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Global sensitivity analysis of the building energy performance and correlation assessment of the design parameters

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“Il secondo principio della termodinamica dice che:

se hai un acquario e vuoi fare una frittura mista,

non è detto che dopo potrai riavere l’acquario”

Marco Paolini

Abstract

The world’s energy use in buildings (residential and commercial) accounts for around 40% of the worldwide energy consumption, and space heating is the responsible for half of the energy need in the building sector. In Europe, only a small share (less than 10%) of existing buildings was built after 1990. Most of the building stock does not satisfy the recent energy technical standards; in addition there is a very low trend to construct new buildings in the last years.

Renovation of the existing buildings is a feasible option to reduce the energy need in Europe, but finding the optimum solutions for a renovation is not a simple task. Each design parameter differently influences the final energy need of buildings and, furthermore, the different variables are differently correlated each other. Building refurbishment will benefit from a tool for the selection of the best measures in term of energy need.

This work, through a global sensitivity analysis, aims at determining the contribution of the design parameters to the building energy demand and the correlation between the different variables. The considered parameters are related to the improvement of the thermal transmittance of both the opaque envelope and the windows, the solar transmittance of the glazing surfaces, the window size, the thermal inertia of the internal walls and the external sunshades for windows. Several dynamic simulations have been performed varying the design parameters from different starting conditions. Finally, due to the large number of cases elaborated, an inferential statistical analysis has been performed in order to identify the predominant factors and the correlation between the design parameters in a global context.

Abstract

Il settore edilizio (residenziale e commerciale) ricopre circa il 40% del consumo mondiale di energia, e metà di questa quota è da attribuirsi al riscaldamento e raffrescamento degli ambienti. In Europa, gli edifici costruiti prima del 1990 sono una piccola parte del parco edilizio esistente (meno del 10%) e molti di essi non rispettano le recenti norme per il contenimento del consumo energetico.

Il rinnovo degli edifici è una possibile soluzione per ridurre il consumo di energia, ma capire quale sia l'intervento più adeguato per massimizzare il risparmio energetico è spesso un compito che richiede supporto tecnico. Ogni parametro edilizio influenza in modo diverso le prestazioni energetiche dell'edificio; inoltre i parametri sono correlati tra loro. In questo ambito sarebbe utile uno strumento che supporti il progettista nella fase decisionale.

Questo lavoro si prefigge di determinare come alcuni parametri edilizi influenzano il fabbisogno energetico degli edifici e quale correlazione li lega tra loro. I parametri edilizi di progettazione che sono stati considerati sono: la trasmittanza degli elementi opachi e trasparenti, la trasmittanza solare delle superfici vetrate, la dimensione delle finestre, l'inerzia termica delle pareti interne e l'ombreggiamento delle finestre. Dopo aver specificato quali valori potevano assumere i suddetti parametri, sono state condotte numerose simulazioni dinamiche dell'edificio preso in esame. Alla fine, grazie all'esteso numero di casi presi in esame, è stata eseguita un'analisi statistica per individuare quale variabile influenza maggiormente le prestazioni energetiche e come si correlano i parametri edilizi tra loro.

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1 Introduction

1.1 Overview of world energy

In 2008, the total worldwide primary energy supply was 12267 Mtoe[1] [1] that is equivalent to an average power rate of about 16 TW. In Fig. 1, it is possible to observe that more than 80% of supplied energy derives from the combustion of fossil fuels. In recent years, many frictions grew around the energy exploitation; the most unquestionable problems are the environment pollution and the competition between states for the control of global reserves of oil and gas. Other reasons, even if more contested, are the global warming due to the CO_2 emissions and fossil fuel depletion. In addition, the unstoppable population growth and expanding industrial development of emerging countries are increasing the challenge to avoid the raise of worldwide energy demand for the next decades.

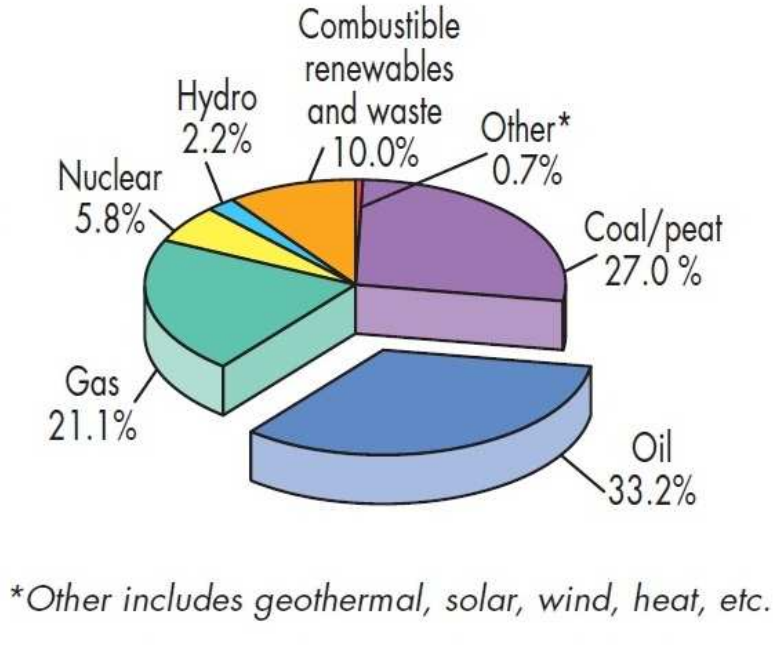

Fig. 1: World total primary energy supply by fuel[2] in 2008 [1].

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[1] One Megatonne of oil equivalent (Mtoe) is equal to 4.1868 x 10^{16} J [1].

[2] Combustible renewables & waste comprises solid biomass, liquid biomass, biogas, industrial waste and municipal waste.

Fossil fuels, coal, oil and natural gas, are generated from plants and animals that lived up to millions of years ago, and reserves are being depleted much faster than new ones are being made. They are indispensable source to produce energy (see Fig. 1), hence they should be efficiently exploited. Non-fossil sources include biomass, nuclear, hydroelectric and others (geothermal, solar, wind, heat, tide, etc.). Renewable energy comes out from resources such as sunlight, wind, rain, tides and geothermal heat which derive from natural processes that are constantly replenished. Even if the "green energy" provides a small share of energy demand so far, its market has to continue to grow to improve the energy sources diversification.

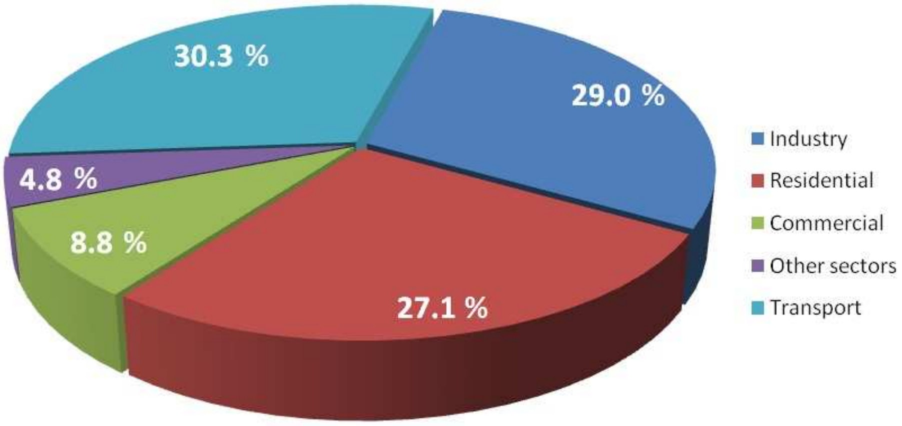

Fig. 2: World energy use in different sectors for 2004-2005 [2].

Approximately 40% of the world's energy is used in buildings (residential and commercial), more than in the transport sector or the industry (see Fig. 2). Energy consumption in building sector usually involves electricity for air-conditioners, appliances, lights, pumps, and heating installations, while natural gas is required for heating, cooking and sanitary water.

1.2 Mitigation of the energy crisis

The international and most famous mean to tackle the global warming is the “Kyoto Protocol”. It is an international agreement linked to the United Nations Framework Convention on Climate Change. Kyoto Protocol sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas emissions. These reductions amount to an average of five per cent against 1990 levels over the five-year period 2008-2012 [3].

The Protocol suggests various means for attaining these objectives: step up or introduce national policies to reduce emissions (greater energy efficiency, promotion of sustainable forms of agriculture, development of renewable energy sources, etc.) and cooperation with the other Contracting Parties (exchanges of experience or information, and international "emissions trading" regime to allow industrialized countries to buy and sell emissions credits amongst). Recognizing that developed countries are principally responsible for the current high levels of GHG emissions in the atmosphere as a result of more than 150 years of industrial activity, the Protocol places a heavier burden on developed nations under the principle of “common but differentiated responsibilities.”

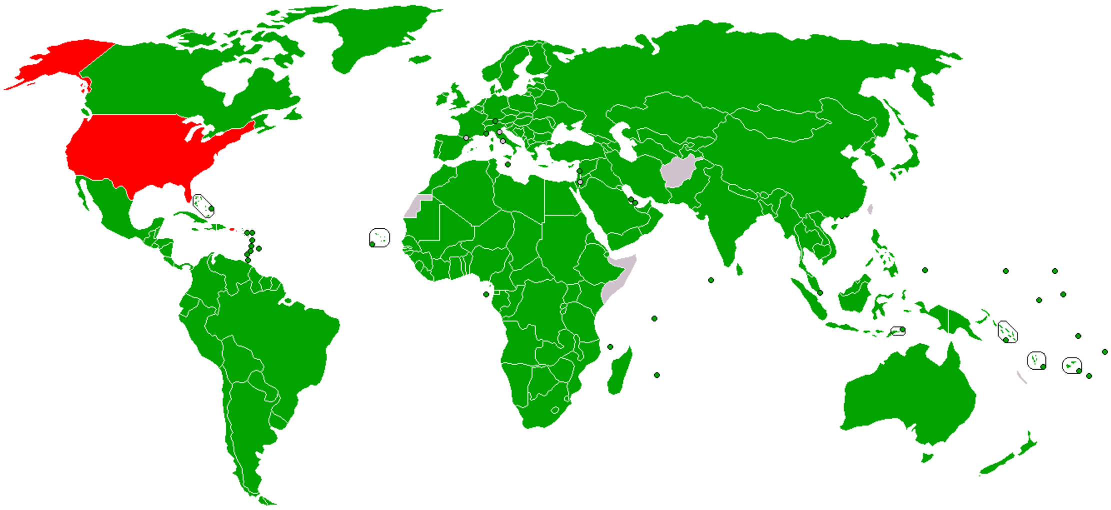

Fig. 3: Participation in the Kyoto Protocol, as of June 2009, where green indicates the countries that have signed and ratified the treaty, grey is not yet decided and red is no intention to ratify [4].

Emissions reduction targets, expressed in relation to total GHG emissions in the base year, are specified in Annex B to the Kyoto Protocol for each industrialized country. They can be summarized as a reduction of 8% by Switzerland, most Central and East European states, and the European Union (the EU will meet its target by distributing different rates among its member states); 7% by the US; and 6% by Canada, Hungary, Japan, and Poland. Russia, New Zealand, and Ukraine have to stabilize their emissions, while Norway may increase emissions by up to 1%, Australia by up to 8%, and Iceland 10%.

The European Union adopted a further provision to tackle the energy crisis. In 2009, EU leaders sanctioned the “climate and energy package” that is known as the 20-20-20 targets [5]. The objectives of this unilateral commitment are:

- a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels;
- satisfy 20% of EU energy consumption with renewable resources;
- a 20% reduction in primary energy use compare with projected levels, to be achieved by improving energy efficiency.

These ambitious targets aim to transform Europe into a highly energy-efficient and low carbon economy.

1.3 Building sector potential

At the beginning of this chapter, we have seen that approximately 40% of world energy is used in buildings (see Fig. 2); this consistent share might be cut with different measures. The energy used for heating and cooling can be reduced through ventilation, heat sinks, the use of solar panel and improved insulation. Electricity can be reduced through improved LED lighting or increased use of natural lighting and the use of energy-efficient appliances. Integrated building design and the modification of building shapes, orientation and materials can also reduce energy use. In addition, raising global energy awareness and changing consumer behavior should be the first steps for a sustainable development.

Buildings have a life span of many decades and, in some cases, for more than a hundred years; therefore, energy efficiency of new buildings has a great potential to reduce energy needs, compared to the other sectors where capital lifetime is a few decades [2]. According with IEA [2], for buildings in general, consistent building refurbishments occur every 30-40 years because major part of the buildings will be worn out and demands for comfort are constantly increasing; while smaller improvements, like high energy efficiency equipments, might even occur more often. The major refurbishments are a good opportunity to improve the energy efficiency of buildings because there is only need to pay for the additional efficiency costs; for instance if windows are replaced due to worn-out, the additional efficiency costs are the difference between a standard window and a highly efficient window. Given the long lifespan of most buildings, improvement of building efficiency at planning stage should be a must. Some measures are possible only in this phase, like defining the optimal shape of the building, its orientation, the orientation of its windows, and its structural materials; in addition, these measures entail no or very low costs in the design phase. Other decisions, when made after construction, would be more expensive or would involve irreparable damage to its structure (for example a rebuilding massive concrete floors placed directly on the ground).

A survey in European countries (see Fig. 4) shows a very low trend to construct new buildings in recent years. It indicates renovation of existing buildings can play an important role to reduce energy need from building sector, at least in Europe. In agreement with IEA [2], a study on the OECD[3] countries shows that the primary energy need can be halved through refurbishment and renovation of buildings; in transition economies the potential is even larger due to lower energy standard of the existing buildings. The highest potential for energy efficiency in new buildings is in developing countries; as reported by IEA [2], half of all the worlds new constructions are in China and India. In line with the same study, energy efficiency in new buildings shows the possibility to reduce up to 70% the primary energy need.

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[3] OECD (Organization for Economic Co-operation and Development), known in Italy as OCSE (Organizzazione per la Cooperazione e lo Sviluppo Economico), countries are Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, the Republic of Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United kingdom and the United States.

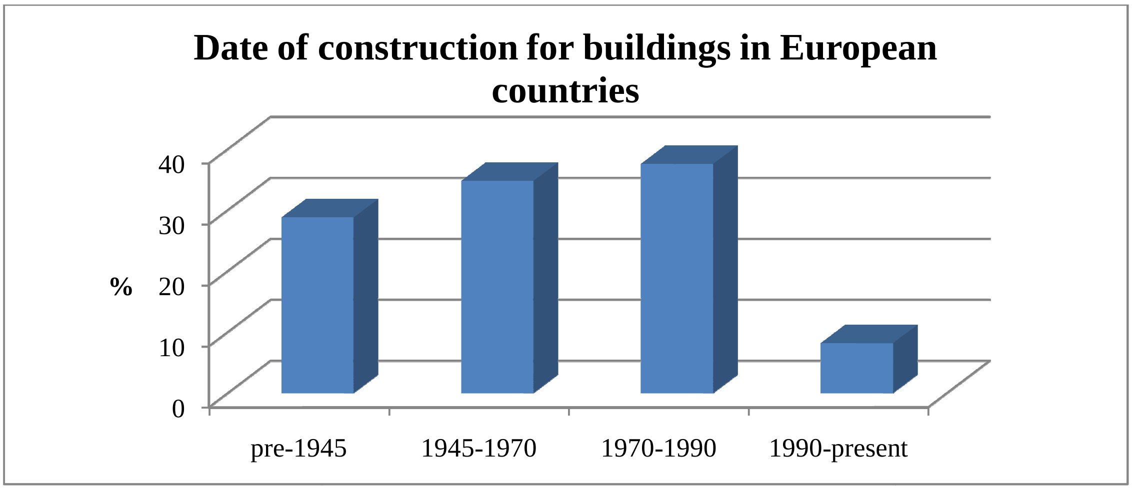

Fig. 4: Date of construction for buildings in European countries reproduced from [6].

1.4 Approach for building improvement

According to the International Energy Agency, energy efficiency improvement is the most economic and readily available means to reduce the energy consumption in buildings, transport sector and industry [7]. As we have seen above, building sector plays an important role to reduce primary energy consumption; especially for European countries, the refurbishment of existing buildings is essential to achieve substantial results (see Fig. 4).

Space heating[4] is the main share of buildings energy need; a study on 19 IEA countries reveals that it accounts for more than 50% of household final energy consumption (see Fig. 5). Space heating energy consumption fell from 58% in 1990 to 53% in 2005 due to the improved thermal performance of new and existing dwellings. In the period 1990-2005, not many measures were taken to reduce energy consumption in buildings but the provisions were sufficient to obtain results; it means that a great effort can provide a large energy saving, as we stated in the previous section.

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[4] Space heating refers to heating and cooling final energy consumption.

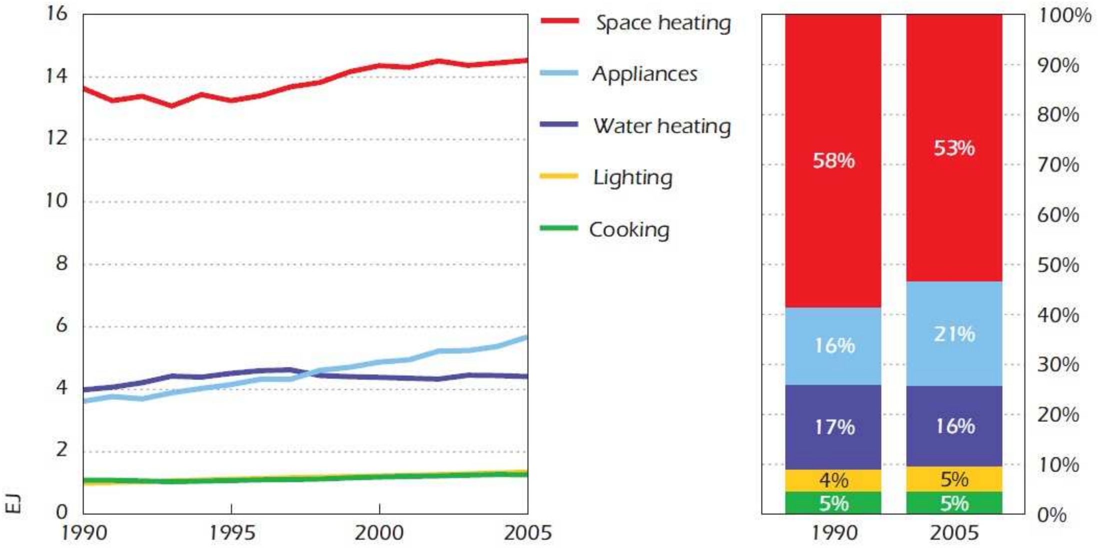

Fig. 5: Household Energy use by end-use, IEA19[5] [7].

Energy consumption for space heating, considering a standard use of the building, basically depends from the efficiency of air-conditioning equipment and the demand of useful energy for space heating. In this work, we do not consider the conversion losses in heating and cooling technologies; we focus on the building envelope. For the construction or refurbishment of a building shell, there are many solutions to get similar results of energy saving but sometimes with relevant difference in terms of improvement efforts. Energy need of a building is more sensitive to certain parameters and less to others, therefore knowing which parameters allow large energy saving is essential for a low-energy building development.

In the second chapter, different approaches for the sensitivity analysis are presented; all of them have the same purpose, to identify the influence of a parameter on the output of the analyzed model. In the third chapter, a simple application of the “Monte Carlo analysis” is fully explained; for our application, it is not important from the point of view of the results but for understanding how a global sensitivity method works. In the fourth and fifth chapter, the software used in this work are presented; Trnsys is the program to perform dynamic simulations of thermal systems and GenOpt allows to conduct a parametric analysis. In the sixth chapter, we develop the global sensitivity analysis based

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[5] IEA19 considers the following countries: Australia, Austria, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, Netherlands, New Zealand, Norway, Sweden, Spain, Switzerland, United Kingdom, United States.

on the dynamic simulation software (Trnsys) to simulate the real thermal behavior of buildings; the results are then discussed with the aim of accurately explaining how the influence of each analyzed parameter affects the output (energy need) of the building in analysis and how the different variables are correlated each other. In the last chapter, there are some studies in depth to explain the approximation taken in the analysis and some interesting phenomena.

2 Approaches and applications for the sensitivity analysis

Sensitivity analysis has a wide field of applications and there are several procedures to perform it. In this chapter, some approaches for the sensitivity analysis and an application with Monte Carlo method are presented.

2.1 Different approaches for the sensitivity analysis

The sensitivity analysis determines the influence of a parameter on the output result of a considered model. Basically, there are three different types of sensitivity analysis: screening methods, local sensitivity methods, and global sensitivity methods. The firsts two methods are so called OFAT-methods (one factor at a time) in which output variability is evaluated for one parameter, while all the others are held constants; the third one is a global method, hence output variability due to one parameter is evaluated by varying all other parameters as well. In this section, we can understand how the three methods work and how they are applied in some scientific papers.

2.1.1 Screening method

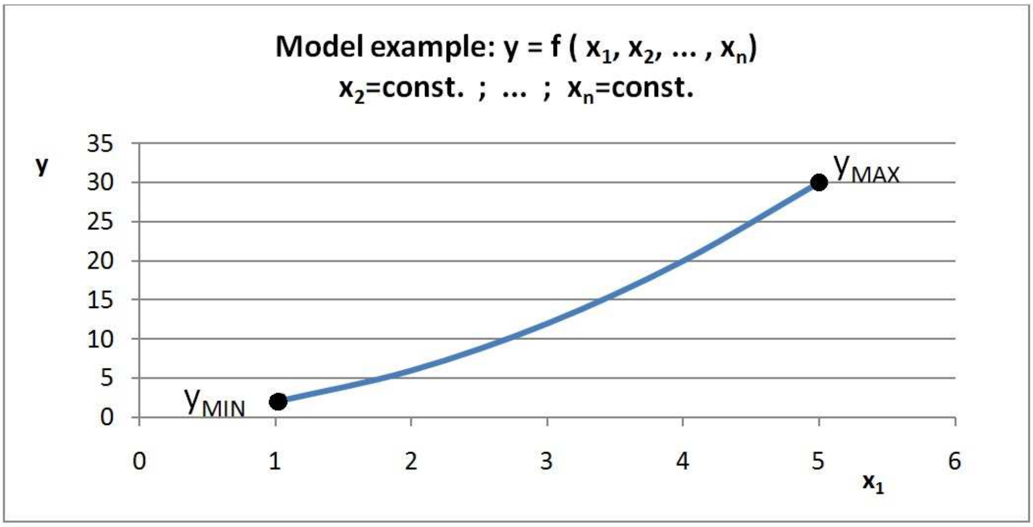


Fig. 6: Example of a OFAT-method, Y as function of X_1 while the rest of the variables are held constant.

Screening methods are used when the analyzed model contains a large number of parameters; it is an approximate method that can provide a ranking of all the parameters. Usually, this method provides a first view to determine which parameters should be included in depth-examination. Parameters are evaluated one at a time and standard values for all parameters are considered as reference point. Usually, two extreme values of each parameter range are selected to calculate the respective “sensitivity index”. The ranking of the parameters is made possible through the so-called “sensitivity index” that allows the calculation of the output % difference choosing the extreme values of the design parameter (see Fig. 6). The relation to evaluate the “sensitivity index” is:

$$SI_i = \frac{y_{MAX} - y_{MIN}}{y_{MAX}} \cdot 100 \quad [\%] \qquad \text{(i=1, 2, ... , n-parameter)}$$

Where y_{MAX} and y_{MIN} represent the maximum and minimum output values that come out varying the considered parameter into its entire range.

An application of the screening method is presented in “Application of sensitivity analysis in design of sustainable buildings” [8]. As we said before, also in the paper just mentioned, this method is used to determine which design parameters should be included in the sensitivity analysis. If the sensitivity index reaches a defined critical value, the design parameter is considered to be important and it is included in a further analysis.

2.1.2 Local sensitivity method

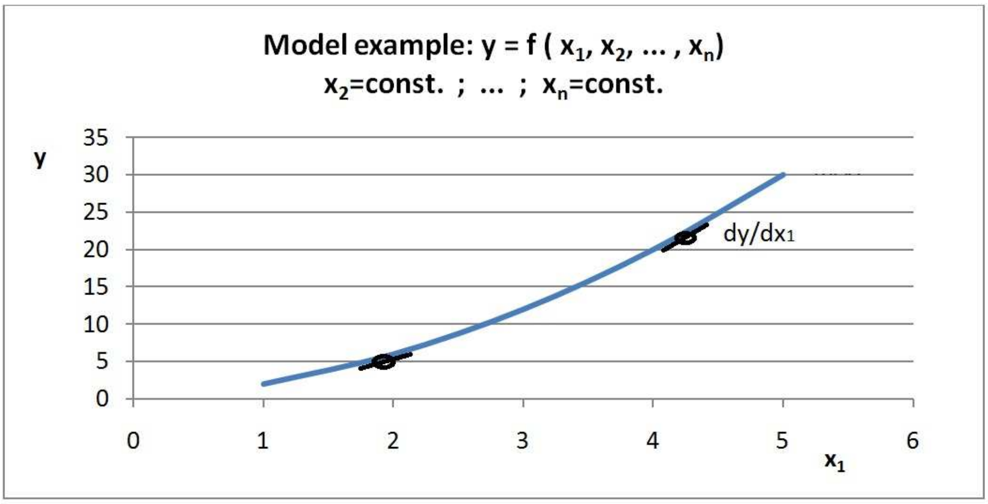


Fig. 7: Example of a OFAT-method, Y as function of X_1 while the rest of the variables are held constant.

This is a OFAT-method as the previous one but the local sensitivity is measured by the partial derivatives of the objective function value with respect to the parameter whose sensitive is sought:

$$SI_i = \left| \frac{\partial Y}{\partial X_i} \right|_{X^0} \qquad \text{(i=1, 2, ... , n-parameter)}$$

Where the subscript X^0 indicates that the derivative is taken at a fixed point in the space of the input. In practice, it is possible to describe a correlation between y and x_1 (see Fig. 7), but that curve depends on the rest of the parameters which are held constant (x_2, x_3, .. ,x_n).

In “Application of sensitivity analysis in design of sustainable buildings” [8], the local sensitivity analysis is applied after a first investigation with the screening method; the main purpose is to determine which design parameters may be considered to have effects which are negligible, linear, or non-linear. In this application the sensitivity analysis can give important information about which design parameters are the most important ones to change in order to reduce the energy consumption or to focus on in the next phases of the design. It is fundamental to keep in mind that all the results obtained with a local approach are affected by the boundary conditions chosen at the beginning; therefore, the solutions of the analysis are reliable only in the specific analyzed case.

Local sensitivity methods, similarly to screening method, have some limitations. The approach is not reliable when the model is non-linear and/or the input variables are affected by uncertainties of different order of magnitude.

2.1.3 Global sensitivity method

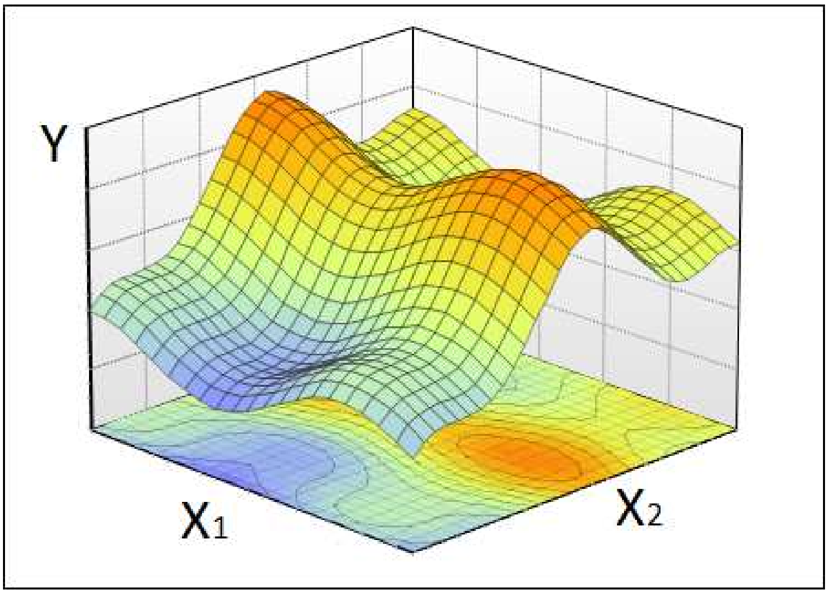


Fig. 8: Example of a global method, Y as function of X_1 , X_2.

Global sensitivity method is based on the effect of a single parameter on the output uncertainty while at the same time all other parameters are varied as well (see Fig. 8). Further, this method includes the influence of the whole range of variation and probability distribution of the input parameters. The relation to evaluate the "sensitivity index" is:

$$SI_i = \left| \frac{\partial Y}{\partial X_i} \right|_X \qquad \text{(i=1, 2, ... , n-parameter)}$$

Where the subscript X is an array of randomly selected parameter values in the space of the input. In practice, X identifies the point which the calculation of the derivative refers.

The global sensitivity method is an approach that is often avoided due to its wastefulness in terms of simulation time but at the same time, it allows to conduct an analysis that does not refer to any boundary condition. The solutions represent a general view of the behavior of the analyzed model that is not obtainable with a tight analysis.

For this work, the global sensitivity method is selected because it considers the completely dependence of the output on the interactions and influences of all design parameters. In addition, the thermal behavior of a building, that is the model in this work, is non-linear. In the next chapter, a representative example of global sensitivity analysis will be given; it is based on a fictitious model, without practical purpose, but should clarify how the method works. For the purpose, Monte Carlo Analysis (MCA) is adopted; MCA performs multiple evaluation with randomly selected model input factor and can deal with correlated input parameters.

2.2 Monte Carlo analysis (MCA)

The Monte Carlo analysis is a technique to solve problems when the model is complex, nonlinear, or involves more than just a couple uncertain parameters. This method evaluates iteratively a deterministic model using sets of random numbers and probability as inputs. MCA is one of many methods for analyzing uncertainty propagation, where the goal is to determine how random variation, lack of knowledge, or error affects the sensitivity, performance, or reliability of the system that is being modeled. The distribution for the inputs must match with the data already known, or that best represents the current state of knowledge. The data generated from the simulation can be represented as probability distributions, reliability predictions, tolerance zones, and confidence intervals.

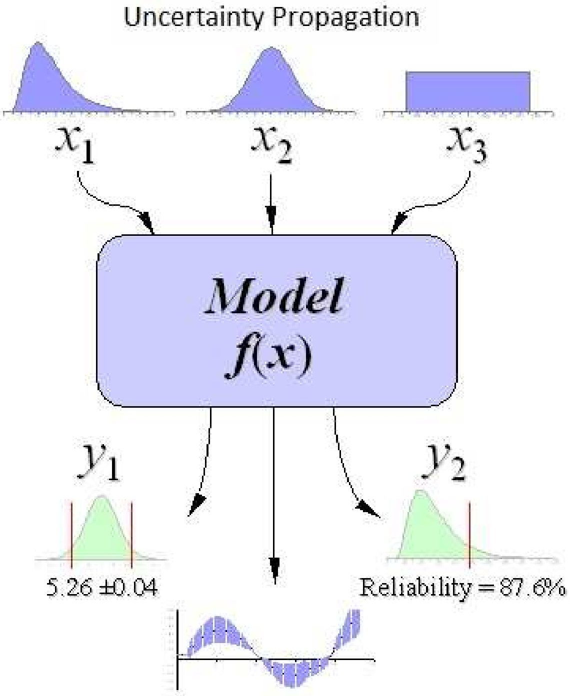


Fig. 9: The basic principle behind Monte Carlo analysis [9].

Monte Carlo method (see Fig. 9) can be easily implemented in a spreadsheet like Excel for simple models. In this chapter, a representative example of building is analyzed (see Fig. 10), considering a mathematical model for the study. The basic steps for a global sensitivity analysis are discussed in this order:

- definition of the parametric model and its input parameters;
- screening analysis;
- assignment of probability density functions to the input parameters;
- generation of design parameter input matrix;
- calculation of output vectors and data processing;

2.2.1 Definition of the parametric model and its input parameters

The analyzed building is stylized as a cube with 4 windows (see Fig. 10). The heat exchange equation, between inside and outside of the conditioned space, is chosen as simulation model. Its parameters are: wall transmittance, window transmittance and ratio between $A_{windows}$ and A_{tot} .

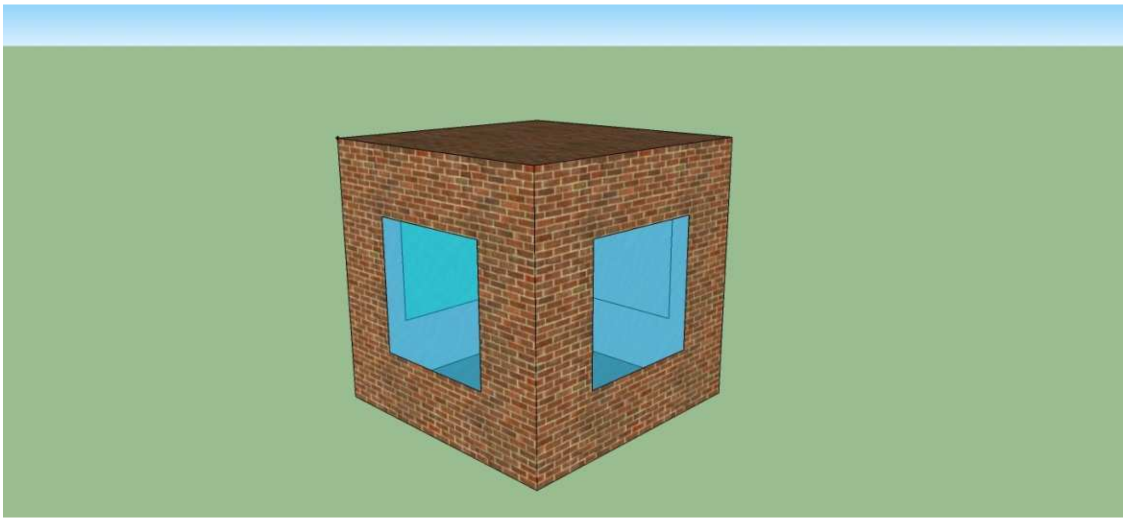


Fig. 10: Simplified building in analysis.

In this simplified example, the output variable is the specific power defined as:

$$y = [x_1 \cdot (1 - x_3) + x_2 \cdot x_3] \quad [W / m^2 K]$$

For the three parameters of the model, an interest range is defined:

$$x_1 \rightarrow \begin{cases} 1\ W/m^2K & (uninsulated) \\ 0.1\ W/m^2K & (heavy\ insulation) \end{cases}$$ -wall transmittance-

$$x_2 \rightarrow \begin{cases} 6\ W/m^2K & (\text{single} - glazed) \\ 1\ W/m^2K & (triple - glazed) \end{cases}$$ -window transmittance-

$$x_3 \rightarrow \begin{cases} 0.5 & (big\ windows) \\ 0.1 & (small\ windows) \end{cases}$$ -ratio $A_{windows}/A_{tot}$ -

2.2.2 Screening analysis

Screening method usually is a necessary step when the simulation model contains a large number of variables. It determines which design parameters should be included in the deep sensitivity analysis. Parameters are evaluated one at a time and standard values for all parameters are considered as reference points. Usually, two extreme values of each parameter range are selected to calculate the respective “sensitivity index”. This index allows the calculation of the output % difference choosing the extreme values of the design parameter. The relation to evaluate the “sensitivity index” is:

$$SI_i = \frac{y_{MAX} - y_{MIN}}{y_{MAX}} \cdot 100 \quad [\%] \qquad\qquad (i = 1, 2, 3)$$

Where y_{MAX} and y_{MIN} represent the maximum and minimum output values that come out varying the design parameter into its entire range.

Tab. 1 shows the results of the “sensitivity index” calculation:

		MIN		*MAX*		
	i	$x_{i,MIN}$	$y_{i,MIN}$	$x_{i,MAX}$	$y_{i,MAX}$	SI_i
	-	W/m^2K	W/m^2K	W/m^2K	W/m^2K	%
Wall transmittance	1	0,10	1,12	1,00	1,75	36
Window transmittance	2	1,00	0,685	6,00	2,18	69
Ratio $A_{windows}/A_{tot}$	3	0,10	0,845	0,50	2,02	58

Tab. 1: Calculation of the “sensitivity index” for each design parameter.

In this simplified example there are only three parameters and hence the screening analysis is not necessary. In case there were many parameters, a threshold value of SI (sensitivity index) should be defined to establish if a design parameter is included in the further analysis or not.

2.2.3 Assignment of probability density functions to the input parameters

For each design parameter that is accepted by the screening analysis, the most appropriate probability density function is assigned. The assignment depends on technical possibilities, economical consideration or other issues. The most used probability density functions are uniform, lognormal and normal distribution. For the simplified example in this analysis, a uniform distribution (see Fig. 11) is chosen for all the parameters because there are no technical limitations on each parameter range and economical considerations are not considered.

Fig. 11: Uniform probability density distribution for input parameters.

2.2.4 Generation of design parameter input matrix

Many sampling procedures can be used to generate input vectors: random sampling, Latin hypercube sampling, quasi-random sampling and other methods. For the analyzed example of this chapter, random sampling is proposed to generate inputs accordingly with the probability density function chosen in the previous step. The procedure is repeated n times creating an nxk sample matrix, where k is the number of parameters. The number of iterations (n) is defined to make sure that the space of variation is reasonably covered for all the design parameters.

Tab. 2 proposes the sample matrix with *k* parameters (x_1,x_2,x_3) and *n* simulations:

Iterations	*Wall transmittance*	*Window transmittance*	*Ratio* A_{window}/A_{tot}	*Output*
j	x_1	x_2	x_3	*y*
-	W/m^2K	W/m^2K	-	W/m^2K
1	0.82	4.78	0.41	2.44
2	0.83	2.99	0.38	1.65
.	.	.	.	.
.	.	.	.	.
18	0.16	1.11	0.18	0.33
19	0.92	4.63	0.42	2.48
20	0.73	4.06	0.45	2.23

Tab. 2: Sample matrix with three design parameters (*k*) and 20 iterations (*n*).

2.2.5 Calculation of output vectors and data processing

2.2.5.1 Assessment of the influence of each design parameter

From input vectors, that have been generated in the previous step, an output vector is calculated through the simulation model that was defined in the first step; as shown in the Tab. 2, the last column represents the first output vector (specific heat loss power). The assessment of the influence of each design parameter is made comparing the variation of the output respect the variables individually taken. We are not going to discuss about the influence in this section because this is just a chapter to present the methodology.

As we will see in the sixth chapter, the determination of a correlation coefficient is useful to detect the relationship between two vectors. For example, the influences on the output simulation model of the different design parameters can be compared through the Pearson’s correlation index that reflects the degree of linear relationship. We obtain three indexes, the first one searches a correlation between the specific heat loss power and the wall transmittance, the second one with the window transmittance and the third one with the area ratio. Comparing these three correlation coefficients, the parameter that most influence the specific heat loss power is detected.

Note that the assessment is conducted with global approach, it means that the analysis is based on the effect of a single parameter on the output uncertainty while at the same time all other parameters are varied as well. Global sensitivity analysis considers the complete dependence of the output on the interactions and influences of all design parameters.

2.2.5.2 Assessment of correlation between the design parameters

The correlation between the different design parameters reflects how a parameter influences the capacity of another parameter to lead the behavior of a simulation model. It means to evaluate the partial derivative of the output vector (specific heat loss power) respect the different input vectors and then to find a correlation between the partial derivatives and the design parameters.

In this section, the partial derivatives can be calculated with a mathematical relation but in case we had a numerical model, instead of a mathematical model, the partial derivative calculation is based on the so called "elementary effect":

$$EE_{ij}(x_{1j},..,x_{kj}) = \frac{y_j(x_{1j},x_{2j},..,x_{(i-1)j},x_{ij}+\Delta,x_{(i+1)j},..,x_{kj}) - y_j(x_{1j},..,x_{kj})}{\Delta} \approx \frac{\partial y_j}{\partial x_{ij}}$$

Where j is the number of iteration (j=1,..,n) and i represents the different design parameters (i=1,..,k); Δ is a predetermined perturbation factor to approximate the elementary effect with a partial derivative.

The simplified model in analysis is evaluated considering 0.0001 as Δ and 20 iterations for each parameter. From the input values of Tab. 2, the index “elementary effect” is calculated and the results are shown in the table below (Tab. 3):

	Wall transmittance	Window *transmittance*	A_{WINDOW}/A_{FLOOR}
j	EE_{1j}	EE_{2j}	EE_{3j}
-	$\partial y_j / \partial x_{1j}$	$\partial y_j / \partial x_{2j}$	$\partial y_j / \partial x_{3j}$
1	0,78	0,22	3,61
2	0,88	0,12	1,44
3	0,84	0,16	2,07
4	0,58	0,42	1,13
5	0,72	0,28	2,18
-	-	-	-
-	-	-	-
15	0,64	0,36	2,47
16	0,82	0,18	2,62
17	0,66	0,34	3,12
18	0,78	0,22	1,77
19	0,54	0,46	5,14
20	0,56	0,44	0,77

Tab. 3: "Elementary effect" for each parameter and different iterations.

The assessment of correlation of each design parameter is made comparing the variation of a design parameter respect the partial derivative of each parameter; in this way, we detect how a parameter is influenced by the other parameters. We are not going to discuss about the correlation of the design parameters in this section because this is just a chapter to present the methodology.

3 Performance analysis tools

The global analysis has been conducted with two main software: Trnsys and GenOpt. In this chapter there is a description of how the programs work and the settings adopted to allow an integrated operation.

3.1 Trnsys (Transient System simulation program)

Trnsys is a commercial software to perform dynamic simulations of thermal systems. The program was developed by Solar Energy Laboratory of the University of Wisconsin; it is used all around the world to solve engineering problems concerning thermal and energy matter. In this section…

3.1.1 Simulation Studio

Simulation studio is the main interface and has a modular structure (see Fig. 12); in this section the user specifies the components that constitute the system and the manner in which they are connected. Each component is called “Type”, it is a subroutine that describes the behavior of an element through differential and algebraic equations. A type is connected to another through “link” that allows the transmission of data.

For this work, the selected types are:

- Type 9c (reader of data from data file);
- Type 16i (processor of solar radiation data);
- Type 2b (ON/OFF differential control);
- Type 28b (generator of monthly summaries of the results);
- Type 56b (model of the thermal behavior of a building).

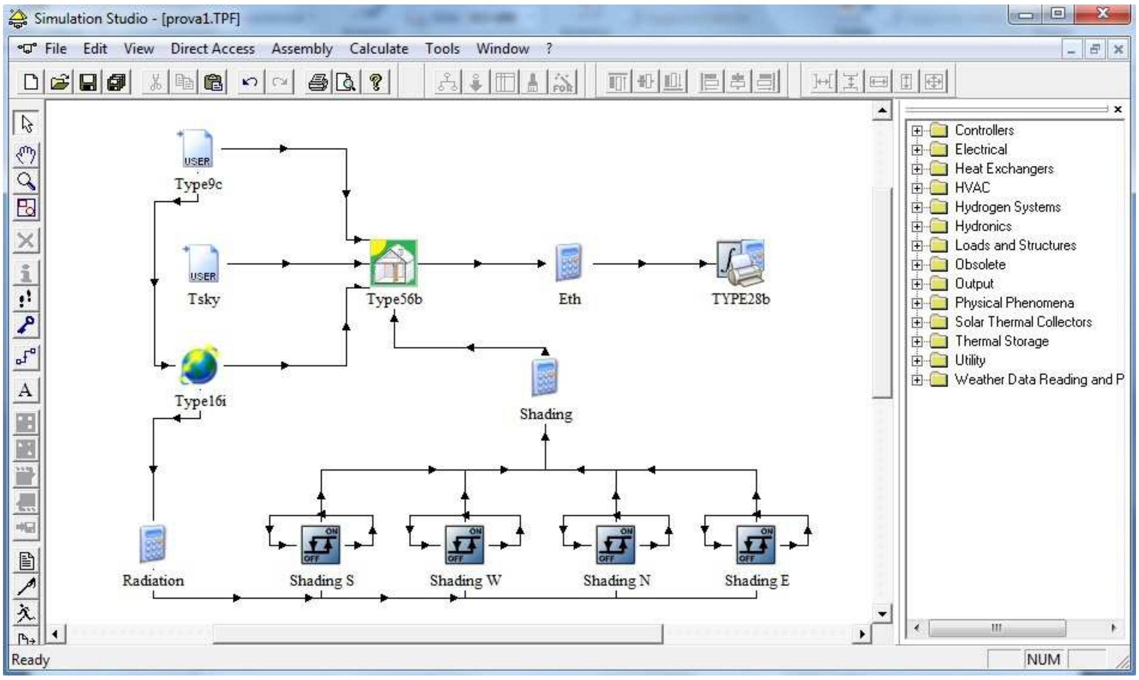


Fig. 12: Main interface of Trnsys Simulation Studio.

3.1.1.1 Type 9c

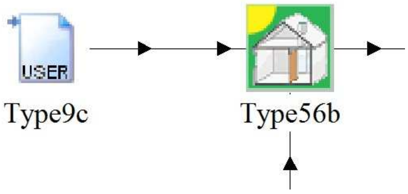


Fig. 13: Type 9c reads data and transmits the information to another type.

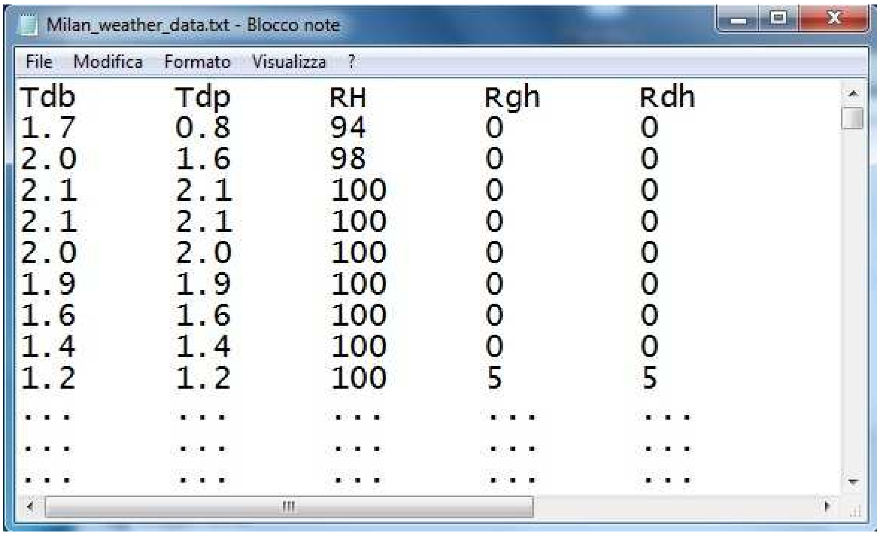
This component serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other Trnsys components as time-varying forcing functions. This component is very general in nature and can read many different types of files. The data from line to line must be at constant time intervals.

In Fig. 14 we can see the file from which the type 9c reads the weather data. Each column contains 8760 values that corresponds to the total number of hours for an entire year.

The first row shows the label of each column:

- T_{db} (dry bulb temperature)
- T_{dp} (dew point temperature)
- RH (relative humidity)
- Rgh (global horizontal radiation)
- Rdh (diffuse horizontal radiation)

EnergPlus website [10] provides the data that are generated from a period of record (typically 30 years) to be representative of the weather of the location in question.

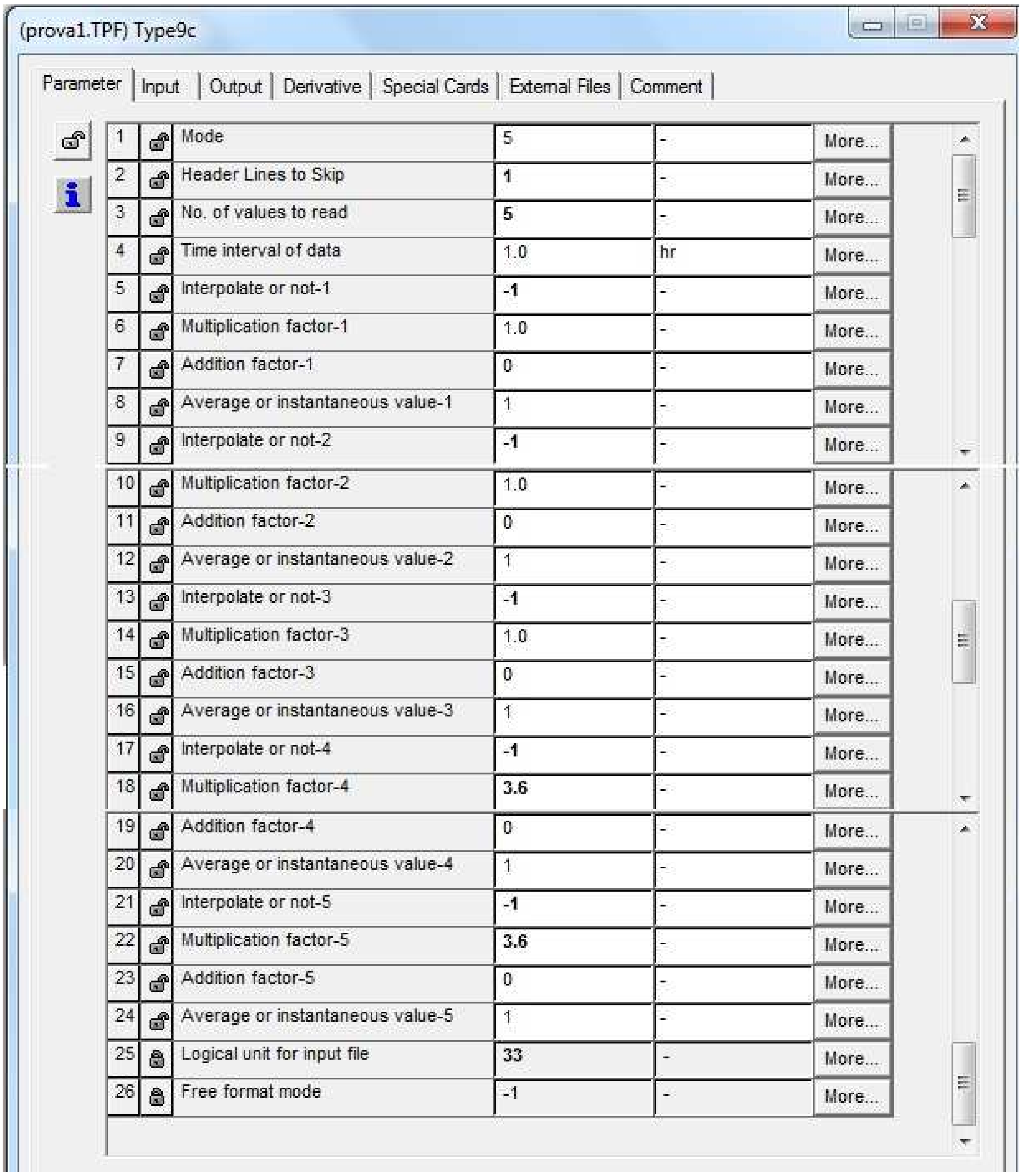


```
Tdb     Tdp     RH      Rgh     Rdh
1.7     0.8     94      0       0
2.0     1.6     98      0       0
2.1     2.1     100     0       0
2.1     2.1     100     0       0
2.0     2.0     100     0       0
1.9     1.9     100     0       0
1.6     1.6     100     0       0
1.4     1.4     100     0       0
1.2     1.2     100     5       5
...     ...     ...     ...     ...
...     ...     ...     ...     ...
...     ...     ...     ...     ...
```

Fig. 14: Weather data for Milan (Italy).

In Fig. 15 we can see the parameter settings for the type 9c that specify how to read the weather data file. “Mode” (5) means that the first line in the data file corresponds to time equal to zero. “Header lines to skip” (1) considers that the first row contains labels. “No. of values to read” (5) specifies how many values are to be read from each line of the data file. “Time interval of data” (1 hr) is the time interval used to record the data in the file.

For each parameter that is read from the file, some operations are defined to convert the values to a desired system of units. “Interpolate or not” (-1) indicates that the values are not interpolated. “Multiplication factor” (3.6) is considered only for the radiation (fourth and fifth parameter) because the weather data file provides the radiation as [Wh/m^2] while the simulation program requires [kJ/hm^2]; “addition factor” (0) is considered for none of the parameters. “Average or instantaneous value” (1) indicates that we read an instantaneous value over the data time interval.



1	Mode	5	-
2	Header Lines to Skip	1	-
3	No. of values to read	5	-
4	Time interval of data	1.0	hr
5	Interpolate or not-1	-1	-
6	Multiplication factor-1	1.0	-
7	Addition factor-1	0	-
8	Average or instantaneous value-1	1	-
9	Interpolate or not-2	-1	-
10	Multiplication factor-2	1.0	-
11	Addition factor-2	0	-
12	Average or instantaneous value-2	1	-
13	Interpolate or not-3	-1	-
14	Multiplication factor-3	1.0	-
15	Addition factor-3	0	-
16	Average or instantaneous value-3	1	-
17	Interpolate or not-4	-1	-
18	Multiplication factor-4	3.6	-
19	Addition factor-4	0	-
20	Average or instantaneous value-4	1	-
21	Interpolate or not-5	-1	-
22	Multiplication factor-5	3.6	-
23	Addition factor-5	0	-
24	Average or instantaneous value-5	1	-
25	Logical unit for input file	33	-
26	Free format mode	-1	-

Fig. 15: Parameter section for Type 9c.

The calculation of the extra heat transfer by thermal radiation to the sky requires the knowledge of the sky temperature, hence it has been calculated through the horizontal infrared radiation from sky (R_{ih}) with the following formula (see Tab. 4):

$$R_{ih} = \sigma T_{sky}^4$$

The horizontal infrared radiation from sky for the considered location is downloaded from the EnergyPlus website [10] and σ (Stefan-Boltzmann Constant) is equal to $5.6704 \cdot 10^{-8}$ W/m^2K^4. Sky temperature is then read by the type 9c at the same way of the parameters previously discussed.

Note that in the absence of sky temperature from climatic data, according to the EN ISO 13790:2008[6], the average difference between the external air temperature and the sky temperature should be taken as 11 K in intermediate zones (between sub-polar and tropics).

N°	R_{ih}	T_{sky}
-	Wh/m^2	°C
1	295	-4,58
2	297	-4,13
3	298	-3,90
..	..	..
..	..	..
..	..	..
8758	288	-6,19
8759	290	-5,73
8760	292	-5,27

Tab. 4: Sky temperature calculated from horizontal infrared radiation from sky.

---

[6] Thermal performance of buildings – Calculation of energy use for space heating and cooling.

3.1.1.2 Type 16i

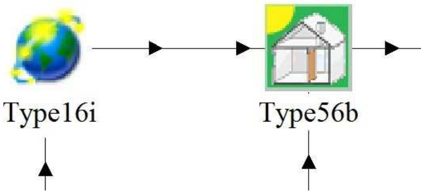
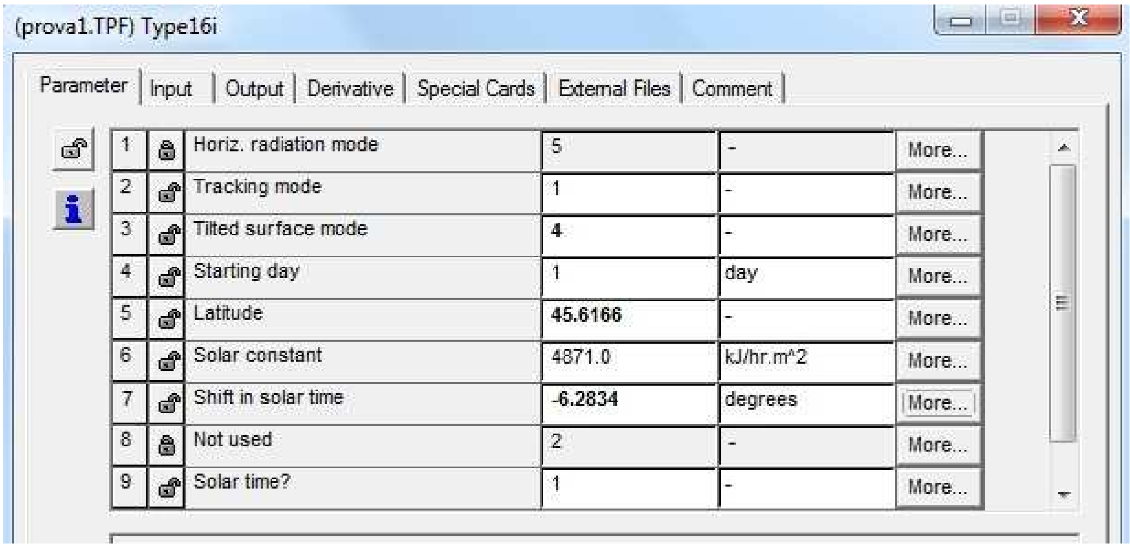


Fig. 16: Type 16i processes radiation data and transmits the information to another type.

This component interpolates radiation data, calculates several quantities related to the position of the sun, and estimates insolation on a number of surfaces of either fixed or variable orientation. Type16i takes hourly integrated values of total horizontal and horizontal diffuse radiation as inputs. It can use various algorithms to compute radiation on tilted surfaces such as Hay and Davies, Perez, Reindl, etc.

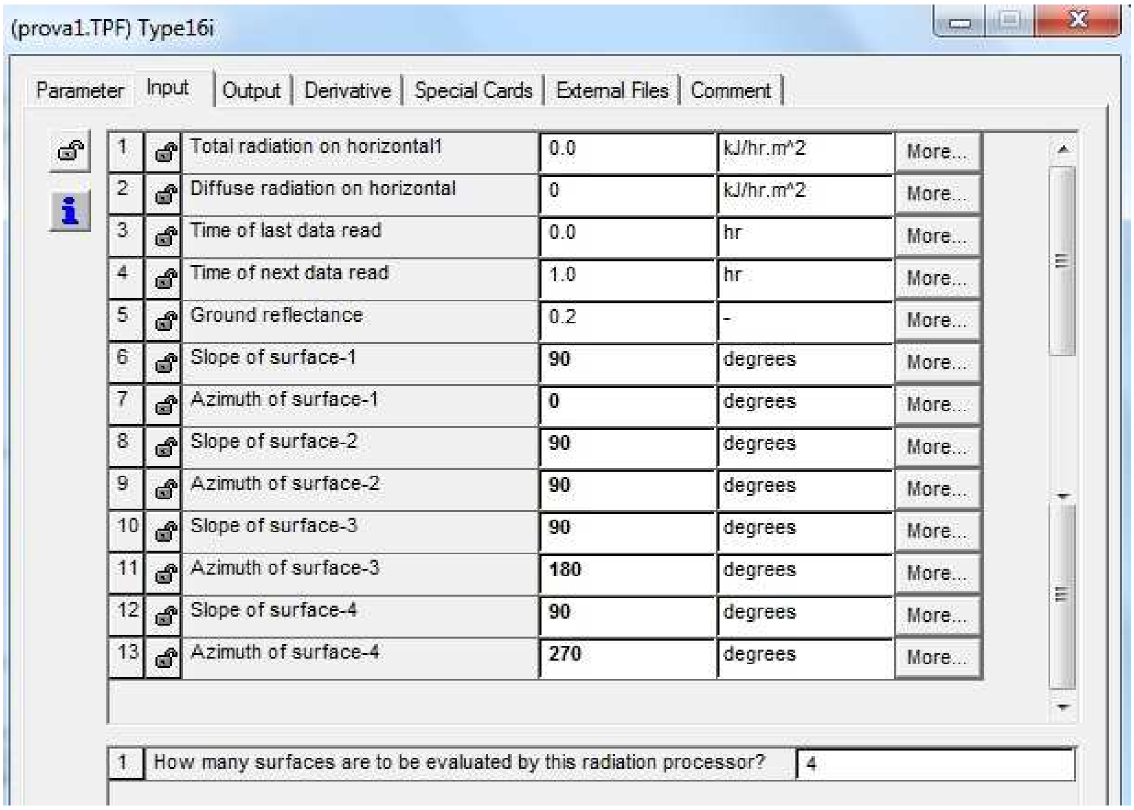


1	Horiz. radiation mode	5	-
2	Tracking mode	1	-
3	Tilted surface mode	4	-
4	Starting day	1	day
5	Latitude	45.6166	-
6	Solar constant	4871.0	kJ/hr.m^2
7	Shift in solar time	-6.2834	degrees
8	Not used	2	-
9	Solar time?	1	-

Fig. 17: Parameter section for Type 16i.

“Horizontal radiation mode” corresponds to mode 5, hence total horizontal and diffuse horizontal radiation are the inputs of Type 16i that processes the radiation on tilted surfaces. “Tracking mode” (1) means we are considering fixed surfaces. “Tilted surface radiation mode” (4) refers to Perez model, we chose this one because it is more accurate respect the other ones [11]; furthermore, it is recommended by technical specifications.

“Latitude” for the considered building in Milan is 45° 37’ that corresponds to 45,6166° (decimal degrees); we consider the building in analysis situated where the weather data were registered. “Shift in solar time” (-6,2834) is used to account for the differences between solar time and local time.



1	Total radiation on horizontal1	0.0	kJ/hr.m^2
2	Diffuse radiation on horizontal	0	kJ/hr.m^2
3	Time of last data read	0.0	hr
4	Time of next data read	1.0	hr
5	Ground reflectance	0.2	-
6	Slope of surface-1	90	degrees
7	Azimuth of surface-1	0	degrees
8	Slope of surface-2	90	degrees
9	Azimuth of surface-2	90	degrees
10	Slope of surface-3	90	degrees
11	Azimuth of surface-3	180	degrees
12	Slope of surface-4	90	degrees
13	Azimuth of surface-4	270	degrees

1 How many surfaces are to be evaluated by this radiation processor? 4

Fig. 18: Input section for Type 16i.

In Fig. 18 we can see the input section for Type 16i. “Total radiation on horizontal” and “diffuse radiation on horizontal” are values hourly provided through type 9c. “Ground reflectance” is typically considered 0.2 for ground not covered by snow. For each surface, “azimuth” and “slope” are defined; in this work, all the perimeter surfaces are vertical and the orientations correspond with the four cardinal points.

3.1.1.3 Type 2d

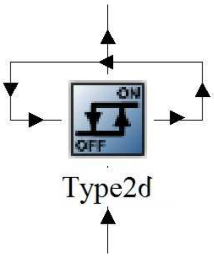
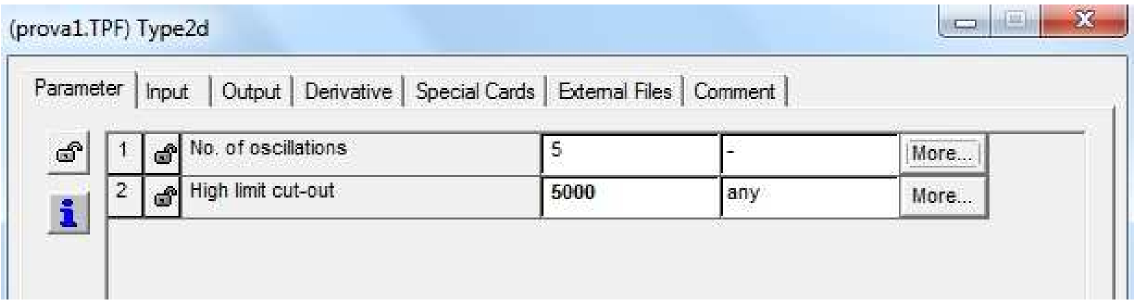


Fig. 19: Type 2d simulates the ON/OFF differential control.

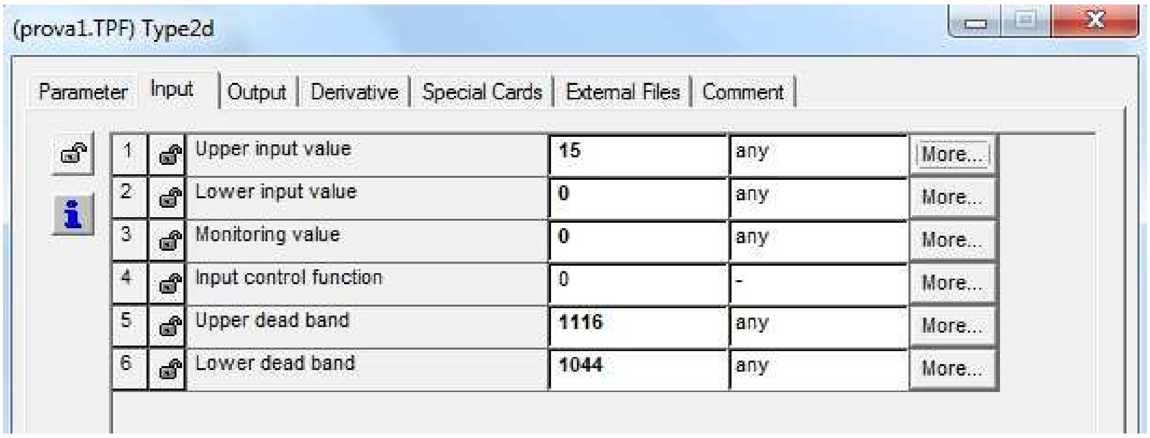
The on/off differential controller generates a control function which can have a value of 1 or 0. The value of the control signal is chosen as a function of the difference between upper and lower values xh and xl, compared with two dead band temperature differences Dxh and Dxl. The new value of the control function depends on the value of the input control function at the previous timestep. The controller is normally used with the input control signal connected to the output control signal, providing a hysteresis effect.



1	No. of oscillations	5	-	More...
2	High limit cut-out	5000	any	More...

Fig. 20: Parameter section for Type 2d.

In Fig. 20 we can see the parameter section for type 2d, “No. of oscillations” (5) is the number of control oscillations allowed in one timestep before the controller is "stuck" so that the calculations can be solved. This parameter should be set to an odd number so that short-term results are not biased. For safety considerations, a “high limit cut-out” (5000) is included with this controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded.



1	Upper input value	15	any
2	Lower input value	0	any
3	Monitoring value	0	any
4	Input control function	0	-
5	Upper dead band	1116	any
6	Lower dead band	1044	any

Fig. 21: Input section for Type 2d.

Fig. 21 shows the input section for type 2d; “upper input value” is hourly provided through type 16i, that reads the total radiation for each orientation, while “upper dead band” and “lower dead band” is used in the following way in the controller: the controller is ON if it was previously OFF and xh (Input 1) minus xl (Input 2) is greater than the upper dead band, otherwise the controller is OFF; the controller is ON if it was previously ON and xh (Input 1) minus xl (Input 2) is greater than the lower dead band, otherwise the controller is OFF. In this work, “upper dead band” is equal to 1116 kJ/hm^2, that corresponds to 310 Wh/m^2, and “lower dead band” is equal to 1044 kJ/hm^2, that corresponds to 290 Wh/m^2. Each side of the building (S, W, N, E) needs an independent controller to manage the radiation gains.

3.1.1.4 Type 28b

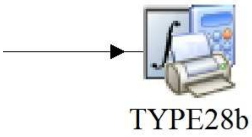
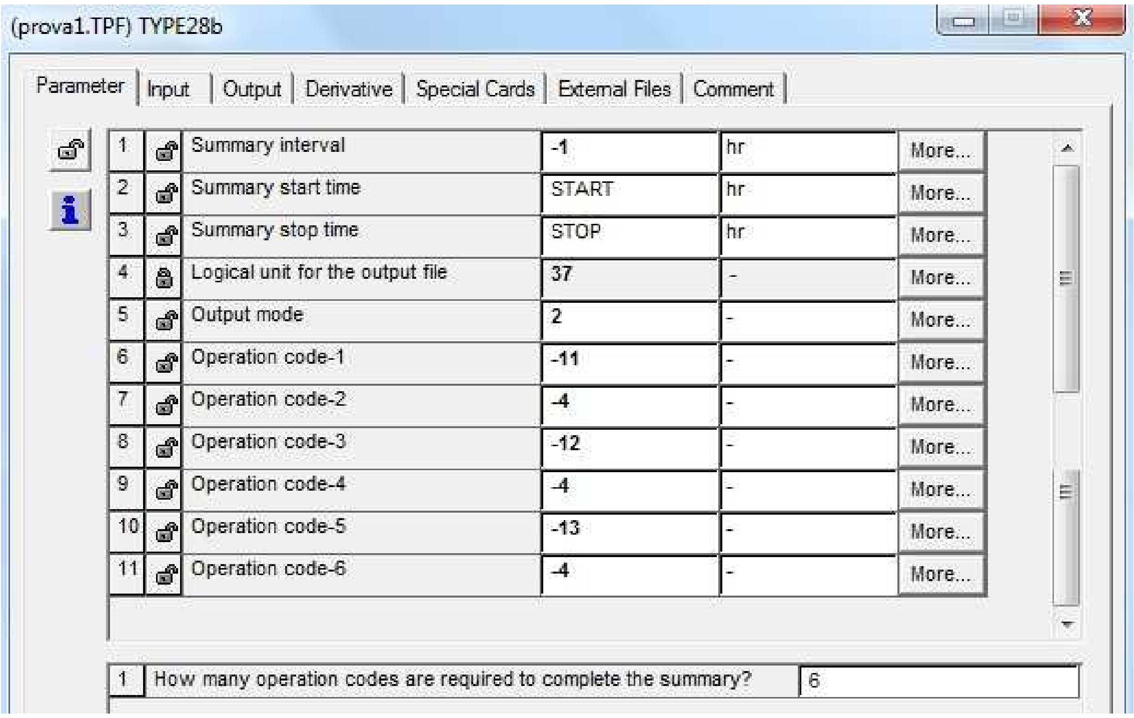


Fig. 22: Type 28b generates monthly summaries of the results.

Type 28b can be conveniently used to generate daily, weekly, monthly or seasonal summaries of information computed in a simulation. Its output can be displayed either in a boxed format or as a table. Type 28b integrates its inputs over the time interval of the summary, performs user specified arithmetic operations on the integrals, and prints the results. This configuration prints results to an external file (see Fig. 25).



1	Summary interval	-1	hr
2	Summary start time	START	hr
3	Summary stop time	STOP	hr
4	Logical unit for the output file	37	-
5	Output mode	2	-
6	Operation code-1	-11	-
7	Operation code-2	-4	-
8	Operation code-3	-12	-
9	Operation code-4	-4	-
10	Operation code-5	-13	-
11	Operation code-6	-4	-

1	How many operation codes are required to complete the summary?	6

Fig. 23: Parameter section for type 28b.

Fig. 23 shows the parametric section for the type 28b. “Summary interval” (-1) indicates that the absolute value of the parameter will be used to specify the rest time in months (see Fig. 25). “Output mode” (2) refers to a table with a single heading for every 12 sets of summaries (best adapted to monthly summaries). “Operation code-n” is the reverse polish operation code that will be used to manipulate the parameters and inputs to produce the outputs. The parameter list may also contains constants to be used in the summary. Note that the operations are performed after the inputs have been integrated.

The operation codes are repeated below for convenience:

-11: place the 1st input on the top of the stack (Sk=X1);

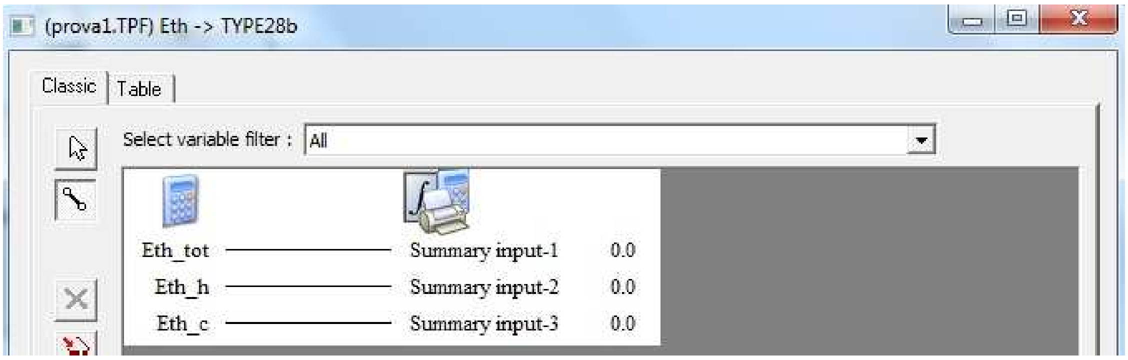
-4: (-3: the value on the top of the stack is set as the next output (j=j+1, Yj=Sk)) like -3, but top value of the stack is removed from stack (j=j+1, Yj=Sk, Sk=Sk-1);

-12: place the 2nd input on the top of the stack (Sk=X2);

-4: (-3: the value on the top of the stack is set as the next output (j=j+1, Yj=Sk)) like -3, but top value of the stack is removed from stack (j=j+1, Yj=Sk, Sk=Sk-1);

-13: place the 3rd input on the top of the stack (Sk=X2);

-4: (-3: the value on the top of the stack is set as the next output (j=j+1, Yj=Sk)) like -3, but top value of the stack is removed from stack (j=j+1, Yj=Sk, Sk=Sk-1).



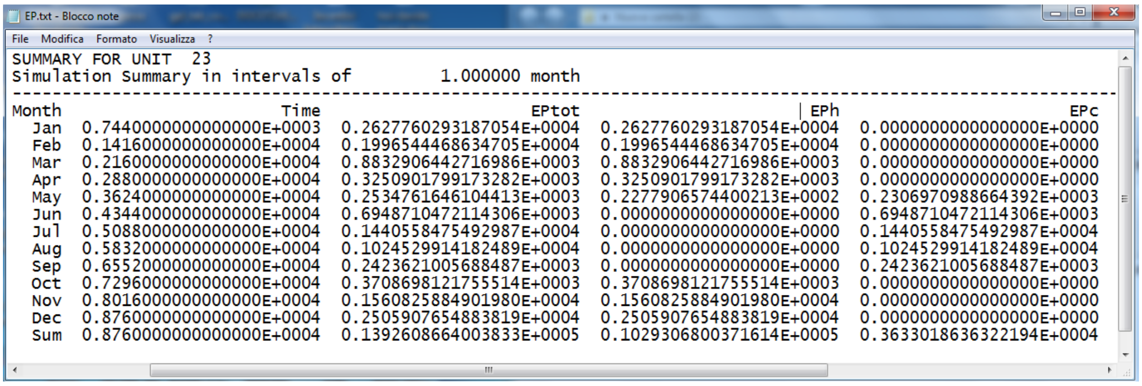
(prova1.TPF) Eth -> TYPE28b

Select variable filter : All

Eth_tot	Summary input-1	0.0
Eth_h	Summary input-2	0.0
Eth_c	Summary input-3	0.0

Fig. 24: Inputs for type 28b.

As we can see in Fig. 24, the first input is the thermal energy use for space heating and cooling, the second one is the thermal energy use for heating and the third one is the thermal energy use for cooling. All these energy needs are hourly provided by type 56b and expressed in kWh/m^2.



```
SUMMARY FOR UNIT  23
Simulation Summary in intervals of        1.000000 month
-------------------------------------------------------------------------------------------------------------
Month                     Time                     EPtot                       EPh                       EPc
  Jan 0.7440000000000000E+0003  0.2627760293187054E+0004  0.2627760293187054E+0004  0.0000000000000000E+0000
  Feb 0.1416000000000000E+0004  0.1996544468634705E+0004  0.1996544468634705E+0004  0.0000000000000000E+0000
  Mar 0.2160000000000000E+0004  0.8832906442716986E+0003  0.8832906442716986E+0003  0.0000000000000000E+0000
  Apr 0.2880000000000000E+0004  0.3250901799173282E+0003  0.3250901799173282E+0003  0.0000000000000000E+0000
  May 0.3624000000000000E+0004  0.2534761646104413E+0003  0.2277906574400213E+0002  0.2306970988664392E+0003
  Jun 0.4344000000000000E+0004  0.6948710472114306E+0003  0.0000000000000000E+0000  0.6948710472114306E+0003
  Jul 0.5088000000000000E+0004  0.1440558475492987E+0004  0.0000000000000000E+0000  0.1440558475492987E+0004
  Aug 0.5832000000000000E+0004  0.1024529914182489E+0004  0.0000000000000000E+0000  0.1024529914182489E+0004
  Sep 0.6552000000000000E+0004  0.2423621005688487E+0003  0.0000000000000000E+0000  0.2423621005688487E+0003
  Oct 0.7296000000000000E+0004  0.3708698121755514E+0003  0.3708698121755514E+0003  0.0000000000000000E+0000
  Nov 0.8016000000000000E+0004  0.1560825884901980E+0004  0.1560825884901980E+0004  0.0000000000000000E+0000
  Dec 0.8760000000000000E+0004  0.2505907654883819E+0004  0.2505907654883819E+0004  0.0000000000000000E+0000
  Sum 0.8760000000000000E+0004  0.1392608664003833E+0005  0.1029306800371614E+0005  0.3633018636322194E+0004
```

Fig. 25: Example of output file generated by type 28b.

3.1.1.5 Type 56b

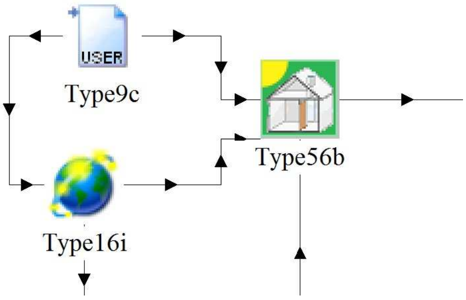
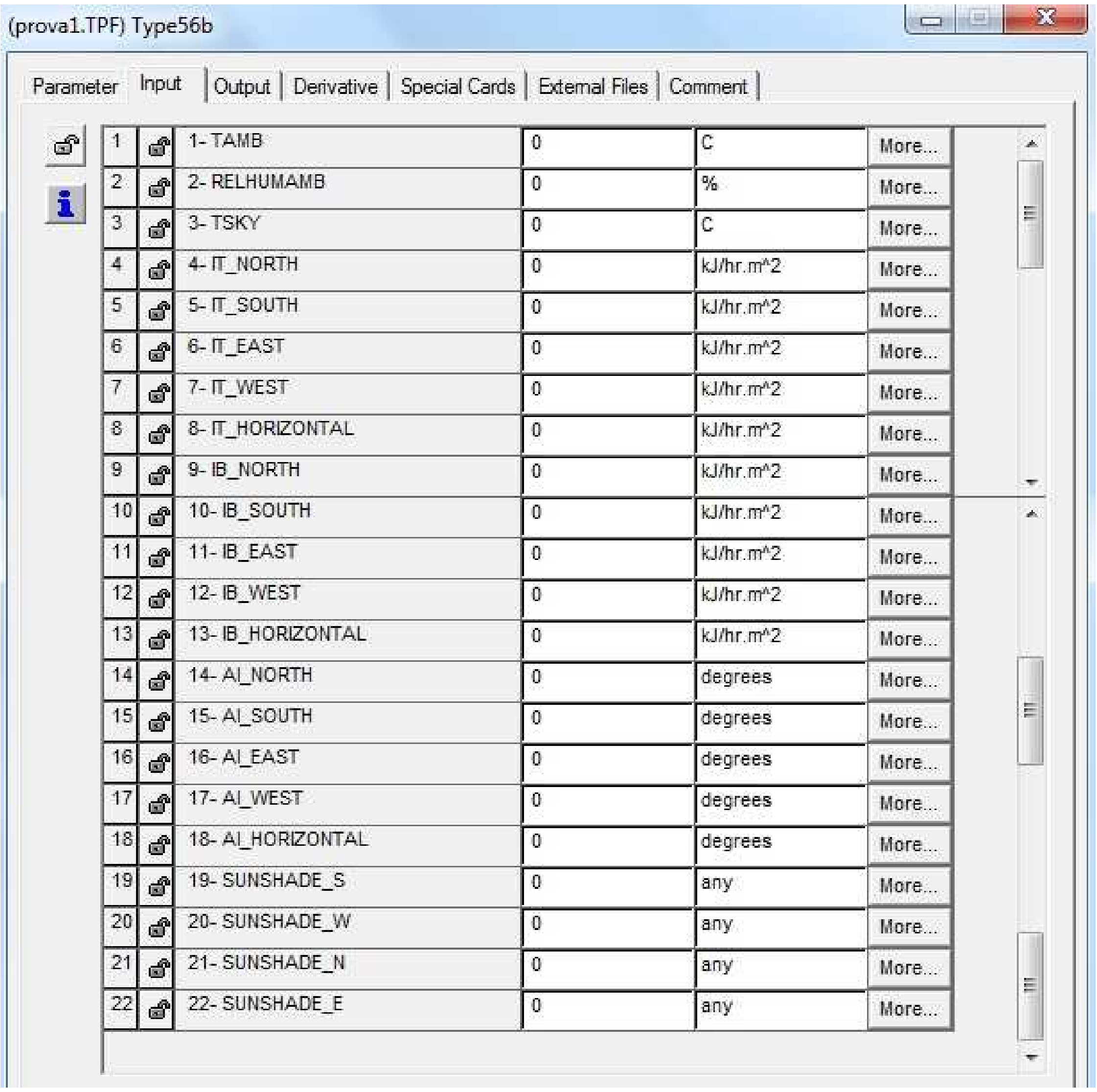


Fig. 26: Type 56b models the thermal behavior of a building.

Type 56b models the thermal behavior of a building divided into different thermal zones. The component mainly receives information from weather data and then calculates the energy need of the building modeled. This instance of Type56 does not generate its own output files. The user is free to print and plot whatever Type56 variables are of interest using standard Trnsys output devices. In order to use type 56b, a separate pre-processing program must first be executed. The TrnBuild program reads in and processes a file containing the building description and generates two files that will be used by the “type 56” component during a Trnsys simulation.



1	1- TAMB	0	C	More...
2	2- RELHUMAMB	0	%	More...
3	3- TSKY	0	C	More...
4	4- IT_NORTH	0	kJ/hr.m^2	More...
5	5- IT_SOUTH	0	kJ/hr.m^2	More...
6	6- IT_EAST	0	kJ/hr.m^2	More...
7	7- IT_WEST	0	kJ/hr.m^2	More...
8	8- IT_HORIZONTAL	0	kJ/hr.m^2	More...
9	9- IB_NORTH	0	kJ/hr.m^2	More...
10	10- IB_SOUTH	0	kJ/hr.m^2	More...
11	11- IB_EAST	0	kJ/hr.m^2	More...
12	12- IB_WEST	0	kJ/hr.m^2	More...
13	13- IB_HORIZONTAL	0	kJ/hr.m^2	More...
14	14- AI_NORTH	0	degrees	More...
15	15- AI_SOUTH	0	degrees	More...
16	16- AI_EAST	0	degrees	More...
17	17- AI_WEST	0	degrees	More...
18	18- AI_HORIZONTAL	0	degrees	More...
19	19- SUNSHADE_S	0	any	More...
20	20- SUNSHADE_W	0	any	More...
21	21- SUNSHADE_N	0	any	More...
22	22- SUNSHADE_E	0	any	More...

Fig. 27: Input section for type 56b.

As we can see in Fig. 27, a considerable amount of data are hourly provided by other types. Fig. 28 shows the path of type 56b to read the building description file (.bui); this file is generated by TrnBuild that we will delve into in the next section. In Fig. 29 we can see the output data generated by type 56b: the heating thermal energy need, the cooling thermal energy need, and the sum of the two energy need.

1 Building description file (*.bui) cube1.bui

Fig. 28: External file section for type 56b.

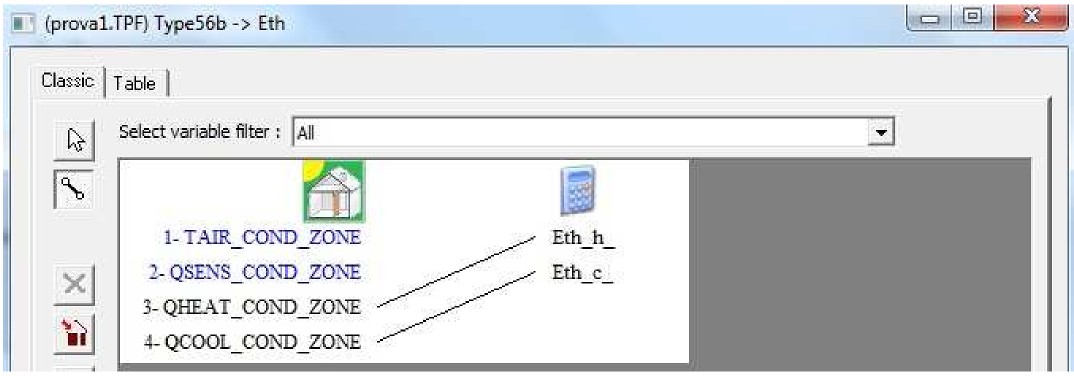
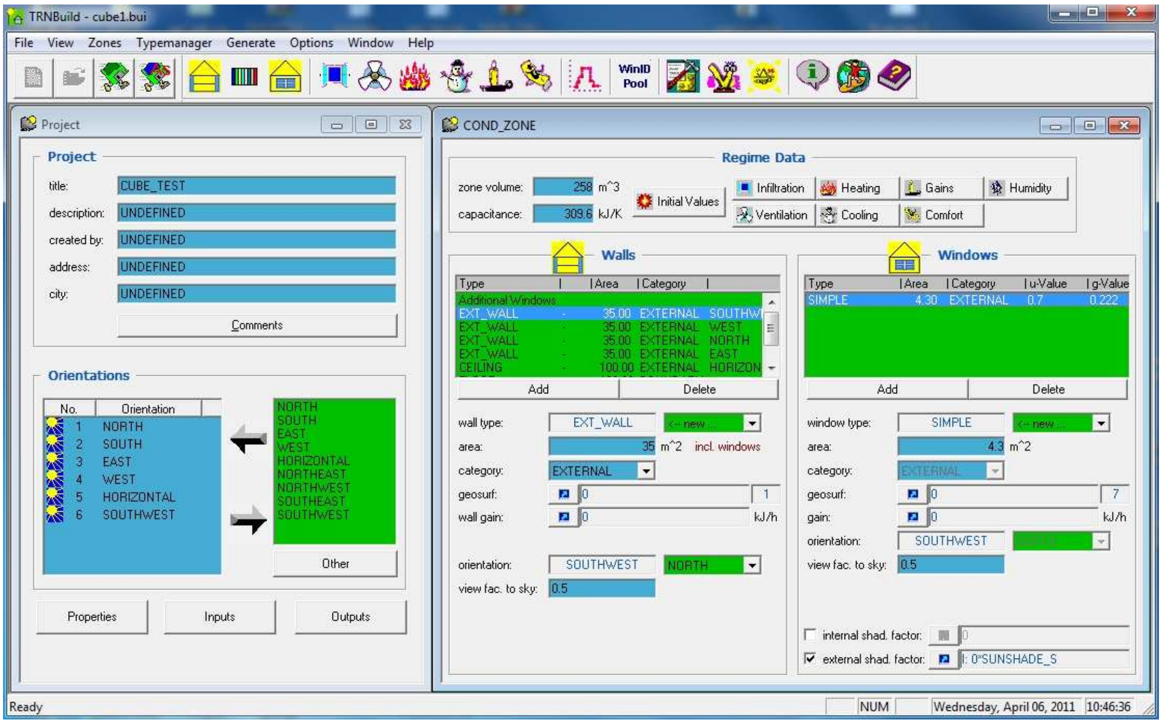


Fig. 29: Output data generated from type 56b.

3.1.2 TrnBuild

The TrnBuild program reads in and processes a file containing the building description and generates two files that will be used by the “type 56” component during a Trnsys simulation. Due to the complexity of a multizone building the parameters of type 56 are not defined directly in the Trnsys input file. Instead, a file so-called building file (*.bui) is assigned containing the required information. TrnBuild (formerly known as Prebid) has been developed to provide an easy-to-use tool for creating the (*.bui) file.



Project

title: CUBE_TEST
description: UNDEFINED
created by: UNDEFINED
address: UNDEFINED
city: UNDEFINED

Orientations

No.	Orientation
1	NORTH
2	SOUTH
3	EAST
4	WEST
5	HORIZONTAL
6	SOUTHWEST

NORTH
SOUTH
EAST
WEST
HORIZONTAL
NORTHEAST
NORTHWEST
SOUTHEAST
SOUTHWEST

zone volume: 258 m^3
capacitance: 309.6 kJ/K

Walls

Type		Area	Category	
Additional Windows				
EXT_WALL	-	35.00	EXTERNAL	SOUTHW
EXT_WALL	-	35.00	EXTERNAL	WEST
EXT_WALL	-	35.00	EXTERNAL	NORTH
EXT_WALL	-	35.00	EXTERNAL	EAST
CEILING	-	100.00	EXTERNAL	HORIZON

wall type: EXT_WALL <-- new ...
area: 35 m^2 incl. windows
category: EXTERNAL
geosurf: 0 1
wall gain: 0 kJ/h
orientation: SOUTHWEST NORTH
view fac. to sky: 0.5

Windows

Type	Area	Category	u-Value	g-Value
SIMPLE	4.30	EXTERNAL	0.7	0.222

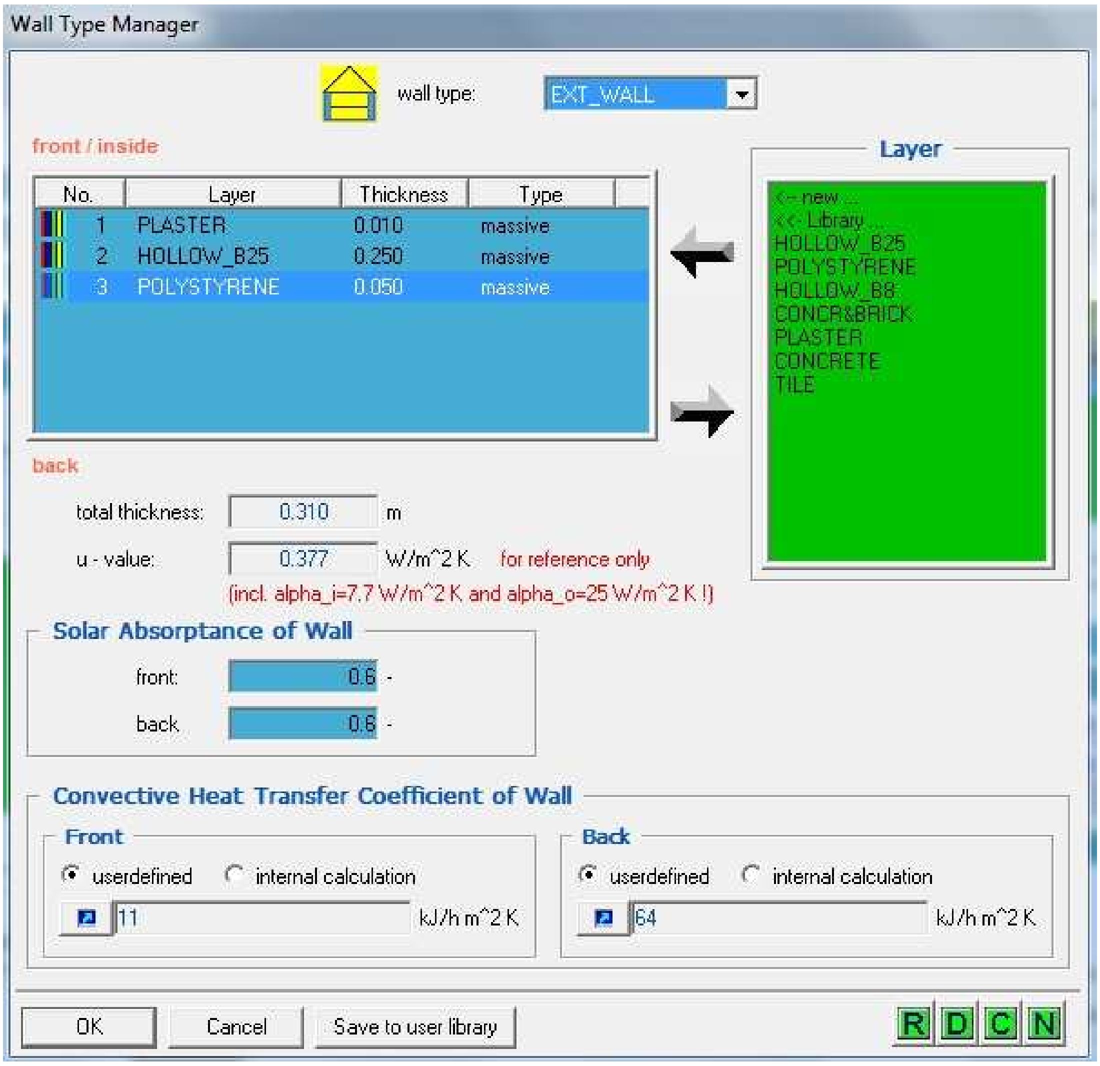
window type: SIMPLE <-- new ...
area: 4.3 m^2
category: EXTERNAL
geosurf: 0 7
gain: 0 kJ/h
orientation: SOUTHWEST
view fac. to sky: 0.5
☐ internal shad. factor: 0
☑ external shad. factor: I: 0*SUNSHADE_S

NUM Wednesday, April 06, 2011 10:46:36

Fig. 30: Main interface of TrnBuild.

As we can see in the main interface shown in Fig. 30, on the left side there is the selection of the orientations involved in the building in analysis. On the right side it is possible to define wall and window structures: dimensions, typology, orientations, shadings. On the top side there are other buttons to specify: wall type, layer type, window type, ventilation type, heating type, cooling type, and gain type.

Wall type manager (see Fig. 31) defines the typology of opaque component used in the building. For instance we have “external wall”, “ceiling” and so on; for each component we have defined layers, thickness, and convective heat transfer coefficient. Some parameters are specified with two values: “front” (façade toward the internal zone) and “back” (façade toward the external zone). Note that convective heat transfer coefficient is expressed as [kJ/hm^{2}K].



wall type: EXT_WALL

front / inside

No.	Layer	Thickness	Type
1	PLASTER	0.010	massive
2	HOLLOW_B25	0.250	massive
3	POLYSTYRENE	0.050	massive

back

total thickness: 0.310 m

u - value: 0.377 W/m^2 K for reference only

(incl. alpha_i=7.7 W/m^2 K and alpha_o=25 W/m^2 K !)

Layer:
<-- new ...
<< Library ...
HOLLOW_B25
POLYSTYRENE
HOLLOW_B8
CONCR&BRICK
PLASTER
CONCRETE
TILE

Solar Absorptance of Wall

front: 0.6 -

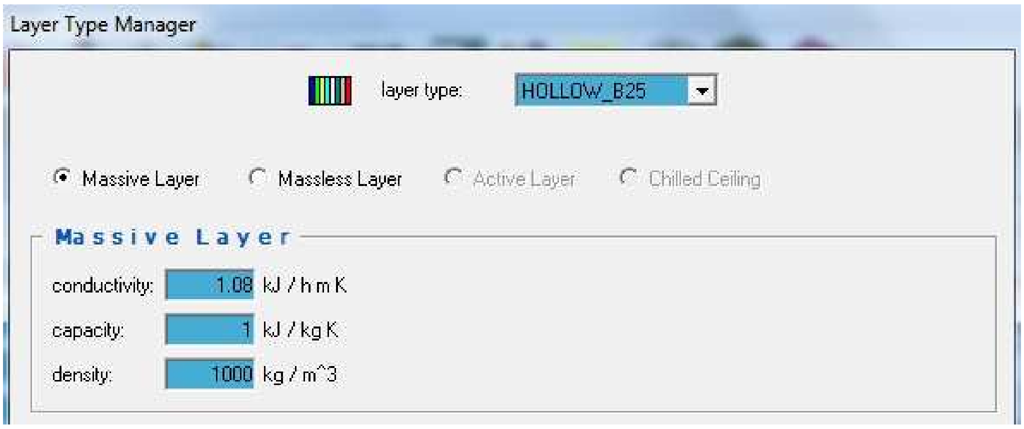
back: 0.6 -

Convective Heat Transfer Coefficient of Wall

Front: ● userdefined ○ internal calculation
11 kJ/h m^2 K

Back: ● userdefined ○ internal calculation
64 kJ/h m^2 K

Fig. 31: Wall type section for TrnBuild.



layer type: HOLLOW_B25

● Massive Layer ○ Massless Layer ○ Active Layer ○ Chilled Ceiling

Massive Layer

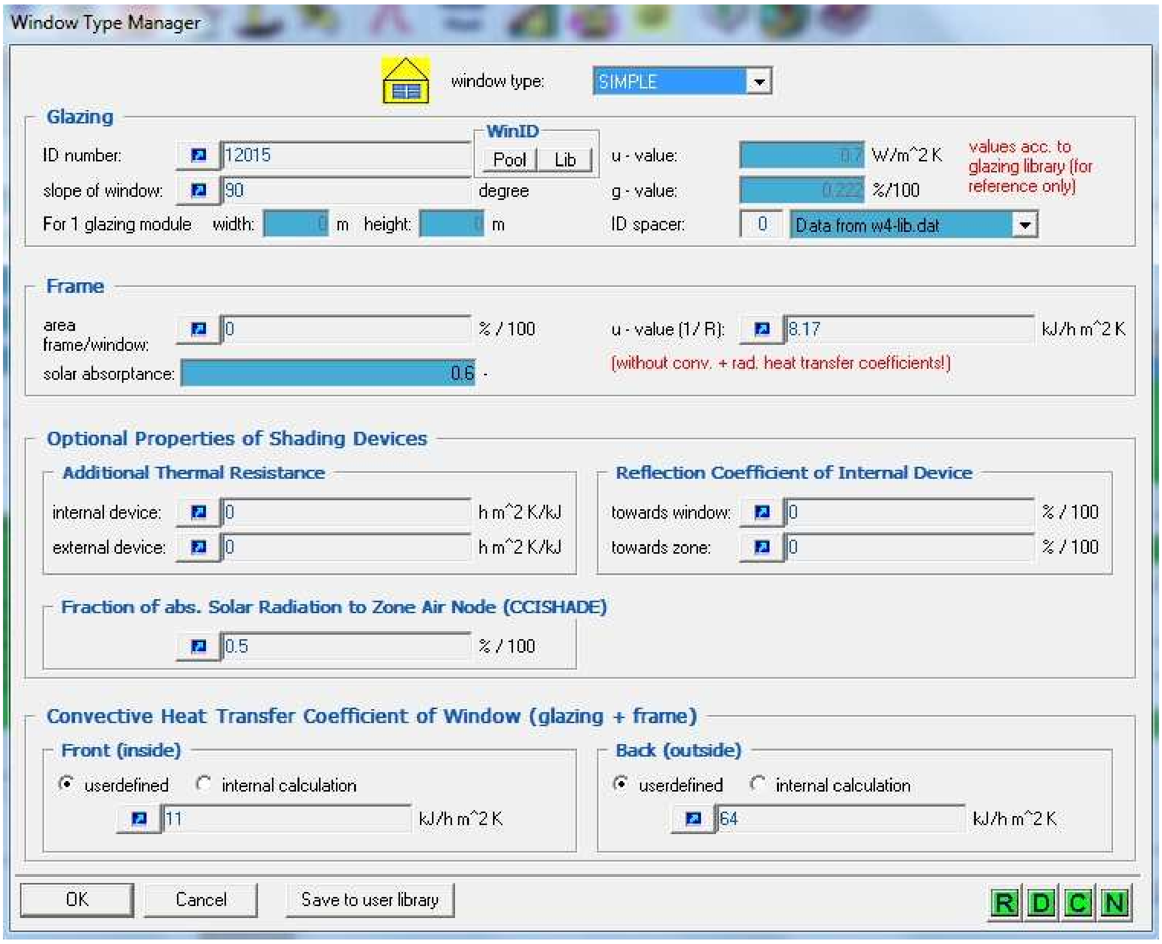
conductivity: 1.08 kJ / h m K

capacity: 1 kJ / kg K

density: 1000 kg / m^3

Fig. 32: Layer section for TrnBuild.

Layer type manager (see Fig. 32) is the section to define the characteristics of each layer involved in the opaque components, for instance: hollow brick, concrete, polystyrene, etc. Four parameters are required to define a layer: massive layer (thermal mass is considered), conductivity, capacity, and density. Note that some parameters are expressed with a non-SI[7] unit of measurement.



window type: SIMPLE

ID number: 12015
slope of window: 90 degree
For 1 glazing module width: 0 m height: 0 m
u - value: 0.7 W/m^2 K
g - value: 0.222 %/100
ID spacer: 0 Data from w4-lib.dat
values acc. to glazing library (for reference only)

area frame/window: 0 % / 100
solar absorptance: 0.6 -
u - value (1/ R): 8.17 kJ/h m^2 K
(without conv. + rad. heat transfer coefficients!)

internal device: 0 h m^2 K/kJ
external device: 0 h m^2 K/kJ
towards window: 0 % / 100
towards zone: 0 % / 100
0.5 % / 100

● userdefined ○ internal calculation
11 kJ/h m^2 K
● userdefined ○ internal calculation
64 kJ/h m^2 K

Fig. 33: Window type manager for TrnBuild.

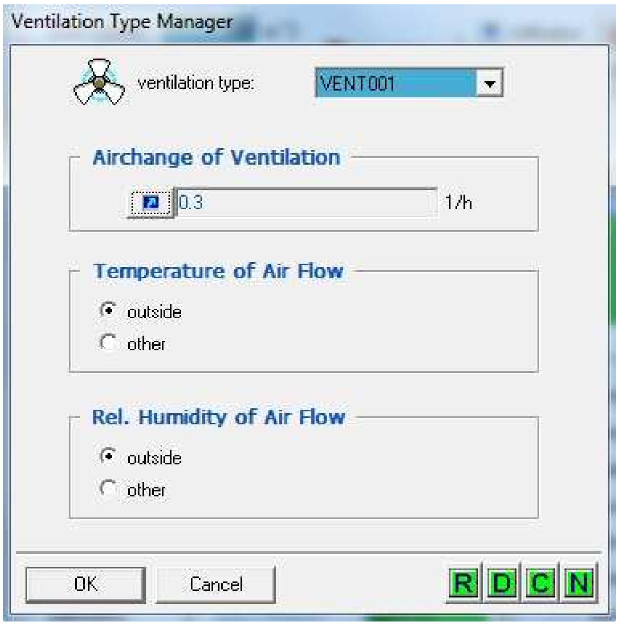
Window type manager (see Fig. 33) specifies the typology of framework with pane used in the building; for instance: “single-glazed”, “double-glazed”, etc. For each component we have defined type of pane (ID number), frame characteristics, convective heat transfer coefficient and other optional properties. Some parameters are specified with two values: “front” (façade toward the internal zone) and “back” (façade toward the external zone). The convective heat transfer coefficient defined (without a radiant part) is used for the

---

[7] International System of Unit.

whole window (glazing + frame); note that it is expressed with a non-SI unit of measurement.

In contrast with the definition of wall types, the window properties used during the simulation cannot be fully defined within TRNBUILD. An additional ASCII file called W4-LIB.DAT containing certain window properties must be assigned for the simulation. The window ID represents the connection between the window type defined in TRNBUILD and window properties of the ASCII file W4-LIB.DAT.


Ventilation Type Manager

ventilation type: VENT001

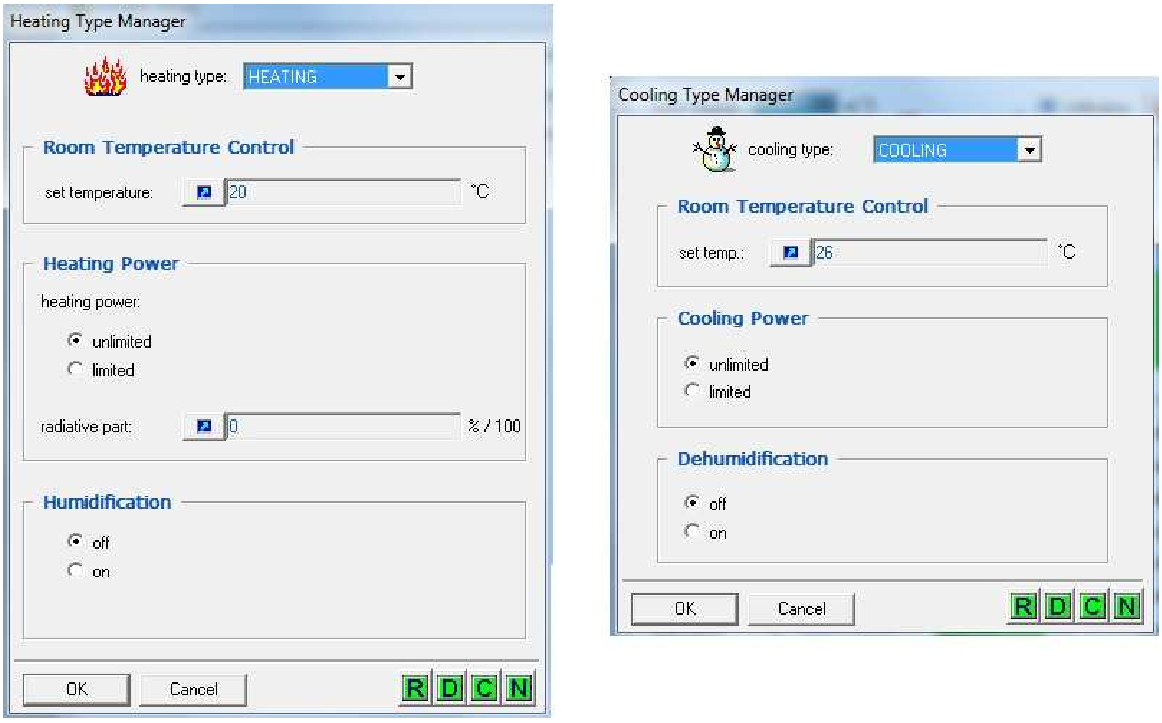
Airchange of Ventilation: 0.3 1/h

Temperature of Air Flow
● outside
○ other

Rel. Humidity of Air Flow
● outside
○ other

Fig. 34: Ventilation type manager for TrnBuild.

Ventilation type manager (see Fig. 34) allows to set an air flow into the zone. All variables can be defined as a constant (single values), an input (hourly values), or a schedule (daily or weekly scheduling). By selecting the option “outside” for the temperature and the relative humidity, the temperature and the relative humidity of the outside air, that flows to the zone, are used.



Heating Type Manager

heating type: HEATING

Room Temperature Control

set temperature: 20 °C

Heating Power

heating power:

● unlimited

○ limited

radiative part: 0 % / 100

Humidification

● off

○ on

Cooling Type Manager

cooling type: COOLING

Room Temperature Control

set temp.: 26 °C

Cooling Power

● unlimited

○ limited

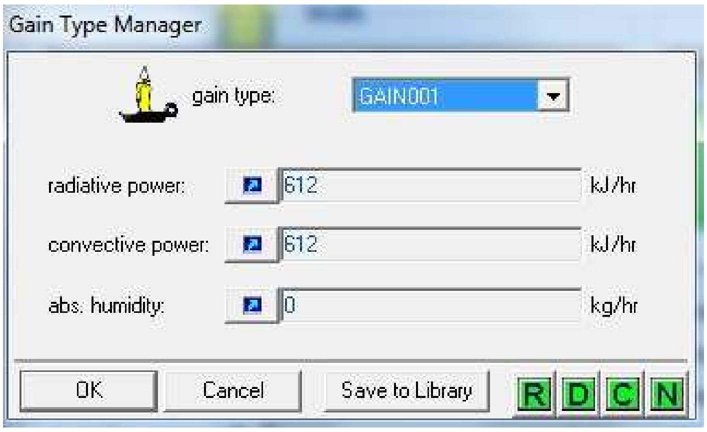
Dehumidification

● off

○ on

Fig. 35: Heating (left side) and cooling (right side) type managers for TrnBuild.

Heating and cooling type manager (see Fig. 35) allow the user to define the room setpoint temperature, the heating power with its radiative part (only for heating settings), and the humidification (dehumidification for cooling section) of the air within the zone. As we have seen above, all variables can be defined as a constant, an input, or a schedule. By selecting the option “unlimited” for the heating power, the heating power is set to a very high number. The humidification/dehumidification button can be turned on to specify the desired relative humidity. For the simulation of heating equipment with both convective and radiative effects, a radiative fraction of the heating power may be defined. This fraction of the heater power is supplied as internal radiative gains and distributed to the walls of the zone.



Gain Type Manager

gain type: GAIN001

radiative power: 612 kJ/hr

convective power: 612 kJ/hr

abs. humidity: 0 kg/hr

Fig. 36: Gain type manager for TrnBuild.

Gain type manager (see Fig. 36) is the section to define the internal gains that are usually composed of persons, electrical devices, artificial lighting, etc. They can be separate in convective and radiative contributions; all variables can be defined as a constant, an input, or a schedule. It is also possible to use some predefined gains (provided by a library of the program) but we do not go into the question.

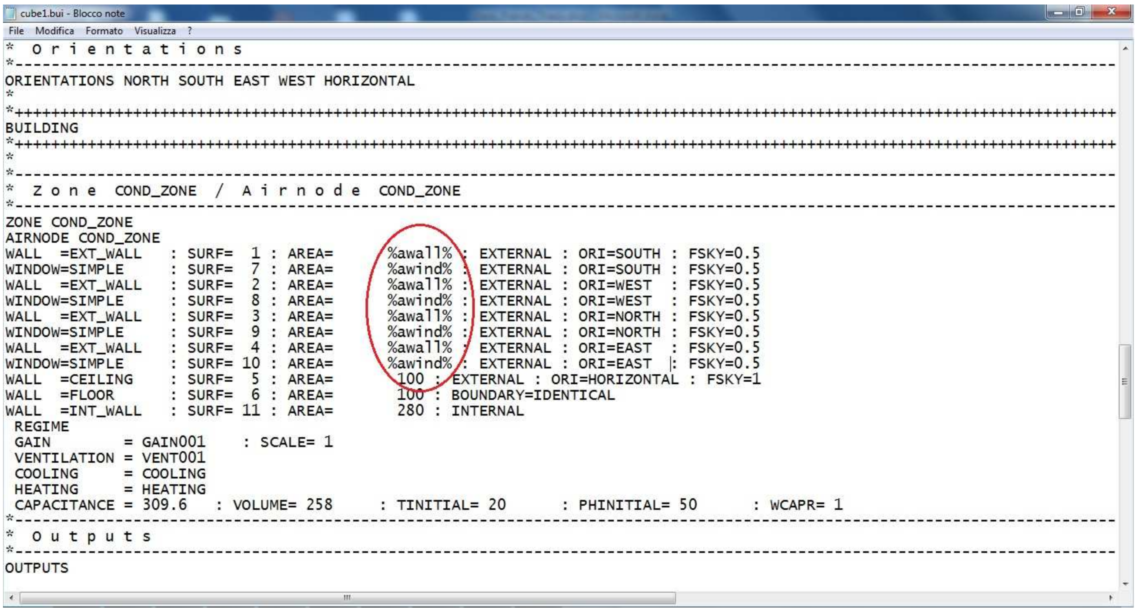
3.2 GenOpt (Generic Optimization Program)

GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program. It has been developed for optimization problems where the objective function is computationally expensive and its derivatives are not available or may not even exist. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. The independent variables can be continuous variables, discrete variables, or both, continuous and discrete variables. GenOpt has a library with local and global multi-dimensional and one-dimensional optimization algorithms, and algorithms for doing parametric runs. An algorithm interface allows adding new minimization algorithms without knowing the details of the program structure. GenOpt is written in Java so that it is platform independent. The platform independence and the general interface make GenOpt applicable to a wide range of optimization problems.

3.2.1 Using GenOpt with Trnsys 16 and type 56

GenOpt works by replacing variable names in the input files (DCK and BUI) with different values selected by the optimization algorithm. In order to do that, it reads so-called "Templates" files (that are left unchanged) and writes new input files at each optimization run.

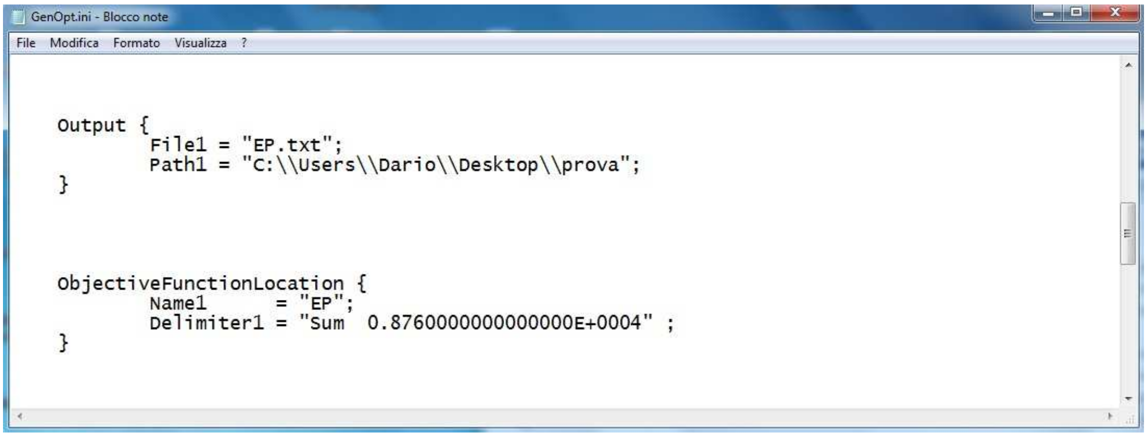
Deck file (DCK) and building file (BUI) can be edited in a text editor such as Notepad. As shown in Fig. 37, the numerical values for the window and wall areas are replaced by the variable names (%awall% and %awind%).



```
*  O r i e n t a t i o n s
*-----------------------------------------------------------------------------------------------------------------------
ORIENTATIONS NORTH SOUTH EAST WEST HORIZONTAL
*
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
BUILDING
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
*
*-----------------------------------------------------------------------------------------------------------------------
*  Z o n e  COND_ZONE  /  A i r n o d e  COND_ZONE
*-----------------------------------------------------------------------------------------------------------------------
ZONE COND_ZONE
AIRNODE COND_ZONE
WALL   =EXT_WALL    : SURF=  1 : AREA=      %awall% : EXTERNAL : ORI=SOUTH : FSKY=0.5
WINDOW=SIMPLE       : SURF=  7 : AREA=      %awind% : EXTERNAL : ORI=SOUTH : FSKY=0.5
WALL   =EXT_WALL    : SURF=  2 : AREA=      %awall% : EXTERNAL : ORI=WEST  : FSKY=0.5
WINDOW=SIMPLE       : SURF=  8 : AREA=      %awind% : EXTERNAL : ORI=WEST  : FSKY=0.5
WALL   =EXT_WALL    : SURF=  3 : AREA=      %awall% : EXTERNAL : ORI=NORTH : FSKY=0.5
WINDOW=SIMPLE       : SURF=  9 : AREA=      %awind% : EXTERNAL : ORI=NORTH : FSKY=0.5
WALL   =EXT_WALL    : SURF=  4 : AREA=      %awall% : EXTERNAL : ORI=EAST  : FSKY=0.5
WINDOW=SIMPLE       : SURF= 10 : AREA=      %awind% : EXTERNAL : ORI=EAST  : FSKY=0.5
WALL   =CEILING     : SURF=  5 : AREA=        100 : EXTERNAL : ORI=HORIZONTAL : FSKY=1
WALL   =FLOOR       : SURF=  6 : AREA=        100 : BOUNDARY=IDENTICAL
WALL   =INT_WALL    : SURF= 11 : AREA=        280 : INTERNAL
 REGIME
 GAIN        = GAIN001    : SCALE= 1
 VENTILATION = VENT001
 COOLING     = COOLING
 HEATING     = HEATING
 CAPACITANCE = 309.6    : VOLUME= 258      : TINITIAL= 20      : PHINITIAL= 50      : WCAPR= 1
*-----------------------------------------------------------------------------------------------------------------------
*  O u t p u t s
*-----------------------------------------------------------------------------------------------------------------------
OUTPUTS
```

Fig. 37: Building file (BUI) template.

GenOpt must know in which file to look for the numerical value of the cost function after each run and how to find that numerical value. The output filename and path are provided in the Simulation.Files.Output section (see Fig. 38). The place where to find the objective function is defined in the Simulation.ObjectiveFunctionLocation section (see Fig. 38).



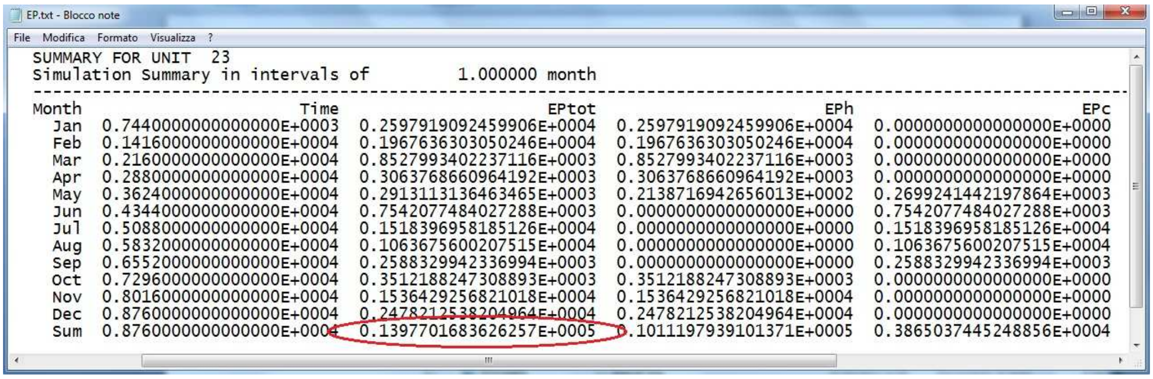
```
Output {
        File1 = "EP.txt";
        Path1 = "C:\\Users\\Dario\\Desktop\\prova";
}



ObjectiveFunctionLocation {
        Name1      = "EP";
        Delimiter1 = "Sum  0.8760000000000000E+0004" ;
}
```

Fig. 38: Filename and path of the Objective function.

GenOpt always proceeds by looking for the last occurrence of a delimiter string and reading the numerical value after that string. What this section says is that the last occurrence of “Sum 0.8760000000000000E+0004”. This is adapted to the output of type 28 in mode “2”, which is used in the example shown in Fig. 39, assuming that the objective function is the first output variable of Type 28 (the first column).



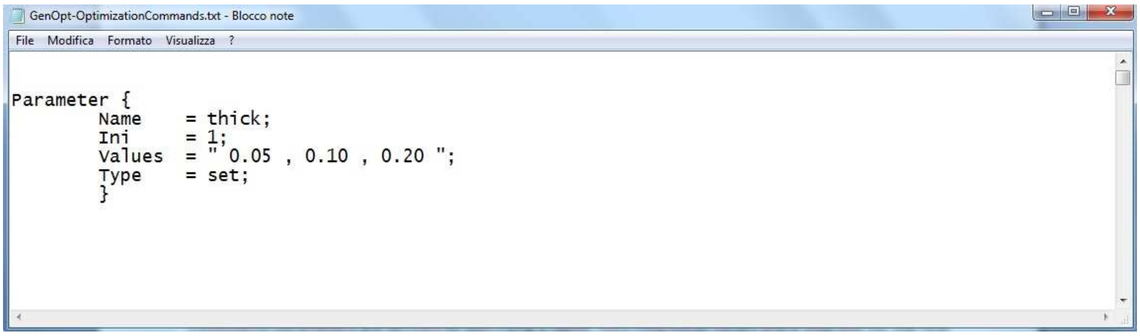
```
 SUMMARY FOR UNIT  23
 Simulation Summary in intervals of        1.000000 month
 -----------------------------------------------------------------------------------------------
 Month                    Time                   EPtot                     EPh                     EPc
   Jan  0.7440000000000000E+0003  0.2597919092459906E+0004  0.2597919092459906E+0004  0.0000000000000000E+0000
   Feb  0.1416000000000000E+0004  0.1967636303050246E+0004  0.1967636303050246E+0004  0.0000000000000000E+0000
   Mar  0.2160000000000000E+0004  0.8527993402237116E+0003  0.8527993402237116E+0003  0.0000000000000000E+0000
   Apr  0.2880000000000000E+0004  0.3063768660964192E+0003  0.3063768660964192E+0003  0.0000000000000000E+0000
   May  0.3624000000000000E+0004  0.2913113136463465E+0003  0.2138716942656013E+0002  0.2699241442197864E+0003
   Jun  0.4344000000000000E+0004  0.7542077484027288E+0003  0.0000000000000000E+0000  0.7542077484027288E+0003
   Jul  0.5088000000000000E+0004  0.1518396958185126E+0004  0.0000000000000000E+0000  0.1518396958185126E+0004
   Aug  0.5832000000000000E+0004  0.1063675600207515E+0004  0.0000000000000000E+0000  0.1063675600207515E+0004
   Sep  0.6552000000000000E+0004  0.2588329942336994E+0003  0.0000000000000000E+0000  0.2588329942336994E+0003
   Oct  0.7296000000000000E+0004  0.3512188247308893E+0003  0.3512188247308893E+0003  0.0000000000000000E+0000
   Nov  0.8016000000000000E+0004  0.1536429256821018E+0004  0.1536429256821018E+0004  0.0000000000000000E+0000
   Dec  0.8760000000000000E+0004  0.2478212538204964E+0004  0.2478212538204964E+0004  0.0000000000000000E+0000
   Sum  0.8760000000000000E+0004  0.1397701683626257E+0005  0.1011197939101371E+0005  0.3865037445248856E+0004
```

Fig. 39: Output variable like objective function.

GenOpt optimization commands (GenOpt-OptimizationCommands.txt) specifies optimization-related settings such as the independent parameters, the stopping criteria and the optimization algorithm being used. The sequence of the entries in all sections of the command file is arbitrary.

There are two types of independent parameters, continuous parameters and discrete parameters. Continuous parameters can take on any values, possibly constrained by a minimum and maximum value. Discrete parameters can take on only user-specified discrete values, to be specified in this file. Some algorithms require all parameters to be continuous, or all parameters to be discrete, or allow both continuous and discrete parameters. For this work, only discrete parameters have been used due to the selected algorithm that is describing in the next section.

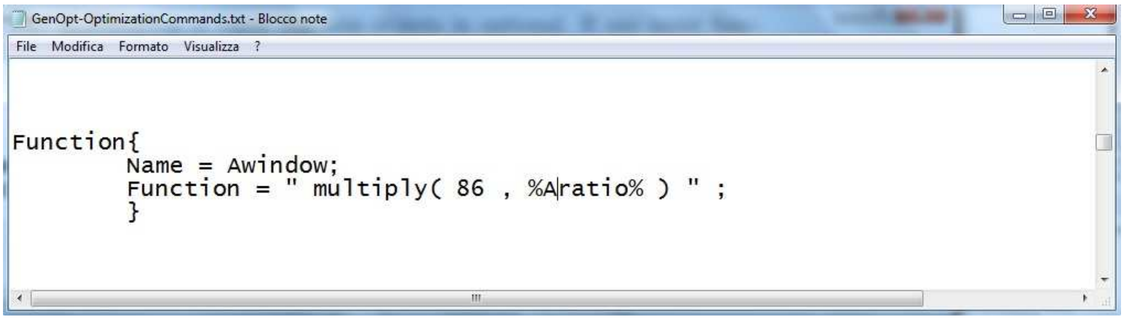
In the Fig. 40 is shown the structure for a discrete parameter; in this case, we specified the set of admissible values with three number but also alphabetic characters are allowed. The index “ini” indicates which declared value of the string is the first to be considered during the simulation and “type” specifies that the parameter is discrete (set).



```
Parameter {
        Name    = thick;
        Ini     = 1;
        Values  = " 0.05 , 0.10 , 0.20 ";
        Type    = set;
        }
```

Fig. 40: Structure to declare a discrete parameter with GenOpt.

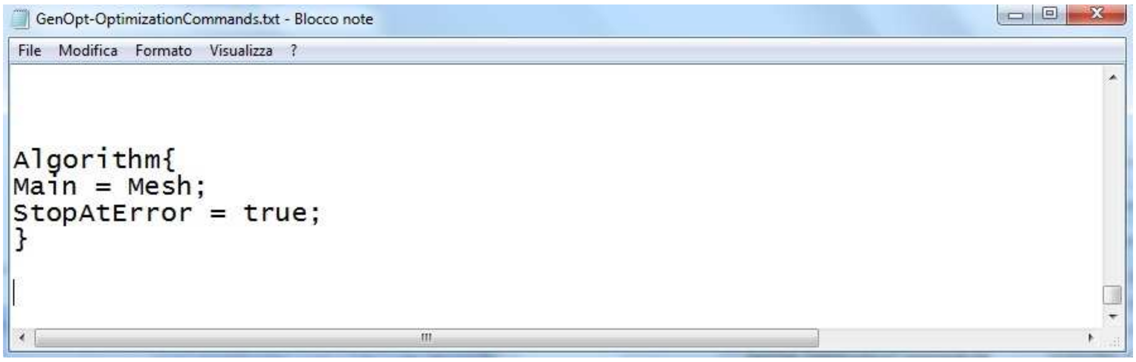
Derived variables are defined using “functions”. For example, as we can see in Fig. 41, the window area is defined as the result of multiplying the heated floor area (86 m^2) by the ratio between the window area and the heated floor area (Aratio).



```
Function{
        Name = Awindow;
        Function = " multiply( 86 , %Aratio% ) " ;
        }
```

Fig. 41: Function to specify a derived parameter with GenOpt.

Finally, the “Algorithm” section specifies which algorithm to use. GenOpt has a library with local and global multi-dimensional and one-dimensional optimization algorithms, and algorithms for doing parametric runs. In this work, an algorithm for doing parametric runs is used and in the next section it is fully explained; in Fig. 42 is shown the structure to define the selected algorithm.



```
Algorithm{
Main = Mesh;
StopAtError = true;
}
```

Fig. 42: Algorithm for the optimization problem.

3.2.2 Algorithm: Parametric runs on a mesh

The algorithm for parametric runs described in this section is used for this work to determine how sensitive a function is with respect to a change in the independent variables. It can also be used to do a parametric sweep of a function over a set of parameters. The algorithm constructs a mesh in the space of the independent parameters, and evaluates the objective function at each mesh point.

The algorithm "Mesh" spans a multi-dimensional grid in the space of the independent parameters, and it evaluates the objective function at each grid point. Note that the number of function evaluations increases exponentially with the number of independent parameters. For example, a 5-dimensional grid with 2 intervals in each dimension requires $3^5 = 243$ function evaluations, whereas a 10-dimensional grid would require $3^{10} = 59049$ function evaluations.

The parameters can be continuous or discrete, the first one requires a lower bound, upper bound and the step to define in how many intervals each coordinate axis will be divided, while the second one needs a string with user-specified discrete values.

In Fig. 44 and Fig. 43 we can see an example of "parametric runs on a mesh", we have two parameters: insulation thickness of the external walls and typology of window. For each parameter, three user-specified discrete values are chosen; it means 3^2 simulations to cover the entire space of the independent parameters.

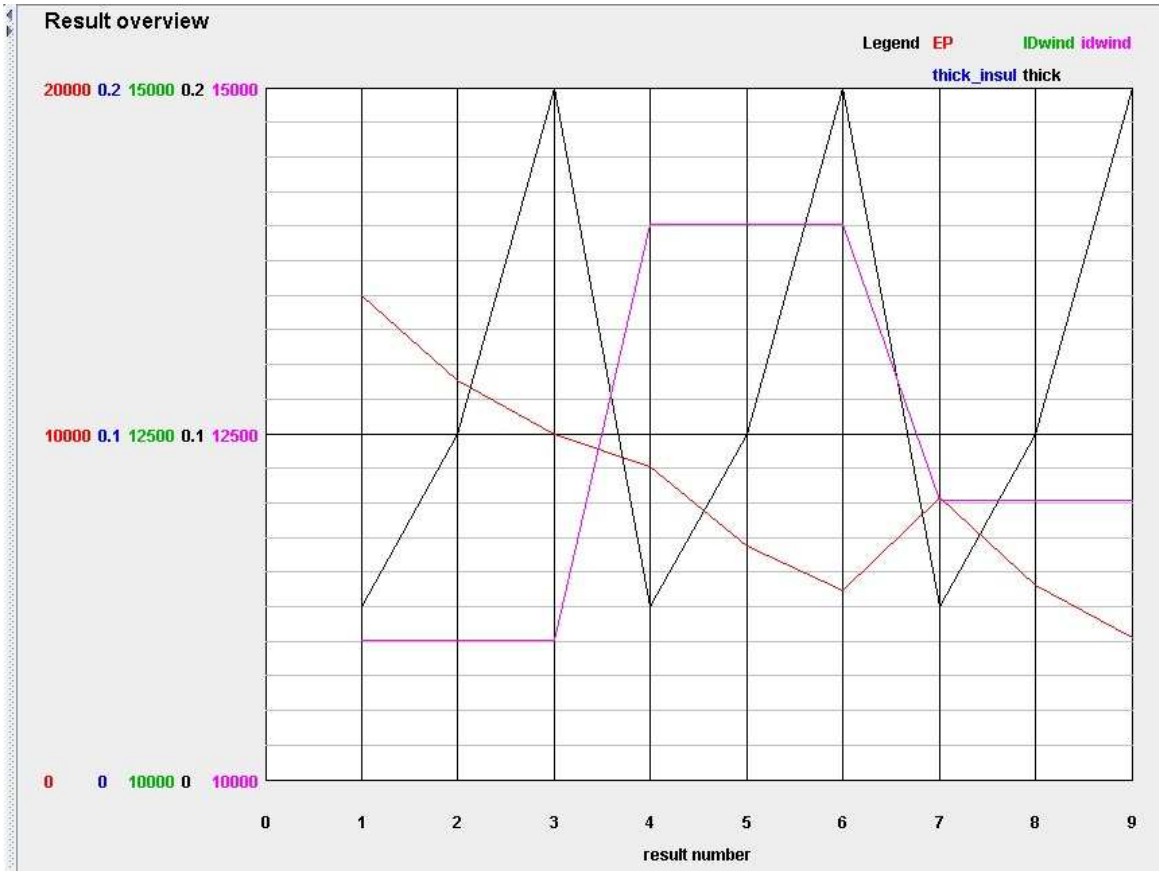
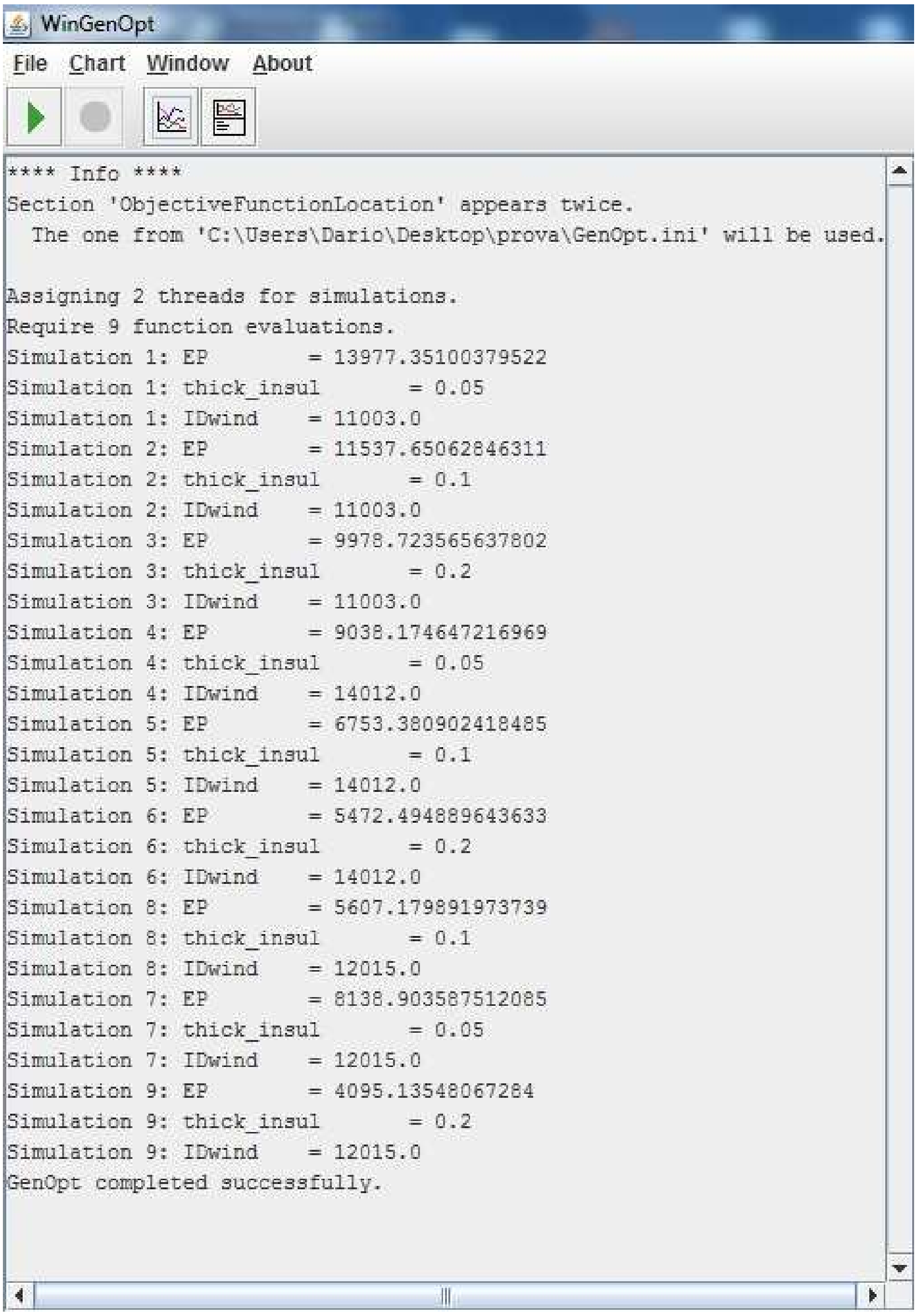


Fig. 43: Example of a simulation graph for parametric runs on a mesh.



```
**** Info ****
Section 'ObjectiveFunctionLocation' appears twice.
  The one from 'C:\Users\Dario\Desktop\prova\GenOpt.ini' will be used.

Assigning 2 threads for simulations.
Require 9 function evaluations.
Simulation 1: EP        = 13977.35100379522
Simulation 1: thick_insul       = 0.05
Simulation 1: IDwind    = 11003.0
Simulation 2: EP        = 11537.65062846311
Simulation 2: thick_insul       = 0.1
Simulation 2: IDwind    = 11003.0
Simulation 3: EP        = 9978.723565637802
Simulation 3: thick_insul       = 0.2
Simulation 3: IDwind    = 11003.0
Simulation 4: EP        = 9038.174647216969
Simulation 4: thick_insul       = 0.05
Simulation 4: IDwind    = 14012.0
Simulation 5: EP        = 6753.380902418485
Simulation 5: thick_insul       = 0.1
Simulation 5: IDwind    = 14012.0
Simulation 6: EP        = 5472.494889643633
Simulation 6: thick_insul       = 0.2
Simulation 6: IDwind    = 14012.0
Simulation 8: EP        = 5607.179891973739
Simulation 8: thick_insul       = 0.1
Simulation 8: IDwind    = 12015.0
Simulation 7: EP        = 8138.903587512085
Simulation 7: thick_insul       = 0.05
Simulation 7: IDwind    = 12015.0
Simulation 9: EP        = 4095.13548067284
Simulation 9: thick_insul       = 0.2
Simulation 9: IDwind    = 12015.0
GenOpt completed successfully.
```

Fig. 44: Example of a simulation list for parametric runs on a mesh.

4 Global sensitivity analysis with a numerical model

The sensitivity analysis is the study of how the variation in the output of a mathematical (or numerical) model can be apportioned to different sources of variation in the input of the model. In the second chapter, we have seen the Monte Carlo analysis which, considering a simple mathematical model, shows the basic steps to conduct a global sensitivity analysis. The objective of this work is to identify how predetermined parameters influence the energy need of a building; therefore, we have to consider a complex model that represents the real thermal behavior of a building. Boundary conditions (temperature, solar radiation, etc.) change with the time with an uncertain trend, hence it is not convenient to describe them with a mathematical model; for this reason we move on a numerical approach. In this chapter, we follow the very same procedure of Monte Carlo analysis but adopting a dynamic simulation software (Trnsys) to examine the building behavior of the buildings and an optimization program (Genopt) to launch automatically the different simulations.

4.1 Definition of a numerical model with Trnsys

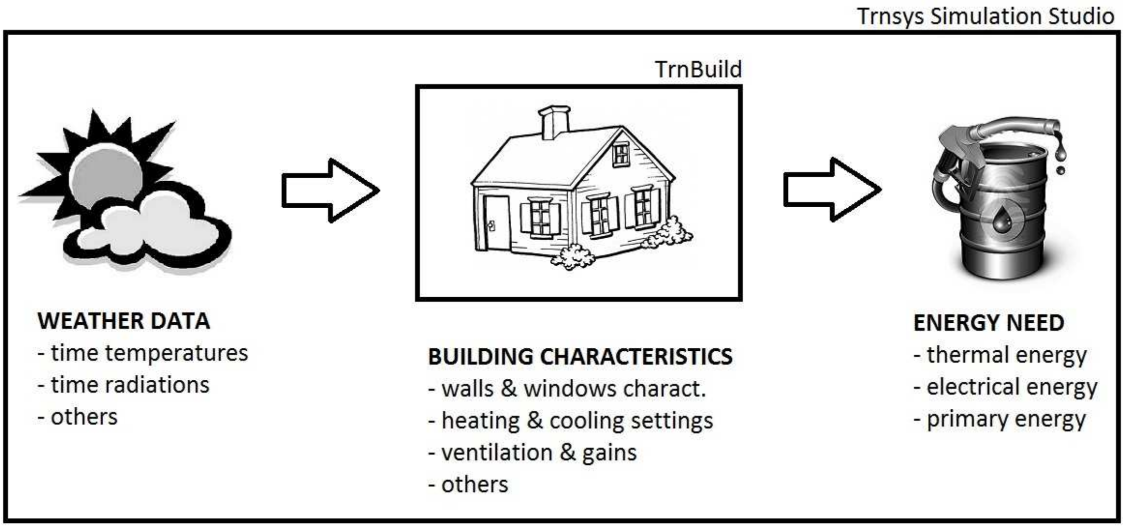


Fig. 45: Scheme about how Trnsys works.

Trnsys simulation studio is a transient system simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. Trnsys is well suited to detailed analyses of any system whose behavior is dependent on the passage of time. One of the main module of Trnsys is the so called “type 56”, it contains all the information that define building envelope. Due to the complexity of a multizone building, the parameters of “type 56” are defined with a sub-program called TrnBuild (see Fig. 45).

In this work, Trnsys is used to simulate the thermal behavior of an apartment (see Fig. 46) and calculate its annual thermal energy need. The simulations are performed with a time step of one hour; this means that different weather data (dry bulb air temperature, sky temperature, relative humidity, direct and diffuse solar radiations) are assigned each hour to the building envelope. Weather data for the analysis are registered at the airport of Milan (Italy), which is the building location. The apartment is considered for standard residential use and hence the set-point internal temperature is 20°C during heating season and 26°C during cooling season. The floor abuts with the internal temperature (another heated apartment) while the rest of the surfaces border with the external temperature.

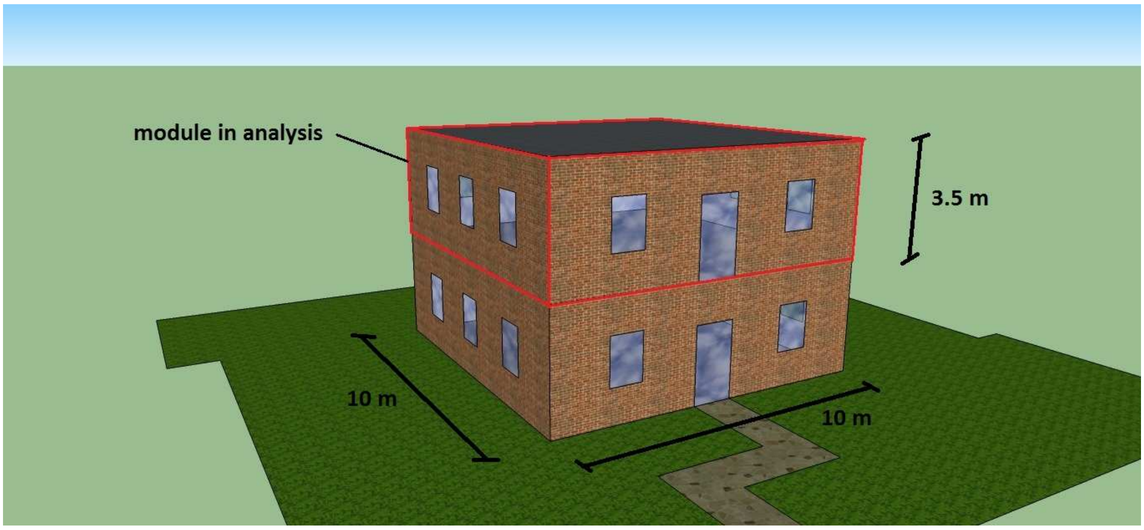


Fig. 46: Module in upper floor is that one in analysis.

The apartment in analysis is design with a rectangular parallelepiped shape, an area of 100 m^2 (10m x 10m), 3.5 m high (external dimensions) and the main façade facing south. Three types of walls are defined for the module: external walls, internal walls floor and ceiling (see Tab. 5). Except the internal walls, the rest of the heavy building elements present a thermal insulation layer (e.g. polystyrene).

EXTERNAL WALL

material	*t*	*λ*	*ρ*	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m^3*	*kJ/kgK*
Plaster	0,01	0,7	1500	1
Hollow brick 25	0,25	0,3	1000	1
Polystyrene	0,05*	0,0305	20	1,25
Thermal transmittance		0,376	W/m^{2}K	

INTERNAL WALL

material	*t*	*λ*	*ρ*	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m^3*	*kJ/kgK*
Plaster	0,01	0,7	1500	1
Hollow brick 8	0,08	0,2888	500	1*
Plaster	0,01	0,7	1500	1
Thermal transmittance		2,444	W/m^{2}K	

FLOOR

material	*t*	*λ*	*ρ*	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m^3*	*kJ/kgK*
Tile	0,01	1	550	0,8
Concrete	0,05	1,4	2000	0,8
Polystyrene	0,05*	0,0305	20	1,25
Concrete&brick slab	0,24	0,72	1300	1
Plaster	0,01	0,7	1500	1
Thermal transmittance		0,454	W/m^{2}K	

CEILING

material	*t*	*λ*	*ρ*	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m³*	*kJ/kgK*
Plaster	0,01	0,7	1500	1
Concrete&brick slab	0,24	0,72	1300	1
Polystyrene	0,05*	0,0305	20	1,25
Concrete	0,05	1,4	2000	0,8
Tile	0,01	1	550	0,8
Thermal transmittance		0,454	W/m²K	

Tab. 5: Characteristics for each different wall type (* variable parameters).

For each side of the perimeter wall, there are three single glazing windows (see Tab. 6) considered without window frame; the total window area amounts to 20%[8] respect the heated floor area of the apartment ($A_{window}/A_{floor.}$). For each window, there is a sunshade to manage the solar gains during summer season; the shading factor (E_{shade}), defined as the ratio of non-transparent area of the shading device to the whole glazing area, is considered equal to 0.3[8].

SINGLE GLAZING WINDOW

material	*t*	*λ*
from int. to ext.	*m*	*W/mK*
glass	0,0025	0,9*
Thermal transmittance	5,77	W/m²K

Tab. 6: Characteristics of the windows (* variable parameter).

According with the Italian technical specification (UNI/TS 11300[9]) on energy performance of buildings, internal gains are defined as a function of the useful floor area

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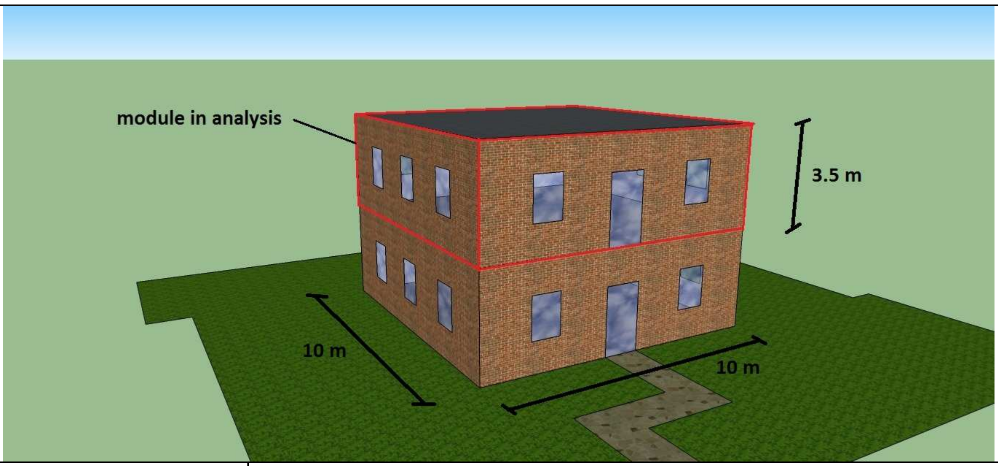
[8] Variable parameter.
[9] Evaluation of energy need for space heating and cooling.

of the building. For a residential building with floor area lower than 170 m^2, internal gains are defined as:

$$\Phi_{INT.} = 5.294 \cdot A_f - 0.01557 \cdot A_f^{\,2} \qquad [\mathrm{W}]$$

The apartment in analysis has a useful floor area of 86 m^2, therefore the internal gains correspond to 340 W. Internal gains of the apartment come out from convective and radiant gains of persons, lights and appliances. In this analysis, we consider 170 W convective gains and 170 W radiant gains as the EN ISO 13790:2008 suggests, unless otherwise stated.

In agreement with the Italian technical specification (UNI/TS 11300) on energy certification of buildings, air change minimum to satisfy for a residential building is 0.3 vol/h. For the apartment in analysis, we adopt the minimum value suggested from the technical specification.

Project brief	
	
Location	Italy, Milan (N 45,6166 ; E 8,7166)
Building type	Apartment building
Use	Owner-occupied
External dimensions	10 m x 10 m x 3,5 m
Living floor space	86 m^2
Orientation	South
Set point temperature	Heating season: 20°C ; Cooling Season: 26°C
Type of construction	Solid (brickwork with external thermal insulation compound system)
Window and glazing	Single glazing; g-factor 0,83; no window frame
U-values* [w/m^2K]	External walls: 0,376 ; ground/uppermost ceiling: 0,454 ; internal walls: 2,444 ; whole window: 5,7
Glazing share*	20% respect the heated floor area (A_{window}/A_{floor})
Boundary conditions	Floor: internal temperature ; rest of the surfaces: external temperature
Ventilation	0,3 vol/h (natural)
Internal gains [W]	Convective: 170 ; Radiant: 170
Window shading*	0,3 (non-trasparent area to whole glazing area)

Tab. 7: Project brief of the apartment in analysis (* variable parameters).

4.2 Definition of the input parameters under analysis

All the parameters described in this chapter are subsequently considered in the global sensitivity analysis to classify which ones have a strong influence on the thermal energy need of the apartment; furthermore, an evaluation of the correlation between the parameters is developing. In the analysis, three values for each parameter range are considered to represent the entire field; more points would describe better the behavior of the building but it would be too wasteful in terms of simulation time. The following table (see Tab. 8) reports the summary of the considered parameters that are deeply explained in this section.

	Reference parameters			*Correspond to:*
Thermal transmittance of the heavy building elements	Thickness of thermal insulation for heavy building elements	0	cm	$U_{ext.\ walls}$=0,983 W/m^{2}K ; $U_{floor/ceiling}$=1,755 W/m^{2}K
		10		$U_{ext.\ walls}$=0,233 W/m^{2}K ; $U_{floor/ceiling}$=0,260 W/m^{2}K
		20		$U_{ext.\ walls}$=0,132 W/m^{2}K ; $U_{floor/ceiling}$=0,140 W/m^{2}K
Window thermal resistance	R_w	0,17	m^{2}K/W	U_w=5,7 W/m^{2}K
		0,77		U_w=1,3 W/m^{2}K
		1,4		U_w=0,7 W/m^{2}K
Window solar transmittance	g-factor	0,83	-	-
		0,5		-
		0,42		-
Window size	A_{window}/A_{floor}	10	%	Small windows
		20		Midsize windows
		30		Big windows
Thermal inertia of the internal walls	I	325	W/m^{2}Ks^{0,5}	Gypsum board thermal inertia
		585		Partition tile thermal inertia
		1489		Concrete thermal inertia
Window sunshades*	Sun shading	0	%	No shading
		40		Medium shading
		80		Almost complete shading

*Depending on the strategy (Activated with solar radiation greater than 300 W/m^2).

Tab. 8: Parameters considered for the global sensitivity analysis.

Note that all the parameters, shown in the table above, are continuous variables because, as we can see in next sections, to conduct the analysis of correlation between the different design parameters we use the concept of mathematical derivative that requires continuous parameters.

4.2.1 Thermal transmittance of the heavy building elements

External walls, ceiling and floor are evaluated to detect their influence on the thermal energy use of the building and their correlation with the other parameters. Heavy building elements are composed of two main layers (see Fig. 47 and Tab. 9), the internal one is made of hollow brick or concrete&brick while the external layer is made of thermal insulation material (for instance polystyrene).

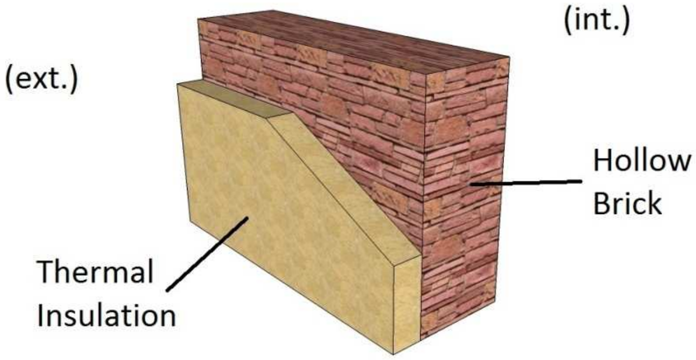


Fig. 47: Main layers of the external walls.

To change the thermal transmittance of the heavy building elements, the thickness of the thermal insulation layer is varied with the following values:

$$\textit{Thermal insulation thickness} \rightarrow \begin{cases} 0\text{ cm} & (U_{\text{EXT. WALLS}}=0.983\ \text{W/m}^2\text{K}\ ;\ U_{\text{FLOOR/CEILING}}=1.755\ \text{W/m}^2\text{K}) \\ 10\text{ cm} & (U_{\text{EXT. WALLS}}=0.233\ \text{W/m}^2\text{K}\ ;\ U_{\text{FLOOR/CEILING}}=0.260\ \text{W/m}^2\text{K}) \\ 20\text{ cm} & (U_{\text{EXT. WALLS}}=0.132\ \text{W/m}^2\text{K}\ ;\ U_{\text{FLOOR/CEILING}}=0.140\ \text{W/m}^2\text{K}) \end{cases}$$

EXTERNAL WALL

material	*t*	λ	ρ	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m*^{3}	*kJ/kgK*
Plaster	0,01	0,7	1500	1
Hollow brick 25	0,25	0,3	1000	1
Polystyrene	0,05*	0,0305	20	1,25
Thermal transmittance		0,376	W/m^{2}K	

FLOOR

material	*t*	λ	ρ	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m*^{3}	*kJ/kgK*
Tile	0,01	1	550	0,8
Concrete	0,05	1,4	2000	0,8
Polystyrene	0,05*	0,0305	20	1,25
Concrete&brick slab	0,24	0,72	1300	1
Plaster	0,01	0,7	1500	1
Thermal transmittance		0,454	W/m^{2}K	

CEILING

material	*t*	λ	ρ	*Cs*
from int. to ext.	*m*	*W/mK*	*kg/m*^{3}	*kJ/kgK*
Plaster	0,01	0,7	1500	1
Concrete&brick slab	0,24	0,72	1300	1
Polystyrene	0,05*	0,0305	20	1,25
Concrete	0,05	1,4	2000	0,8
Tile	0,01	1	550	0,8
Thermal transmittance		0,454	W/m^{2}K	

Tab. 9: Heavy building transmittance as a function of the thermal insulation thickness (* variable parameter).

4.2.2 Window thermal resistance

Fig. 48: Single glazing window as reference (U-value=5.7 W/m^{2}K , g-factor=0.83).

The thermal transmittance of the windows is evaluated in the sensitivity analysis to identify its influence on the thermal energy use of the building and its correlation with the other parameters. In this case, the simulation software does not allow to directly vary the window thermal transmittance, hence we act on the glass thermal conductance defining fictitious values. For assuring the correctness of the approach, in section 4.3 we compare the results of the simulations with a single/double/triple glazing, defined in the library of Trnsys, and an equivalent single glazing that simulates the behavior of the three desired windowpanes.

With reference to a single glazing window (see Fig. 48), the fictitious thermal conductance of the glass is varied into the following values:

$$\begin{array}{l} \text{Fictitious glass} \\ \text{thermal conductance} \end{array} \rightarrow \begin{cases} 538.7\ \mathrm{W/m^2K} \quad (R_w = 0.17\ \mathrm{m^2K/W}\ ;\ U_w = 5.7\ \mathrm{W/m^2K}) \\ 5\ \mathrm{W/m^2K} \quad (R_w = 0.77\ \mathrm{m^2K/W}\ ;\ U_w = 1.3\ \mathrm{W/m^2K}) \\ 2.4\ \mathrm{W/m^2K} \quad (R_w = 1.4\ \mathrm{m^2K/W}\ ;\ U_w = 0.7\ \mathrm{W/m^2K}) \end{cases}$$

The equivalent thermal transmittance of the whole window (*U-value*), that comes from a modified value of the glass thermal conductance ($\lambda g/s$), is calculated with the following relation:

$$U - value = \frac{1}{R_{\mathrm{int.}} + 3 \cdot \dfrac{s}{\lambda_{glass,\,fictitious}} + R_{ext.}} \quad [W/m^2K]$$

Where $R_{int.}$ (0.13 W/m^{2}K) and $R_{ext.}$ (0.04 W/m^{2}K) are the respective internal and external surface resistances of the window; they compound the convective and radiant terms.

4.2.3 Window solar transmittance

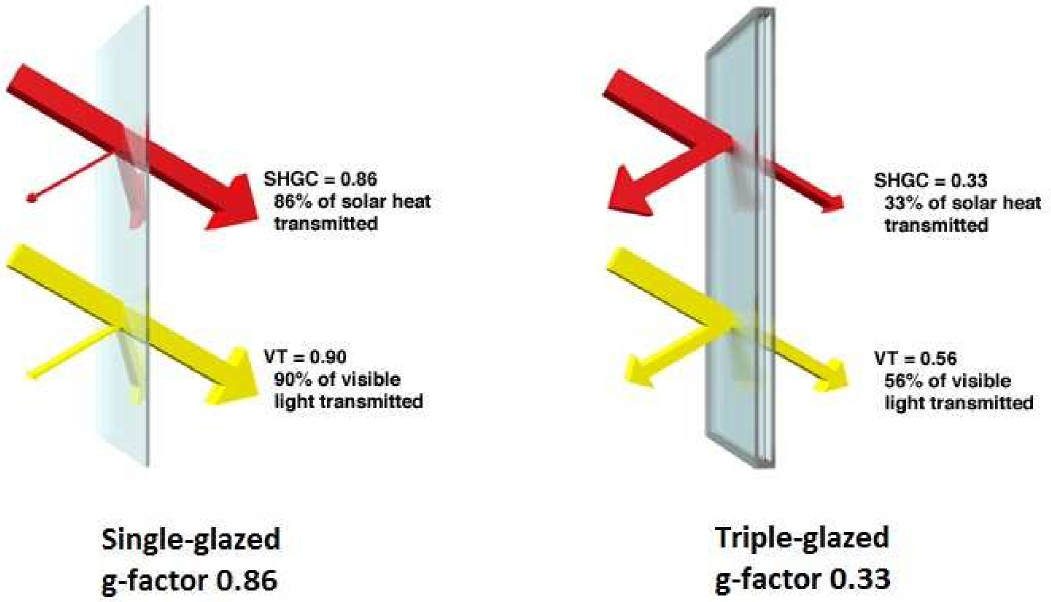


Fig. 49: Example of a single-glazed window (left side) and a triple-glazed window (right side)[10] [12].

The solar transmittance of the windows is represented by *g-factor* that is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. It expressed as a number between 0 and 1; the lower a window solar heat gain coefficient, the less solar heat it transmits. *G-factor* is evaluated in the sensitivity analysis to identify its influence on the thermal energy use of the building and its correlation with the other parameters. The simulation software does not allow to directly vary the window solar transmittance, hence we act on the solar and visible spectral factors for each angle of incidence (see Fig. 50).

For assuring the correctness of the approximation, in section 4.3 we compare the results of the simulations with a single/double/triple glazing, defined in the library of Trnsys, and

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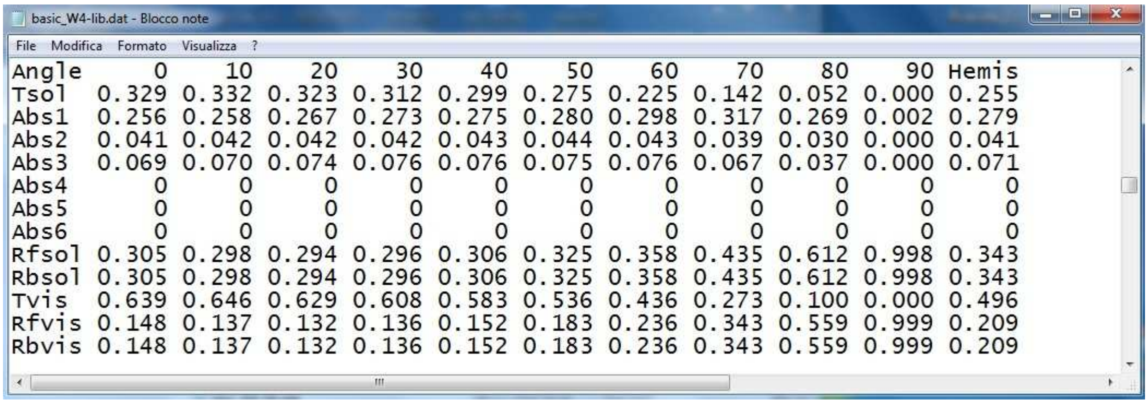
[10] Solar Heat Gain Coefficient (*SHGC*) corresponds to *g-factor*, *SHGC* is a term used in the United States.

the windows with the spectral factor modified (to obtain the correspondent *g-factor*). We adopted some expedients but the comparison assures that the approach is correct.



```
Angle      0     10     20     30     40     50     60     70     80     90 Hemis
Tsol   0.329  0.332  0.323  0.312  0.299  0.275  0.225  0.142  0.052  0.000 0.255
Abs1   0.256  0.258  0.267  0.273  0.275  0.280  0.298  0.317  0.269  0.002 0.279
Abs2   0.041  0.042  0.042  0.042  0.043  0.044  0.043  0.039  0.030  0.000 0.041
Abs3   0.069  0.070  0.074  0.076  0.076  0.075  0.076  0.067  0.037  0.000 0.071
Abs4       0      0      0      0      0      0      0      0      0      0     0
Abs5       0      0      0      0      0      0      0      0      0      0     0
Abs6       0      0      0      0      0      0      0      0      0      0     0
Rfsol  0.305  0.298  0.294  0.296  0.306  0.325  0.358  0.435  0.612  0.998 0.343
Rbsol  0.305  0.298  0.294  0.296  0.306  0.325  0.358  0.435  0.612  0.998 0.343
Tvis   0.639  0.646  0.629  0.608  0.583  0.536  0.436  0.273  0.100  0.000 0.496
Rfvis  0.148  0.137  0.132  0.136  0.152  0.183  0.236  0.343  0.559  0.999 0.209
Rbvis  0.148  0.137  0.132  0.136  0.152  0.183  0.236  0.343  0.559  0.999 0.209
```

Fig. 50: Solar and visible spectral factors for each angle of solar incidence for a triple-glazed window.

In this analysis, three values of solar transmittance are considered to detect the behavior of the building, in terms of thermal energy use. The window solar transmittance is varied with the following values:

$$\text{Window solar transmittance} \rightarrow \begin{cases} \text{g-factor=0.83} \\ \text{g-factor=0.5} \\ \text{g-factor=0.42} \end{cases}$$

4.2.4 Window size

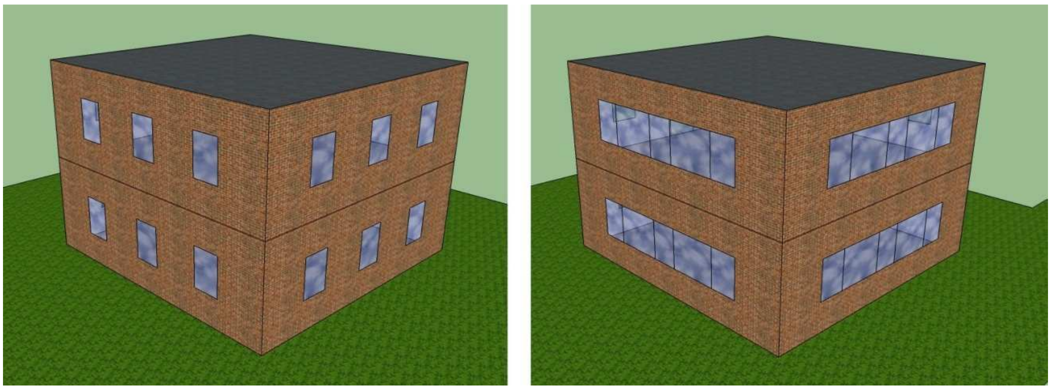


Fig. 51: Example of a building with small windows (left side) and big windows (right side).

The window size of the building is evaluated to detect its influence on the thermal energy use and its correlation with the other parameters. The representative parameter is the ratio between the window area and the heated floor area (A_{WINDOW}/A_{FLOOR}), which is varied with the following values:

$$\frac{A_{WINDOW}}{A_{FLOOR}} \rightarrow \begin{cases} 0.1 \ \ \text{(small windows)} \\ 0.2 \ \ \text{(midsize windows)} \\ 0.3 \ \ \text{(big windows)} \end{cases}$$

4.2.5 Thermal inertia

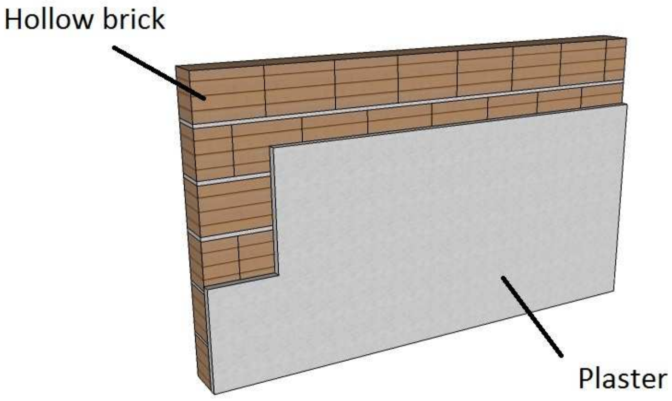


Fig. 52: Example of internal walls made of hollow brick.

Thermal inertia is a bulk material property related to thermal conductivity (λ) and volumetric heat capacity ($\rho \cdot Cs$), it represents the ability of a material to conduct and store heat:

$$I = \sqrt{\lambda \cdot \rho \cdot C_s} \ \ [J/m^2K \ s^{1/2}]$$

This parameter influences the dynamic effects of the model (to store and release heat from the building mass), and hence a dynamic simulation software is suitable to evaluate its contribute to change the thermal energy need.

In this analysis, the apartment is evaluated with different material for the internal walls (see Tab. 10), therefore thermal inertia is varied in a wide range. It should be interesting to evaluate different thermal inertia values for the external walls but we could not due to some checkpoints of the program that does not allow to use a fictitious values of the specific heat capacity in certain conditions.

	λ	ρ	C_S	I
	W/mK	kg/m^3	*kJ/kgK*	$J/m^2Ks^{0,5}$
Concrete	1,26	2000	0,88	1489
Partition tile	0,38	900	1	585
Hollow brick	0,3	1000	1	548
Wood	0,15	550	2,1	416
Gypsum board	0,16	600	1,1	325

Tab. 10: Thermal inertias of some materials for the internal walls.

The reference material for the internal walls is "partition tile", original values are held for density and conductivity while specific heat capacity is varied with fictitious values to obtain the desired thermal inertia (see Tab. 11).

		Partition tile				
λ	W/mK	0,38				
ρ	kg/m^3	900				
$C_{S,EQ}$	kJ/kg·K	6,48	1	0,88	0,51	0,31
I	$J/m^2Ks^{0,5}$	1489 (concrete)	585 (partition tile)	548 (hollow brick)	416 (wood)	325 (gypsum board)

Tab. 11: Fictitious specific heat capacities for "partition tile" to obtain different thermal inertia values.

In this analysis, three values of thermal inertia are considered to detect the behavior of the building, in terms of thermal energy use. The specific heat capacity is varied with the following values:

$$C_{S,EQ} \rightarrow \begin{cases} 0.31\ \text{kJ/kg}\cdot\text{K} & \text{(corresponds to the gypsum board t. inertia 325 W/m}^2\text{Ks}^{0.5}\text{)} \\ 1\ \text{kJ/kg}\cdot\text{K} & \text{(corresponds to the partition tile t. inertia 585 W/m}^2\text{Ks}^{0.5}\text{)} \\ 6.48\ \text{kJ/kg}\cdot\text{K} & \text{(corresponds to the concrete t. inertia 1489 W/m}^2\text{Ks}^{0.5}\text{)} \end{cases}$$

4.2.6 External Sunshades

External sunshades on windows (see Fig. 53) are helpful when the solar gains are high, for instance in summer, and a cooling system is required to compensate these free gains. Due to the curtains, the thermal energy use of the building can decrease; the warmer the climate is and the more energy is likely to be saved. There are different types of sunshade; material, color, and shape vary the amount of solar radiation that penetrates into the building through the windows.

Fig. 53: Example of sunshades on windows to limit the cooling in summer.

In this analysis, the curtains are considered completely opaque to the solar radiation. The percentage of shading on the window is varied to evaluate its influence to decrease the thermal energy use of the building; this parameter, called E_{SHADE}, is varied with the following values:

$$E_{SHADE} \rightarrow \begin{cases} 0 & \text{(no shading)} \\ 0.5 & \text{(medium shading)} \\ 0.8 & \text{(almost complete shading)} \end{cases}$$

The external sunshades are managed by a solar sensor that activates the curtains when the solar radiation exceeds a threshold. In agreement with the Italian technical specification (UNI/TS 11300) on energy performance of buildings, the threshold is 300 W/m^2. A fluctuating trend of solar radiation could cause a frequent on-off of the motor that moves the curtains; therefore, to prevent this problem, an on-off differential is added to the controller operations. This differential requires that the solar radiation exceeds the set point by a certain amount before the output will turn off or on again; in this analysis, the controller considers 20 W/m^2 as differential solar radiation (see Fig. 54).

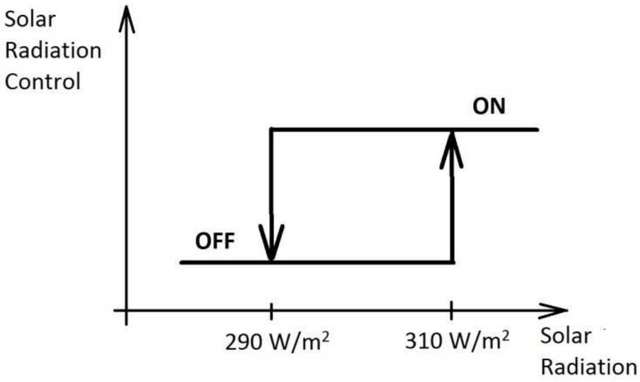


Fig. 54: Solar radiation controller with on-off differential of 20 W/m^2.

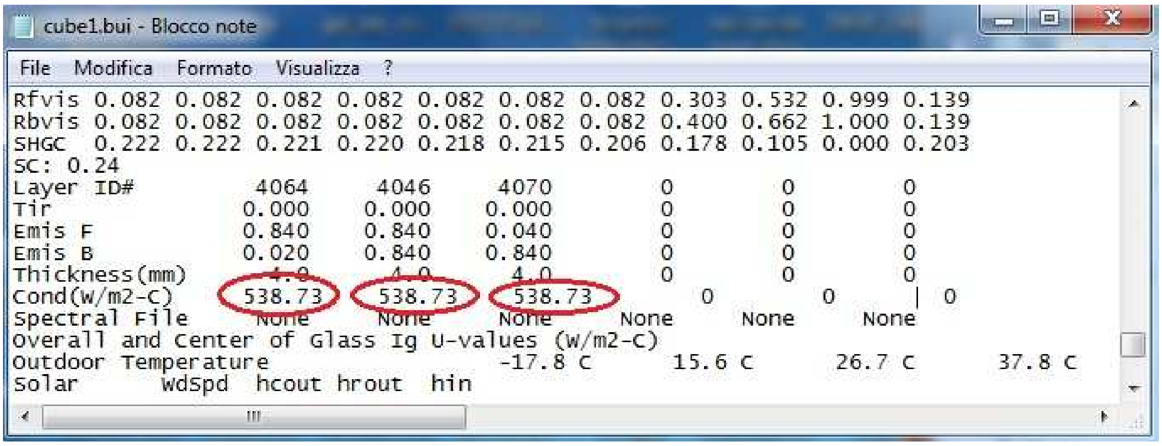
4.3 Examination of the window approach

As we have seen in the previous sections, we adopt some expedients to consider window thermal resistance and window solar transmittance as design parameters. The problem comes from the program (Trnsys) used to conduct the analysis that does not allow to change the thermal resistance and solar transmittance of a window. Window thermal resistance is internally calculated by Trnsys and the user can modify the glass and air gap thickness, glass conductivity etc. Window solar transmittance is just a label value while Trnsys reads from a window library an amount of solar and visible spectral factors for different angles of incidence of the radiation with the windowpane.

Concerning the window thermal resistance, as we have seen in section 4.2.2, we obtained an equivalent thermal transmittance of the whole window (*U-value*) modifying the glass thermal conductance of a reference window (see Fig. 55):

$$U - value = \frac{1}{R_{\text{int.}} + 3 \cdot \dfrac{s}{\lambda_{glass,\, fictitious}} + R_{ext.}} \quad [W / m^2 K]$$

Where *Rint*. (0.13 W/m^{2}K) and *Rext*. (0.04 W/m^{2}K) are the respective internal and external surface resistances of the window; they compound the convective and radiant terms.



```
Rfvis 0.082 0.082 0.082 0.082 0.082 0.082 0.082 0.303 0.532 0.999 0.139
Rbvis 0.082 0.082 0.082 0.082 0.082 0.082 0.082 0.400 0.662 1.000 0.139
SHGC  0.222 0.222 0.221 0.220 0.218 0.215 0.206 0.178 0.105 0.000 0.203
SC: 0.24
Layer ID#          4064      4046      4070         0         0         0
Tir               0.000     0.000     0.000         0         0         0
Emis F            0.840     0.840     0.040         0         0         0
Emis B            0.020     0.840     0.840         0         0         0
Thickness(mm)       4.0       4.0       4.0         0         0         0
Cond(W/m2-C)     538.73    538.73    538.73         0         0         0
Spectral File      None      None      None      None      None      None
Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
```

Fig. 55: Fictitious values of the glass thermal transmittance for a reference window.

As we can see in Fig. 55, the reference window is composed of three panes without air gap between the windowpanes. We chose three panes instead of one with a triple thickness because it better simulates the solar behavior of a double or triple glazing; Trnsys takes into account that the radiation deflects when it hits against a pane.

Concerning the window solar transmittance, as seen in section 4.2.3, we need to refer all the spectral factors (t-transmission, a-absorption, r-reflection) to a reference value, for instance *g-factor* (see Fig. 50). Analyzing three windows: single-glazed (*ID11003*), double-glazed (*ID14012*) and triple-glazed (*ID14005*), we observed that from 0° to 60° (angle of incidence for the solar radiation) there is an almost linear trend of the spectral factors (see Fig. 56).

Note that *ID11003*, *ID 14012* and *ID14005* are three windows selected from the library of Trnsys to represent a single, double and triple glazing (see Annex A – Windows.txt).

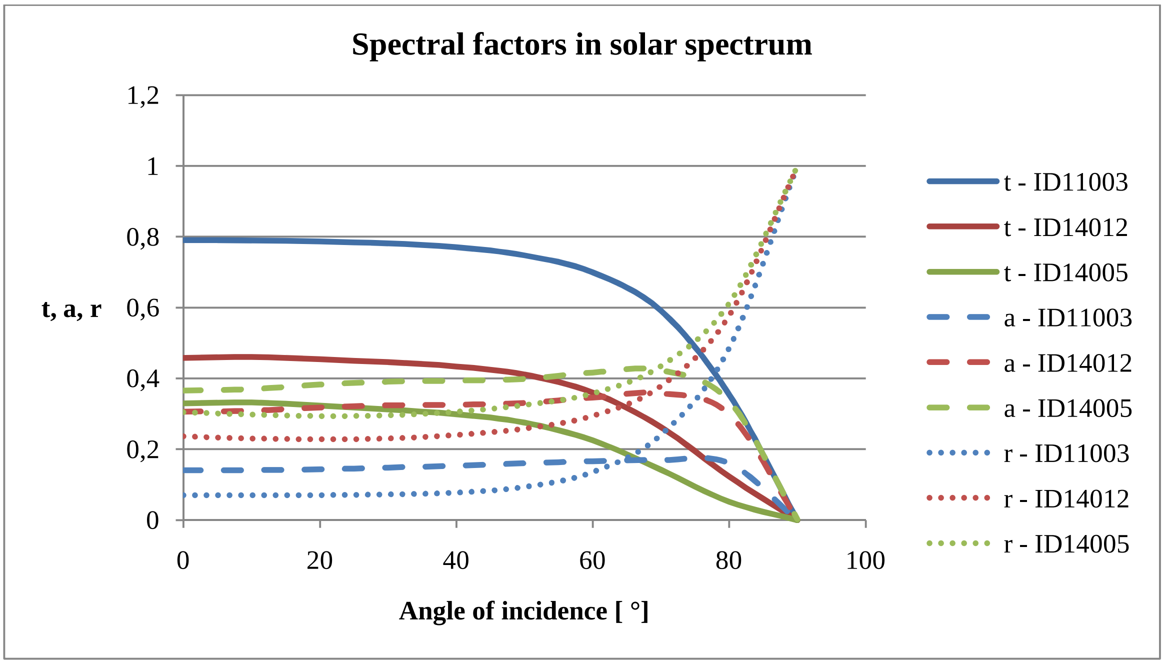


Fig. 56: Spectral factors in solar spectrum as a function of the angle of incidence for three types of windows.

Considering mean values for the spectral factors (*t*, *a*, *r*) between 0° and 60°, in Fig. 57 we show that the correlation between solar transmittance and solar spectral factors is approximately linear. An equation has been defined for each spectral factor; in this way *g-factor* becomes the only independent parameter and all the spectral factors are automatically calculated. Similarly, we defined the equations as function of g-factor also for visible spectral factors and hemispherical factors (see annex A – GenOpt-OptimizationCommands.txt).

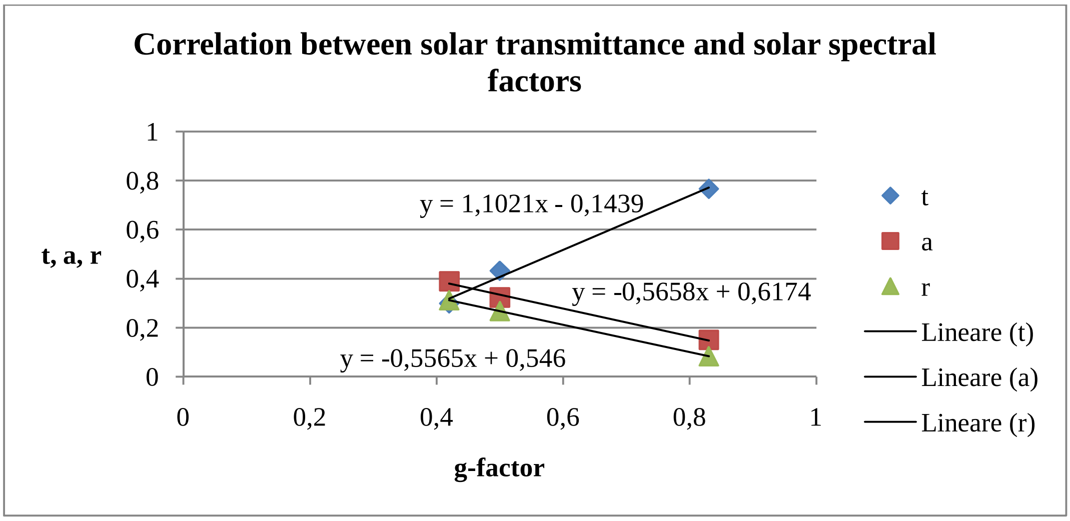


Fig. 57: Linear correlation between solar transmittance and solar spectral factors (t, a, r).

For assuring the correctness of the approach seen above, we compared the results of the simulations with a single/double/triple glazing, defined in the library of Trnsys, and the equivalent windows. “Equivalent” refers to the reference window composed of three endorsed panes in which the thermal resistance and solar transmittance are varied as we have just explained above, with the goal to simulate the behavior of *ID11003*, *ID14012* and *ID14005*. Observing the comparison summarized in Tab. 12, we can conclude that predefined windows and equivalent windows give similar results. In the table we can see a difference in terms of thermal energy need smaller than 2% for double and triple glazing and smaller than 5% for single glazing. As we already knew, we obtained less accurate results for equivalent single because we chose a reference window composed of three panes (see Fig. 55).

		Heating+cooling		*Heating*		*Cooling*	
		Eth	*Diff.*	*Eth*	*Diff.*	*Eth*	*Diff.*
		kWh/m^2	*%*	*kWh/m^2*	*%*	*kWh/m^2*	*%*
Single-glazed	*ID11003*	162,5	0,3	117,6	-1,4	44,9	4,7
	ID11003eq	162		119,3		42,8	
Double-glazed	*ID14012*	105,1	0,2	67,9	-0,4	37,2	1,3
	ID14012eq	104,9		68,2		36,7	
Triple-glazed	*ID14005*	96,4	-1,2	63,5	-2	32,9	0,3
	ID14005eq	97,6		64,8		32,8	

Tab. 12: Comparison between the windows predefined in Trnsys library and the equivalent windows.

4.4 Generation of design parameter input matrix with Genopt

Genopt is an optimization program for the minimization of an objective function that is evaluated by an external simulation program. In this work, Genopt is used to conduct a parametric analysis; the chosen algorithm is the so called “parametric runs on a mesh”. The algorithm spans a multi-dimensional grid in the space of the independent parameters, and it evaluates the objective function (thermal energy need) at each grid point.

In the following table (see Tab. 13) all the design parameters are shown with the possible values which they assume. The number of function evaluations increases exponentially with the number of independent parameters. The number of function evaluations is n^k where n is number of values in each parameter range and k is the number of parameters.

	Reference parameters		
Thermal transmittance of the heavy building elements	Thickness of thermal insulation for heavy building elements	0	cm
		10	
		20	
Window thermal resistance	R_w	0,17	m^2K/W
		0,77	
		1,4	
Window solar transmittance	g-factor	0,83	-
		0,5	
		0,42	
Window size	A_{window}/A_{floor}	10	%
		20	
		30	
Thermal inertia of the internal walls	I	325	$W/m^2Ks^{0,5}$
		585	
		1489	
*Window sunshades**	Sun shading	0	%
		40	
		80	

*Depending on the strategy (Activated with solar radiation greater than 300 W/m^2).

Tab. 13: Six variable parameters for the global analysis.

Six parameters have been considered; each parameter can assume 3 different values that are equally spread in each parameter range (see Tab. 13). The assessment is conducted with global approach, this means that the analysis is based on the effect of a single parameter on the output uncertainty while at the same time all other parameters are varied as well. Global sensitivity analysis considers the complete dependence of the output on the interactions and influences of all design parameters.

Note that all the parameters, shown in the table above, are treated as continuous variables. To perform a correlation analysis of the different design parameters, we used the concept of mathematical derivative that requires continuous parameters.

4.5 Calculation of output vectors and data processing

As we have just seen in the previous section, Genopt with the algorithm “parametric runs on a mesh”, generates all the possible combinations with the design parameters (see Tab. 13). Each combination is transferred to Trnsys that calculates the heating need (see Tab. 14), the cooling need (see Tab. 15) and the heating and cooling need (see Tab. 16). The assessment of the influence of each design parameter is made comparing the variation of the output (thermal energy need) with respect to the variation of a design parameter; in next section there is a discussion of the obtained results about the sensitivity analysis.

The total thermal energy demand has been calculated as sum of the heating and cooling demand. This is a useful indicator of the thermal behavior of a building, but it has to be kept in mind that heating and cooling demand are supplied by different systems.

	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading	E_{th}
	x_1	x_2	x_3	x_4	x_5	x_6	y
	cm	m^2K/W	-	-	$W/m^2Ks^{0.5}$	-	kWh/m^2
1	0	0,18	0,83	0,1	1489	0,0	243
2	10	0,18	0,83	0,1	1489	0,0	64
3	20	0,18	0,83	0,1	1489	0,0	45
4	0	0,18	0,83	0,1	1489	0,0	209
-	-	-	-	-	-	-	-
728	10	1,43	0,42	0,3	326	0,8	47
729	20	1,43	0,42	0,3	326	0,8	29

Tab. 14: Thermal energy need for heating.

	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading	E_{th}
	x_1	x_2	x_3	x_4	x_5	x_6	y
	cm	m^2K/W	-	-	$W/m^2Ks^{0.5}$	-	kWh/m^2
1	0	0,18	0,83	0,1	1489	0,0	40
2	10	0,18	0,83	0,1	1489	0,0	28
3	20	0,18	0,83	0,1	1489	0,0	28
4	0	0,18	0,83	0,1	1489	0,0	46
-	-	-	-	-	-	-	-
728	10	1,43	0,42	0,3	326	0,8	23
729	20	1,43	0,42	0,3	326	0,8	24

Tab. 15: Thermal energy need for cooling.

	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading	E_{th}
	x_1	x_2	x_3	x_4	x_5	x_6	y
	cm	m^2K/W	-	-	$W/m^2Ks^{0.5}$	-	kWh/m^2
1	0	0,18	0,83	0,1	1489	0,0	283
2	10	0,18	0,83	0,1	1489	0,0	92
3	20	0,18	0,83	0,1	1489	0,0	73
4	0	0,18	0,83	0,1	1489	0,0	255
-	-	-	-	-	-	-	-
728	10	1,43	0,42	0,3	326	0,8	70
729	20	1,43	0,42	0,3	326	0,8	53

Tab. 16: Thermal energy need for heating and cooling.

For the correlation assessment of the design parameters we need to calculate the partial derivative of the output vector (thermal energy need) respect the different design parameters. With a numerical model, the partial derivative calculation is based on the so called “elementary effect”:

$$EE_{ij}(x_{1j},..,x_{kj}) = \frac{y_j(x_{1j},x_{2j},..,x_{(i-1)j},x_{ij}+\Delta,x_{(i+1)j},..,x_{kj}) - y_j(x_{1j},..,x_{kj})}{\Delta} \approx \frac{\partial y_j}{\partial x_{ij}}$$

Where *j* is the number of iteration (*j*=1,..,*n*) and *i* represents the different design parameters (*i*=1,..,*k*); Δ is a predetermined perturbation factor to approximate the elementary effect with a partial derivative (e.g. 5%).

Considering the values of the design parameters seen in Tab. 13 and adding a perturbation factor (Δ), the calculation of partial derivatives is performed for each variable. In the tables below, we can see the results for heating (see Tab. 17), cooling (see Tab. 18), and heating and cooling together (see Tab. 19).

The assessment of correlation between the design parameters is made comparing the variation of a design parameter with respect to the variation of partial derivative; in this way, we detect how a parameter is influenced by the other parameters. In next sections there is a discussion of the obtained results concerning the assessment of correlations between design parameters.

	E_{th}	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading
	y	dy/x_1	dy/x_2	dy/x_3	dy/x_4	dy/x_5	dy/x_6
	kWh/m^2	$\frac{kWh/m^2}{cm}$	$\frac{kWh/m^2}{m^2K/W}$	kWh/m^2	kWh/m^2	$\frac{kWh/m^2}{J/m^2Ks^{0.5}}$	kWh/m^2
1	243	-65	-231	-34	116	0,00	15
2	64	-3	-229	-29	199	0,00	13
3	45	-1	-224	-27	211	0,00	12
-	-	-	-	-	-	-	-
728	47	-3	-11	-39	2	-0,01	14
729	29	-1	-10	-34	12	-0,01	13

Tab. 17: Derivative of the thermal energy need respect each design parameter for heating.

	E_{th}	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading
	y	dy/x_1	dy/x_2	dy/x_3	dy/x_4	dy/x_5	dy/x_6
	kWh/m^2	$\frac{kWh/m^2}{cm}$	$\frac{kWh/m^2}{m^2K/W}$	kWh/m^2	kWh/m^2	$\frac{kWh/m^2}{J/m^2Ks^{0.5}}$	kWh/m^2
1	40	-6	41	30	167	0,00	-14
2	28	0	60	39	202	0,00	-19
3	28	0	69	42	207	0,00	-20
-	-	-	-	-	-	-	-
728	23	0	3	59	54	0,01	-24
729	24	0	4	65	56	0,01	-26

Tab. 18: Derivative of the thermal energy need respect each design parameter for cooling.

	E_{th}	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading
	y	dy/x_1	dy/x_2	dy/x_3	dy/x_4	dy/x_5	dy/x_6
	kWh/m^2	$\frac{kWh/m^2}{cm}$	$\frac{kWh/m^2}{m^2K/W}$	kWh/m^2	kWh/m^2	$\frac{kWh/m^2}{J/m^2Ks^{0.5}}$	kWh/m^2
1	283	-72	-190	-4	283	0,00	0
2	92	-3	-169	11	401	0,00	-6
3	73	-1	-155	16	418	0,00	-8
-	-	-	-	-	-	-	-
728	70	-3	-8	20	56	0,00	-10
729	53	-1	-7	31	68	0,00	-13

Tab. 19: Derivative of the thermal energy need respect each design parameter for heating and cooling.

4.5.1 Pearson's correlation

The influence of each design parameter on the energy demand and the correlations between the design parameters are evaluated through an index called "Pearson's correlation". It reflects the degree of linear relationship between two variables. Pearson's correlation is obtained by dividing the covariance of the two variables by the product of their standard deviations:

$$correl(X,Y) = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2 \sum(y-\overline{y})^2}}$$

The Pearson's correlation is +1 in the case of a perfect positive (increasing) linear relationship (correlation), -1 in the case of a perfect negative (decreasing) linear relationship (anti-correlation), some value between -1 and +1 in all other cases, indicating the degree of linear dependence between the variables. As it approaches zero, there is less of a relationship (closer to uncorrelated). The closer the coefficient is to either -1 or +1, the stronger the correlation between the variables.

Person's index has a limitation, it only measures linear relationship between X and Y; it is anyway useful to highlight different degree of linear relationship that can be evaluated more in details through graphs.

4.5.2 Assessment of the influence for each design parameter

The influence of each design parameter is assessed comparing the variation of the output (thermal energy need) with respect to the variation of the different design parameters. In this section, we present the results obtained considering the heating demand, cooling demand, and heating and cooling together.

	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading
	x_1	x_2	x_3	x_4	x_5	x_6
	cm	m^2K/W	-	-	$W/m^2Ks^{0.5}$	-
Eth,heating	**-0,83**	-0,32	-0,07	0,06	-0,03	0,05

Tab. 20: Correlation coefficients representing the influence of the design parameters to the thermal energy demand for heating.

Considering the heating need, the parameter that mostly influences the thermal energy need is the thermal insulation of the heavy building elements (see Tab. 20), represented in this work with the parameter “wall thermal insulation thickness”. This parameter has a dominant influence on the output and none of the other parameters seems to have. Note that this coefficient measures the linear relationship, hence in case the parameter influences the output with non-linear trends, observing only the correlation coefficient could be misleading (see Fig. 58).

The following graphs are composed of many points in which each one represents a different building configuration. Each graph visualizes the points considering the values of a design parameter with respect to the thermal energy need. Furthermore, a graph can represent the results for heating, cooling, and heating and cooling together.

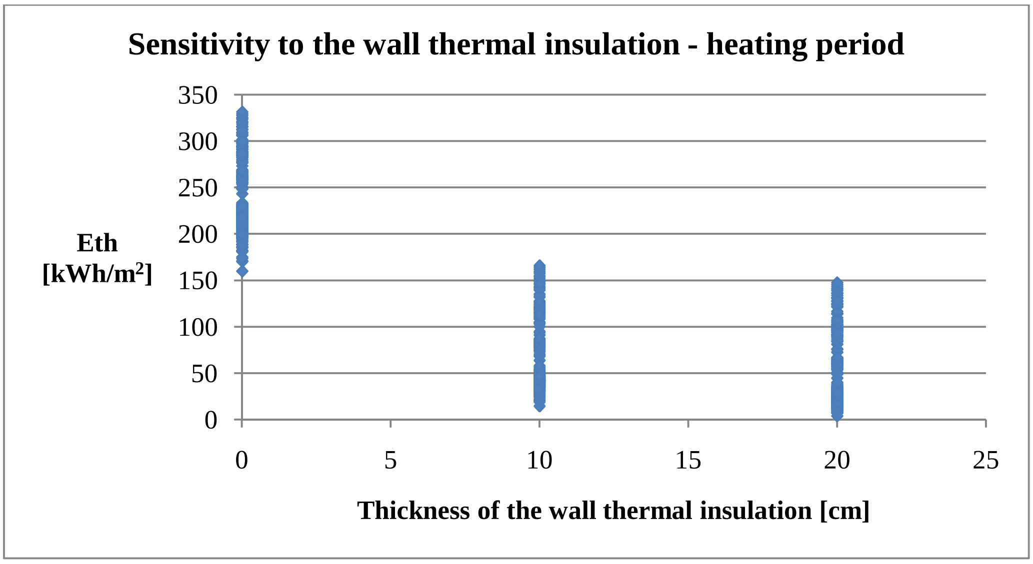


Fig. 58: Sensitivity of the thermal energy need to the wall thermal insulation for heating.

In Fig. 58 we can see how high Pearson's coefficient (-0.83) can be misleading. In this case we have a good correlation for the first centimeters of the thermal insulation but not for the last ones. It means that in a building with 10 cm of thermal insulation is not true that improving this parameter is the best choice to reduce the thermal energy need for heating.

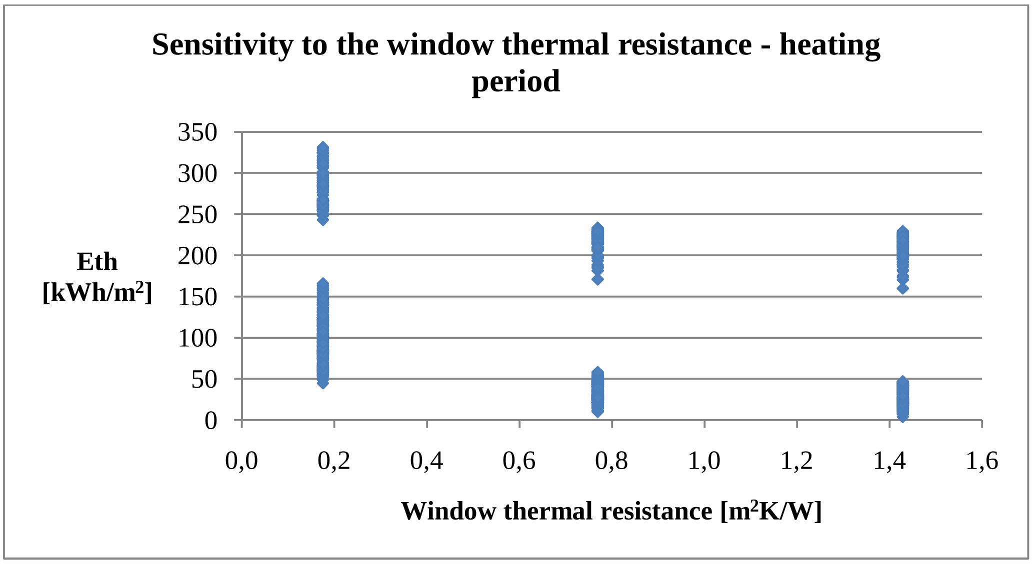


Fig. 59: Sensitivity of the thermal energy need to the window thermal resistance for heating.

As we can see in Fig. 59, there is a slight correlation (-0.32) between thermal energy need and window thermal resistance. The points drawn in the graph are clustered on the top or down area for each one of the three values of the window thermal resistance. The upper groups of points correspond to the building with 0 cm of the thermal insulation thickness while the bottom groups are related to 10 cm and 20 cm.

With the considerations done above, we can give an example to demonstrate the concept of misleading correlation coefficient. For a building with 10 cm of thermal insulation thickness and low window thermal resistance, the reduction of energy demand is obtained increasing the window thermal resistance instead of increasing the thermal insulation of the heavy building elements. In this case the correlation coefficient of the wall insulation thickness is misleading because the trend of the thermal energy need is non-linear with respect to the wall thermal insulation.

	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading
	x_1	x_2	x_3	x_4	x_5	x_6
	cm	m^2K/W	-	-	$W/m^2Ks^{0.5}$	-
Eth,cooling	-0,19	0,35	**0,50**	**0,46**	0,09	**-0,38**

Tab. 21: Correlation coefficients representing the influence of the design parameters to the thermal energy demand for cooling.

Concerning the cooling need (see Tab. 21), there is no parameter with a prevalent influence on the thermal energy need; almost all the variables have a certain influence on the output. Solar transmittance (see Fig. 60), size (see Fig. 61) and shading (see Fig. 62) of the windows show a certain influence on the thermal energy need. Note that all these parameters influence the solar gains which are the main cause of cooling need.

As we can see in Fig. 60, thermal energy need can be decreased by the solar transmittance (g-factor); the correlation coefficient between these variables is 0.5. Fig. 61 shows the influence of the window size that is represented by Pearson’s correlation with an index of 0.46. The last graph for cooling (see Fig. 62) shows that the increase of the window shading is useful to reduce the thermal energy need and corresponds to an index of correlation equals to -0.38.

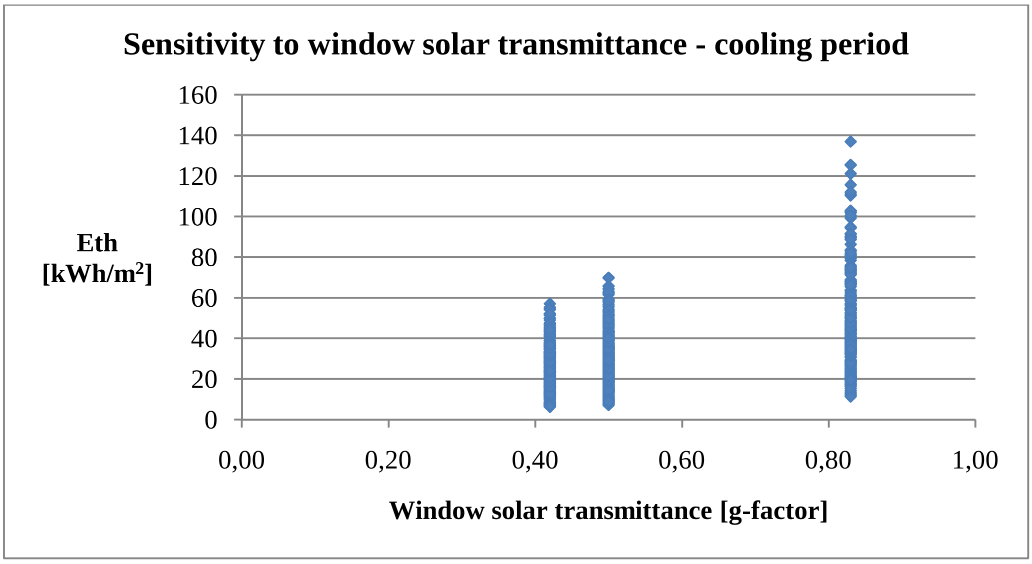


Fig. 60: Sensitivity of the thermal energy need to the window solar transmittance for cooling.

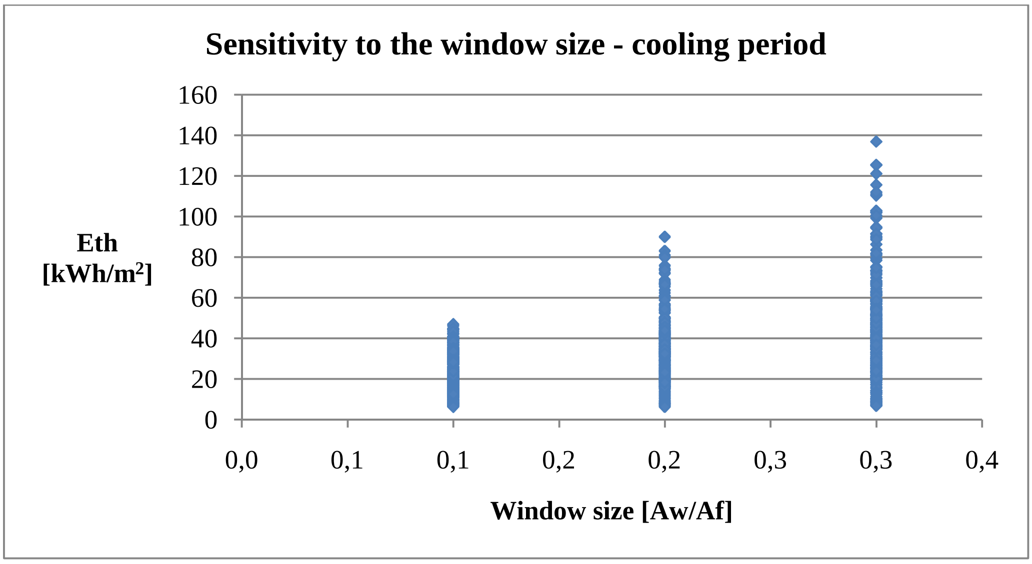


Fig. 61: Sensitivity of the thermal energy need to the window size for cooling.

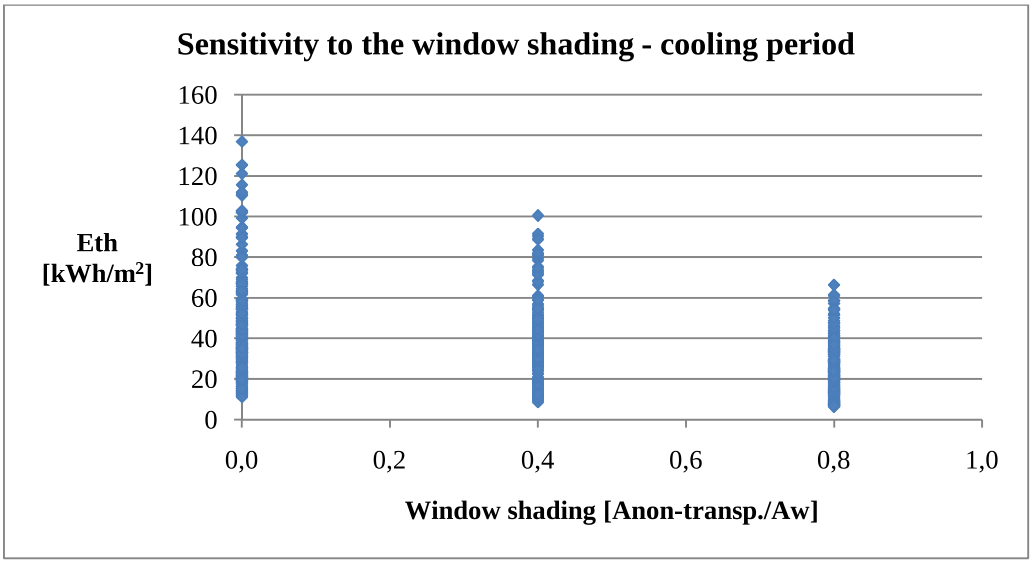


Fig. 62: Sensitivity of the thermal energy need to the window shading for cooling.

Concerning heating and cooling together, Tab. 22 shows a similarity with the correlation coefficients found considering only heating:

	wall insul.	R wind.	g-factor	Aw/Af	inertia	shading
	x_1	x_2	x_3	x_4	x_5	x_6
	cm	m^2K/W	-	-	$W/m^2Ks^{0.5}$	-
Eth,heating	**-0,83**	-0,32	-0,07	0,06	-0,03	0,05
Eth,cooling	-0,19	0,35	**0,50**	**0,46**	0,09	**-0,38**
Eth,heating + cooling	**-0,85**	-0,23	0,04	0,16	-0,01	-0,03

Tab. 22: Correlation coefficients representing the influence of the design parameters to the thermal energy demand.

The first parameter (wall insulation thickness) has a relevant influence on the output while the other parameters assume values markedly lower then. It means that the heating need is dominant compared to the cooling need for the climate of Milan. Furthermore, comparing Fig. 63 with Fig. 58 and Fig. 64 with Fig. 59 we can observe that the thermal behavior of the buildings for heating is similar to the behavior considering heating and cooling together.

Thermal inertia of the internal walls is the only parameter that unnoticeably influences either the heating energy need or the cooling energy need. The internal walls have boundary conditions with limited fluctuations compared to the external walls. For example, the internal walls perceive the internal temperature that is almost constant due to the heating and cooling systems. Furthermore, the considered buildings are externally insulated hence the perimeter brick structure acts as thermal storage. If we were evaluated internally insulated buildings, internal walls probably could have been fundamental as thermal storage. For these reasons, the internal walls do not exploit their thermal storage in noticeably way for the considered boundary conditions of this analysis.

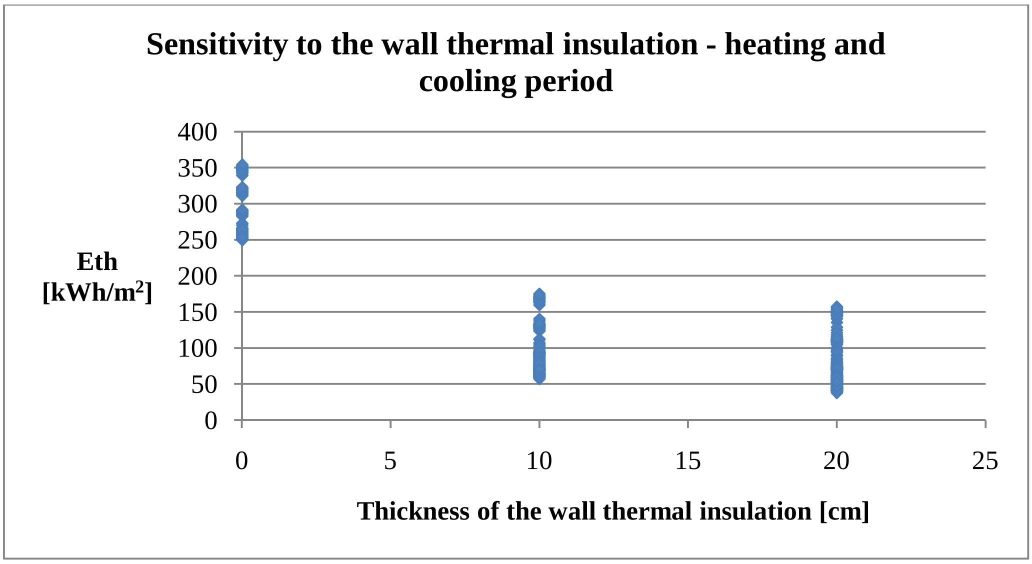


Fig. 63: Sensitivity of the thermal energy need to the wall thermal insulation for heating and cooling.

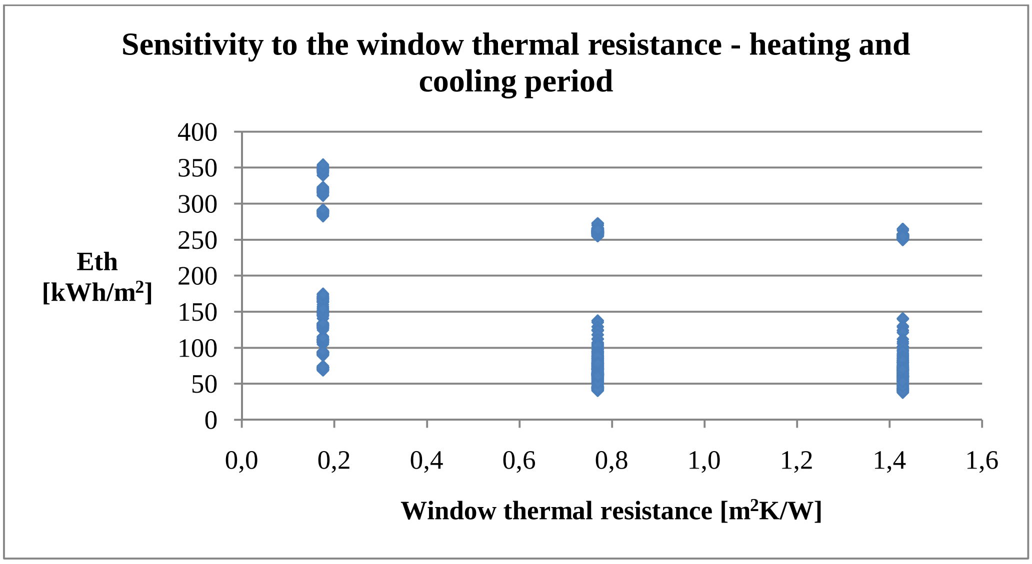


Fig. 64: Sensitivity of the thermal energy need to the window thermal resistance for heating and cooling.

In conclusion of the sensitivity analysis (how the parameters influence the thermal energy need), we can summarize the main results:

- Dominant influence of the thermal insulation of the heavy building elements if the building is lacking in thermal insulation (see Fig. 63);
- Sensible influence of the window thermal resistance if the building has an amount of thermal insulation in the heavy building elements and is lacking in the windows (see Fig. 64);
- Thermal inertia of the internal walls is the only parameter that unnoticeably influences either the heating energy need or the cooling energy need for the considered boundary conditions;
- For the climate of Milan, the heating energy need is dominant compared to the cooling energy need (see Tab. 22).

4.5.3 Assessment of correlation between the design parameters

The correlation between the different design parameters reflects how a parameter influences the capacity of another parameter to affect the thermal behavior of a building. It means to evaluate the correlation between the partial derivative of the thermal energy need (dy/dx_k) with respect to the different design parameters (x_k).

In the graphs of this section, the points drawn represent the potential of a parameter (partial derivative) with respect to the different design parameters; each point represents a different building configuration. Furthermore, a graph can represent the results calculated for either heating, or cooling, or heating and cooling together.

Considering heating need (see Tab. 23), we have highlighted the correlation coefficients that assume a considerable value and we are discussing them with the help of some graphs.

		Wall insul	R wind	g-factor	Aw/Af	inertia	shading
		x_1	x_2	x_3	x_4	x_5	x_6
Wall insul	dy/dx_1	**0,88**	0,00	0,00	0,02	0,00	0,00
R wind	dy/dx_2	-0,01	**0,77**	0,01	-0,28	0,00	-0,01
g-factor	dy/dx_3	0,31	0,27	0,22	**-0,69**	-0,13	0,31
Aw/Af	dy/dx_4	0,22	**-0,84**	-0,16	0,04	-0,04	0,12
inertia	dy/dx_5	0,24	0,26	-0,32	-0,40	0,54	0,19
shading	dy/dx_6	-0,27	-0,33	0,39	**0,65**	0,10	0,16

Tab. 23: Correlation coefficients between the different design parameters for heating.

Window solar transmittance and window shading, as shown in Tab. 23, are correlated with the window size; this is a trivial consideration because solar transmittance and shading of the windows are applied on the glazing surface and for this reason varying the application area (window size) is directly related to the parameters.

Thermal insulation of the heavy building elements, the first row in the table above, presents a correlation only with the parameter itself; it means that the parameter has a non-linear trend respect the thermal energy need. Recalling the previous section, we know that wall insulation thickness is a powerful parameter to reduce the thermal energy need if the building has limited thermal insulation (see Fig. 65). For instance, buildings with 10-20 cm of thermal insulation can obtain little energy savings, increasing the thermal insulation of the heavy building elements.

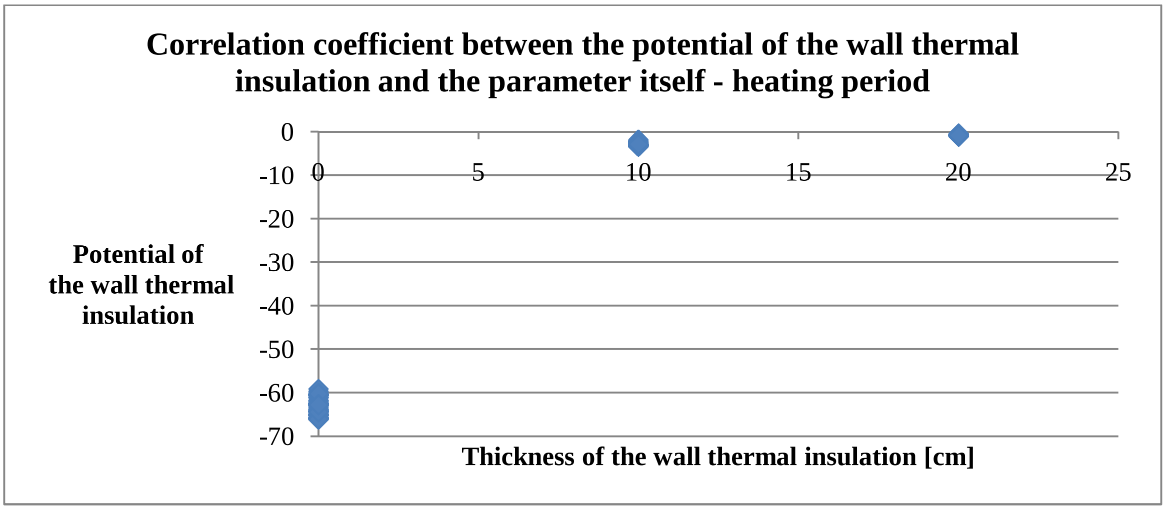


Fig. 65: Correlation coefficient between the potential of the heavy building elements and the parameter itself for heating.

Window thermal resistance, similarly to the parameter already discussed, is correlated with the parameter itself; this means that window thermal resistance has a non-linear trend with respect to the thermal energy need of buildings (see Fig. 66). Furthermore, the graph shows three groups of points in correspondence to 0.2 m^2K/W (window thermal resistance); the upper group corresponds to the maximum window size while the bottom one refers to the minimum window size. Obviously, window thermal resistance allows larger benefits with an extended window area.

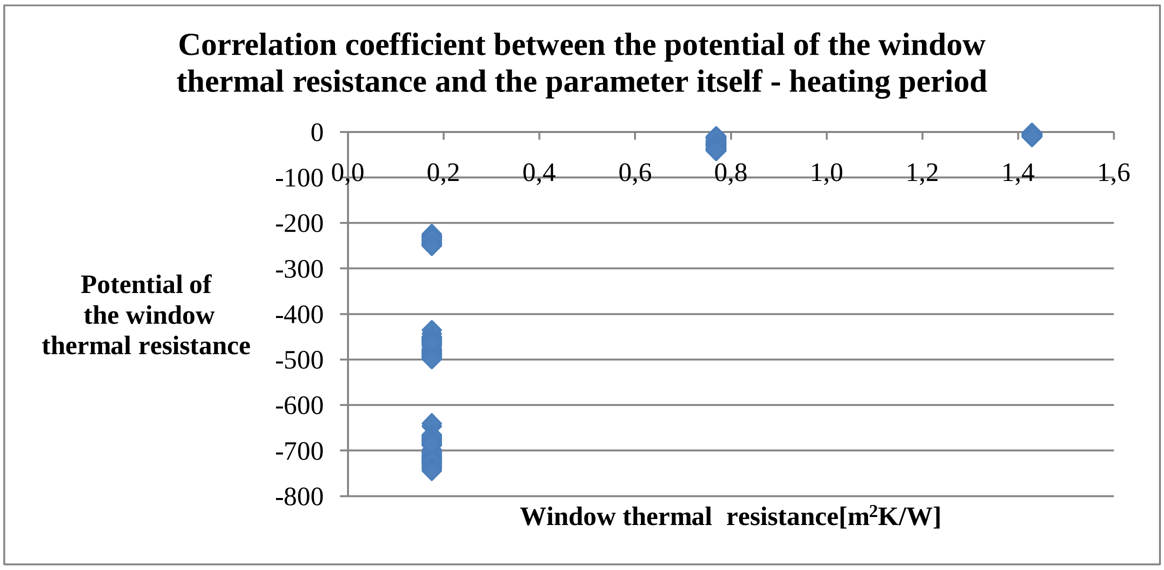


Fig. 66: Correlation coefficient between the potential of the window thermal resistance and the parameter itself for heating.

Window size is correlated to the window thermal resistance (see Fig. 67). In correspondence of low values of the thermal resistance there are positive derivatives, this means that the increase of window size creates an expenditure of thermal energy, while for high values there are negative derivatives but they count small values.

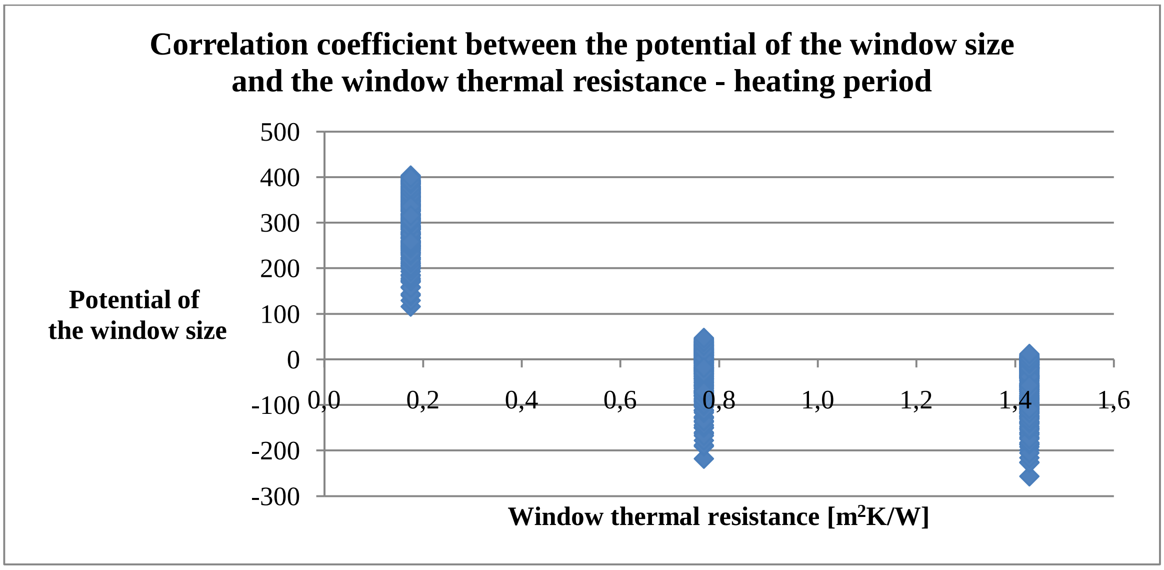


Fig. 67: Correlation coefficient between the potential of the window size and the window thermal resistance for heating.

Considering the cooling need (see Tab. 24), relevant correlation coefficients have been highlighted. In the following graphs we discuss these results:

		Wall insul	R wind	g-factor	Aw/Af	inertia	shading
		x_1	x_2	x_3	x_4	x_5	x_6
Wall insul	dy/dx_1	**0,85**	0,05	0,09	0,07	0,03	-0,06
R wind	dy/dx_2	0,08	**-0,70**	0,21	0,29	0,05	-0,13
g-factor	dy/dx_3	0,25	0,28	0,14	**0,66**	0,14	-0,46
Aw/Af	dy/dx_4	0,17	0,45	**0,61**	0,04	0,11	-0,46
inertia	dy/dx_5	0,17	0,20	0,45	0,38	-0,50	-0,27
shading	dy/dx_6	-0,21	-0,20	-0,58	**-0,63**	-0,11	0,11

Tab. 24: Correlation coefficients between the different design parameters for cooling.

Window solar transmittance and window shading are correlated with the window size (see Tab. 24); this is a trivial consideration because solar transmittance and shading of the windows are applied on the glazing surface and for this reason varying the application area (window size) is directly related to the parameters.

Thermal insulation of the heavy building elements, the first row in the table above, correlates only with the parameter itself, as for the analysis for only heating; it means that the parameter has a non-linear trend respect to the thermal energy need. In addition, Fig. 68 shows negative derivatives (energy saving with extra insulation) only around 0 cm of thermal insulation thickness; note that the values of the derivatives are smaller than the values for heating due to heating need dominance (see Fig. 65).

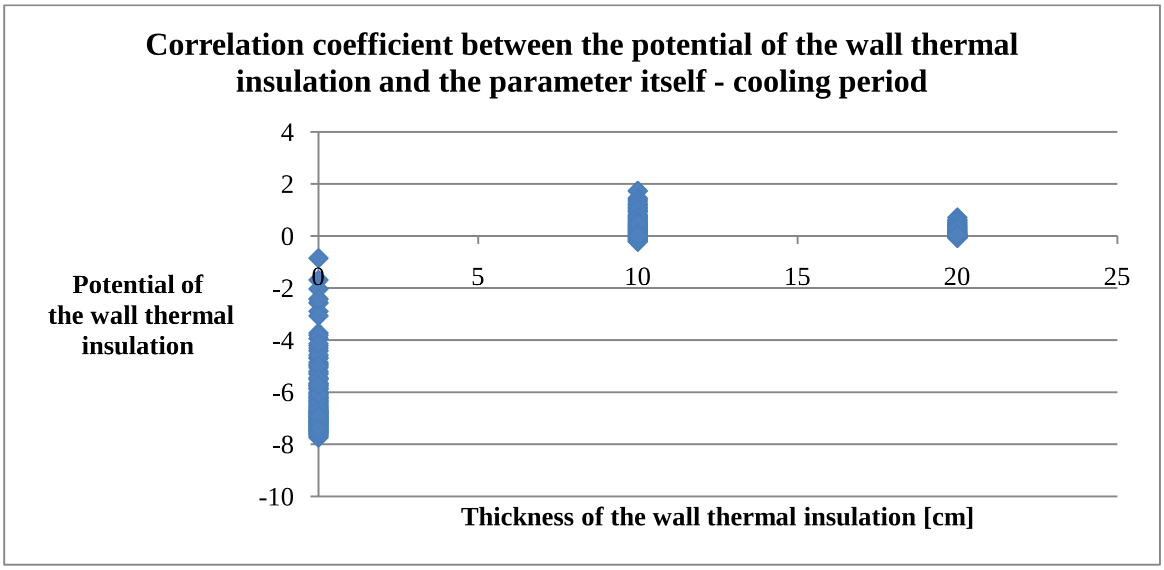


Fig. 68: : Correlation coefficient between the potential of the heavy building elements and the parameter itself for cooling.

Window thermal resistance, similarly to the parameter already discussed, is correlated with the parameter itself; it means that window thermal resistance has a non-linear trend respect to the thermal energy need of buildings (see Fig. 68). Furthermore, the graph shows that all the points account positive values of the derivatives; it means that the increase of window thermal resistance leads up an increase of the thermal energy need.

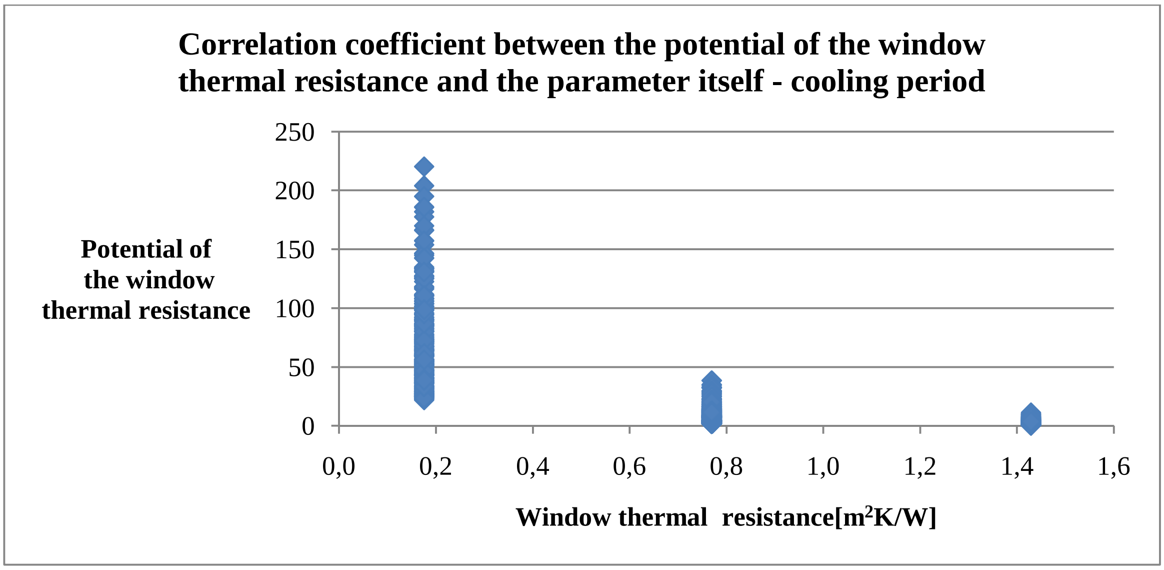


Fig. 69: Correlation coefficient between the potential of the window thermal resistance and the parameter itself for cooling.

Considering heating and cooling together (see Tab. 25), we have highlighted the correlation coefficients that assume a considerable value and we are discussing them with the help of some graphs.

		Wall insul	R wind	g-factor	Aw/Af	inertia	shading
		x_1	x_2	x_3	x_4	x_5	x_6
Wall insul	dy/dx_1	**0,88**	0,00	0,01	0,03	0,00	-0,01
R wind	dy/dx_2	0,00	**0,77**	0,05	-0,27	0,01	-0,04
g-factor	dy/dx_3	0,42	**0,43**	0,26	0,32	0,08	-0,31
Aw/Af	dy/dx_4	0,37	**-0,72**	0,20	0,07	0,03	-0,15
inertia	dy/dx_5	0,35	0,40	0,30	0,17	-0,22	-0,19
shading	dy/dx_6	-0,37	-0,38	**-0,43**	-0,35	-0,07	0,21

Tab. 25: Correlation coefficients between the different design parameters for heating and cooling together.

Also for heating and cooling together the characteristics of the windows (thermal resistance, solar transmittance and shading) show a correlation with the window size for obvious reasons already mentioned before.

As we have already stated in the previous section, the heating need is dominant compared to the cooling need for the climate of Milan. Comparing Fig. 65 with Fig. 70 and Fig. 66

with Fig. 71 we can observe that the thermal behavior of the buildings during for heating is similar to the behavior considering heating and cooling together. In the end we can support that thermal insulation of the heavy building elements and window thermal resistance are parameters with a strong non-linear trend respect the thermal energy need.

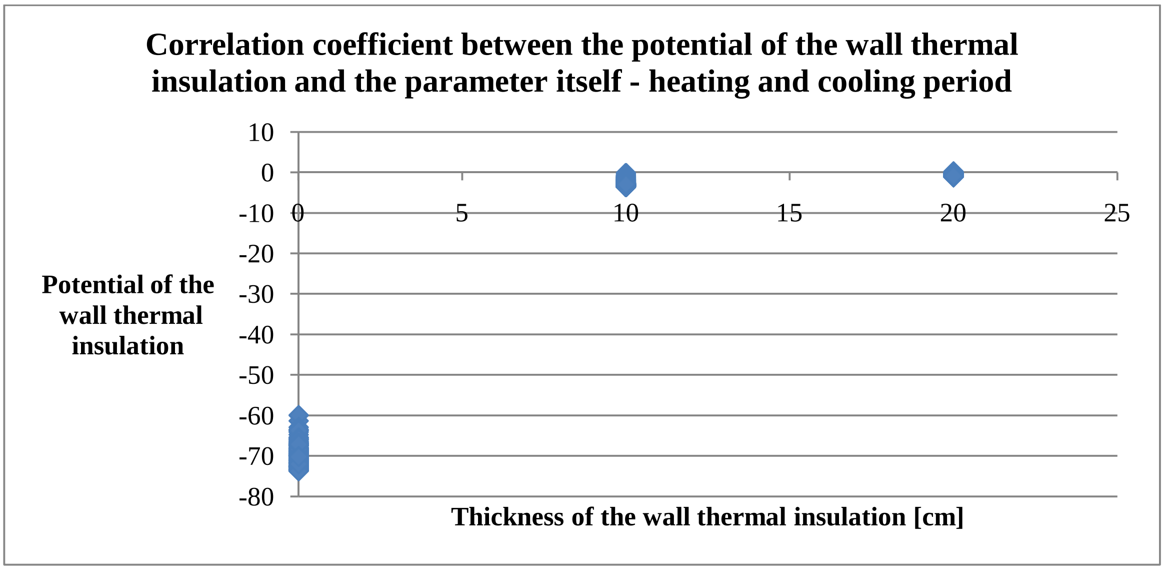


Fig. 70: Correlation coefficient between the potential of the heavy building elements and the parameter itself for heating and cooling.

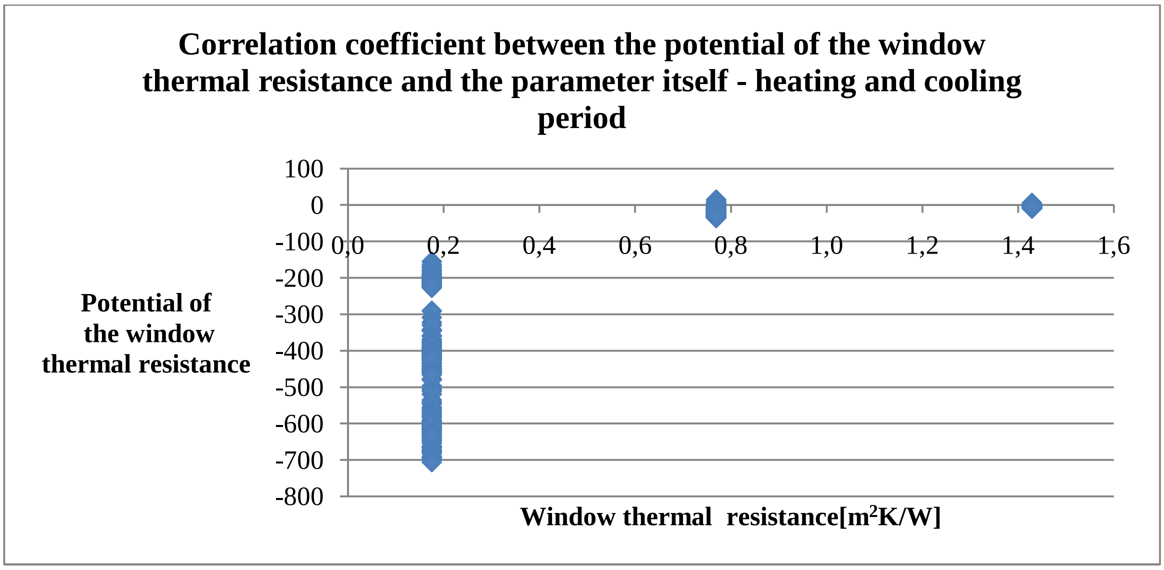


Fig. 71: Correlation coefficient between the potential of the window thermal resistance and the parameter itself for heating and cooling.

Window solar transmittance presents a correlation with the window thermal resistance (see Fig. 72). We find low positive and negative values of the derivatives in correspondence to low thermal resistances of the windows; it means that we do not obtain relevant benefits due to solar transmittance if a building has low window thermal resistance. On the contrary, with high window thermal resistance, g-factor leads to energy saving if we reduce it.

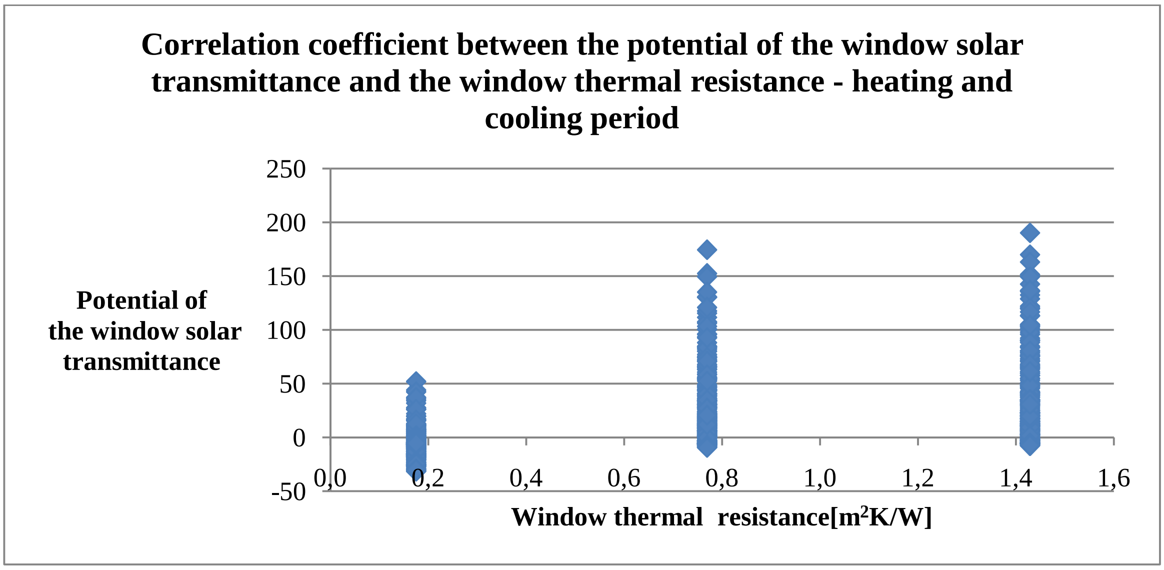


Fig. 72: Correlation coefficient between the potential of the window solar transmittance and the window thermal resistance for heating and cooling.

Window shading, as shown in Fig. 73, is correlated with the window solar transmittance. In correspondence to high values of the window solar transmittance, window shading leads to a reduction of the thermal energy need.

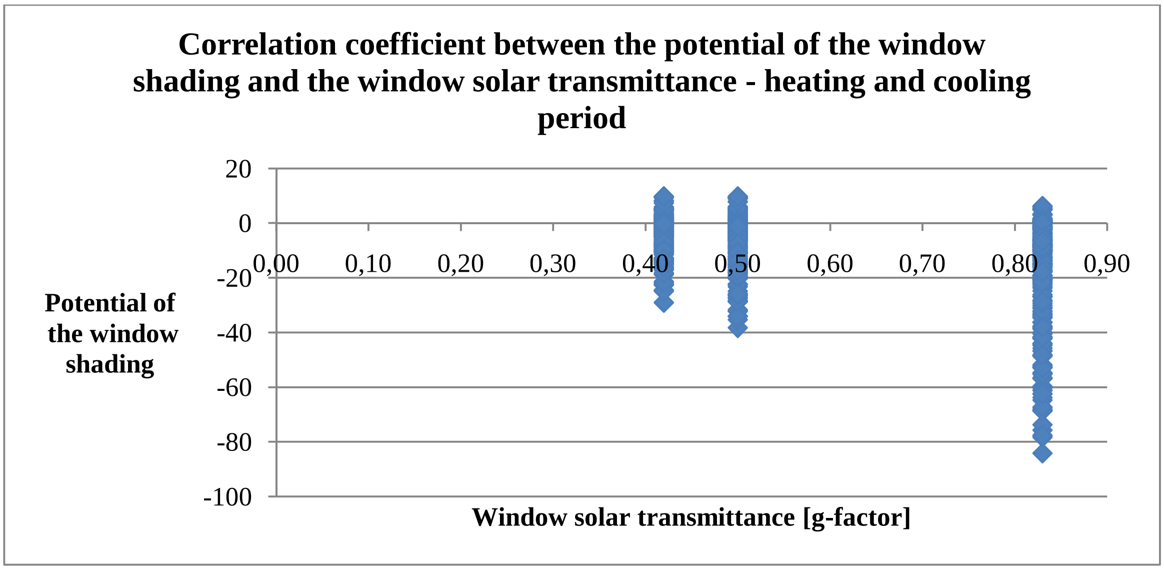


Fig. 73: Correlation coefficient between the potential of the window shading and the window solar transmittance for heating and cooling.

In conclusion of the correlation assessment, we can summarize the main results:

- Thermal insulation of the heavy building elements and window thermal resistance have strong non-linear trends respect the thermal energy need (see Fig. 70 and Fig. 71);
- The characteristics of the windows (thermal resistance, solar transmittance and shading) present a correlation with the window size (see Tab. 25);
- The reduction of the window solar transmittance (g-factor) leads to energy saving if a building has an high window thermal resistance (see Fig. 72);
- In correspondence to high values of the window solar transmittance, window shading leads to a reduction of the thermal energy need (see Fig. 73);
- Concerning only the cooling need, the increase of window thermal resistance leads up an increase of the thermal energy need for all the building configurations (see Fig. 69);

Conclusions

Sensitivity analysis on building performance and assessment of correlation between the design parameters unveil the potential of this approach to give a general view of the thermal behavior of a building. The results have been processed in a global context without focusing on particular building configuration. The total thermal energy demand has been calculated as sum of the heating and cooling demand. This is an indicator of the thermal behavior of a building, but it has to be kept in mind that heating and cooling demand are supplied by different systems.

The buildings involved in this analysis have been analyzed considering the climate of Milan. The results show that, for the considered weather data, the heating energy need is dominant compared to the cooling energy need. Due to heating prevalence, the measures to reduce the heating need markedly affect the total energy need of buildings.

The thermal transmittance of the building opaque envelope is the parameter with the highest influence to the energy demand. Nevertheless, it has a strongly non-linear trend and hence the parameter has a huge potential to save energy in buildings with low thermal insulation, while the potential markedly decreases in buildings with thermal insulation. Window thermal resistance has a moderate influence and a clear non-linear trend on the building energy need; this is strictly true for buildings that have an amount of thermal insulation in the heavy building elements and is lacking in the windows. Concerning only the cooling need, the increase of window thermal resistance leads up an increase of the thermal energy need for any building configurations.

Thermal inertia of the internal walls is the only parameter that unnoticeably influences either the heating energy need or the cooling energy need. The internal walls have boundary conditions with limited fluctuations compared to the external walls. For example, the internal walls are in contact with the internal temperature that is almost constant due to the heating and cooling systems. Furthermore, the considered buildings are externally insulated and hence the perimeter brick structure acts as thermal storage. Considering the internal walls with or without thermal inertia means to increase a thermal storage that already exists.

The reduction of the window solar transmittance (*g-factor*) leads to energy saving if a building has a high window thermal resistance. In case of a poor shielding of a window against the incoming solar radiation (high *g-factor*), window shading leads to a reduction of the thermal energy need.

Finally, the future developments of this work involve other climates, additional design parameters, other boundary conditions and to include Monte Carlo method to generate the inputs for the building model. Nonetheless, to conduct the analysis considering the primary energy need, and hence the operational cost, and the investment cost of the analyzed buildings. In this way, the life cycle cost (*LCC*), an interesting index from the economical point of view, becomes the objective function of the analysis.

Annex A

In this section, the program code of Trnsys and GenOpt used in this work; it is composed of many files that are fully described in chapter three.

Trnsys includes two main files, which we shortly describe below:

- “Cube1.bui” is a file containing the building description that is used by “type 56b” component during the simulations; it can be generated by the user with any text editor or with the interactive program TrnBuild.
- “Test1.dck” specifies the components that constitute the system and the manner in which they are connected; the file is generated by Trnsys Simulation Studio.

For GenOpt there are three files:

- “GenOpt.ini” contains the path for the files, that are required to launch the simulations; furthermore it provides the path where to find the objective function.
- “GenOpt-OptimizationCommands.txt” specifies optimization-related settings such as the independent parameters, the stopping criteria and the optimization algorithm being used.
- “GenOpt-Trnsys16.cfg” contains the instructions to start Trnsys Simulation Studio.

```
************************************************************************************
************************************************************************************
*********************************
*  TRNBuild   1.0.94
************************************************************************************
************************************************************************************
*********************************
*   BUILDING DESCRIPTIONS FILE TRNSYS
*   FOR BUILDING:   C:\Users\Dario\Desktop\prova\cube1.bui
*   GET BY WORKING WITH TRNBuild 1.0 for Windows
************************************************************************************
************************************************************************************
*********************************
*
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  C o m m e n t s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  P r o j e c t
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*+++ PROJECT
*+++ TITLE=CUBE_TEST
*+++ DESCRIPTION=UNDEFINED
*+++ CREATED=UNDEFINED
*+++ ADDRESS=UNDEFINED
*+++ CITY=UNDEFINED
*+++ SWITCH=UNDEFINED
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  P r o p e r t i e s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
PROPERTIES
 DENSITY=1.204 : CAPACITY=1.012 : HVAPOR=2454.0 : SIGMA=2.041e-007 : RTEMP=293.15
*--- alpha calculation -------------------
 KFLOORUP=7.2 : EFLOORUP=0.31 : KFLOORDOWN=3.888 : EFLOORDOWN=0.31
 KCEILUP=7.2 : ECEILUP=0.31 : KCEILDOWN=3.888 : ECEILDOWN=0.31
 KVERTICAL=5.76 : EVERTICAL=0.3
*
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++
TYPES
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++
*
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  L a y e r s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
LAYER HOLLOW_B25
 CONDUCTIVITY=   1.08 : CAPACITY=      1 : DENSITY=   1000
LAYER POLYSTYRENE
 CONDUCTIVITY=   0.11 : CAPACITY=   1.25 : DENSITY=     20
LAYER HOLLOW_B8
 CONDUCTIVITY=  1.368 : CAPACITY=      %inertia% : DENSITY=    900
LAYER CONCR&BRICK
 CONDUCTIVITY=  2.592 : CAPACITY=      1 : DENSITY=   1300
LAYER PLASTER
 CONDUCTIVITY=   2.52 : CAPACITY=      1 : DENSITY=   1500
LAYER CONCRETE
 CONDUCTIVITY=   5.04 : CAPACITY=   0.88 : DENSITY=   2000
LAYER TILE
 CONDUCTIVITY=    3.6 : CAPACITY=    0.8 : DENSITY=    550
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
```

```
*  I n p u t s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
INPUTS SUNSHADE_S SUNSHADE_W SUNSHADE_N SUNSHADE_E
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  S c h e d u l e s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  W a l l s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
WALL EXT_WALL
 LAYERS   = PLASTER HOLLOW_B25 POLYSTYRENE
 THICKNESS= 0.01    0.25       %thick%
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 HFRONT   = 11 : HBACK= 64
WALL INT_WALL
 LAYERS   = PLASTER HOLLOW_B8 PLASTER
 THICKNESS= 0.01    0.08      0.01
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 HFRONT   = 11 : HBACK= 64
WALL FLOOR
 LAYERS   = TILE  CONCRETE POLYSTYRENE CONCR&BRICK PLASTER
 THICKNESS= 0.01  0.05     %thick%        0.24        0.01
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 HFRONT   = 11 : HBACK= 64
WALL CEILING
 LAYERS   = PLASTER CONCR&BRICK POLYSTYRENE CONCRETE TILE
 THICKNESS= 0.01    0.24        %thick%        0.05     0.01
 ABS-FRONT= 0.6   : ABS-BACK= 0.6
 HFRONT   = 11 : HBACK= 11
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  W i n d o w s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
WINDOW SIMPLE
 WINID=14005 : HINSIDE=11 : HOUTSIDE=64 : SLOPE=90 : SPACID=0 : WWID=0 : WHEIG=0 :
FFRAME=0 : UFRAME=8.17 : ABSFRAME=0.6 : RISHADE=0 : RESHADE=0 : REFLISHADE=0 :
REFLOSHADE=0 : CCISHADE=0.5
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  D e f a u l t  G a i n s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  O t h e r  G a i n s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
GAIN GAIN001
 CONVECTIVE=612 : RADIATIVE=612 : HUMIDITY=0
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  C o m f o r t
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  I n f i l t r a t i o n
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*-----------------------------------------------------------------------------------
```

```
------------------------------------------------------------------------------------
---------------------------------
*  V e n t i l a t i o n
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
VENTILATION VENT001
 TEMPERATURE=OUTSIDE
 AIRCHANGE=0.3
 HUMIDITY=OUTSIDE
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  C o o l i n g
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
COOLING COOLING
 ON=26
 POWER=999999999
 HUMIDITY=100
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  H e a t i n g
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
HEATING HEATING
 ON=20
 POWER=999999999
 HUMIDITY=0
 RRAD=0
*
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  Z o n e s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
ZONES COND_ZONE
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  O r i e n t a t i o n s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
ORIENTATIONS NORTH SOUTH EAST WEST HORIZONTAL
*
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++
BUILDING
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++
*
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  Z o n e  COND_ZONE  /  A i r n o d e  COND_ZONE
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
ZONE COND_ZONE
AIRNODE COND_ZONE
WALL  =EXT_WALL   : SURF=  1 : AREA=      %awall% : EXTERNAL : ORI=SOUTH : FSKY=0.5
WINDOW=SIMPLE     : SURF=  7 : AREA=       %awind% : EXTERNAL : ORI=SOUTH : FSKY=0.5
: ESHADE=INPUT %shading%*SUNSHADE_S
WALL  =EXT_WALL   : SURF=  2 : AREA=      %awall% : EXTERNAL : ORI=WEST : FSKY=0.5
WINDOW=SIMPLE     : SURF=  8 : AREA=       %awind% : EXTERNAL : ORI=WEST : FSKY=0.5
: ESHADE=INPUT %shading%*SUNSHADE_W
WALL  =EXT_WALL   : SURF=  3 : AREA=      %awall% : EXTERNAL : ORI=NORTH : FSKY=0.5
WINDOW=SIMPLE     : SURF=  9 : AREA=       %awind% : EXTERNAL : ORI=NORTH : FSKY=0.5
: ESHADE=INPUT %shading%*SUNSHADE_N
WALL  =EXT_WALL   : SURF=  4 : AREA=      %awall% : EXTERNAL : ORI=EAST : FSKY=0.5
WINDOW=SIMPLE     : SURF= 10 : AREA=       %awind% : EXTERNAL : ORI=EAST : FSKY=0.5
: ESHADE=INPUT %shading%*SUNSHADE_E
WALL  =CEILING    : SURF=  5 : AREA=       100 : EXTERNAL : ORI=HORIZONTAL : FSKY=1
```

```
WALL  =FLOOR      : SURF=  6 : AREA=       100 : BOUNDARY=IDENTICAL
WALL  =INT_WALL   : SURF= 11 : AREA=       280 : INTERNAL
 REGIME
 GAIN        = GAIN001    : SCALE= 1
 VENTILATION = VENT001
 COOLING     = COOLING
 HEATING     = HEATING
 CAPACITANCE = 309.6   : VOLUME= 258     : TINITIAL= 20      : PHINITIAL= 50      :
WCAPR= 1
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  O u t p u t s
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
OUTPUTS
 TRANSFER : TIMEBASE=1.000
 DEFAULT
 AIRNODES = COND_ZONE
 NTYPES =  30 : QHEAT - sensible heating demand of zone (positive values)
       =  31 : QCOOL - sensible cooling demand of zone (positive values)
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
*  E n d
*-----------------------------------------------------------------------------------
------------------------------------------------------------------------------------
---------------------------------
END

_EXTENSION_WINPOOL_START_
WINDOW 4.1  DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name        : TRNSYS15 WINDOW LIB
Desc        : Interpane IPLUS3C KR 4/8/4/8/4
Window ID   : 14005
Tilt        : 90.0
Glazings    : 3
Frame       : 11 TRNSYS WIN - 1        2.270
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1600.0 mm
Total Width : 1250.0 mm
Glass Height: 1460.3 mm
Glass Width : 1110.3 mm
Mullion     : None
Gap        Thick   Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Krypton    0 0.00860  2.800  2.280  7.500  3.740 -0.0137  0.660 0.00002
2 Krypton    0 0.00860  2.800  2.280  7.500  3.740 -0.0137  0.660 0.00002
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  %ts% %ts% %ts% %ts% %ts% %ts% %ts% 0.263 0.123 0.000 %ts_h%
Abs1  %as% %as% %as% %as% %as% %as% %as% 0.358 0.299 0.002 %as_h%
Abs2      0     0     0     0     0     0     0     0     0     0     0
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol %rs% %rs% %rs% %rs% %rs% %rs% %rs% 0.378 0.577 0.998 %rs_h%
Rbsol %rs% %rs% %rs% %rs% %rs% %rs% %rs% 0.448 0.650 0.999 %rs_h%
Tvis  %tv% %tv% %tv% %tv% %tv% %tv% %tv% 0.397 0.187 0.000 %tv_h%
Rfvis %rv% %rv% %rv% %rv% %rv% %rv% %rv% 0.303 0.532 0.999 %rv_h%
Rbvis %rv% %rv% %rv% %rv% %rv% %rv% %rv% 0.400 0.662 1.000 %rv_h%
SHGC  0.418 0.423 0.418 0.410 0.397 0.373 0.323 0.231 0.107 0.000 0.347
SC: 0.42
Layer ID#         3302F    3300     3302        0        0        0
Tir              0.000    0.000    0.000        0        0        0
Emis F           0.840    0.840    0.048        0        0        0
Emis B           0.048    0.840    0.840        0        0        0
Thickness(mm)      4.0      4.0      4.0        0        0        0
Cond(W/m2-C     )%uglass%    %uglass%    %uglass%        0        0        0
Spectral FileIPIPLR4.INTIP_KLAR4.INTIPIPLR4.INT     None     None     None
Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
   0        0.00  12.25  3.20  7.14  0.59 0.59  0.60 0.60  0.62 0.62  0.64 0.64
   0        6.71  25.47  3.19  7.15  0.60 0.60  0.61 0.61  0.63 0.63  0.65 0.65
 783        0.00  12.25  3.47  7.80  0.64 0.64  0.66 0.66  0.68 0.68  0.70 0.70
```

```
 783        6.71  25.47  3.33  7.72  0.66 0.66  0.67 0.67  0.68 0.68  0.70 0.70
*** END OF LIBRARY ***
**************************************************************************************
***************
*WinID   Description                                  Design         U-Value g-value
T-sol Rf-sol T-vis
**************************************************************************************
***************
 14005 Interpane,IPLUS3C,KR                             4/8/4/8/4    0.7    0.42
0.329    0.305   0.64   +3   26.00
_EXTENSION_WINPOOL_END_
```

```
VERSION 16.1
********************************************************************************
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on lunedì, marzo 28, 2011 at 10:53
*** from TrnsysStudio project: C:\Users\Dario\Desktop\test\test1.TPF
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:software@cstb.fr
***
********************************************************************************


********************************************************************************
*** Units
********************************************************************************

********************************************************************************
*** Control cards
********************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760
STEP=1
* User defined CONSTANTS

SIMULATION       START   STOP    STEP   ! Start time    End time        Time step
TOLERANCES 0.001 0.001                  ! Integration    Convergence
LIMITS 30 30 30                         ! Max iterations        Max warnings
Trace limit
DFQ 1                                   ! TRNSYS numerical integration solver method
WIDTH 80                                ! TRNSYS output file width, number of
characters
LIST                                    ! NOLIST statement
                                        ! MAP statement
SOLVER 0 1 1                            ! Solver statement      Minimum relaxation
factor  Maximum relaxation factor
NAN_CHECK 0                             ! Nan DEBUG statement
OVERWRITE_CHECK 0                       ! Overwrite DEBUG statement
TIME_REPORT 0                   ! disable time report
EQSOLVER 0                              ! EQUATION SOLVER statement

* Model "Type56b" (Type 56)
*

UNIT 3 TYPE 56   Type56b
*$UNIT_NAME Type56b
*$MODEL .\Loads and Structures\Multi-Zone Building\Without Standard Output
Files\Type56b.tmf
*$POSITION 514 285
*$LAYER Main #
*$#
PARAMETERS 3
31              ! 1 Logical unit for building description file (.bui)
0               ! 2 Star network calculation switch
0.50            ! 3 Weighting factor for operative temperature
INPUTS 22
7,1             ! Type9c:Output 1 -> 1- TAMB
7,3             ! Type9c:Output 3 -> 2- RELHUMAMB
9,1             ! Tsky:Output 1 -> 3- TSKY
8,17            ! Type16i:Total radiation on surface 3 -> 4- IT_NORTH
8,7             ! Type16i:Total radiation on surface 1 -> 5- IT_SOUTH
8,22            ! Type16i:Total radiation on surface 4 -> 6- IT_EAST
8,12            ! Type16i:Total radiation on surface 2 -> 7- IT_WEST
8,4             ! Type16i:Total horizontal radiation -> 8- IT_HORIZONTAL
8,18            ! Type16i:Beam radiation on surface 3 -> 9- IB_NORTH
8,8             ! Type16i:Beam radiation on surface 1 -> 10- IB_SOUTH
8,23            ! Type16i:Beam radiation on surface 4 -> 11- IB_EAST
8,13            ! Type16i:Beam radiation on surface 2 -> 12- IB_WEST
8,5             ! Type16i:Beam radiation on horizontal -> 13- IB_HORIZONTAL
8,20            ! Type16i:Incidence angle of surface 3 -> 14- AI_NORTH
8,10            ! Type16i:Incidence angle for surface 1 -> 15- AI_SOUTH
8,25            ! Type16i:Incidence angle of surface 4 -> 16- AI_EAST
8,15            ! Type16i:Incidence angle of surface 2  -> 17- AI_WEST
8,2             ! Type16i:Solar zenith angle -> 18- AI_HORIZONTAL
SHADE_S         ! Shading:SHADE_S -> 19- SUNSHADE_S
SHADE_W         ! Shading:SHADE_W -> 20- SUNSHADE_W
SHADE_N         ! Shading:SHADE_N -> 21- SUNSHADE_N
```

```
SHADE_E         ! Shading:SHADE_E -> 22- SUNSHADE_E
*** INITIAL INPUT VALUES
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*** External files
ASSIGN "cube1.bui" 31
*|? Building description file (*.bui) |1000
*------------------------------------------------------------------------------

* Model "Type9c" (Type 9)
*

UNIT 7 TYPE 9    Type9c
*$UNIT_NAME Type9c
*$MODEL .\Utility\Data Readers\Generic Data Files\Skip Lines to Start\Free
Format\Type9c.tmf
*$POSITION 350 189
*$LAYER Weather - Data Files #
PARAMETERS 26
5               ! 1 Mode
1               ! 2 Header Lines to Skip
5               ! 3 No. of values to read
1.0             ! 4 Time interval of data
-1              ! 5 Interpolate or not-1
1.0             ! 6 Multiplication factor-1
0               ! 7 Addition factor-1
1               ! 8 Average or instantaneous value-1
-1              ! 9 Interpolate or not-2
1.0             ! 10 Multiplication factor-2
0               ! 11 Addition factor-2
1               ! 12 Average or instantaneous value-2
-1              ! 13 Interpolate or not-3
1.0             ! 14 Multiplication factor-3
0               ! 15 Addition factor-3
1               ! 16 Average or instantaneous value-3
-1              ! 17 Interpolate or not-4
3.6             ! 18 Multiplication factor-4
0               ! 19 Addition factor-4
1               ! 20 Average or instantaneous value-4
-1              ! 21 Interpolate or not-5
3.6             ! 22 Multiplication factor-5
0               ! 23 Addition factor-5
1               ! 24 Average or instantaneous value-5
33              ! 25 Logical unit for input file
-1              ! 26 Free format mode
*** External files
ASSIGN
"C:\Users\Dario\Desktop\weather_data_for_simulation\ITA_Milan.160660_IWEC\Milan_weat
her_data.txt" 33
*|? Input file name |1000
*------------------------------------------------------------------------------

* Model "Type16i" (Type 16)
*

UNIT 8 TYPE 16   Type16i
*$UNIT_NAME Type16i
*$MODEL .\Physical Phenomena\Radiation Processors\Total Horiz, Horiz Diffuse Known
(Mode=5)\Type16i.tmf
*$POSITION 352 370
*$LAYER Weather - Data Files #
PARAMETERS 9
5               ! 1 Horiz. radiation mode
1               ! 2 Tracking mode
4               ! 3 Tilted surface mode
1               ! 4 Starting day
45.6166         ! 5 Latitude
4871.0          ! 6 Solar constant
-6.2834         ! 7 Shift in solar time
2               ! 8 Not used
1               ! 9 Solar time?
INPUTS 13
7,4             ! Type9c:Output 4 ->Total radiation on horizontal1
7,5             ! Type9c:Output 5 ->Diffuse radiation on horizontal
7,99            ! Type9c:Time of last read ->Time of last data read
7,100           ! Type9c:Time of next read ->Time of next data read
0,0             ! [unconnected] Ground reflectance
0,0             ! [unconnected] Slope of surface-1
0,0             ! [unconnected] Azimuth of surface-1
0,0             ! [unconnected] Slope of surface-2
0,0             ! [unconnected] Azimuth of surface-2
0,0             ! [unconnected] Slope of surface-3
```

```
0,0             ! [unconnected] Azimuth of surface-3
0,0             ! [unconnected] Slope of surface-4
0,0             ! [unconnected] Azimuth of surface-4
*** INITIAL INPUT VALUES
0.0 0 0.0 1.0 0.2 90 0 90 90 90 180 90 270
*------------------------------------------------------------------------------

* Model "Tsky" (Type 9)
*

UNIT 9 TYPE 9    Tsky
*$UNIT_NAME Tsky
*$MODEL .\Utility\Data Readers\Generic Data Files\Skip Lines to Start\Free
Format\Type9c.tmf
*$POSITION 358 285
*$LAYER Weather - Data Files #
PARAMETERS 10
5               ! 1 Mode
1               ! 2 Header Lines to Skip
1               ! 3 No. of values to read
1.0             ! 4 Time interval of data
-1              ! 5 Interpolate or not
1.0             ! 6 Multiplication factor
0               ! 7 Addition factor
1               ! 8 Average or instantaneous value
34              ! 9 Logical unit for input file
-1              ! 10 Free format mode
*** External files
ASSIGN
"C:\Users\Dario\Desktop\weather_data_for_simulation\ITA_Milan.160660_IWEC\Milan_Tsky
.txt" 34
*|? Input file name |1000
*------------------------------------------------------------------------------

* Model "Shading S" (Type 2)
*

UNIT 10 TYPE 2   Shading S
*$UNIT_NAME Shading S
*$MODEL .\Controllers\Differential Controller w_ Hysteresis\for Temperatures\Solver
0 (Successive Substitution) Control Strategy\Type2b.tmf
*$POSITION 453 520
*$LAYER Controls #
*$# NOTE: This control strategy can only be used with solver 0 (Successive
substitution)
*$#
PARAMETERS 2
5               ! 1 No. of oscillations
5000            ! 2 High limit cut-out
INPUTS 6
TR_S            ! Radiation:TR_S ->Upper input temperature Th
0,0             ! [unconnected] Lower input temperature Tl
0,0             ! [unconnected] Monitoring temperature Tin
10,1            ! Shading S:Output control function ->Input control function
0,0             ! [unconnected] Upper dead band dT
0,0             ! [unconnected] Lower dead band dT
*** INITIAL INPUT VALUES
15 0 0 0 1116 1044
*------------------------------------------------------------------------------

* Model "Shading W" (Type 2)
*

UNIT 11 TYPE 2   Shading W
*$UNIT_NAME Shading W
*$MODEL .\Controllers\Differential Controller w_ Hysteresis\for Temperatures\Solver
0 (Successive Substitution) Control Strategy\Type2b.tmf
*$POSITION 573 520
*$LAYER Controls #
*$# NOTE: This control strategy can only be used with solver 0 (Successive
substitution)
*$#
PARAMETERS 2
5               ! 1 No. of oscillations
5000            ! 2 High limit cut-out
INPUTS 6
TR_W            ! Radiation:TR_W ->Upper input temperature Th
0,0             ! [unconnected] Lower input temperature Tl
0,0             ! [unconnected] Monitoring temperature Tin
11,1            ! Shading W:Output control function ->Input control function
0,0             ! [unconnected] Upper dead band dT
```

```
0,0             ! [unconnected] Lower dead band dT
*** INITIAL INPUT VALUES
15 0 0 0 1116 1044
*------------------------------------------------------------------------------

* Model "Shading N" (Type 2)
*

UNIT 12 TYPE 2   Shading N
*$UNIT_NAME Shading N
*$MODEL .\Controllers\Differential Controller w_ Hysteresis\for Temperatures\Solver
0 (Successive Substitution) Control Strategy\Type2b.tmf
*$POSITION 699 520
*$LAYER Controls #
*$# NOTE: This control strategy can only be used with solver 0 (Successive
substitution)
*$#
PARAMETERS 2
5               ! 1 No. of oscillations
5000            ! 2 High limit cut-out
INPUTS 6
TR_N            ! Radiation:TR_N ->Upper input temperature Th
0,0             ! [unconnected] Lower input temperature Tl
0,0             ! [unconnected] Monitoring temperature Tin
12,1            ! Shading N:Output control function ->Input control function
0,0             ! [unconnected] Upper dead band dT
0,0             ! [unconnected] Lower dead band dT
*** INITIAL INPUT VALUES
15 0 0 0 1116 1044
*------------------------------------------------------------------------------

* Model "Shading E" (Type 2)
*

UNIT 13 TYPE 2   Shading E
*$UNIT_NAME Shading E
*$MODEL .\Controllers\Differential Controller w_ Hysteresis\for Temperatures\Solver
0 (Successive Substitution) Control Strategy\Type2b.tmf
*$POSITION 816 520
*$LAYER Controls #
*$# NOTE: This control strategy can only be used with solver 0 (Successive
substitution)
*$#
PARAMETERS 2
5               ! 1 No. of oscillations
5000            ! 2 High limit cut-out
INPUTS 6
TR_E            ! Radiation:TR_E ->Upper input temperature Th
0,0             ! [unconnected] Lower input temperature Tl
0,0             ! [unconnected] Monitoring temperature Tin
13,1            ! Shading E:Output control function ->Input control function
0,0             ! [unconnected] Upper dead band dT
0,0             ! [unconnected] Lower dead band dT
*** INITIAL INPUT VALUES
15 0 0 0 1116 1044
*------------------------------------------------------------------------------

* EQUATIONS "Radiation"
*
EQUATIONS 4
TR_S = [8,7]
TR_W = [8,12]
TR_N = [8,17]
TR_E = [8,22]
*$UNIT_NAME Radiation
*$LAYER Main
*$POSITION 313 520

*------------------------------------------------------------------------------


* EQUATIONS "Shading"
*
EQUATIONS 4
SHADE_S = [10,1]
SHADE_W = [11,1]
SHADE_N = [12,1]
SHADE_E = [13,1]
*$UNIT_NAME Shading
*$LAYER Main
*$POSITION 640 381
```

```
*------------------------------------------------------------------------------


* EQUATIONS "Eth"
*
EQUATIONS 3
Eth_tot = Eth_h*%h%+Eth_c*%c%
Eth_h = [3,3]/(3600*86)
Eth_c = [3,4]/(3600*86)
*$UNIT_NAME Eth
*$LAYER Main
*$POSITION 665 285

*------------------------------------------------------------------------------


* Model "TYPE28b" (Type 28)
*

UNIT 23 TYPE 28  TYPE28b
*$UNIT_NAME TYPE28b
*$MODEL .\Output\Simulation Summary\Results to External File\Without Energy Balance\TYPE28b.tmf
*$POSITION 803 285
*$LAYER Main #
PARAMETERS 11
-1               ! 1 Summary interval
START            ! 2 Summary start time
STOP             ! 3 Summary stop time
37               ! 4 Logical unit for the output file
2                ! 5 Output mode
-11              ! 6 Operation code-1
-4               ! 7 Operation code-2
-12              ! 8 Operation code-3
-4               ! 9 Operation code-4
-13              ! 10 Operation code-5
-4               ! 11 Operation code-6
INPUTS 3
Eth_tot          ! Eth:Eth_tot ->Summary input-1
Eth_h            ! Eth:Eth_h ->Summary input-2
Eth_c            ! Eth:Eth_c ->Summary input-3
*** INITIAL INPUT VALUES
0.0 0.0 0.0
LABELS 3
EPtot EPh EPc
*** External files
ASSIGN "EP.txt" 37
*|? File for the summary results |1000
*------------------------------------------------------------------------------

END
```

```
Simulation {

    // Template, Input and Output files

    Files {

        // Templates for simulation input files, i.e. DCK and/or BUI files
        // which have been edited to indicate optimization parameters with
        // their names between percent sign, e.g. %myVar%
        Template {
            File1 = "test1.dck";
            Path1 = "C:\\Users\\Dario\\Desktop\\test";
            File2 = "cube1.bui";
            Path2 = "C:\\Users\\Dario\\Desktop\\test";
        }

        // Files that will be created by GenOpt from the template before
        // each simulation run.
        // !!! Be careful that the deck file must refer to
        // !!! the correct building file
        Input {
            File1 = "test1.dck";
            Path1 = "C:\\Users\\Dario\\Desktop\\test";
            File2 = "cube1.bui";
            Path2 = "C:\\Users\\Dario\\Desktop\\test";
        }

        // Log file to parse for error. In TRNSYS 16 this file has the
        // same name as the deck with a .log extension
        Log {
            File1 = "test1.log";
            Path1 = "C:\\Users\\Dario\\Desktop\\test";
        }

        // Output file to parse for the cost function. Instructions to find
        // the numerical value of the cost function are provided below in the
        // ObjectiveFunctionLocation section
        Output {
            File1 = "EP.txt";
            Path1 = "C:\\Users\\Dario\\Desktop\\test";
        }

        // Configuration file for TRNSYS 16 (common to all optimization projects)
        Configuration {
            File1 = "GenOpt-Trnsys16.cfg";
            Path1 = "C:\\Users\\Dario\\Desktop\\test";
        }
    }

    CallParameter { // optional section
    }

    ObjectiveFunctionLocation {
        // Name of the cost function in GenOpt
        Name1      = "EP";
        // How to find the numerical value of the objective function.
        // It will be read AFTER the LAST occurrence of the "Delimiter" string
        // In this case the delimiter string is set for Type28 output in mode 2
        // (which is NOT the default mode) assuming the objective function is
        // the first printed output (first column)
      Delimiter1 = "Sum  0.8760000000000000E+0004" ; // Last line written by Type 28
        Name2 = thick_d;     Function2 = %thick%;
        Name3 = uwindow_d;   Function3 = %uwindow%;
        Name4 = gfactor_d;    Function4 = %gfactor%;
        Name5 = aratio_d;   Function5 = %aratio%;
        Name6 = inertia_d;   Function6 = %inertia%;
        Name7 = shading_d;   Function7 = %shading%;
        Name8 = energyneed;      Function8 = %x%;
          Name9 = u-glass;    Function9 = %uglass%;
          Name10 = areawall; Function10 = %awall%;
          Name11 = areawindow;    Function11 = %awind%;
    }



} // end of section Simulation


Optimization {

    // Where to find the optimization settings: which variables to optimize,
```

```
    // which optimization algorithm

    Files {
        Command {
            File1 = "GenOpt-OptimizationCommands.txt";
            Path1 = "C:\\Users\\Dario\\Desktop\\test";
        }
    }

} // end of configuration file
```

```
Vary {


Function{
        Name = thick;
        Function = "add( 0 , %thick_0% )";
        }

Parameter {
        Name    = thick_0;
        Ini     = 1;
        Values  = " 0.0001, 0.1, 0.2 ";
        Type    = set;
        }




Function{
        Name = uwindow;
        Function = "add( 0 , %uwindow_0% )";
        }

Parameter {
        Name    = uwindow_0;
        Ini     = 1;
        Values  = " 5.7, 1.3, 0.7 ";
        Type    = set;
        }

Function{
        Name = uglass;
        Function = " multiply( 3, divide ( 1 ,  subtract (  divide ( 1 , %uwindow% )
, 0.16987 ) ) ) ";
        }





Function{
        Name = gfactor;
        Function = "add( 0 , %gfactor_0% )";
        }

Parameter{
        Name    = gfactor_0;
        Ini     = 1;
        Values  = " 0.83, 0.5, 0.42  ";
        Type    = set;
         }

Function{
        Name = ts;
        Function = "add( -0.1439 , multiply( 1.1021, %gfactor%) )";
        }
Function{
        Name = as;
        Function = "add( 0.6174 , multiply( -0.5658, %gfactor%) )";
        }
Function{
        Name = rs;
        Function = "add( 0.546 , multiply( -0.5565, %gfactor%) )";
        }
Function{
        Name = tv;
        Function = "add( 0.3014 , multiply( 0.6833, %gfactor%) )";
        }
Function{
        Name = rv;
        Function = "add( 0.237 , multiply( -0.1697, %gfactor%) )";
        }
Function{
        Name = ts_h;
        Function = "add( -0.1751 , multiply( 1.0682, %gfactor%) )";
        }
Function{
        Name = as_h;
        Function = "add( 0.6187 , multiply( -0.5624, %gfactor%) )";
        }
Function{
```

```
        Name = rs_h;
        Function = "add( 0.5683 , multiply( -0.5296, %gfactor%) )";
        }
Function{
        Name = tv_h;
        Function = "add( 0.1946 , multiply( 0.7406, %gfactor%) )";
        }
Function{
        Name = rv_h;
        Function = "add( 0.2872 , multiply( -0.1706, %gfactor%) )";
        }





Function{
        Name = aratio;
        Function = "add( 0 , %aratio_0% )";
        }

Parameter{
        Name    = aratio_0;
        Ini     = 1;
        Values  = " 0.1, 0.2, 0.3 ";
        Type    = set;
         }

Function{
        Name = awind;
        Function = "divide ( multiply( 86, %aratio% ), 4)";
        }

Function{
        Name = awall;
        Function = "subtract( 35, %awind% )";
        }




Function{
        Name = inertia;
        Function = "add( 0 , %inertia_0% )";
        }

Parameter {
        Name    = inertia_0;
        Ini     = 1;
        Values  = " 6.48, 1, 0.31 ";
        Type    = set;
        }




Function{
        Name = shading;
        Function = "add( 0 , %shading_0% )";
        }

Parameter {
        Name    = shading_0;
        Ini     = 1;
        Values  = " 0, 0.4, 0.8 ";
        Type    = set;
        }





Parameter {
        Name    = x;
        Ini     = 1;
        Values  = " 1, 2, 3 ";
        Type    = set;
        }

Function{
        Name = h;
```

```
        Function = "add( multiply(%x%,%x%) , multiply(-4,%x%) , 4)";
        }

Function{
        Name = c;
        Function = "add( multiply(-0.5,%x%,%x%) , multiply(2.5,%x%) , -2)";
        }

}




OptimizationSettings {
    MaxIte = 100;
    MaxEqualResults = 5;
    WriteStepNumber = false;
}

Algorithm{
Main = Mesh;
StopAtError = true;
}
```

```
// Strings that indicate an error in the simulation when parsing the TRNSYS log file

SimulationError {
    ErrorMessage = "*** Fatal Error at time";
    ErrorMessage = "*** Simulation stopped with errors";
}


// Output format

IO {
    NumberFormat = Double;
}


// Command to launch TRNSYS 16. Note that GenOpt should pass the filename enlosed
within quotes.
// The GenOpt interpreter requires special characters like backslash (\) and quotes
(")
// to be preceded by a backslash \, i.e. " becomes \" and \ becomes \\
// The /h switch is used for TRNSYS, which means that TRNExe will run in the
background,
// completely hidden, if there is no active online plotter (Type 65) in the
simulation.
// Change the switch to "/n" if you want to display the TRNSYS progress bar.

SimulationStart {
    Command = "C:\\Program Files (x86)\\Trnsys16_1\\Exe\\TRNExe.exe
\"%Simulation.Files.Input.Path1%\\%Simulation.Files.Input.File1%\" /n" ;
    WriteInputFileExtension = true;
}


// The ObjectiveFunctionLocation section will be overridden by equivalent sections
in the ini files for individual optimization problems

ObjectiveFunctionLocation {
    // Example if using Type 28 (Simulation summary) in mode 2 (Which is NOT the
default) and if the objective function is the first output
    // Note that Genopt minimizes an objective function ("cost"). If you want to
maximize a quantity (e.g. solar output) you need to change
    // the sign of the objective function
    Name1      = "Result";
    Delimiter1 = "Sum  0.8760000000000000E+0004" ; // Last line of Type 28
}
```

```
WINDOW 4.1  DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name        : TRNSYS15 WINDOW LIB
Desc        : FLOAT_6
Window ID   : 11003
Tilt        : 90.0
Glazings    : 1
Frame       :  8 TRNSYS WIN - 1        2.270
Spacer      :  5 Class5                0.000   1.000   0.000
Total Height: 1600.0 mm
Total Width : 1250.0 mm
Glass Height: 1460.3 mm
Glass Width : 1110.3 mm
Mullion     : None
Gap        Thick   Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1              0       0      0      0      0      0       0      0       0
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.790 0.789 0.786 0.781 0.770 0.747 0.699 0.591 0.355 0.000 0.707
Abs1  0.140 0.141 0.143 0.148 0.153 0.160 0.166 0.169 0.160 0.000 0.154
Abs2      0     0     0     0     0     0     0     0     0     0     0
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.070 0.070 0.070 0.072 0.077 0.093 0.135 0.240 0.485 1.000 0.128
Rbsol 0.070 0.070 0.070 0.072 0.077 0.093 0.135 0.240 0.485 1.000 0.128
Tvis  0.885 0.885 0.884 0.881 0.873 0.854 0.806 0.689 0.428 0.000 0.807
Rfvis 0.080 0.080 0.080 0.082 0.088 0.106 0.152 0.267 0.528 1.000 0.144
Rbvis 0.080 0.080 0.080 0.082 0.088 0.106 0.152 0.267 0.528 1.000 0.144
SHGC  0.827 0.826 0.824 0.820 0.810 0.789 0.743 0.636 0.397 0.000 0.748
SC: 0.81
Layer ID#         4048        0        0        0        0        0
Tir              0.000        0        0        0        0        0
Emis F           0.840        0        0        0        0        0
Emis B           0.840        0        0        0        0        0
Thickness(mm)      6.0        0        0        0        0        0
Cond(W/m2-C     )150.0        0        0        0        0        0
Spectral File     None     None     None     None     None     None
Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
   0        0.00  12.25   3.42   8.22   5.20 5.20   4.89 4.89   4.88 4.88   5.46 5.46
   0        6.71  25.47   3.33   8.29   6.17 6.17   5.65 5.65   5.61 5.61   6.36 6.36
 783        0.00  12.25   3.51   8.13   5.18 5.18   4.60 4.60   5.27 5.27   5.64 5.64
 783        6.71  25.47   3.39   8.24   6.15 6.15   5.28 5.28   5.96 5.96   6.52 6.52




WINDOW 4.1  DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name        : TRNSYS15 WINDOW LIB
Desc        : Interpane IPLUS3C KR 4/8/4/8/4
Window ID   : 14005
Tilt        : 90.0
Glazings    : 3
Frame       : 11 TRNSYS WIN - 1        2.270
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1600.0 mm
Total Width : 1250.0 mm
Glass Height: 1460.3 mm
Glass Width : 1110.3 mm
Mullion     : None
Gap        Thick   Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Krypton    8.0 0.00860  2.800  2.280  7.500  3.740 -0.0137  0.660 0.00002
2 Krypton    8.0 0.00860  2.800  2.280  7.500  3.740 -0.0137  0.660 0.00002
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.329 0.332 0.323 0.312 0.299 0.275 0.225 0.142 0.052 0.000 0.255
Abs1  0.256 0.258 0.267 0.273 0.275 0.280 0.298 0.317 0.269 0.002 0.279
Abs2  0.041 0.042 0.042 0.042 0.043 0.044 0.043 0.039 0.030 0.000 0.041
Abs3  0.069 0.070 0.074 0.076 0.076 0.075 0.076 0.067 0.037 0.000 0.071
Abs4      0     0     0     0     0     0     0     0     0     0     0
```

```
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.305 0.298 0.294 0.296 0.306 0.325 0.358 0.435 0.612 0.998 0.343
Rbsol 0.305 0.298 0.294 0.296 0.306 0.325 0.358 0.435 0.612 0.998 0.343
Tvis  0.639 0.646 0.629 0.608 0.583 0.536 0.436 0.273 0.100 0.000 0.496
Rfvis 0.148 0.137 0.132 0.136 0.152 0.183 0.236 0.343 0.559 0.999 0.209
Rbvis 0.148 0.137 0.132 0.136 0.152 0.183 0.236 0.343 0.559 0.999 0.209
SHGC  0.418 0.423 0.418 0.410 0.397 0.373 0.323 0.231 0.107 0.000 0.347
SC: 0.42
Layer ID#         3302F    3300     3302         0        0        0
Tir              0.000    0.000    0.000        0        0        0
Emis F           0.840    0.840    0.048        0        0        0
Emis B           0.048    0.840    0.840        0        0        0
Thickness(mm)      4.0      4.0      4.0        0        0        0
Cond(W/m2-C     )200.0    200.0    200.0        0        0        0
Spectral FileIPIPLR4.INTIP_KLAR4.INTIPIPLR4.INT     None     None     None
Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
   0        0.00  12.25  3.20  7.14   0.59 0.59  0.60 0.60  0.62 0.62  0.64 0.64
   0        6.71  25.47  3.19  7.15   0.60 0.60  0.61 0.61  0.63 0.63  0.65 0.65
 783        0.00  12.25  3.47  7.80   0.64 0.64  0.66 0.66  0.68 0.68  0.70 0.70
 783        6.71  25.47  3.33  7.72   0.66 0.66  0.67 0.67  0.68 0.68  0.70 0.70
```

```
WINDOW 4.1  DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name        : TRNSYS15 WINDOW LIB
Desc        : Interpane IPASOL sofia 6950 6/16/4
Window ID   : 14012
Tilt        : 90.0
Glazings    : 2
Frame       : 11 TRNSYS WIN - 1        2.270
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1600.0 mm
Total Width : 1250.0 mm
Glass Height: 1460.3 mm
Glass Width : 1110.3 mm
Mullion     : None
Gap        Thick   Cond  dCond    Vis   dVis   Dens   dDens       Pr     dPr
1 Argon     16.0 0.01620  5.000  2.110  6.300  1.780 -0.0060  0.680 0.00066
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.458 0.461 0.454 0.446 0.434 0.411 0.360 0.263 0.123 0.000 0.382
Abs1  0.276 0.279 0.287 0.293 0.294 0.299 0.315 0.331 0.279 0.002 0.297
Abs2  0.030 0.030 0.031 0.031 0.032 0.032 0.031 0.027 0.020 0.000 0.030
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.236 0.230 0.228 0.230 0.240 0.258 0.294 0.378 0.577 0.998 0.281
Rbsol 0.281 0.276 0.275 0.276 0.285 0.303 0.346 0.448 0.650 0.999 0.332
Tvis  0.689 0.693 0.684 0.672 0.655 0.621 0.544 0.397 0.187 0.000 0.577
Rfvis 0.126 0.119 0.117 0.119 0.131 0.155 0.200 0.303 0.532 0.999 0.183
Rbvis 0.160 0.153 0.152 0.157 0.170 0.199 0.260 0.400 0.662 1.000 0.237
SHGC  0.500 0.503 0.497 0.489 0.478 0.455 0.405 0.306 0.157 0.000 0.425
SC: 0.50
Layer ID#         3311     3300        0        0        0        0
Tir              0.000    0.000        0        0        0        0
Emis F           0.840    0.840        0        0        0        0
Emis B           0.092    0.840        0        0        0        0
Thickness(mm)      6.0      4.0        0        0        0        0
Cond(W/m2-C     )133.3    200.0        0        0        0        0
Spectral FileIP6950S.INTIP_KLAR4.INT     None     None     None     None

Overall and Center of Glass Ig U-values (W/m2-C)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
   0        0.00  12.25  3.24  7.59   1.43 1.43  1.17 1.17  1.20 1.20  1.31 1.31
   0        6.71  25.47  3.21  7.62   1.51 1.51  1.20 1.20  1.24 1.24  1.36 1.36
 783        0.00  12.25  3.49  6.91   1.35 1.35  1.23 1.23  1.33 1.33  1.50 1.50
```

```
 783        6.71  25.47  3.35  7.21  1.47 1.47  1.25 1.25  1.31 1.31  1.48 1.48



************************************************************************************
******************************
*WinID Description                                 Aufbau     U-Value  g-value
T-sol   Rf-sol  T-vis  Lay  Width (mm)
************************************************************************************
******************************
 11003 FLOAT_6                                      6            5.7    0.83
0.790    0.070  0.89    1    6.00
 14005 Interpane,IPLUS3C,KR                         4/8/4/8/4    0.7    0.42
0.329    0.305  0.64   +3   26.00
 14012 Interpane,IPASOL,sofia_6950                  6/16/4       1.3    0.50
0.458    0.236  0.69   +2   26.00
```

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