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Simulating Heat Transfers through the Building Envelope: a Useful Tool in the Economical Assessment

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Abstract

The thermal performance of building plays a fundamental role in energy consumption since a large amount of energy is needed to balance heat transfers occurring through the envelope itself. The aim of the present paper is to simulate the heat transfer affecting a specific building envelope considering two different scenarios: current situation and future improvements by replacing transparent enclosures and adding an exterior insulation of different thicknesses. In order to identify the most convenient and suitable solution and to focus the attention on the most compelling action, an economical assessment is carried out taking into account the national incentives.

Keywords: heat transfer; simualtion; building; economical assessment.

1. Introduction

Nowadays a large portion of energy is increasingly supplied by the utilisation of fossil fuels which are finite resources and harmful to the ecosystems. Environmental concerns, be they climate change, pollution or Greenhouses Gases (GHGs) emissions, are fundamental challenges that the world is facing today [1]. Although fossil fuels shortages are predicted for the near future, the energy demand for electricity generation and space heating is still growing [2].

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Nomenclature

B_i	Benefit in the i-th year (€)
B^*	Discounted Benefit (€)
c	specific heat of the material (J/kg K)
C	total cost (€)
$C_{specific}$	specific cost (€)
C^*	Discounted Costs (€)
d	thickness of the material (m)
DCF	Discounted cash flow (€)
EP_{DHW}	total primary energy consumption for domestic hot water (kWh/m^2 year)
EP_{GL}	global energy performance indicator for winter heating (kWh/m^2 year)
EP_W	energy performance indicator for winter heating (kWh/m^2 year)
HDD	heating degree day
I_{tot}	total amount of incentive (€)
r	rate (%)
R	thermal resistance (m^2 K/W)
S_{int}	surface of the intervention
t	number of years in economical assessment (years)
T	temperature (K)
T_1	boundary condition for the indoor temperature in Comsol (°C)
T_2	boundary condition for the outdoor temperature in Comsol (°C)
T_g	boundary condition for the glass temperature in Comsol (°C)
U	thermal transmittance (W/m^2 K)
x	heat wave propagation (m)
α	thermal diffusivity (m^2/s)
λ	thermal conductivity of the material (W/m K)
ρ	density of the material (kg/m^3)
τ	time (s)

Broadly speaking, the building sector accounts for the greatest share of energy use and is higher than transport and industry needs. Buildings are responsible for more than 40% of final energy demand in most developed countries and an increasing portion is expected in many emerging economies. In this scenario, they can be seen as a key-element of the needed transition toward sustainability. Reducing energy demand, together with an appropriate exploitation of Renewable Energy Sources (RES), represents a reachable target in the built environment. Building sustainability is a fundamental tool to provide healthy and comfortable indoor conditions and simultaneously limiting the impacts on Earth's natural resources. Thus, energy impact decrease can be efficiently achieved by emissions control, use of RES and energy efficiency improvements. This becomes even more important if the following fact is considered: the majority of existing structures were built before energy efficiency was a concern at all and most of them will be in function at least until 2025. Since the living standards are rising and installing electric heaters and air conditioners has become a common practice, the cost-effective retrofits of building envelopes can be considered as an acceptable way to reduce building energy consumptions [3, 4, 5].

Energy-efficient measures are increasingly implemented in all the EU Member States, leading to establish many regulations for assessing building energy performances and the thermal properties of the building envelope elements. Most European standards address building behaviour with specific regard to the heating demand aspect or provide limits for the thermal transmittance. The latter has therefore become a common indicator for defining the thermal quality of the building shell and the steady-state heat transmission can be seen as the main reference, although it neglects the ability of materials in storing and releasing heat over time (i.e. the dynamic characteristics related with the so called inertia effect) [6]. The thermo-physical properties of the building envelope may be distinguished into two groups, depending on the type of heat transfer mechanism. The overall heat transfer coefficient and the transparency ratio belong to the first category, while the latter encompasses time lag and decrement factor [7].

Describing the thermal behaviour under steady-boundary conditions results to be acceptable with respect to the building heating demand when the temperature trend does not vary significantly, e.g. during rigid winter seasons or cold climates. Conversely, the dynamic aspects of heat transfer through the building envelope strongly affect the overall energy performance [6].

The materials belonging to the building shell - i.e. walls and transparent enclosures - are the most crucial because they define how the building itself interacts with the external environment, protecting the indoor. In order to predict the thermal behaviour of structural walls, the development of heat transfer analysis is a problem of fundamental concern in a broad range of engineering applications [8].

The aim of the present paper is to simulate the heat transfer affecting a specific building envelope considering two different scenarios: current situation and future improvements by adding an exterior insulation. The survey investigates a case study in Central Italy (Sabaudia). In order to identify the most convenient and suitable solution and to focus the attention on the most compelling action, an economical assessment is carried out taking into account the national incentives with regard to efficiency improvements according to the so called “Renewable Energy for Heating and Cooling Support Scheme”.

2. Material and methods

2.1. Legislative framework

Energy efficiency improvement in Italian buildings is an extremely important aspect to ensure energy saving and GHG emissions reduction. According to ENEA, most of the dwelling in our country were built before the first law on reducing building energy consumption (Legislative Decree 373/76) came into force. Italy accounts for more than 2.7 millions of residential buildings, heterogeneously distributed in the whole territory and mostly belonging to the coldest climatic areas and having a low-thermal performance building envelope. This is even confirmed by the fact that the residential sector is characterised by the highest energy consumptions corresponding to 36% (48262 ktoe) of the national demands and whose mean value is equal to 150-200 kWh/(m^2 x year). The thermal utilisation represents 85% of the building energy demand, including space heating (70%) and domestic hot water (15%) [9, 10].

Hence, the Italian Supporting Measures - the so-called “Renewable Energy for Heating and Cooling Support Scheme”- were established on 28th December 2012 in order to speed up the transition from existing heating systems towards more efficient alternatives. The current regulation implements the previous Legislative Decree no. 28 of 3rd March 2011 and is addressed to achieve the ambitious targets set by the European Directive 2009/28 whose aim is to reduce GHG emissions by 20%, to produce 20% of energy from renewable sources and to decrease the consumption by 20% improving the energy efficiency. These goals must be reached by 2020 and constitute important parts of the package of measures necessary to comply with the Kyoto Protocol [11].

The Italian incentive mechanism carefully defines the supporting scheme for small-scale projects concerning energy efficiency improvements in existing buildings (called “category 1”) and thermal energy production by the use of RES and high efficiency systems (“category 2”), as shown in table 1 and 2. With the term “replacement”, it is meant the substitution of an existing power system with a new solution, whose capacity must not exceed more than 10% of the old system. If this constraint is not respected, the corresponding incentive will not be awarded [11].

Table 1. Eligible projects in Category 1, according to Legislative Decree 28th December 2012.

Project Identification Code	Eligible Projects
1.A	Thermal insulation of opaque enclosures
1.B	Replacement of transparent enclosures
1.C	Replacement of existing winter heating systems with condensing heat generator
1.D	Shadowing and shielding systems for transparent enclosures

Table 2. Eligible Projects included in Category 2, according to Legislative Decree 28th December 2012.

Project Identification Code	Eligible Projects
2.A	Replacement of existing winter heating systems with heat pumps, whose thermal capacity must be less than 1000 kW
2.B	Replacement of existing heating or cooling systems for greenhouses or agricultural buildings with heat generators supplied by biomass, whose thermal capacity must be less than 1000 kW
2.C	Solar thermal collector, whose total area must not exceed 1000 m^2
2.D	Replacement of electrical boilers with heat pump boilers

"Gestore dei Servizi Energetici" (GSE) is recognized as the body in charge in managing the supporting scheme, awarding the incentives and monitoring technical requirements fulfilment [11].

According to the national regulation, two different parties are eligible, namely Public Administrations (PA) and Private Parties (PP). More precisely, Regions, Provinces, Municipalities, Hospitals, Schools and Universities belong to the former; the latter instead encompasses individuals, apartment block owners and parties with business or agricultural income. However, it has to be noted that Energy Service Companies (ESCOs) may access incentives on behalf of PA or PP. PA may apply for both categories, while PP may require incentives only for category 2. Moreover, focusing the attention on new buildings or on those subject to major renovation, the supporting measure will cover only the part of the project exceeding the mandatory targets set by Legislative Decree no. 28. In order to benefit the incentives, the Responsible Party must fill in the application form available on GSE website, after registering in the customers' area and receiving a personal identification code. Technical data - concerning the existing building and energy systems - must be provided during completing the application form in order to meet the specific requirements lain down by the regulation [11].

A maximum yearly cumulative incentive has been allocated by the Decree, corresponding to 200 million Euros for PA and 700 million for PP. GSE will not accept other incentive requests 60 days after achieving the above-mentioned limits. Furthermore, the supporting measures will be granted only for those projects which do not benefit other incentives from the Government [11].

The present paper investigates projects belonging to category 1.A and 1.B respectively. In order to benefit the public incentives, the so called Energy Performance Certificate (EPC) is always required in the first case; in the second category the EPC is needed if the replacement is provided in the whole building, having more than 100 kW-system [11].

The EPC was laid down by the European Directive 2002/91 and is meant as the amount of energy actually consumed or estimated to meet the different needs associated with a standardised use of the building itself, which may include heating, hot water heating, cooling, ventilation and lighting. This amount shall be reflected in one or more numeric indicators which have been calculated taking into account insulation, technical and installation characteristics, design and positioning in relation to climatic aspects, solar exposure and influence of neighbouring structures, own-energy generation and other factors, including indoor climate, that influence the energy demand. When buildings are constructed, sold or rented out, the EPC is made available to the owner or by the owner to the prospective buyer or tenant, as the case might be. The validity of the certificate shall not exceed 10 years (European Directive 2002/91).

The above-mentioned regulation was repealed by the European Directive 2010/31 with effect from 1 February 2012. Since buildings account for 40% of total energy consumption in the Union and the sector is still expanding, Member States shall ensure that all new buildings occupied and owned by public authorities are nearly zero-energy buildings, by 31 December 2020 and 31 December 2018 respectively. In more detail, a "nearly zero-energy building" is referred to a very high energy performance structure as determined in accordance with Annex I. A very limited amount of energy required should be covered -to a very significant extent- by energy from renewable sources, especially on-site or nearby (European Directive 2010/31).

The European Directive 2012/27 establishes a common framework of measures for promoting energy efficiency within the Union in order to ensure the achievement of the Union's 2020 20% headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date (European Directive 2012/27) .

With specific regard to Italy, the concepts of energy savings in buildings, rational utilisation of energy and sustainable use of RES were introduced by the National Law 10/91. In the recent years, the legislative framework has been further developed and still changing in order to comply with the above-described European Directives. The following national regulations must be taken into account to carry out the EPC:

- Legislative Decree 192/05 on energy efficiency of buildings;
- Legislative Decree 311/06 which encompasses corrections and integrations to the Legislative Decree 192/05;
- Presidential Decree 59/09 which enforced Legislative Decree 192/05;
- National guidelines for energy performance set by the Ministerial Decree 26/06/2009;
- UNI TS 11300;
- Ministerial Decree 22/11/2012, including corrections and integrations to the Ministerial Decree 26/06/2009.

Recently, the Legislative Decree 63/13 has been adopted, modifying some parts of the previous regulations. National guidelines are expected to be published in August. Until a new calculation methodology is not available, the previous regulation (namely Legislative Decree 192/05) must be followed.

2.2. Heat transfer calculations

The heat transfer analysis is an approach based on the general heat conduction equation which is obtained from Fourier’s law and the energy conservation principle. With specific regard to the heat flows through the building envelope –i.e. opaque and transparent enclosures- the general equation can be simplified by considering its one-dimensional form and assuming a single propagation direction. This leads to the following expression [6]:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho c}\frac{\partial^2 T}{\partial x^2} \tag{1}$$

The term λ/ρc represents the so called thermal diffusivity and is an extremely important parameter since it is directly related to the total amount of energy transfer in comparison with the stored one within the system. If α increases, the velocity by which temperature variations propagate within the material grows. This becomes extremely interesting in civil engineering: during winter seasons, α decreases assuming λ as a constant value and increasing ρ and c. This situation occurs when heavy cladding materials are used in order to increase the transient time [6].

Since Eq. (1) is a partial differential equation, the recourse of numerical methods is required to achieve an accurate solution. Otherwise, particular boundary conditions are considered. Among all approaches, the most commonly adopted methodology is a steady-state calculation where the transient effects of heat wave propagation are completely neglected. However, since the aim of the analysis is to consider extreme temperature conditions , the effect of unsteady elements - namely outdoor climatic variability and indoor heat production- can be neglected in the simulation. Thus, Eq. (1) can be simplified to its stationary form represented by assuming constant outdoor and indoor desired temperatures [6].

2.3. Description of the case study

The existing building considered in the present survey is represented by the School of the State Forestry Corp in Sabaudia (Central Italy, Province of Latina). The structure is a 2 story building consisting of 17 typologies of single or double glass windows with an aluminium frame. The external walls are made of 37.5 cm of brick, without any insulation cover. Moreover, an internal and external layer of plaster - whose thickness is equal to 20 mm in both cases - is added. Table 3 shows the main thermal parameters of the current wall layers in the building, leading to determine the total thermal transmittance which is equal to 1.448 W/m^2 K. The overall thermal transmittance of the transparent enclosures is calculated according to the analytical method reported in UNI 10077 and varies depending on the considered typology. A minimum value equal to 5 W/m^2 K can be assumed.

Table 3. Thermal properties of the external walls.

Material	d	λ	ρ	c	R
Internal plaster	0.02	0.7	1400	1000	0.029
Brick	0.375	0.809	1800	840	0.470
External plaster	0.02	0.9	1400	1000	0.022

Table 4. Data of the building.

Use classes	Residential
Category of use classes	E.1 according to Presidential Decree 412/93
Latitude/Longitude	41,3001 N/ 13,0317 E
HDD	1171 according Presidential Decree 412/93
Duration of the heating period	November 15 – March 31
Number of heating days	136
Climatic zone	C according to Presidential Decree 412/93

Table 5. Data of the building: conditioned space and volume.

Floor area	1833 m^2
Gross conditioned space	3766 m^2
Net conditioned space	2636 m^2
Conditioned volume	11 006 m^3
Ratio S/V	0.5 1/m

The total dispersion surface towards the external environment accounts for 5498 m^2 whose the vertical dispersion represents the most significant amount, consisting of 2785 m^2 (51%) and resulting as the most compelling action in order to improve the thermal behaviour of the existing building.

Considering the use class of the building and complying with the Presidential Decree 412/93, the set point for indoor temperature is given by 20 °C in winter and 26 °C during summer. Both values ensure thermal comfort within the built environment. With specific regard to the outdoor conditions, the external air temperature is assumed equal to 2 °C in winter according to UNI 5364 and to 33 °C during summer following UNI 10339. The glass temperature can be considered constant if its thickness is limited: however, it depends on thermal irradiation on vertical surface during hot season.

As stated in the previous paragraph, the EPC is needed for the considered structure in order to access public incentives. As it is commonly known, the energy efficiency is given on a scale from A$^+$ - the most efficient homes - to G - the most energy consuming one. According to the national regulations, the EPC of the specific case study was carried by a commercial software complying with the requirements laid down by Comitato Termotecnico Italiano (CTI). Two different scenarios were considered:

1. asset rating, which is based on standard weather conditions and building use;
2. tailored rating, which is based on measured energy use and takes into account how the building itself is managed and used. Monthly energy and thermal consumptions are available for 2010, 2011 and the first semester of 2012 and show that the standard values coming from 1. exceed real consumptions up to 35%. Thus, in order to correct the asset rating, the occupancy of the building has been considered and has lead to calculate the number of heating days (corresponding to 100 instead of 136 as it is in the asset rating). The number of heating hours has been modified and assumed equal to 10.

The results describing the EPC of the two above-mentioned cases are reported in table 6 and clearly show that EP$_{GL}$ in the asset rating is higher than in the tailored one. In order to improve the thermal behaviour of the existing building, several options –which will be mentioned as Energy Saving Opportunities (ESOs)- can be further investigated, namely:

1. insulation of the external wall by adding an external insulation cover of different thickness (8, 10 and 12 cm corresponding to ESO 1, 2 and 3 respectively). The external thermal insulation leads to several advantages in the existing building, such as the reduction of the thermal bridges, an appropriate thermo-hygrometric behaviour of the wall and a significant increase of the thermal inertia. Although the internal insulation is less expensive, it is not recommended in the present study in order to avoid useful volume reduction and to totally eliminate thermal bridges (e.g. window-wall, window-floor) [12].
2. replacement of the total existing windows by means of low-E triple glass solution filled with argon (E. S. O. 4). Argon fill is chosen since it strongly reduces thermal transmittance if compared with air. The cavity width cannot be limited, otherwise affecting the thermal insulation. However, wide cavities do not represent the best solution, leading to increase the total width and volume of the glass. Recommended values are in the range between 8 and 14 mm. Considering the traditional double pane windows, the argon fill-triple glass leads to save 20 l of fuel per m^2 of window, thus decreasing GHGs emissions and fine particles pollution [13].

The current energy class of the building –both in asset and tailored rating- is represented by G. If the possible interventions are taken into account, a significant improvement in term of energy class is not reached: this may be due to the fact that any replacement of the existing plant is not considered in the simulation. However, it emerges that the EP_{GL} decreases at least of 49 kWh/m^2 year if compared with the tailored rating EPC, corresponding to 24%. In order to focus the attention on the most compelling action, an economical assessment is required since it leads to determine some financial indicators, namely the discounted cash flow and the payback time.

Figure 1 shows the current stratigraphy of the external opaque enclosures and the possible improvements which can be successfully reached by ESO 1, 2 and 3.

Table 6. Energy class of the existing building and future and possible improvements generated by the commercial software.

Options	EP_{DHW}	EP_{W}	EP_{GL}	Energy class
		Current situation		
Asset rating	22	245	267	G
Tailored rating	16	187	203	G
		Future improvements		
ESO 1 tailored rating	16	132	148	G
ESO 2 tailored rating	16	129	145	G
ESO 3 tailored rating	16	128	144	G
ESO 4 tailored rating	16	138	154	G

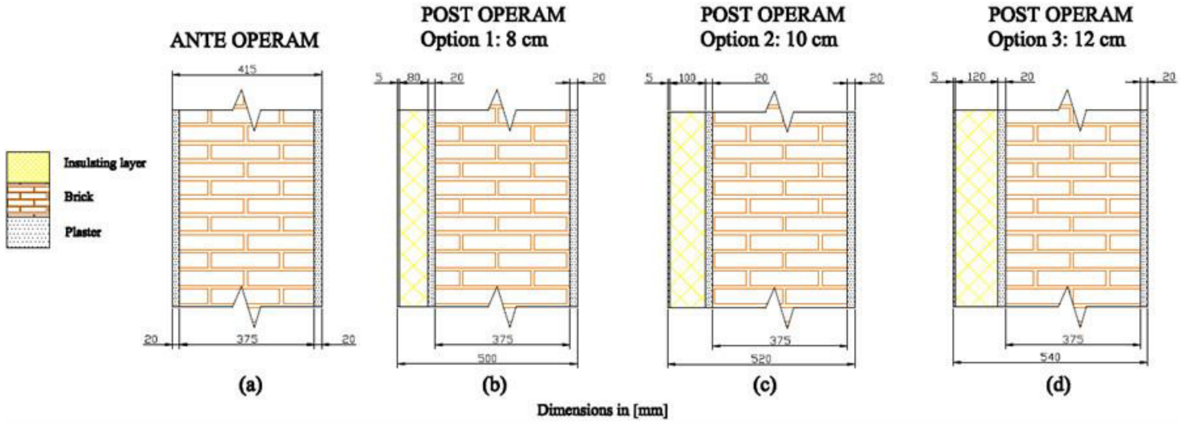


Fig. 1. Building envelope: current situation (a) and future improvements (b, c, d).

2.4. Calculations of incentives according to the Italian Support Scheme

According to the Italian supporting measures, the incentive corresponding to thermal insulation of existing enclosures or total replacement of the existing windows is calculated as follows [11]:

$$I_{tot} = 40\% \cdot C \cdot S_{\text{int}} \tag{2}$$

In order to benefit the supporting measures, the specific technical requirements reported in Annex 1 must be accomplished, depending on the climatic area of the chosen site (table 7). According to Presidential Decree 412/93, Italy is divided into six different zones, from zone A (the hottest one) to zone F (the coldest one) [14].

Table 7. Technical requirements to access incentives according to Ministerial Decree 28 December 2012.

Climatic area	Opaque enclosures	Transparent enclosures
A	$U \le 0{,}45$ W/m^2 K	$U \le 3{,}08$ W/m^2 K
B	$U \le 0{,}34$ W/m^2 K	$U \le 2{,}00$ W/m^2 K
C	$U \le 0{,}28$ W/m^2 K	$U \le 1{,}75$ W/m^2 K
D	$U \le 0{,}24$ W/m^2 K	$U \le 1{,}67$ W/m^2 K
E	$U \le 0{,}23$ W/m^2 K	$U \le 1{,}50$ W/m^2 K
F	$U \le 0{,}22$ W/m^2 K	$U \le 1{,}33$ W/m^2 K

Table 8. Comparison between the thermal transmittance of the ESOs with the limit values (climatic area: C).

	Thermal transmittance	Limit value according to Ministerial Decree 28 December 2012
Current situation	1,448 W/m^2 K	-
ESO 1	0, 299 W/m^2 K	0,28 W/m^2 K
ESO 2	0,249 W/m^2 K	0,28 W/m^2 K
ESO 3	0,214 W/m^2 K	0,28 W/m^2 K
ESO 4	1,1 W/m^2 K	1,75 W/m^2 K

Since ESO 1 does not comply with the mandatory limit value, this solution cannot be taken into account as a feasible option to access incentives and to improve the thermal behaviour of the existing building. It can be easily seen in table 8 that U in ESO 2 is less than the limit value for thermal transmittance of opaque enclosures, hence representing an efficient solution. As a consequence, ESO 3 can be excluded in the following calculations and simulations. Considering the specific need to choose the most compelling action, ESO 4 can be considered as a second and non mandatory option, because EP_{GL} does not significantly decrease if compared with ESO 1. Thus, the simulation and the economical considerations in the following paragraph are referred to ESO 2 (table 9). In order to evaluate the advantages emerging from ESO 2, the discounted benefits and cash flow need to be calculated as follows [15]:

$$B_t^* = \sum_i \frac{B_i}{(1+r)^t} \tag{3}$$

$$DCF = B^* - C^* \tag{4}$$

Table 9. Economical parameters in ESO 2.

S_{int}	3600 m^2
C_{specific}	50 €/ m^2
C	180000 €
I_{tot}	72000 €
Yearly saving	12600 €
Yearly incentive	14400 €

3. Conclusion

In order to better understand how heat transfers affect a specific building envelope, a simulation in Comsol Multiphysics environment is carried out since the software represents an efficient tool facilitating all the steps in the modelling process [16]. After defining geometry, meshing (figure 2) and the physics, the problem is rapidly solved and the graphic results are visualized. By means of these accurate images given by the powerful simulator, the starting complex model –which requires to solve the Fourier Equation- can be easily interpreted by the user. The results can be plotted as a temperature profile within the section of the wall (figure 3a and 4a) or as isothermal contours (figure 3b and 4b). Moreover, time solving results to be extremely limited and leads to optimise the different solutions by simply varying the input parameters. As a consequence, the analysis of the images given by the simulation can be successfully seen as a fundamental tool to rapidly solve a real problem, which otherwise requires complex hand calculations.

Moreover, the results of the simulation strongly confirm that the insulation cover improves the energy efficiency and the thermal behaviour of the building, hence representing a useful tool for decision making and in the economical assessment of the specific investment. For instance, if we consider the isothermal contours, it can be seen how they modify their trend passing from the current situation (figure 3a and 4a) to ESO 2 (figure 3b and 4b), both in winter and summer conditions.

With specific regard to the economical assessment, figure 5 shows the trend of benefits, cash flow, discounted benefits and discounted cash flow. The payback time of the specific investment ESO 2 is reached after 9 years.

The analysis and simulation of the heat transfers affecting the building envelope –in *ante operam* and *post operam* conditions- together with an appropriate economical assessment of a specific intervention, represent an important package in the process confirming the selection of an action among several alternative scenarios.

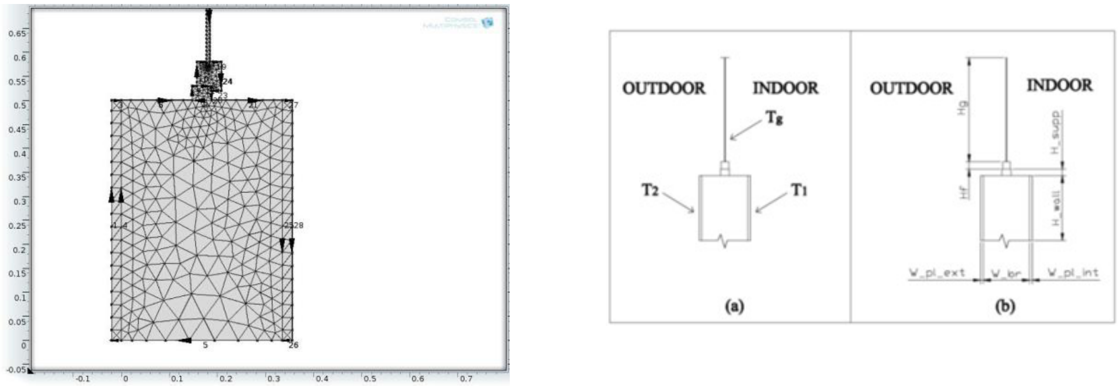
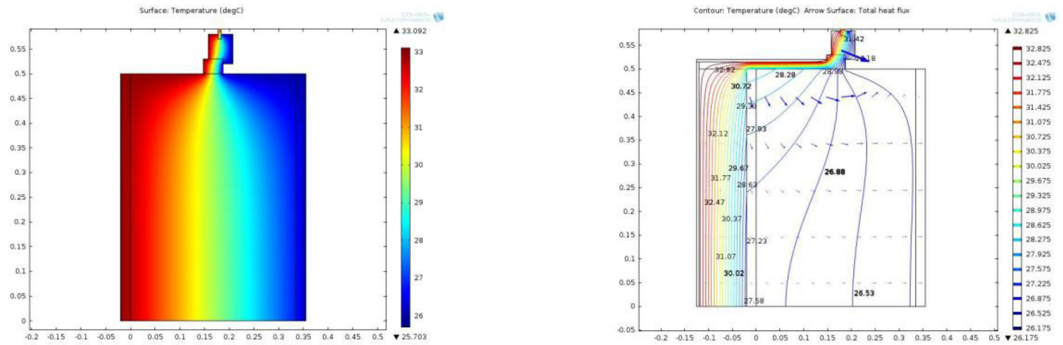
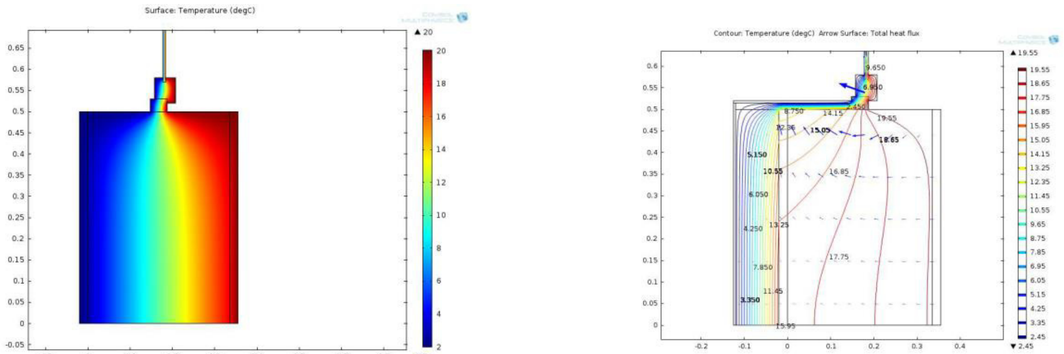


Fig. 2. Example of meshing in Comsol Multiphyisics (left). Boundary conditions (a) and explanation (b) of the parameters in Comsol environment (right).



(a) (b)

Fig. 3. Heat transfer simulation through the building envelope in summer: ante operam (a) and post operam (b).



(a) (b)

Fig. 4. Heat transfer simulation through the building envelope in winter: ante operam (a) and post operam (b).

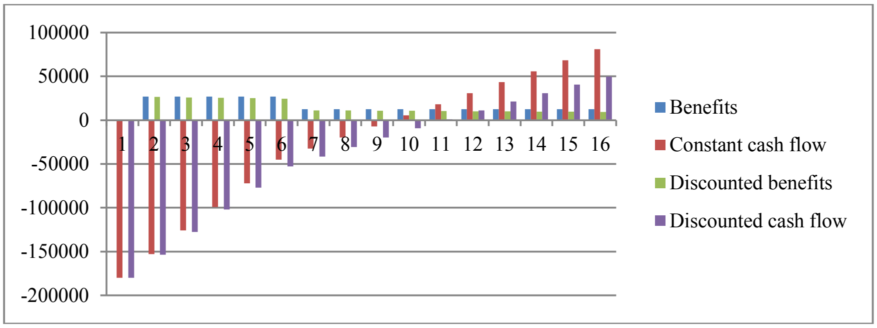


Fig. 5. Economical assessment: benefits, constant cash flow, discounted benefits and DCF.

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