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A NEW THERMAL ANALYSIS BY NUMERICAL SIMULATION TO INVESTIGATE THE ENERGY PERFORMANCE OF BUILDINGS

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ABSTRACT

The aim of the work is to present a new methodology that allows to identify the most important parameters affecting the energy performance of buildings under certain conditions. The methodology consists of analysing the different contributions to the convective energy balance on internal air: each contribution is split according the dynamic driving forces of outdoor and indoor environment.

The paper describes the developed procedure which consists of a set of numerical simulations using *EnergyPlus*. A case study is analysed to exemplify the methodology and a new way to represent the results. A thermal design optimization is shown as an example of the application of the method.

INTRODUCTION

The contributions to the air heat balance equation

A modeling of the building energy performance and a sensitivity analysis of the different aspects affecting the building energy behaviour are necessary to optimize the building energy design or perform an energy audit. Several studies have been carried out; some are based on data driven models (Catalina *et al.*, 2008; Mechri *et al.*, 2010; Yu *et al.*, 2010).

The methodology presented in this paper allows to identify the most important parameters affecting the energy performance of buildings under certain conditions. The methodology consists of analysing the different contributions to the thermal energy balance of building and their interrelations with different boundary conditions.

The analysis of the contributions to the thermal energy balance of building starts from the application of the convective balance equation on internal air:

$$\Phi_{\mathrm{conv}} + \Phi_{\mathrm{V}} + \Phi_{\mathrm{conv,IG}} + \Phi_{\mathrm{syst}} = C_{\mathrm{ai}} \cdot \frac{dT_{\mathrm{ai}}}{d\,\tau} \qquad (1)$$

where, Φ_{conv} is the heat flow exchanged by convention between the surfaces of the internal environment and the internal air, Φ_{V} is the heat flow concerning infiltrations and ventilation, $\Phi_{\mathrm{conv,IG}}$ is the convective heat flow from the internal heat sources to the indoor environment, Φ_{syst} is the convective heat flow supplied to or subtracted from the internal air by the technical system, C_{ai} is the heat capacity of the internal air, T_{ai} is the internal air temperature, τ is time.

The term Φ_{conv} can be split further according to the surface typology on which the thermal exchange with the internal air occurs, by distinguishing among the opaque envelope surfaces ($\Phi_{\mathrm{conv,OE}}$), the transparent envelope surfaces ($\Phi_{\mathrm{conv,W}}$), the opaque surfaces of the internal building components ($\Phi_{\mathrm{conv,OI}}$, e.g. vertical and horizontal partitions). The building envelope surfaces can be further divided according to the boundary environment, i.e. the external environment, the ground, unconditioned spaces, spaces that are conditioned at a different temperature.

DESCRIPTION OF THE NEW THERMAL ANALYSIS

The terms of the air heat balance equation and the dynamic driving forces

The proposed methodology of thermal analysis is based on the expression of the heat balance terms as functions of the different dynamic driving forces of outdoor and indoor environments, in order to find out the elements that mainly affect the building energy performance under certain conditions. Each contribution to the heat balance equation (i.e. the effect) is split according the dynamic driving forces of outdoor and indoor environment (i.e. the causes), among which the external temperature, the solar radiation and the internal heat sources are mentioned.

In Table 1 the relationship between each thermal balance contribution and each driving force is underlined. The five contributions in Table 1 could be summarized as follows.

The contribution of the convective heat flow that occurs on the internal surfaces of the opaque envelope ($\Phi_{\mathrm{conv,OE}}$) to the heat balance of the internal air depends on the following boundary conditions (see Figure 1 a, b, c):

- the outdoor air temperature that causes the heat transfer through the opaque envelope (*T tr,op*). It considers the heat flow transferred to the internal air from the internal surfaces of the opaque envelope by thermal convection;
- the outdoor air temperature that causes the heat transfer through the transparent envelope (*T tr,w*). It considers the heat flow exchanged between the internal surfaces of windows and the internal surfaces of the opaque envelope by thermal radiation, and then exchanged with the internal air by thermal convection;
- the radiative part of the internal heat sources (*Int*) that is transferred to the internal surfaces of the opaque envelope by thermal radiation and

Table 1
Relationship between each thermal balance contribution and each driving force

	Outdoor air temperature (see Figure 1a)			Internal heat sources (see Figure 1b)	Solar radiation (see Figure 1c)	
	Heat transfer through the opaque envelope components (*T tr,op*)	Heat transfer through the transparent envelope components (*T tr,w*)	Ventilation (*T ve*)	(*Int*)	Incident on the opaque surfaces (*Sol op*)	Incident on the transparent surfaces (*Sol w*)
$\Phi_{conv,OE}$	x	x	-	x	x	x
$\Phi_{conv,W}$	x	x	-	x	x	x
$\Phi_{conv,OI}$	x	x	-	x	x	x
$\Phi_{conv,IG}$	-	-	-	x	-	-
Φ_{V}	-	-	x	-	-	-

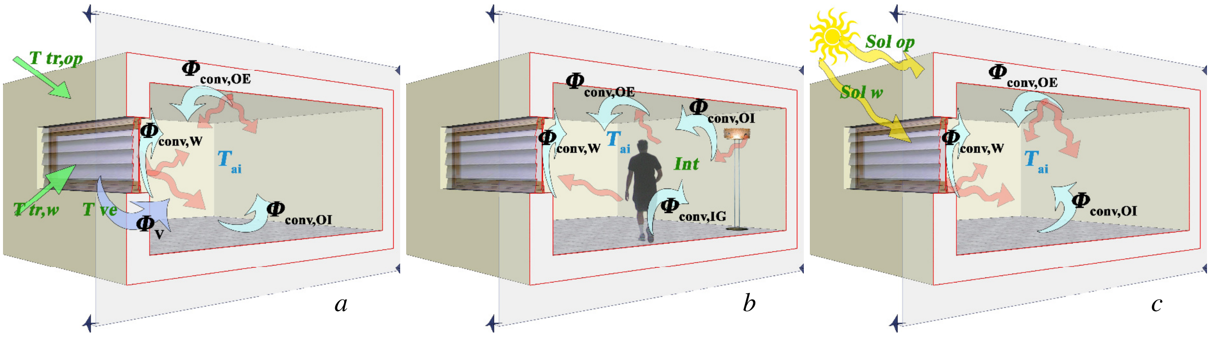

Figure 1 Illustrations of the thermal balance contributions and the driving forces

then it is transferred to the internal air from these surfaces by thermal convection;

- the solar radiation incident on the external surfaces of the opaque envelope (Sol op) that is absorbed and then transferred from the internal surfaces of these elements to the internal air by thermal convection;
- the solar radiation entering through the transparent envelope (*Sol w*) that is absorbed by the internal surfaces of opaque envelope and transferred to the internal air by convection.

The contribution of the convective heat flow that occurs on the internal surfaces of the transparent envelope ($\Phi_{conv,W}$) to the heat balance of the internal air depends on the following boundary conditions (see Figure 1 a, b, c):

- the outdoor air temperature that causes the heat transfer through the opaque envelope (*T tr,op*). It considers the heat flow exchanged between the internal surfaces of the opaque envelope and the internal surfaces of windows by thermal radiation, and then exchanged with the internal air by thermal convection;
- the outdoor air temperature that causes the heat transfer through the transparent envelope (*T tr,w*). It considers the heat flow transferred to the internal air from the internal surfaces of windows by thermal convection;
- the radiative part of the internal heat sources (*Int*) that is transferred to the internal surfaces of the transparent envelope by thermal radiation and then it is transferred to the internal air by thermal convection;
- the solar radiation incident on the external surfaces of the opaque envelope (*Sol op*) that is absorbed and is transferred to the internal surfaces of the transparent envelope by thermal radiation. Then the heat transfer by convention occurs between these transparent surfaces and the internal air;
- the solar radiation incident on the external surfaces of the transparent envelope (*Sol w*) that causes the rise of temperature in the transparent components, determining the convective heat transfer with the internal air.

The contribution of the convective heat flow that occurs on the surfaces of the internal partitions ($\Phi_{conv,OI}$) to the heat balance of the internal air depends on the following boundary conditions (see Figure 1 a, b, c):

- the outdoor air temperature that causes the heat transfer through the opaque envelope (*T tr,op*). It considers the heat flow exchanged between the internal surfaces of the opaque envelope and the surfaces of partitions by thermal radiation, and then it is transferred from these surfaces to the internal air by convection;
- the outdoor air temperature that causes the heat transmission through the transparent envelope (*T tr,w*). It considers the heat flow exchanged

between the internal surfaces of the transparent envelope and the surfaces of partitions by thermal radiation, and then it is transferred from these surfaces to the internal air by thermal convection;

- the radiative part of the internal heat sources (*Int*) that is transferred to the surfaces of the partitions by thermal radiation and then it is transferred to the internal air by thermal convection;
- the solar radiation incident on the external surfaces of the opaque envelope (*Sol op*) that is absorbed and transferred to the surfaces of partitions by thermal radiation. Then the heat transfer by convention occurs between these surfaces and the internal air;
- the solar radiation entering indoor through the transparent envelope (*Sol w*) that is absorbed by the surfaces of partitions and transferred to the internal air by thermal convection.

The contribution of the convective heat flow of internal gains ($\Phi_{conv,IG}$) is caused by the convective internal heat sources (*Int*) and it is a direct load on the internal air (see Figure 1 b).

The contribution of the convective heat flow by ventilation (Φ_V) is determined by the outdoor air temperature (*T ve*) (see Figure 1 a).

The development of the methodology by a detailed numerical simulation tool

The thermal analysis of building is developed through the application of the detailed numerical simulation code *EnergyPlus*. The principle of superposition of the effects is applied in order to identify the quantity of each contribution to the convective heat balance that should be attributed to each driving force. The principle of superposition of the effects can be followed by running sequentially five simulations on the same model and in the same conditions, but adding a different driving force from time to time.

1) In the first simulation, the solar radiation and the internal heat sources are removed, so the only driving force considered is the outdoor air temperature. However it is necessary to split the effect of the outdoor air temperature on the opaque envelope components (*T tr,op*) from the effect of the same temperature on the transparent envelope components (*T tr,w*). Therefore the windows are considered adiabatic by introducing null values of thermal conductivity and thermal emissivity of glass and frame. In this way it is possible to obtain the effect of the outdoor air temperature on the convective heat balance of the internal air, considering only the thermal transmission through the opaque envelope components. This effect is due to the convective heat flow exchanged between the internal air and the internal surfaces of the building components, such as the opaque envelope, the transparent envelope and the internal building elements. The effect of the outdoor air temperature that causes the heat flow by ventilation (*T ve*) is directly obtained.

2) In the second simulation, the effect of the outdoor air temperature is added with reference to the transparent envelope components (*T tr,w*), by re-establishing the correct values of the thermal parameters of glass and frame. In this way it is possible to obtain, by difference from the first simulation, the contribution of the outdoor air temperature on the convective heat balance of the internal air in relation to the heat transfer through the transparent building envelope. The convective heat flow exchanged between the internal air and the internal surfaces of the building components (the opaque envelope, the transparent envelope and the internal building elements) is determined.

3) In the third simulation the internal heat sources (*Int*) are entered. In this way it is possible to show the effect of the internal heat sources on the convective heat balance of the internal air by difference from the second simulation. The purely convective part of the internal sources is a direct load on the internal air; the remaining part is the convective heat flow exchanged between the building internal surfaces (envelope and partitions) and the internal air, resulting from subsequent heat transfers by thermal radiation between the internal heat sources and the internal building surfaces.

4) In the fourth simulation the contribution of the solar radiation incident on the opaque building envelope is added (*Sol op*). This is done considering the glasses completely reflective, so their contribution to the thermal load is removed. It is possible to determine, by difference from the third simulation, the effect of the solar radiation incident on the opaque envelope on the convective heat balance of the internal air. The convective heat flow exchanged between the internal air and the internal surfaces of the building components (the opaque envelope, the transparent envelope and the internal building elements) is determined.

5) The overall effect of each contribution on the heat balance of the internal air is obtained running the fifth simulation in which the solar radiation entering through the windows is considered (*Sol w*). By isolating this contribution it is possible to obtain the effect of the solar radiation incident on the transparent envelope on the convective heat balance of the internal air. The convective heat flow exchanged between the internal air and the internal surfaces of the building components (the opaque envelope, the transparent envelope and the internal building elements) is determined.

The five simulations have to be run in the same conditions of indoor air temperature so that the consistency of the results is assured. A preliminary work consists in the individuation of the hourly

SIMULATION NUMBER	DRIVING FORCES CONSIDERED IN THE SIMULATION	DRIVING FORCES NOT CONSIDERED IN THE SIMULATION	OPERATIONS IN *ENERGYPLUS*	OUTPUTS
0	ALL	-	-	Hourly values of indoor air temperature
1	*T ve* + *T tr,op*	*T tr,w* *Int* *Sol op* *Sol w*	- Adiabatic transparent envelope - No internal heat sources - No solar radiation	*T ve* → Φ_V *Directly obtained* *T tr,op* → $\Phi_{conv,W}$ $\Phi_{conv,OE}$ $\Phi_{conv,OI}$
2	*T ve* + *T tr,op* + *T tr,w*	*Int* *Sol op* *Sol w*	- Correct values of transparent envelope - No internal heat sources - No solar radiation	*By difference:* *T tr,w* → $\Phi_{conv,W}$ $\Phi_{conv,OE}$ $\Phi_{conv,OI}$
3	*T ve + T tr,op + T tr,w* + *Int*	*Sol op* *Sol w*	- Internal heat sources - No solar radiation	*By difference:* *Int* → $\Phi_{conv,W}$ $\Phi_{conv,OE}$ $\Phi_{conv,OI}$ $\Phi_{conv,IG}$ *Directly obtained*
4	*T ve + T tr,op + T tr,w + Int* + *Sol op*	*Sol w*	- Solar radiation - Reflective transparent envelope	*By difference:* *Sol op* → $\Phi_{conv,W}$ $\Phi_{conv,OE}$ $\Phi_{conv,OI}$
5	*T ve + T tr,op + T tr,w + Int + Sol op* + *Sol w*	-	- Correct values of transparent envelope	*By difference:* *Sol w* → $\Phi_{conv,W}$ $\Phi_{conv,OE}$ $\Phi_{conv,OI}$

Figure 2 Schematic description of the numerical simulations to develop the new thermal analysis methodology

values of the indoor air temperature, by running a numerical simulation (numbered "zero") with a deadband thermostat with a lower limit equal to the heating set-point and an upper limit equal to the cooling set-point temperature. All driving forces are considered in this preliminary numerical simulation. The hourly values of the indoor air temperature obtained as outputs from this "zero" simulation are the fixed set-point temperature inputs in the subsequent five simulations.

The described path of the numerical simulations is shown in Figure 2.

APPLICATION OF THE METHODOLOGY

Explanation of the methodology through a case study

The new thermal analysis methodology is completed by a specific way to represent the results that are the outputs of the numerical simulations. The effects of each driving force/energy balance contribution on the energy need or on the thermal load are underlined and compared through some types of representation.

An exemplificative case study is proposed in order to show a possible application of the method.

The object of study is the attic floor of a residential building in Turin (see Figure 3). The floor presents two similar apartments that are divided by a central unconditioned staircase. The principal orientation of the building is North-South, since walls at East and West are contiguous to other buildings. The beneath floor is conditioned at the same temperature; the roof is flat.

The main typological and construction data of the attic floor are given in Table 2. The thermal transmittance values of the opaque envelope meet the requirements established by the Italian regulations on energy efficiency in buildings (*Legislative Decree* no. 311/2006 annex C).

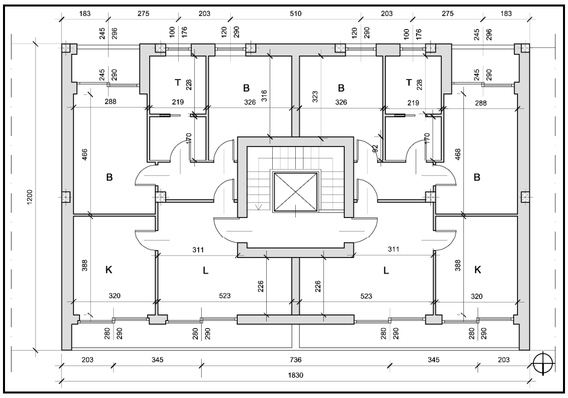

Figure 3 The attic floor object of analysis

As regards the building management by user, some input data are get by the technical standard EN ISO 13790 and the Italian technical specification UNI/TS 11300-1 (National Annex to EN ISO 13790), above all for the modeling of natural ventilation and internal heat sources. The hourly occupancy profile is obtained from the technical standards that give conventional values of building use to be considered in an energy assessment.

The calculation assumptions are the followings:

- the air change rate by natural ventilation is fixed at 0.3 h^{-1};
- the overall internal heat gains are variable in function of the occupancy profile (EN ISO 13790); the maximum value is around 12 W/m^2 in the conditions of maximum use. The thermal radiative and convective portions are each

50%;

- the heating and cooling systems are characterized of a continuous operation (night and day) without intermittency or reduction;
- the minimum set-point temperature is fixed at 20 °C;
- the maximum set-point temperature is fixed at 26 °C.

The attic floor is modelled as a single thermal zone.

Table 2
Principal typological and construction data

TYPOLOGICAL DATA					
A_f [m^2]	172	V_n [m^3]	576	A_w/A_{env}	0.14
A_w [m^2]	57.2	V_g [m^3]	639	A_w/A_f	0.33
A_{env} [m^2]	396	A_{env}/V_g [m^{-1}]	0.62	A_{env}/A_f	2.30
CONSTRUCTION DATA					
BUILDING COMPONENTS		U [W/(m^{2}K)]		m_s [kg/m^2]	
Flat roof		0.32		662	
Horizontal internal partitions (floor)		0.74		634	
External walls		0.37		912	
Vertical internal partitions (internal walls)		0.79		326	
Windows (no shading devices; low-e triple glass, $g_{gl,n}$ = 0.58)		1.82		-	

A first numerical simulation with *EnergyPlus* is performed considering all the driving forces. The hourly values of the indoor air temperature obtained from this simulation are entered in the next simulations as fixed set-point temperatures (using fixed set-point thermostat) and the next five simulations are performed considering the superposition of the effects according to the procedure described above. As an exemplification, the analysis is performed for one month (July).

Ways to represent the results

The different ways to represent the outputs of the numerical simulations are presented below. They are fundamental to describe the proposed methodology of thermal analysis.

Split representation of mean values

The monthly mean values of the contributions to the convective heat balance equation on the internal air are shown in this first typology of representation. They are expressed in terms of mean heat flow rate normalized on the conditioned net floor area (see Figure 4). The contributions to the energy balance are expressed in function of the thermal driving forces of internal and external environment. All the terms of the convective heat balance attributed to the same driving force are the output of a specific simulation that is performed considering only the effect of that specific driving force. These terms are easily identified in the graph of Figure 4 because of the same pattern.

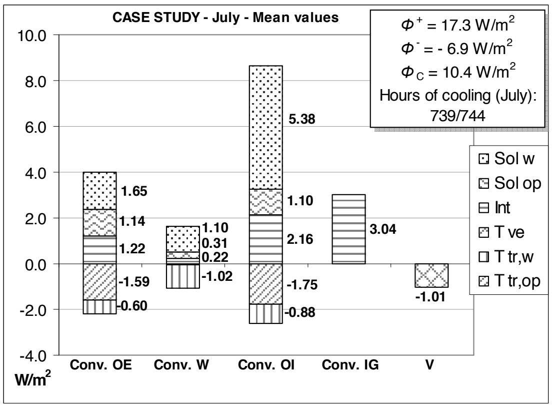

Figure 4 Mean monthly values of heat flow rates on conditioned net floor area of the convective heat balance contributions split according to the driving forces (July)

By analysing Figure 4, the first group of three terms represents the heat flows exchanged between the internal air and the internal surfaces by thermal convection. These surfaces are respectively the internal surfaces of the opaque envelope components (*Conv. OE*), of the transparent envelope components (*Conv. W*) and of the internal building partitions (*Conv. OI*).

The convective heat flow is partly due to the outdoor air temperature that causes the heat transfer by thermal transmission through the opaque envelope (*T tr,op*) and the transparent envelope (*T tr,w*). The outdoor air temperature induces a heat loss in the both cases (negative value of the heat transfer), because the outdoor temperature is lower than the indoor temperature on monthly average. Part of the convective heat flow on the internal surfaces is attributed to the solar radiation (*Sol w*) that enters indoor through the windows and hits the internal surfaces of the envelope or the internal partitions. Another cause of the convective heat flow is the solar radiation incident on the opaque envelope components (*Sol op*), partially absorbed, transmitted indoor and exchanged among the internal surfaces by thermal radiation, and then transferred to the internal air by convection.

Another driving force is represented by the internal heat sources (*Int*) that release heat by thermal radiation to the internal surfaces that, in turn, deliver it to the internal air by convection. The fourth term in Figure 4 is the convective heat flow rate on the internal air (*Conv. IG*) produced by the internal heat sources (*Int*); the fifth contribution is the heat flow rate by ventilation (*V*) that is dependent from the outdoor temperature (*T ve*).

It is possible to compare the weights of each thermal balance contribution/thermal driving force on the thermal building load from this way of representation. For instance, by analysing the results in Figure 4 it is possible to notice the contribution that more influence the cooling mean load among the others. This contribution is the convective heat flow that occurs on the internal surfaces heated by the solar radiation entering indoor through the transparent envelope. It is important to underline that the relevance of this term in the energy balance is also due to the great extension of these elements compared with the opaque envelope components. The positive contribution to the convective heat balance due to the opaque envelope is determined equally by the solar radiation entering through the windows, the solar radiation absorbed by the opaque envelope and the internal heat sources. The negative terms are instead attributed to the effect of the outdoor air temperature that is lower than the indoor air temperature on monthly average.

The sum of the terms characterized distinctly by a positive value and a negative value is represented in the box at the top right of the graph (see Figure 4). In the same box is the value of the mean monthly net cooling load and the number of hours in July in which cooling occurs.

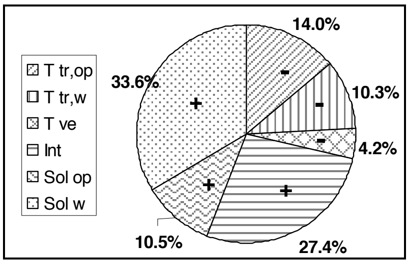

Figure 5 Percentage weight of each driving force (positive or negative value) on the net mean monthly thermal load (July)

Another type of representation is shown in Figure 5 for the same month. This is useful to determine better the influence of each driving force on the energy performance of building. The graph is obtained from Figure 4 adding the contributions of the driving forces distinctly.

Split representation of the mean standard deviations

Another type of representation is shown in Figure 6, where the mean standard deviations of the same contributions are indicated. The representation of the standard deviation offers an additional information to the mean values. Since the standard deviation depends both on the internal heat capacity of building and the variability of thermal driving forces, this type of graph can be considered an useful tool to identify critical situations and to adopt coherent solutions in order to improve the thermal performance of buildings under dynamic conditions. As regards this aspect, it is necessary to reduce the variability of the thermal load in order to limit the peaks: this representation allows to verify the effectiveness of a strategy based on the increment of thermal inertia in building retrofit.

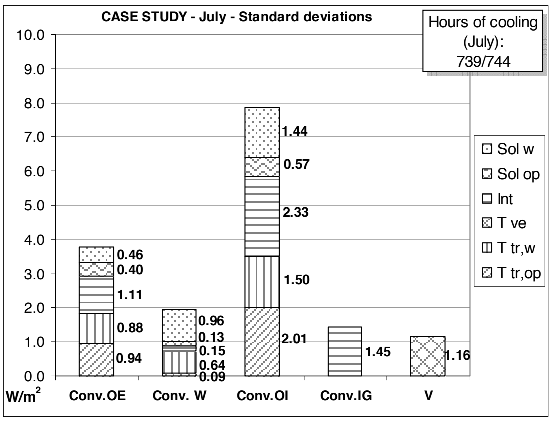

Figure 6 Mean standard deviation of heat flow rates on conditioned net floor area of the convective heat balance contributions split according to the driving forces (July)

For instance in the case study (see Figure 6), the greatest deviation from the mean value is to be attributed to the convective heat flow on the internal surfaces due to the internal heat sources first, and to variability of the outdoor temperature secondly. The reason of this effect consists both in nature of thermal driving forces, that are not steady-state, and in the characterisation of the internal building components, that are not able to reduce effectively the effect of the driving forces.

Joined representation of energy balance terms

A further representation of the new thermal analysis methodology is shown in Figure 7. This allows to join the terms of convective heat balance in a different way. The graph in Figure 7 is obtained dividing the contributions to the energy balance related to the energy transmission through the envelope (*T tr,op*, *T tr,w*, *Sol op*, *Sol w*) from those not related to it (*Int*, *V*). The operation is performed starting from the graph in Figure 4. The various terms are added together so that the contribution of the envelope and the contribution of the aspects not related to the envelope to the energy need or the thermal load are compared. This step is important to identify the importance of the building envelope design for the determination of the building energy performance. In Figure 7 the contributions are indicated both in the mean values and in the standard deviations.

In the case study and according to the graph in Figure 7, the transmission through the envelope doesn't influence the mean monthly thermal load as the other aspects not directly related to the envelope (e.g. the internal heat sources). However, by observing the standard deviation, it can be noticed that the variability of contribution of the envelope to the summer energy performance is higher than the variability of the contribution of the internal heat sources and ventilation. This observation suggests that the envelope has sometimes an higher influence on the thermal building peak load than the internal heat sources.

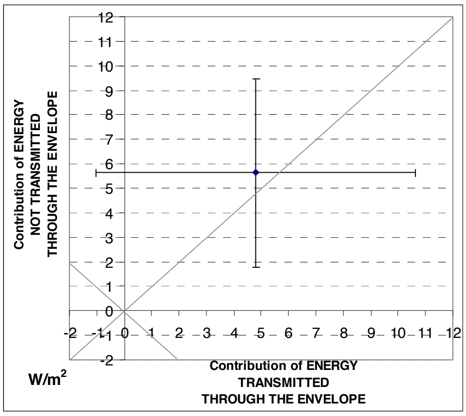

Figure 7 Contribution of energy transmitted through the envelope vs. contribution of energy not transmitted through the envelope to the mean monthly thermal load (July)

An analogous representation is that in Figure 8.

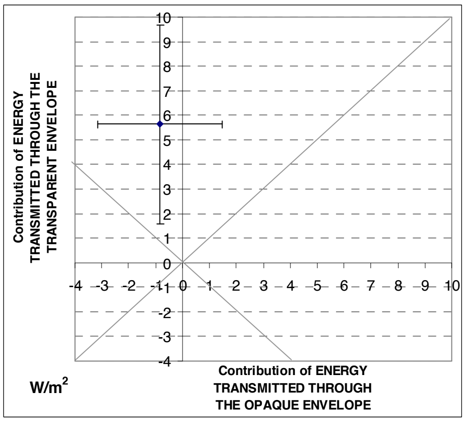

Figure 8 Contribution of energy transmitted through the opaque envelope vs. contribution of energy transmitted through the transparent envelope to the mean monthly thermal load (July)

This graph allows to identify the contribution of the opaque envelope and that of the transparent envelope to the building thermal load. The graph is obtained from the representation in Figure 4 adding on the one hand the contributions to the energy balance related to the energy transmission through the opaque envelope (*T tr,op*, *Sol op*) and on the other hand the contributions to the energy balance related to the energy transmission through the transparent envelope (*T tr,w*, *Sol w*).

This step is important to identify the importance of the opaque envelope design vs. the transparent envelope design for the determination of the building energy performance.

In the case study and according to the graph in Figure 8, the transparent envelope influences more the mean thermal load than the opaque envelope; also the standard deviation of the contribution of the transparent envelope is higher than that of the opaque envelope. This observation suggests that the transparent envelope assumes an higher influence on the thermal building load than the opaque envelope, in both mean and instantaneous values.

The application of the methodology for the optimization of the building thermal design

The proposed thermal analysis methodology could be useful to many applications, first of all the thermo-physical design of new buildings and the energy audit of existing buildings. In fact, the methodology allows to identify critical situations and apply strategies to improve the energy performance. Another application could be made to compare different calculation models of the energy performance of buildings (Ballarini *et al.*, 2010).

An example of the methodology application for the energy audit and the optimization of the thermal design of buildings is applied on the case study analysed in the previous paragraph. By analysing the graph in Figure 4 it is noticed the high contribution of the solar radiation entering through the windows to the mean monthly thermal load.

A design variant is made in the base case in order to limit this contribution and to reduce the net energy need for cooling. It consists in the introduction of external shading devices on windows able to block the solar radiation and reduce its entrance indoor. The solar devices are external venetian blinds with horizontal slats and supposed to be installed at South. They are in operation when the global solar radiation on the external window surface is higher than 100 W/m^2. In this way the shading activation allows to block the most part of solar radiation at South and part of diffuse and reflected radiation at North. In this analysis, the choice about the set-point value of activation is quite an example.

A new sequence of numerical simulations is performed on the case study variant to split the energy balance contributions in function of the driving forces in this case too. The results of the case study with the solar devices compared to those referred to the base case are shown in Figure 9. The net energy need for cooling is reduced by 55% with respect to the base case without shading devices. This reduction is due to a mean reduction of the solar gains through the transparent envelope (47%). At the same time the hours of July in which the cooling is on change from 739 to 698. The same comparison could be made on the standard deviations of the contributions.

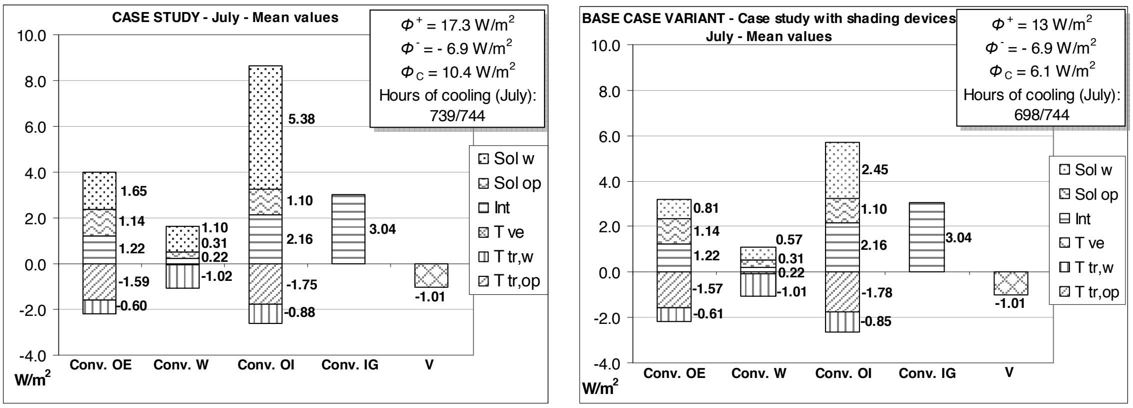

Figure 9 Comparison between the base case and the variant (case study with shading devices)

This example shows how the methodology allows to identify critical situations in the building thermal design and to quantify the effect of improving solutions by its particular way to represent results.

CONCLUSION

The proposed methodology of thermal analysis allows to identify the most important parameters affecting the energy performance of buildings under certain conditions. It is based on the expression of the thermal balance terms as function of the different driving forces of outdoor and indoor environments. The methodology can be applied through a numerical simulation tool (*EnergyPlus*), performing a series of simulations and using the principle of superposition of the effects.

Through the analysis of a case study, some particular graphs are presented to exemplify the methodology. They allow to identify some critical situations and quantify the effects of improving solutions. An example of optimization of the thermal design is performed on the case study.

The methodology could have other applications; for instance it could be applied to compare different calculation models of the energy performance of buildings (Ballarini *et al*., 2010).

NOMENCLATURE

A	area	[m^2]
C	thermal capacity	[J/K]
g_{gl}	total solar energy transmittance	[-]
m_s	surface density	[kg/m^2]
T	temperature	[°C],[K]
U	thermal transmittance	[W/(m^{2}K)]
V	volume	[m^3]
τ	time	[s],[h]
Φ	heat flux	[W]

Subscripts:

ai	internal air	n	net, normal
conv	convection	OE	opaque external
env	envelope	OI	opaque internal
f	floor	syst	system
g	gross	W,w	windows
IG	internal gains	V	ventilation

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