.e model based on physical equation with few simplifying assumptions).

INTRODUCTION

The initial aim of the research carried out was to define a simplified procedure for the energy requirement calculations of an air conditioned building as an alternative to hourly dynamic simulation. The simplified procedure is intended to be applied in the framework of the existing regulations, for which similar standard, on building heating energy requirements, is already used by the designers and employed by authorities in the verification process imposed by law (Legge 10/91.). In fact the research, while partially reaching the pre-defined scope, showed the difficulties in balancing formal simplicity and precision together with the applicability field of the proposed models.

The research aimed to four different objectives, closely linked, and brought the development of consequent products:

1. Development of classes of buildings for office or commercial use, and definition of archetypes for relative energy performance estimation.
2. development of software with the following purposes: the descriptive buildings data management, winter energy performance calculations according to the UNI 10344 [1] standard, assessment of the summer energy data used in the definition of the quasi-steady state model described further, and integrated handling of the hourly detailed simulations referenced to TRNSYS [4].
3. development of a quasi-steady state model for energy demand estimation useful for intelligent summer cooling system based on the offices archetypes.
4. development of a simplified dynamic model derived from existing standards and probable mandatory application.

This paper is dealing with only theme 3 and 4.

THE NEEDS AND THE CONSTRAINTS

The development of a simplified model for calculating summer cooling energy demands is strongly influenced by the need of deriving a procedure as similar as possible to, and in any case easily integrated with, the calculation procedure defined for winter heating energy demands in accordance with UNI 10344 [1] and EN 832 standards [2]. The declared aim was to integrate, in a single simplified calculation procedure both the heating and cooling demands, so as to prevent possible users from useless complications and redundant calculations.

The basic theory (from which UNI 10344 [1] and EN 832 [2] standards start out) is a monthly energy balance of the heated building, based on a quasi-steady state model. This is a model that uses equations of the steady state for the calculation of the thermal interactions and which then takes *a posteriori* account of the deviations due to the thermal capacity. This factor is called the *utilisation* *factor of free gains* η_u, which, by multiplying the steady sate values of the energy provided by the building's internal free contributions, defines the quota of the part useful for the reduction of the relative energy demands for heating. This factor is given as a functional form of two parameters, that is, the *characteristic non-dimensional time* (τ) of the building (value that takes into account the ratio between the thermal capacity and the building's global dispersion co-efficient) and the ratio between the energy gained and the energy dispersed, γ.

The monthly energy demands used for heating in continuous operation mode is thus given by:

$$Q_h = (Q_L - Q_{Se}) - \eta_u \cdot (Q_I + Q_{Si}) \tag{1}$$

where:

Q_L is the monthly energy exchanged by transmission and ventilation;

Q_{Se} is the monthly contributions due to solar radiation incident on the external surface of the opaque components;

Q_{Si} is the monthly contributions due to solar radiation incident on the internal surface of the opaque components after having penetrated the zone through the transparent components;

Q_I is the monthly energy due to internal contributions.

η_u is the factor of usage of the free contributions.

The monthly energies indicated in the equation (1) are in fact calculated in terms of energy exchanged in the day of average monthly characteristics (for transmission and ventilation in terms of average daily power with the average daily temperatures) and thus projected for the duration of the month. These quantities, furthermore, are calculated using the relations of the stationary state.

The relations that enable the utilisation factor η_u to be calculated are:

$$\eta_u = \frac{1-\gamma^{\tau}}{1-\gamma^{\tau+1}} \qquad \text{if } \gamma \neq 1 \tag{2}$$

$$\eta_u = \frac{\tau}{\tau+1} \qquad \text{if } \gamma = 1 \tag{3}$$

with τ non-dimensional time defined as:

$$\tau = \tau_o + \frac{t_c}{t_0}$$

and the ratio between energy gained and energy dispersed, γ

$$\gamma = \frac{Q_{Si} + Q_I}{Q_L - Q_{Se}} \tag{4}$$

The utilisation factor η_u is physically limited in the range 0-1.

For summer cooling, the search was thus directed to the development of a monthly energy balance equation, or an equation relative to the day having monthly average characteristics, which would be as similar as possible to (1) and which would use the same procedures for calculating the various energy contributions (Q_T, Q_{Si}, Q_{Se}, Q_I).

PRELIMINARY STUDIES ON EXISTING SIMILAR MODELS

To define a new simplified model for calculating the summer energy demands for sensible cooling, the possibility of using two existing models, that are similar in principle to the one it is wished to achieve, has been investigated. These are based on the hypothesis of calculating the thermal interactions in steady state conditions and then correcting the result with a corrective coefficient that takes into account the effects of the thermal capacity. Specifically, the model defined by the Dutch NEN 2916 [5] standard and the one developed by Schibuola [6], on a limited building typology, were examined.

The **Dutch model** is defined by the following equation:

$$Q_c = (Q_I + Q_{Si} + Q_{Se}) - \eta_u \cdot (Q_L) \tag{5}$$

where η_u is calculated, as before, with the equations of the winter model described, i.e. (2) and (3), but where the parameter γ is calculated as:

$$\gamma = \frac{Q_{Si} + Q_{Se} + Q_I}{Q_L} \tag{6}$$

The **Schibuola model** is defined by the following equation:

$$Q_c = \eta_u \cdot (Q_I + Q_{Si}) - (Q_L - Q_{Se}) \tag{7}$$

where η_u is still calculated with the equations of the winter model, i.e. (2) and (3), but with different values for τ_0 and t_0 and where the γ parameter is calculated as:

$$\gamma = 1 - \frac{Q_L}{Q_{Si} + Q_{Se} + Q_I} \tag{8}$$

To check the degree of reliability of the forecasts that can be made with these models, a generic set of buildings with light, medium, and heavy structural characteristics, with normal and/or reflecting glass has been selected, and for these the monthly summer and monthly winter energy demands have been estimated, using both the two simplified models quoted and the TRNSYS [4] dynamic hourly simulation program. The analysis was extended to three climatic sites typical of Italy: Milan, Rome and Palermo.

The results of this preliminary comparative analysis are summarised in Figure 1, where $Q_{\text{h trn}}$ represents the summer demands calculated with TRNSYS (hourly dynamic simulation), $Q_{\text{h schib}}$ that with the Schibuola model, and $Q_{\text{h NL}}$ that with the Dutch model.

As can be observed by a comparison with the dynamic hourly simulation, as shown in Figure 2, both models, due to over estimation in the Dutch case, and under estimation in the Schibuola case, present quite a large deviation relative to the forecasts of the hourly dynamic model: on average equal to 50% in the Dutch case, and 40% in the Schibuola case.

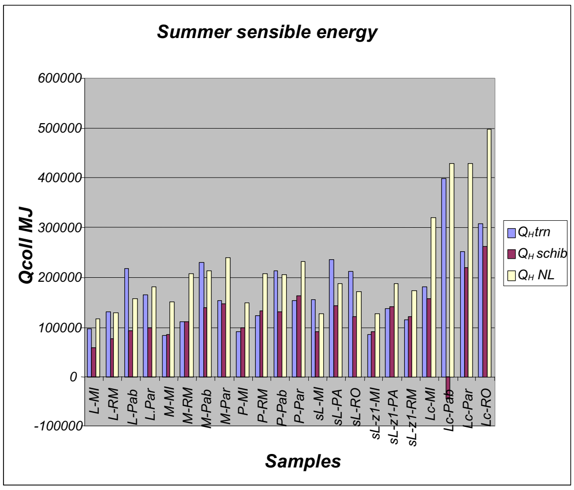

Figure 1 – Summer energy demands: comparison of simplified models and dynamic simulation

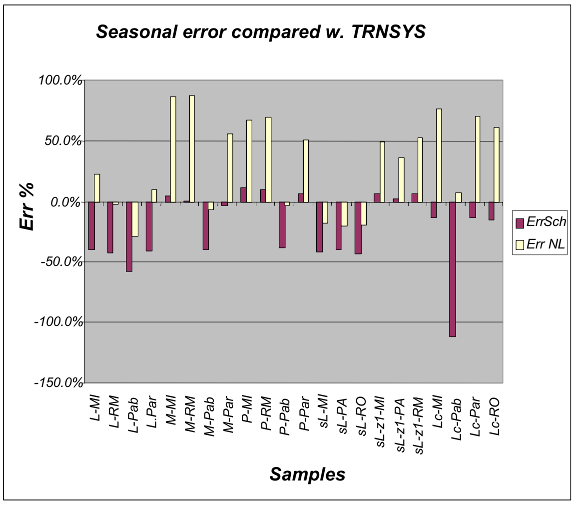

Figure 2 – Summer energy demands: % deviation relative to dynamic simulation

A major detail of this behaviour is highlighted in Figure 3, which shows the individual points that represent the monthly summer energy demands relative to the same quantity calculated with the hourly dynamic model: as can be seen, there is a deviation at 45° which is more marked as the monthly energy demands increase, i.e the forecast worsens precisely when it is more important. There is only one coincidence for a certain number of points of the Schibuola correlation with low values of the monthly energy required: they exactly correspond with the building types and climatic sites used by the author for constructing the correlation, and which were deliberately introduced among the other sample buildings.

In conclusion, the above preliminary analysis of the simplified models similar to the one used for calculating the heating demands has shown just how low their degree of reliability is in the generalized forecasting; their adoption, therefore, is not recommended. Consequently, there is a need to formulate a new model that can provide more accurate forecasts.

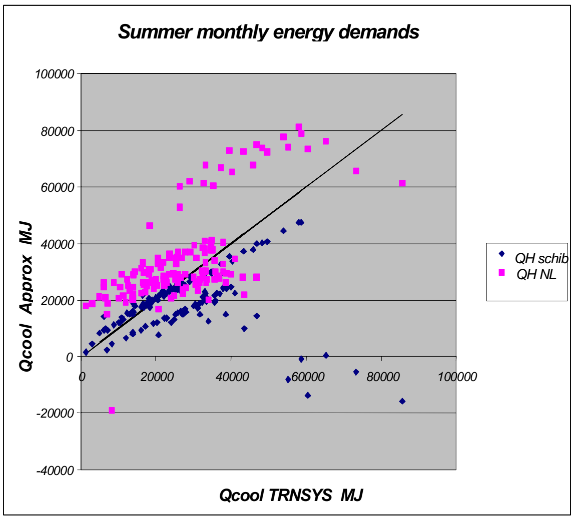

Figure 3 – Summer monthly energy demands: simplified models compared with dynamic simulation

QUASI-STEADY STATE SIMPLIFIED MODEL

The development of the simplified model for calculating the energy demands for sensible summer cooling, in a continuous operating mode, is fully described in [7] and can be summarised in the following monthly or seasonal energy balance:

$$Q_{sys} = Q_c = \left(Q_L - Q_{I,cv}\right) - \eta_d \cdot \left(Q_{I,rd} + Q_{Si} + Q_{Se}\right) \tag{9}$$

where $Q_{sys} = Q_c$ is the value of the monthly energy required by the cooling system (negative value), the η_d factor is no longer an utilisation factor in free internal contributions (between 0 and 1) but becomes the co-relating factor that takes account of the building's capacitive effects (in most cases above unity). All the energy quantities present in (9) are calculated according to the steady-state approximation, exactly as they are defined for the heating energy requirement model implemented in the heating energy demand standards [1] and [2].

The correlation factor η_d adopted by the model given by (9), was operationally defined and calculated as follows:

$$\hat{\eta}_d \equiv \frac{-Q_{sys}^{DYN} + Q_L - Q_{I,cv}}{Q_{I,rd} + Q_{Si} + Q_{Se}} \tag{10}$$

where Q_{sys}^{DYN} is the value of the monthly or seasonal energy required by the cooling system determined by means of a detailed dynamic procedure, i.e TRNSYS.

To determine a suitable correlation for η_d the following procedure has been established:

1. choosing and defining the sample buildings to be used for generating the data required for

producing the "experimental" values of $\hat{\eta}_d$ on which to construct the correlations;

2. limiting the work only to the "office" type buildings identifying 27 sample buildings (archetypes);
3. defining the building's general conduction characteristics:
   - summer cooling active 24 hours a day;
   - hourly air volume changes n=0.5;
   - free internal contributions equal to 4 W/m^2.
4. identifying a first group of sample Italian towns, equally distributed throughout Italy (30 over 60 available chief provincial towns) on which to position the 27 individuals required for construction of the correlations;
5. generating the "**measured**" values of the correlation factors $\hat{\eta}_d$ in accordance with (10) for each building archetype and climatic site of the 1st group, by performing the steady state calculation and running TRNSYS;
6. collecting the $\hat{\eta}_d$ values for all the archetypes and all the climatic sites of the 1st group on the Cartesian plane $\hat{\eta}_d$ - t_c , where t_c is the time constant of the building defined in EN 832 standard as : $t_c = \dfrac{C}{H_k \cdot 3600}$ (11)

   where C is the thermal capacity of the building and H_k is the overall dispersion coefficient:
   - the "physical" trend of the distribution $\hat{\eta}_d$ (t_c) clearly shows the impossibility of searching for just one co-relating form for the $\hat{\eta}_d$ factor only based on "physical parameter" as t_c, independently of the typological and technological characteristics of the samples subjected to the study (see Figure 4);
7. critical analysis of distributions $\hat{\eta}_d$ - t_c for identifying the parameters that have most influence on η_d on which to work for searching for the best functional form $\tilde{\eta}_d$ () for the co-relating factor:
   - one parameter is the morphology of the building itself, which necessitates sub-dividing the problem into parts, by creating a number of functional forms of η_d valid for groups of building types (first type grouping: ind1&5, ind6&8, ind7&9, ind2, ind3, ind4): **six separate correlations are thus required**;
   - the other parameters are climactic ones; the following elements are thus taken into consideration and analysed: summer day degrees (GG), average monthly/seasonal average daily solar radiation (I_m), difference between the defined internal summer temperature value, and the monthly average daily value of the external air temperature, considered only if positive, $DT_m = T_{int} - T_{ext,average} > 0$.

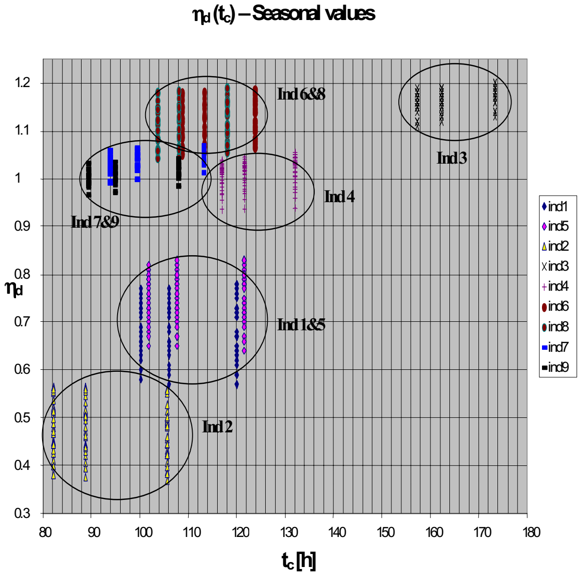

Figure 4 – Distribution of $\hat{\eta}_d$ depending on time constant t_c

8. as it is possible to apply both UNI 10344 and the EN 832 standards (energy demands for heating) both on a monthly basis and directly on a seasonal basis, to ensure the congruence and usability, two research procedures (on a monthly and seasonal basis) of the best functional form $\tilde{\eta}_d$ have been conducted, in the sense of least square fitting, which would have the highest values of the statistical size ***R*** (*coefficient of correlation*) and the lowest of the size **σ** (*standard deviation*)..

Given that summer season is the period that extends from June to September inclusive, the results obtained in the seasonal study relative to the identification of the best co-relating parameter from those possible, are summarised in Table 1.

In order to choose a single functional shape valid seasonally for all office categories and to simplify use, the function $\tilde{\eta}_d$ – which on an average functions best is found to be $\tilde{\eta}_d$ (DT_m) –the polynomial shape given below was used:

$$\tilde{\eta}_d = \sum_{i=0}^{3} a_i \cdot \left(DT_m\right)^i \qquad (12)$$

for which the coefficients are shown in Table 2 for the various office building categories.

The search of better correlation based on monthly energy balance data was just showing a bit worst results; thus it is not reported here being preferable the seasonal basis calculation.

Instead the dispersion analysis of the summer sensible energy requirement forecast by the simplified model versus TRNSYS simulation is reported in figure 5, showing a deviation never greater than 12.7% only for large tower office buildings or big parallelepiped structures with ribbon transparency.

In conclusion, it can be said that, limited to the office buildings category, and to continuous 24 hour cooling, the procedure proposed and the correlations identified show a satisfactory degree of precision. There remain, however, the limitations of the model for the case of continuous functioning, the absence of correlations for other building types, and the intrinsic incapacity of models based on the average daily values of the forcing factors to treat the case of simultaneous heating and cooling in different areas of the same building. However these correlations are applicable only to office building not too different from the selected archetypes.

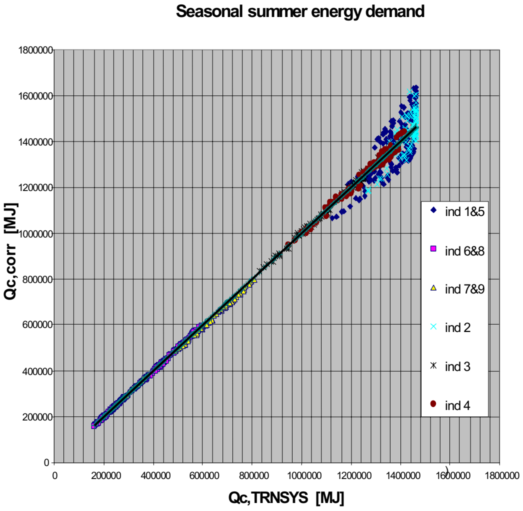

Figure 5 – Summer energy demands: simplified model compared to dynamic simulation

DYNAMIC SIMPLIFIED MODEL

Using the procedures for calculating the flows exchanged in simplified dynamic operating mode between the external environment and the building indicated in the UNI 10375 standard [8] or prEn 13792 [3] a new simplified algorithm was developed (and the relative calculation code) for estimating the summer energy demands. The main algorithm, based on the method of the admittance (simplified), makes it possible to calculate the hourly thermal power that must be subtracted from the building to keep the temperature of the internal air constant (26°C), depending on the variation of the external loads (air and solar radiation temperature) and internal loads (linked to the usage destination). The summer energy demands were calculated as a projection of the daily energy demands of the reference average day. The final energy demands value, (Q_{tot}), is calculated as the sum of the hourly values for the average day and projected for the duration of the air conditioning season:

$$Q_{tot} = \left(\sum_{i=1,24} Q_i \right) \cdot N_{raff} \qquad (13)$$

where

$$Q_i = \Phi_{T,t} - (\mathrm{H_T} + \mathrm{c} \cdot \mathrm{m_{a,t}}) \cdot 26 \qquad (14)$$

The symbols that appear in expression of the Q_i refer to the sizes used in the text of the above-mentioned standards. Specifically, the $\Phi_{T,t}$ is the thermal load of the environment at time *t*, in Watt; H_T is the co-efficient of the building structure's overall thermal transmission in W/K; and ($c \cdot m_{a,t}$) is the product of the mass thermal capacity of the external air (assumed to be 1000 J/Kg·K) and the capacity of the mass of ventilation air, in kg per sec. The calculation of the Q_i in the formulation described is very compact and easy to use; the price paid, which is described below, is linked to the approximations made in simplifying the method of the admittance (and intrinsic to the method itself), which is "calibrated" relative to the calculation of the operative room temperature and not of the hourly thermal power.

To validate the model, a site was considered that is particularly sensitive to the problem of summer air conditioning, namely the city of Palermo, for which site a set of significant types was identified on which to perform a comparative parameter study with TRNSYS.

The sample building configuration considered, ranging from single family house to large office building, was constructed introducing a parameter that makes it possible to "*weigh*" the solar radiation control. This parameter is *the shading coefficient.*

This coefficient was varied on the basis of the following values:

- F_{ce}= 1 (absence of shade)
- F_{ce}= 0.67 (average shade)
- F_{ce}= 0.33 (high degree of shade)

With the aim of simplifying the comparison and making it more direct, it was decided to limit calculation of the energy demands only to the average July day (17^{th}).

The following figures 7 present a comparison between the results obtained with the simplified model and the dynamic reference model TRNSYS, in each case as an absolute value and as a percentage. As will be observed, in most cases there are discrepancies in the results. The errors increase in absolute value as the dimensions of the building considered increase, while the relative degree of error oscillation is invariable, with dimensions of about 30%.

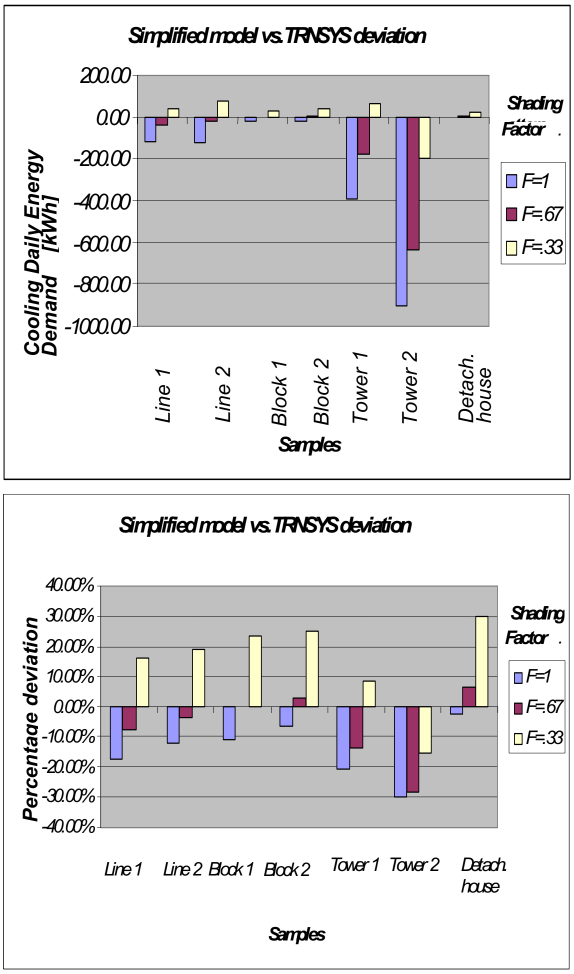

Figure 7 – July 17th cooling energy demand: simplified model compared to dynamic simulation

On comparing these results, the dynamic simplified model **with low solar radiation density tends to overestimate** the thermal demands of sensible cooling; i.e. the smaller building, the greater the degree (the case of a building with V > 20000 m^3 underestimated. Instead **with high solar radiation it always underestimates** the thermal demands of sensible cooling, and the percentage underestimate increases as the size of building increases.

This apparently contradictory behaviour (the overestimate would be expected to increase as the density of the solar radiation available increases) is justified and explained by errors in the phase relative to the various thermal flows transmitted or converted by the structure, which, combined with the "*night cooling*", mainly aligned with the temperature of the external air, produces, in the presence of relevant thermal capacities, significant distortions in the superimposition of effects.

CONCLUSIONS

It can be stated that it is necessary to completely re-think the setting of the objective: *instead of searching for a model for energy cooling evaluation similar to – and thus capable of being integrated with – the one already employed for heating [1][2], it will be necessary to work out an entirely different approach to the problem.* Simplified models have the same data input effort than detailed hourly simulation models, but they are less precise and flexible; thus it is better to invest on the developing of a detailed dynamic simulation tool that integrates all the functions required by the various existing standards (thermal and energy performances all over the year), in the form of "certified" software to enable it to be used as standard.

NOMENCLATURE

C	thermal capacity of the building
$c \cdot m_{a,t}$	air thermal capacity flow
DT_m	difference between internal temperature and monthly average daily outdoor air temperature
F_{ce}	shading coefficient
GG	cooling degree days
H_k	overall heat losses coefficient
H_T	overall thermal transmission cefficient
I_m	seasonal averaged total horizontal solar irradiance
N_{raff}	cooling season days' number
Q_c	monthly or seasonal energy requirement for cooling
Q_{sys}^{DYN}	monthly or seasonal energy required by the cooling system determined by means of a detailed dynamic procedure
Q_h	monthly or seasonal energy requirement for heating
Q_i	hourly cooling energy demand
Q_I	monthly or seasonal energy due to internal contributions
Q_L	monthly or seasonal energy exchanged by transmission and ventilation
Q_{Se}	monthly or seasonal contributions due to solar radiation incident on the external surface of the opaque components
Q_{Si}	monthly or seasonal contributions due to solar radiation incident on the internal surface of the opaque components after having penetrated the zone through the transparent components
Q_{tot}	seasonal energy required by the cooling system determined by means of simplified dynamic procedure
t_c	building characteristic time
t_0	offset value of building characteristic time
T_{em}	seasonal averaged daily outdoor air temperature
η_d	correlation factor taking into account dynamical effects
η_u	is the factor of usage of the free contributions
γ	ratio between energy gained and energy dispersed
τ	non-dimensional time
τ_0	offset value of non-dimensional time
$\Phi_{T,t}$	cooling thermal load at time *t*

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REFERENCES

[1] UNI 10344 – „Heating buildings – Calculating Energy Demands", UNI, Milano, Italy, 1993

[2] UNI-EN 832 – „Thermal performance of buildings – Calculating energy demands for heating", UNI, Milano, Italy, 2001

[3] prEN 13792 – „Thermal performance of buildings– Internal temperature of a room in summer without mechanical cooling – Simplified calculation methods", CEN TC89, WG6, march 2000, unpublished

[4] SEL, „TRNSYS – A Transient Simulation Program", Version 14.2, Solar Energy Laboratory, University of Wisconsin-Madison, USA

[5] NEN 2916:1994 „Energy Performance of Non-Residential Buildings – Determination Method", Nederlands Normalisatie Instituut, Delft, The Netherlands, 1994

[6] Schibuola, L. „Simplified summer energy demands of buildings", CDA, No.2, February 1999, pages 131-138

[7] Mazzarella, L. „Modello quasi-stazionario per la stima del fabbisogno energetico utile di raffrescamento", Report R3-Cofin Murst 1998, Politecnico di Milano, Milano, October 2000

[8] UNI 10375 – „Method for calculating the summer internal temperature of environments", UNI, Milano, Italy, 1995

Table 1 – Coefficients of correlation and standard deviation for the various functional forms

SEASONAL DATA		DT_m	I_m	GG	I_m/Te_m	Te_m/DT_m	I_m/DT_m	I_m/GG
Towers with complete transparency (**ind2**)	*R*	0.847	0.766	0.201	0.270	0.834	0.898	0.019
	σ	0.021	0.026	0.048	0.045	0.022	0.017	0.053
Large parall. with insulated windows (**ind3**)	*R*	0.627	0.157	0.021	0.393	0.663	0.517	0.115
	σ	0.012	0.018	0.019	0.015	0.011	0.013	0.018
Towers and large parall. with ribbon transparency (**ind1&5**)	*R*	0.630	0.569	0.138	0.185	0.622	0.657	0.015
	σ	0.038	0.041	0.058	0.057	0.039	0.037	0.062
Offices of small and medium dimensions with block transparency (**ind6&8**)	*R*	0.939	0.395	0.246	0.231	0.933	0.882	0.109
	σ	0.007	0.021	0.024	0.024	0.007	0.009	0.026
Offices of small and medium dimensions with ribbon transparency (**ind7&9**)	*R*	0.548	0.195	0.149	0.151	0.540	0.496	0.075
	σ	0.016	0.022	0.022	0.022	0.016	0.017	0.023
Large parall. with block transparency (**ind4**)	*R*	0.727	0.761	0.239	0.241	0.740	0.742	0.077
	σ	0.014	0.013	0.024	0.024	0.014	0.014	0.026

Table 2 – Coefficients Of polynomial correlation $\tilde{\eta}_d$ *(DT_m)*

SEASONAL DATA	a0	a1	a2	a3
Towers with total transparency (ind2)	0.39779	-0.04183	0.02349	-0.00211
Big parall. with insulating windows (ind3)	1.09306	0.04681	-0.00697	1.24E-04
Towers and big parall. with ribbon transparency (ind1&5)	0.59282	-0.0112	0.01855	-0.0019
Average and small sized offices with transparency in blocks (ind6&8)	1.24576	-0.02405	2.90E-04	6.68E-06
Average and small sized offices with ribbon transparency (ind7&9)	1.0945	-0.02812	0.00424	-3.50E-04
Big parall. with transparency in blocks (ind4)	0.86513	0.05236	-0.00175	-4.00E-04