Energy Nexus 10 (2023) 100198

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Combined numerical approach for the evaluation of the energy efficiency and economic investment of building external insulation technologies

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ARTICLE INFO

Keywords:
Energy efficiency
Buildings, insulation
Ventilated façade
CFD

ABSTRACT

The objective of this paper is to examine the energy efficiency and economic feasibility of different coating technologies used to improve the thermal insulation of external walls in buildings. The comparison is made between traditional coat insulation and ventilated façade, evaluating their impact on energy consumption to maintain a constant indoor temperature throughout the year by means of a combined numerical approach. . Furthermore, the paper investigates the effect of opening and closing the air gap in ventilated façades on thermal insulation during the winter and summer seasons. Energy efficiency calculations are employed to estimate the economic investment required for implementing the different insulation solutions.

The paper proposes an innovative combined approach to determine the performance of the building insulation technologies. Firstly, a computational fluid dynamics (CFD) simulation is carried out on the full three-dimensional geometry of the building during two reference days representing extreme temperature and sun radiation conditions during the summer and winter. This modeling includes the effects of solar radiative heat transfer during the day: for a chosen date, time, and geographical location, the model computes sun altitude and azimuthal angles, along with the corresponding direct and diffuse solar fluxes. In addition, the model uses a multiband thermal radiation approach to capture the different nature of radiative heat exchange according to the light wavelengths. The total heat transfer coefficient of the building walls in each scenario is calculated through the computational fluid dynamic analysis and implemented in an in-house developed library based on the open source Open-Modelica platform to simulate the energy requirement of the building throughout the year. This combined numerical approach provides a comprehensive performance analysis of the studied technologies in terms of electric energy and fuel consumption required for maintaining a constant indoor temperature and internal ambient comfort.

The results of the simulations demonstrate that by adopting the two proposed solutions, there was a potential to save approximately 37% of the fuel required for the heating system and more than 51% of electric energy required for the air conditioning systems. Finally, the payback period for each scenario is calculated, and it was found that coat insulation offers the best balance between thermal performance improvement and economic effort, with a payback time close to 20 years.

1. Introduction

In the recent years, there has been a substantial increase in attention towards the efficient use of energy sources across every sector, driven by the growing awareness of the limitations of fossil fuels [1]. As a result, energy efficiency has become a key pillars of the EU Energy Union strategy, as it offers a highly effective pathway to improve economic competitiveness and sustainability, reduce emissions and energy dependency [2]. By reducing dependency on fossil fuel imports, energy efficiency can also contribute to strengthening energy security in both the short and long term..

To achieve this ambitious goal of no net emissions of greenhouse gasses in 2050, every sector, i.e. residential, tertiary, transport and industry, must be mobilized. Energy-efficient buildings have recently attracted considerable interest due to the increasing awareness of the drawbacks of non-renewable fuels. Improvements on heating, ventilation and air conditioning (HVAC) equipment, as well as on the building envelope insulation technologies, are necessary to reduce the energy consumption of buildings [3]. Indeed, buildings accounts for approximately 40% of energy consumption and 36% of CO_2 emissions in the European countries. Currently, a large percentage – i.e. 35% – of the EU's buildings are over 50 years old, and 75% of the building stock is

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https://doi.org/10.1016/j.nexus.2023.100198
Received 10 January 2023; Received in revised form 14 April 2023; Accepted 25 April 2023
Available online 26 April 2023

Nomenclature

CFD	computational fluid dynamic
HVAC	heating, ventilation and air conditioning
UV	ultra-violet range
IR	infra-red range
$U_{Th,wall,}$	building walls transmittance, $\frac{W}{m^2K}$
th_i	thickness of the i-th layer; m
λ_i	thermal conductivity of the i-th layer, $\frac{W}{mK}$
P_{diss}	thermal power absorbed or lost by the building envelope, W
A	building walls area, m^2
ΔT	delta temperature between the internal and the external ambient, K
T_e	external ambient temperature,°C
T_i	internal ambient temperature,°C
C_0	Cash flow at the zero-th year, Euro
C_i	Cash flow at the i-th year, Euro
C_{tot,en_i}	Total energy cost for the i-th year, Euro
Inv	Initial investment, Euro
NPV	Net Present Value, Euro
S_i	savings from the original energy cost at the i-th year, Euro
WACC	Weighted average cost capital
htc_i	heat transfer coefficient at the i-th time step, $\frac{W}{m^2K}$
P_i=	thermal power absorbed or released by the building at the i-th step, W
htc_g	global heat transfer coefficient, $\frac{W}{m^2K}$
n=	time step number.

considered energy inefficient [4]. Enhancing the building heating and cooling system and improving the thermal insulation of external walls can lead to significant energy savings. Malka et al. [5] evaluated the optimum insulation thickness of external walls, the energy savings over a lifetime of 30 years, and the payback period obtained with four different insulation materials in cities from three different representative climatic zones of Albania. The study found that the heat transfer value for the case of the insulated external wall ranged from 0.38 to 0.30 W/m^{2}K; As the thickness of the insulation layer increases, net savings increase from zero for the uninsulated case to a maximum level of 84.49 €/m^2.

There are numerous technologies available for improving the building's envelope performance. Two of the most effective methods are coat insulation and the ventilated façade. Ventilated façade systems consist of an external screen detached from the building walls, forming a naturally or forced ventilated cavity. .This system is based on a double skin with an air chamber which slows down the rate of heat transfer [6]. The external panel can help to reduce the summer thermal loads through direct solar radiation reflection, using a panel with high reflection coefficient paints [7]. The thermal behavior of the system is influenced by various factors, such as the materials selected for construction and the geometry of the external panel and air cavity.

Thus, numerical simulations can be highly beneficial in predicting the thermal behavior and the fluid dynamics of complex systems and components [8]. In literature, there are many examples that investigate the thermal behavior of the air convection in cavities of façade elements using numerical modeling.

Ref [9] provides a comprehensive review of the pros and cons of numerical modeling of ventilated façade. The study examined various numerical approaches that can be used to investigate the thermal performance of these systems, such as analytical and lumped models, non-dimensional analysis, network models, control volume, zonal approach, and computational fluid dynamic (CFD). The research concluded that CFD is a unique way to solve design details in ventilated facades, and the integration with building energy simulation can provide more accurate prediction of the thermal performance of the system or the entire building.

Regarding the analytical model, Ciampi et al. [10] presented an electrical analogy-based method to calculate the electrical energy savings in buildings due to the use of ventilated facades in Southern Europe climates during summer. In Ref [11] a simulation algorithm based on energy transport and Bernoulli equations was developed to investigate the thermal behavior of double skin façade. Borodulin V. Yu. [12] developed a mathematical model for calculating the processes of heat and moisture transfer in building facades thermally insulated by panels with ventilated channels under various climatic conditions.

In [13] the computational fluid dynamics methodology was used to predict the convective heat transfer coefficient, thermal resistance and transmittance for a double-glazing unit. A similar analysis was reported in [14] where the overall heat transfer coefficient in an air layer within a rectangular cavity was investigated using a CFD code. F. Patania et al. [15] studied the energy advantages provided by three different typologies of ventilated façade under steady state condition and fixed solar fluxes. Furthermore, the dynamic thermal resistance of ventilated air spaces behind passive and active facades under transient conditions was analysed numerically and experimentally in [16].

The CFD was also used to investigate the performance of open joint ventilated façade with different panel arrangements [17]. The study evaluated the energy performance of these solutions by analysing parameters such as panel temperature, mean air velocity inside the cavity, fluid pathlines through the open joints, and thermal flux in the air cavity and to the room. The study demonstrated that the ventilated arrangement is much more efficient than the sealed one, allowing about 30% less heat transfer in summer. Finally, a 3D CFD model was developed in Ref [18] to evaluate the energy performance of a timber–concrete composite prefabricated ventilated façade during summer and to compare the results obtained with the International Standards UNI EN ISO 6946 and ISO 15,099. The study performed demonstrated the potential and utility of CFD in studying the behavior of ventilated facades, allowing detailed analysis and accurate system design. The CFD approach was employed in [19] to determine the thermal performance of a real vertical wall by varying different parameters such as air-gap thickness, emissivity of the thermos-reflective panel surfaces and wall height. The study demonstrated that the application of a tehrmo-reflective panel produce a tehrmal resistance increase of 2 W/m^{2}K on a vertical wall with an height of 3 m. This value corresponds to a traditional insulating material thick 6 cm. . While several studies have investigated the thermal and energy performance of ventilated facades and traditional insulation systems using computational fluid dynamics (CFD), most of them have been carried out under steady-state conditions and fixed solar fluxes. This approach can provide valuable insights into the design of specific parameters of the facade or insulation system. However, the dynamic behavior of the building's thermal resistance, which changes throughout the day depending on outdoor conditions and thermophysical properties of the wall, can significantly affect the building's thermal loads.

To address this research gap, this study proposes a combined numerical approach that takes into account the influence of outdoor conditions on the thermal resistance of building walls to estimate the amount of energy required to maintain a constant indoor temperature and internal ambient comfort for an entire year. The objective is to calculate the electric energy and fuel consumption required for different coating technologies and determine the payback of each solution. By considering the dynamic behavior of the thermal resistance, this study aims to provide a more comprehensive understanding of the energy performance of different building coatings and inform decision-making for optimizing energy use and improving occupant comfort.This study employed a comprehensive approach to investigate the thermal behavior and global heat transfer coefficient of a reference building's walls using computational fluid dynamics (CFD) modeling. Two technologies were compared: traditional coat insulation and ventilated facades. For the latter, the option of opening and closing the upper air gap during winter was analyzed. The proposed solutions were compared to the energy requirements of the building in its original state, with no insulation adopted.

The numerical approach considered the building's full 3D geometry, including windows and walls with varying thickness and materials. A transient approach was used to calculate the thermal behavior of each scenario throughout a full day, accounting for time-dependent ambient temperature and the influence of thermal radiative exchange with the solar environment, including direct and diffuse components.

Due to the high computational effort required for CFD modeling, a lumped and distributed parameter numerical modeling of the building energy system was adopted to estimate the energy performance of the configurations adopted over the entire year. The heat transfer coefficients calculated by the multidimensional analysis were used to account for the effects of the proposed technologies. This combined approach provides a more comprehensive understanding of the energy performance of different building coatings and can inform decision-making for optimizing energy use and improving occupant comfort.

The study aimed to evaluate the energy savings resulting from the application of external wall insulation technologies. To achieve this objective, the study employed a combined numerical approach, which included a multidimensional CFD analysis and a lumped and distributed parameter modeling. The Open Modelica platform was used to develop an ad-hoc library for energy conversion system simulations, and a numerical model of a heating and cooling system was implemented.

The study investigated the behavior of the system on a time-dependent basis, and different sub-models, governed by equations and correlations, were considered. The predictive capabilities of the combined numerical approach were validated by correlating the numerical results with the real primary energy consumption of the building in its current status, without any external wall insulation. The calculated results were found to be in good agreement with the available energy consumption data. The study showed that the application of external wall insulation technologies can significantly decrease the fuel consumption of the heating system by 37% and the electric energy required to power the cooling system by 51%. The economic assessment of the two technologies was also investigated, and the payback time was found to be close to 20 years for the coat insulation technology.

In summary, the study demonstrated the potential energy savings resulting from the adoption of external wall insulation technologies and provided a combined numerical approach to predict the energy consumption and economic investment of different coating technologies.

2. Materials and methods

2.1. Test case

The combined numerical approach is applied to a residential building in Cesena. The analyzed test case proves to be an interesting test bench for the predictive capabilities of the numerical approach, since its walls are characterized by remarkable thermal losses and their performance needs to be improved.

Table 1 lists the characteristics that must be considered in the study: the electric energy and the fuel consumption are the measured primary energy consumption for the real building during a period of one-year.

Once the building energy consumption has been investigated in its original configuration without any external wall insulation, two different configurations are presented to improve the thermal performance of the building envelope. Thus, in both configurations, a rock-wool panel is added to the exterior of the building walls. In addition, the ventilated façade is equipped with a stoneware porcelain exterior screen that is detached 5 cm from the building walls. Table 2 shows the geometrical features and the material properties of the main components of the two configurations.

Moreover, in the case of the ventilated façade, the possibility of closing the air gap during the winter simulation is considered in order to increase the air temperature in the cavity between the walls and the external screen.

Table 1
Main characteristics of the building accounted in the study.

Parameter	Value	
Building Plant	18.6 × 12	m
Height	30.85	m
Building envelope transmittance	1.2147	W/m^2K
Double glazed windows global transmittance	3.73	W/m^2K
Floors	#9	
Apartments	#18	
Primary Energy Consumption		
Total Electric Energy	29,937	kWh/year
Total Fuel	16,087	Sm^3/year

Table 2
Main features and properties of the technologies considered in the analysis.

Solutions	Coat insulation	Ventilated Façade
Rock wool panel:	Yes	Yes
-) Thickness	100 mm	100 mm
-) Thermal Conductivity	0.033 W/mK	0.033 W/mK
Air gap:	No	Yes
-) Thickness	–	50 mm
Stoneware Porcelain	No	Yes
-) Thickness	–	10 mm
-) Thermal Conductivity	–	/mK

2.2. Numerical modeling

In order to estimate the energy savings by introducing a system to improve the thermal performance of the building walls, two different architectures are numerically studied. The numerical approach adopted in the study combines a CFD methodology with a lumped and distributed parameters numerical modeling to determine the savings obtained by the coat insulation and the ventilated facade technologies in terms of electrical energy and fuel consumption for air conditioning and heating systems to maintain the internal ambient comfort.

In this paper, the main focus is on the heat fluxes through the building walls and on the calculation of the global heat transfer coefficient for each scenario on two reference days using a CFD approach. Then, these results are set as input parameters in the mono-dimensional numerical model.

The numerical simulations in the forst phase of the analysis are performed using the computational fluid dynamic code Star CCM+ 2022.1 [20]. Fig. 1 shows the geometry of the building in the configuration with the ventilated façade; a 10 cm high opening in the ventilated façade is considered at the bottom. The following elements are considered in the analysis of the ventilated façade: the building, the air gap, the external screen, the windows and the ambient. Fig. 1 displays that the external ambient consists of a hemisphere with a diameter of 200 m. The other scenarios, i.e. coat insulation technology and building in its current status, are characterized by the same elements, with the exception of the external screen.

Special care is taken in the construction of the computational grid, as well as in the modeling of the heat transfer. The ideal gas approach is adopted for the calculations, while the energy balance equations are solved for enthalpy and a segregated approach is considered for solving the Navier-Stokes equation. Turbulence is considered using the k-ω model [21,22]. In addition, dynamic simulations are performed to capture the transient performance of the building envelope during a full day, i.e., 24 h.

As mentioned before, different configurations are studied as potential technologies to reduce the energy consumption of the building: the coat insulation and the ventilated façade. For the latter one, the option

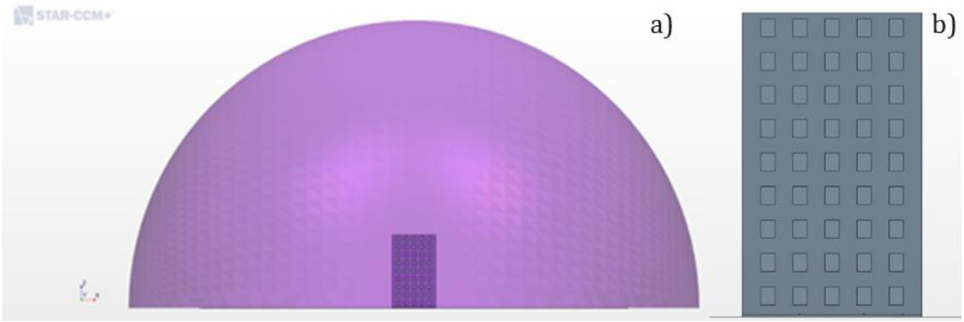

Fig. 1. The geometry of the ventilated façade configuration (a) and a zoom on the East building front (b).

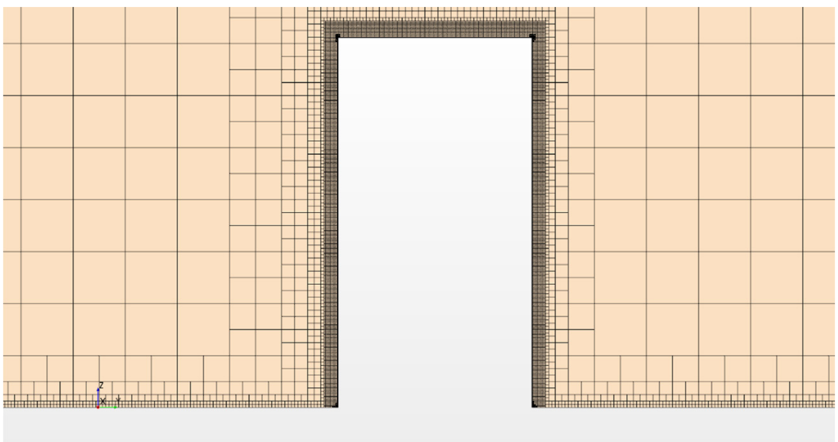

Fig. 2. Section of the mesh on a cut plane through the ambient, panel and air gap regions.

Table 3
Simulated scenarios.

Case#	Configuration	Simulate Days
#1	Building in its current status	06/21/2021 01/15/2021
#2	Coat insulation	06/21/2021 01/15/2021
#3.a	Ventilated Façade	06/21/2021 01/15/2021
#3.b	Ventilated Façade with option of closing upper air gap	01/15/2021

of closing the air gap during the winter day is analysed. In addition, numerical simulations of the building in its current situation are required to calculate the actual energy demand of the building and compare the numerical with the real energy consumption to validate the model.

In all simulated cases, the properties of the roof and the windows have been kept constant in order to highlight the contribution to the building energy efficiency of the coat insulation and the ventilated façade only. Similar assumption has been made also for the floor on the ground.

Each configuration was simulated on two days: June the 21st and January the 15th. Table 3 summarizes the main features of the simulation that were considered in the analysis.

The computational grid shown in Fig. 2 was constructed using a hexahedral mesh for the environment with proper refinement close to the entrance and exit sections of the cavity, i.e. 5 mm, and in the areas where heat transfer takes place between the walls and the external environment, i.e., 10 cm; the average size of the trimmed grid is 3.0 m, with appropriate refinements considered for detailing the geometrical features studied. The mesh for the panel and air gap is discretized using the directed mesh with an average surface size of 10 cm and a volume distribution of 5 and 8 layers for the panel and air gap respectively. The CFD domain consists of approximately 5 million cells.

The contribution of radiation to the heat transfer phenomenon is accurately modelled using the Surface-to-Surface approach (S2S); this model calculates the radiative exchange between surfaces that form a circumscribed space, considering the medium that fills the space non participating. This approach is described in detail in [23]. In addition, the Multiband Thermal Radiation Model is implemented to account for the dependence of radiation on wavelength; it defines the radiation properties and thermal boundary conditions for each surface, and the model calculates the amount of radiation that a surface receives and emits as a function of wavelength. The governing equations are solved for each defined band using specific properties [24,25].

The main contribution to the heat transfer phenomena within the electromagnetic spectrum is provided by the thermal radiation spectrum, i.e. 0.1–100 μm: hot objects (T>800 K) emit thermal radiation over the entire thermal radiation spectrum, while relatively cool objects (T<800 K) emit predominantly in the infrared range.

Therefore, in this analysis the incident solar radiation is divided in two different ranges: 0.1 μm < λ < 7.8 μm (UV and visible) and 7.8 μm < λ < 100 μm (IR) [20]. In this case, the optical properties of the windows and the panel are defined respectively according to [26] and [27].

The thermal properties of the materials are considered to accurately determine the thermal behavior of the system. The thermal transmittance of the building envelope, $_{UTh,wall}$, is defined by the following equation [28]:

$$U_{th,walls} = \frac{1}{\sum_{i}^{n\_layers} \frac{th_i}{\lambda_i}} \quad (1)$$

where th_i is the thickness of the i-th layer and λ_i is the thermal conductivity of the i-th layer.

In addition, the Solar Radiation Model calculates the thermal radiative exchange with the solar environment including direct and diffuse radiation; the contribution is evaluated as a function of elevation and azimuth angles and corresponding solar fluxes for a selected date, time and geographic location.

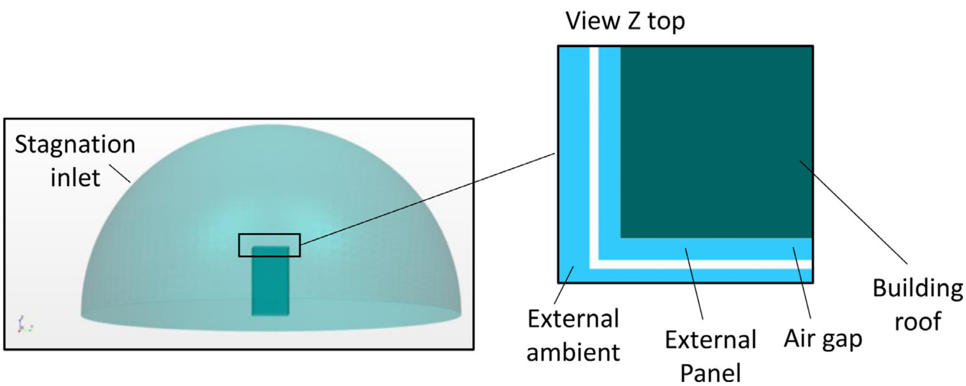

Fig. 3. Boundary conditions and main geometry components in the fluid domain.

The same initial temperature as the ambient temperature was assumed for the ventilated façade.

Fig. 3 depicts the boundary conditions adopted for the simulations. In particular, a stagnation inlet pressure condition is set for the fluid inlet conditions; the flow is completely at rest on the boundary and the motion is given by the gravity force.

The temperature inside the building is assumed constant and fixed at 20 °C for each simulation. Each configuration is studied on two different days to analyze the thermal behavior and performance of the systems during the hot and cold seasons. Fig. 3 shows the temperature profile of the two days considered; during the summer case, i.e., 06/21/2021, the daily temperature increases from a minimum of 20 °C at night to a maximum of 35 °C in the afternoon, while on the 01/15/2021 the minimum and maximum temperatures registered are – 4 °C and + 6 °C respectively. These temperatures are representative of the humid subtropical climate (Category “Cfa” under the Kopper climate classification) of Cesena.

In the simulations, the initial ambient temperature conditions were selected according to the first values of the curves shown in Fig. 4.

Once the results were derived using the CFD approach, the economic evaluation of the technologies is determined using the 0D/1D approach. The numerical model for calculating the heating and cooling system is developed in Modelica language. The bond graph approach is adopted to model the whole system, and the different sub-models are linked via power ports to calculate the energy balance. Fig. 5 displays the final layout of the analyzed heating and cooling system.

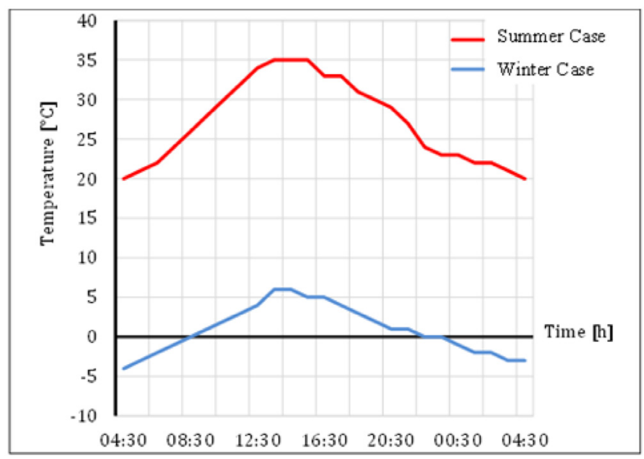

Fig. 4. Temperature profiles during the simulated days.

First, the external ambient conditions are considered by including the air temperature profile and weather data of the simulated reference

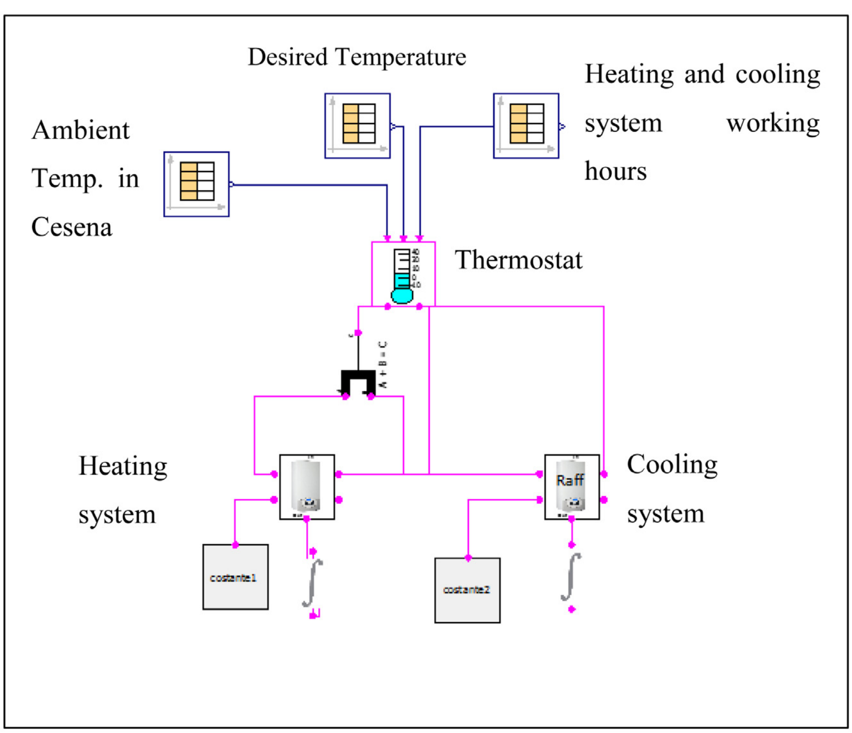

Fig. 5. Layout of the analysed energy system.

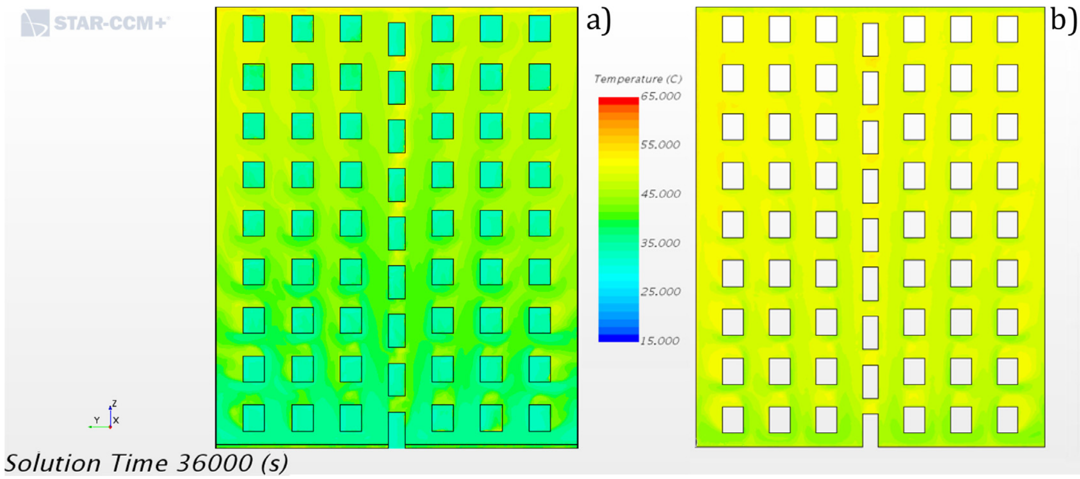

Fig. 6. Temperature distribution at 2 pm in the summer simulation on the south front: building wall and windows (a), external panel (b).

year, i.e., 2021, in the model; similarly, an index of sky cloudiness is implemented, where a value of 1 simulates a clear day, while 0 indicates a completely cloudy day.

The heat transfer losses of the building envelope are calculated as a function of the temperature difference between the inside of the building and the outside environment and the transmittance htc_g of each configuration. The values of this coefficient during the year are calculated based on the results of CFD for the two simulated days of the year. Therefore, the thermal losses are calculated according to the following correlation [28]:

$$P_{diss} = \sum htc_g * A * \Delta T \tag{2}$$

The calculated heat losses determine the energy required by the air conditioning system to maintain the internal comfort temperature of 20°C.

The performance of the heating and cooling systems is calculated based on the operation control strategy adopted for the thermostat. In particular, the heating system is turned on to maintain the internal temperature at the desired value, i.e. 20 °C, during the period from October the 15th to April the 15th; the cooling system is in operation when the temperature in the building is higher than 22 °C during the period from June the 1st and August the 31st.

The numerical model allows predicting the fuel and the electrical energy consumption required to maintain the desired room temperature; the correlations include also the efficiency of the heating system (0.92) and the EER for the cooling system varies in the range 2.5 – 4. these results are finally used for the economic assessment of the two technologies.

Eqs. (3) and (4) calculate the cash flows for the beginning of the investment and at the i-th year respectively and they are employed to determine the Weighted Average Cost of Capital (WACC). Thus, the Net Present Value (NPV) is calculated on the basis of Eq. (5) and the profitability of the investment projected over a period of 30 years is analysed. The year at which the NPV becomes positive provides the payback period of the investment while the final value of the NPV defines the net gain of the investment [29].

$$C_0 = -Inv \tag{3}$$

$$C_i = -C_{tot,en_i} + S_i \tag{4}$$

$$NPV = \sum_{i=0}^{YEARS} \frac{C_i}{(1 + wacc)^i} \tag{5}$$

The cash flow parameters are determined by taking into account the savings in terms of reduced cost of fuel and electrical energy that must be purchased to maintain indoor comfort.

3. Results and discussion

The combined numerical approach explained in the previous paragraph is used for estimating the performance provided by the studied technologies in terms of electric energy and fuel consumption for the air conditioning and the heating systems of the reference residential building placed in Cesena.

Firstly, the results of the CFD simulations of the different configurations investigated are described in the following paragraph. The attention is focused on the thermal losses through the building walls during the hot and the cold day.

The heat transfer through each wall enables to calculate the global heat transfer coefficients of each configuration in the two reference days by means of the following equations:

$$htc_i = \frac{P_i}{T_e - T_i} \tag{6}$$

$$htc_g = \frac{1}{n} \sum_{i=1}^{n} htc_i \tag{7}$$

Where htc_i is the heat transfer coefficient at the i-th time step; P_i is the specific thermal power absorbed or released by the building at the i-th step; T_e is the external ambient temperature and T_i the internal ambient temperature; n is the time step number.

The following results are referring to the case 3.a, i.e. simulation of the ventilated façade scenario in the summer and winter days.

The figures below display the temperature distribution for the building walls and windows and the external screen surface for the summer and winter day respectively: two reference fronts, i.e. South front for the 21st June simulation and North front for the 15th January, are presented in two characteristic times of the 24 h simulations.

As it can be noticed, Fig. 6 shows that the porcelain stoneware temperature distribution calculated at 2 pm is characterized by higher values with respect to the numerical building walls temperatures during the simulation carried out in the summer day.

The opposite trend is calculated for the winter day results, i.e. Fig. 7; the external screen temperatures are lower than the results for the building walls, i.e. 3–4 °C, since the air cavity is heated by the thermal losses of the internal ambient.

Fig. 8 plots the time history of the specific heat transfer of the building and the contribution of the walls is highlighted. The curves are time dependent since the specific thermal power peaks for each front occur when the sun is aligned to that front; for instance, Fig. 8a) shows the maximum heat transfer on the south façade registered at noon. In addition, the roof is characterized by the maximum specific thermal power, i.e. 13 W/m^2, due to its long exposure time during the summer day.

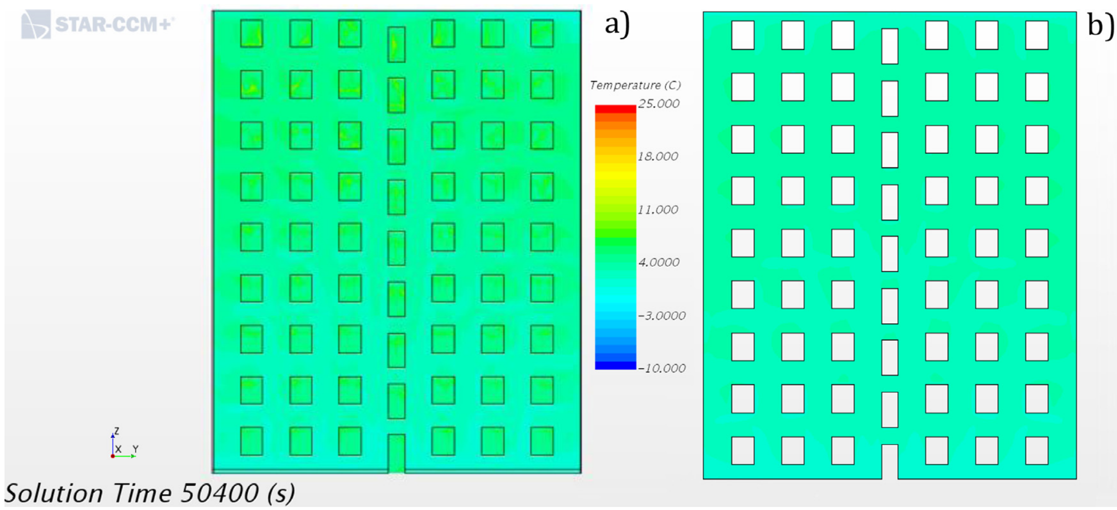

Fig. 7. Temperature distribution at 6:30 pm in the winter simulation on the north front: building wall and windows (a), external panel (b).

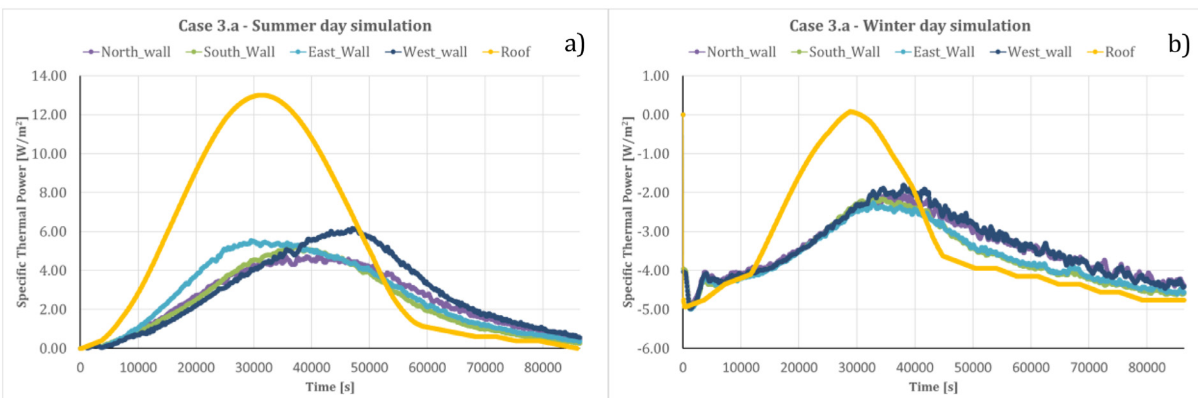

Fig. 8. Specific thermal power (a) absorbed and (b) lost by each front component in the (a) summer day and (b) winter day.

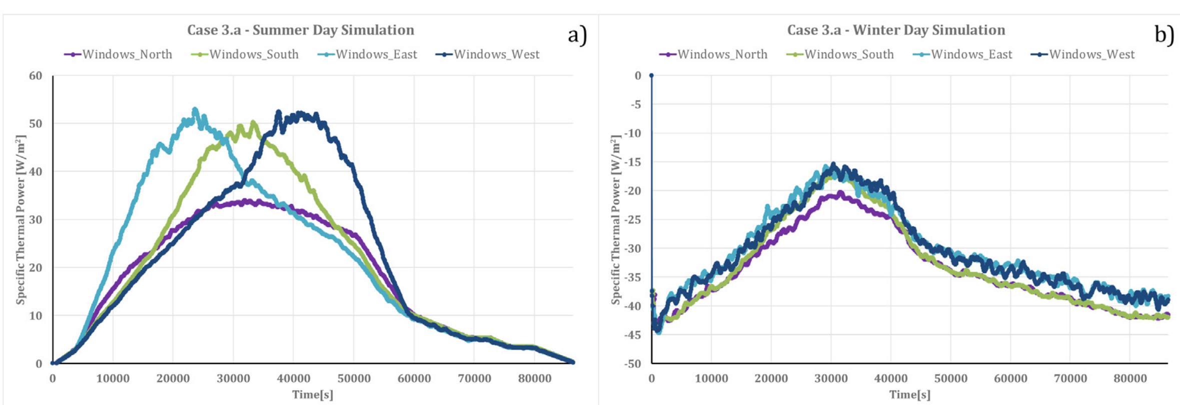

Fig. 9. Specific thermal power (a) absorbed and (b) lost by the windows in the (a) summer day and (b) winter day.

Fig. 8b) displays the specific heat transfer losses for each front during the winter day; the time dependence of the variable with the sun radiative fluxes is less evident due to the cloudy sky condition accounted for in the simulation.

A similar trend is defined for the windows components in Fig. 9; the specific thermal power absorbed in summer, i.e. Fig. 9a), and lost in winter, i.e. Fig. 9b), are characterized by much higher values with respect to the thermal power absorbed and lost by the building envelope, i.e. Fig. 8. For instance, during the summer simulation the windows of the west front absorb a maximum of 50 W/m^2 while the walls of the same front are characterized by a specific thermal power of 6 W/m^2.

Figs. 10 and 11 compare the performance in terms of thermal energy and global heat transfer coefficient of the simulated scenarios carried out on June the 21st, i.e. Figs. 10a) and 11a), and on January the 15th, i.e. Figs. 9b) and 11.b); the contribution of the windows is neglected in the following pictures since the attention is focused on the thermal performance of different technologies for the building coating insulation.

As expected, the thermal energy absorbed and lost by the actual building envelope, i.e. case 1, during the simulated days is remarkable

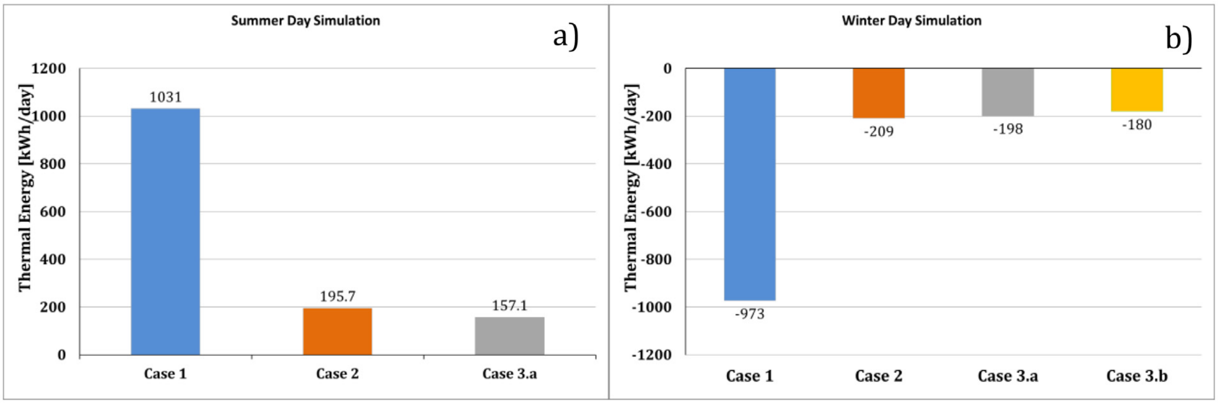

Fig. 10. Thermal energy (a) absorbed and (b) lost in every case in the (a) summer day and (b) winter day.

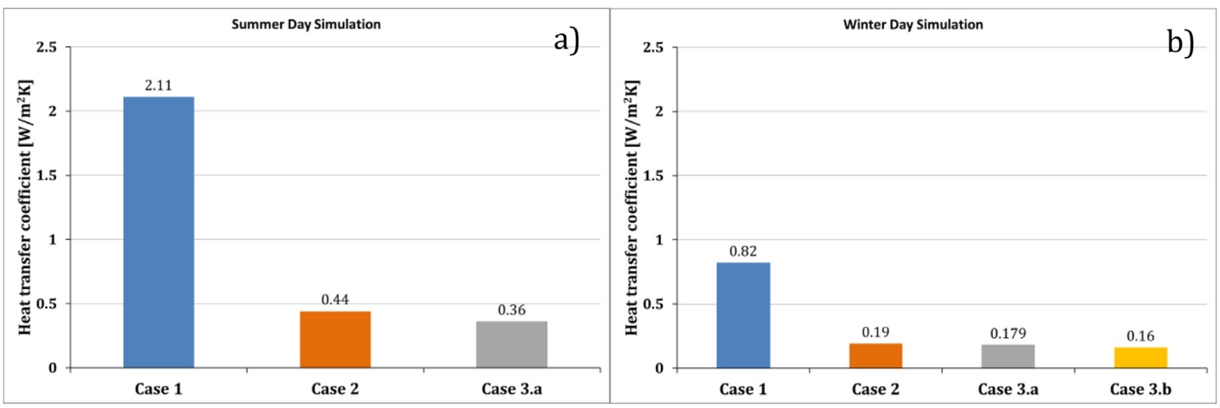

Fig. 11. Global heat transfer coefficient in every case in the (a) summer day and (b) winter day.

with respect to the coating technologies investigated. For instance, the energy requirement decreases for each studied technologies approximately by the 80% in both simulated days.

This energy saving becomes smaller when comparing Case 2 to Case 3: the energy saved is approximately 35 kWh/day in summer and 30 kWh/day in winter.

A similar trend is calculated for the heat transfer coefficient, see Fig. 10a) and b): the htc value reduces of approximately 1.6 W/m^2K and 0.6 W/m^2K during the summer and winter days respectively. Indeed, the heat transfer coefficients of the building in the summer and winter day simulations in its current status are equal to 2.11 and 0.82 W/m^2K, the ventilated façade reduces these values up to 0.36 W/m^2K in summer and up to 0.16 W/m^2K on the 15th of January.

A brief comparison of the CFD results with the data available in literature is carried out. Gagliano et al. [30] presented a similar analysis of the energy performance of an opaque ventilated façade under winter and summer weather conditions. It can be noticed that the comparison between the results determined in [30] are comparable with the one obtained in our study. Gagliano evaluated that the summer thermal fluxes on the south and east exposure fluxes where in the range between 5 and 10 W/m^2; in our study, the heat fluxes on the same exposure walls are 5.8 W/m^2 and 6 W/m^2. The agreement can be noticed not only in terms of magnitude, but also in terms of path-lines; indeed, the maximum fluxes occurs on the external screen when the sun is aligned to that front. The agreement can be noticed also for the results of the winter day simulations.

The CFD methodology proposed in this study resulted to be an accurate approach to determine the building thermal loads and the heat transfer coefficients of the building walls in the two reference days, considering the transient outdoor conditions that influences the thermophysical properties of the walls. However, this numerical approach requires an high computational effort and an ad-hoc simulation to investigate the thermal performance of a different building. These are the main limitations of this combined approach.The htc obtained by the CFD analysis for each type of configuration in the two reference days is employed in the subsequent lumped and distributed parameter numerical model for the prediction of the energy consumption over the entire year.

The 0D/1D model mentioned in the previous paragraph is employed for investigating the performance in terms of electric energy and fuel consumption for the heating and cooling system. The predictive capabilities of the Open Modelica numerical model for the simulation of the heating and cooling systems are validated by comparing the numerical results of Case#1 with the experimental data available for the reference building. Fig. 12 compares the measured and calculated electricity and fuel annual consumption for the case#1, i.e. building in its current status. A good agreement was found between the calculations and the measurements since the numerical annual consumption in terms of electric energy and fuel matches very close to the real primary energy consumption.

Fig. 13 shows the annual consumption of the analyzed configurations in terms of primary energy for the entire building. It can be noticed that the electric energy and fuel consumption curves are time dependent on the basis of the thermostat operating control strategy.

The primary energy consumption is remarkable in Case 1, i.e. original building; the two proposed solutions save approximately more than 50% of electric energy necessary to power the air conditioning system and more than 35% of the fuel required for the heating system.

Table 4 outlines the main results obtained by the lumped and distributed analysis of the two proposed solutions. In particular, the total

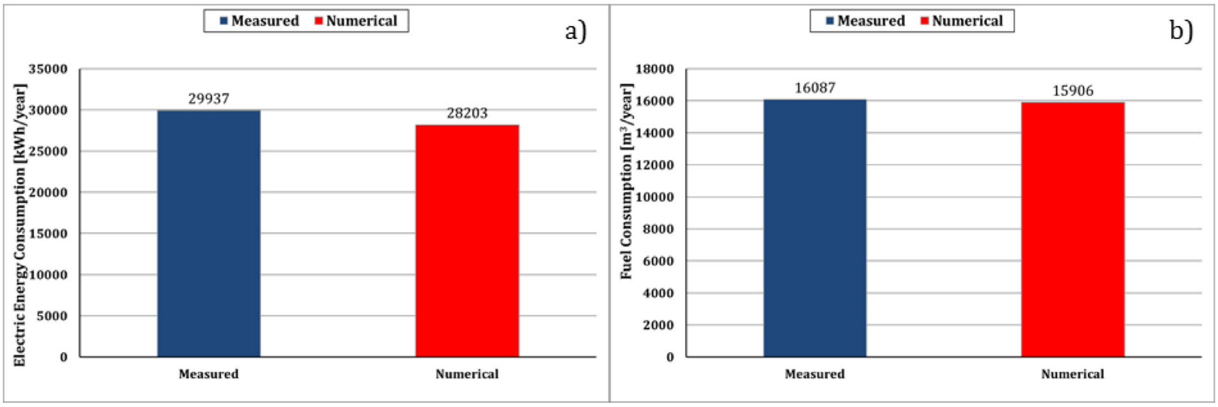

Fig. 12. Measured and calculated (a) electric energy consumption and (b) fuel consumption for the heating and cooling systems for the building in its current status.

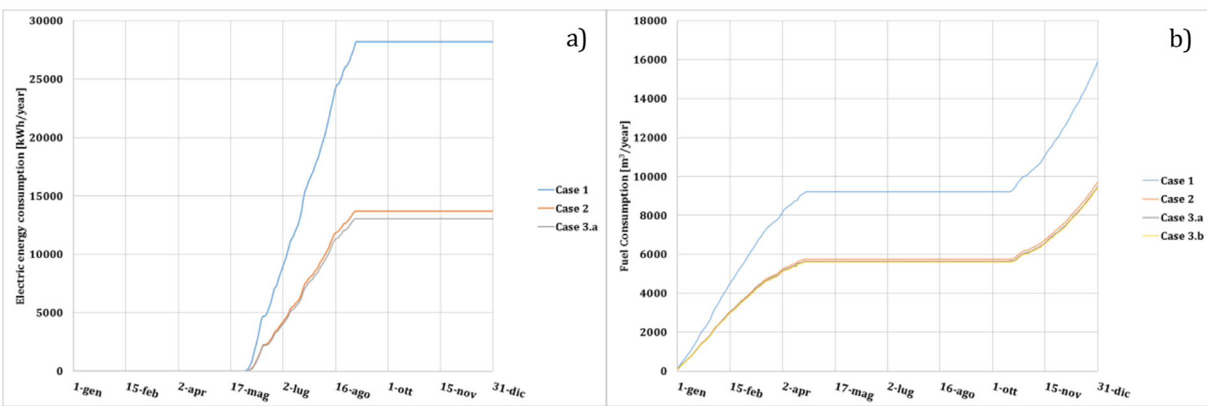

Fig. 13. (a) Electric energy and (b) fuel consumption in each case for the (a) cooling and (b) heating system.

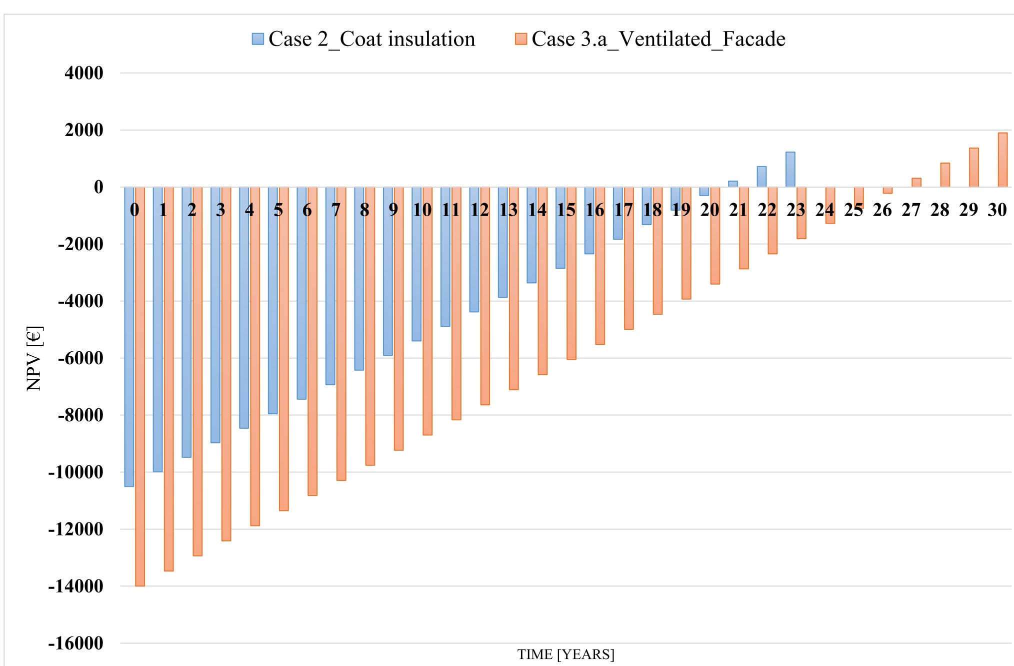

Fig. 14. NPV calculation for the Case#2 and Case#3.a.

Table 4
Total primary energy consumption and cost in each case. Primary energy cost and savings per housing unit in each case.

Fuel and Electric Energy	Case#1	Case#2	Case#3a	Case#3.b
Fuel				
Consumption [Sm^3/year]	15,906	9721	9510	9443
Cost [€/year]	13,520	8263	8083	8027
Cost per apartment [€/year]	751	459	449	446
Savings [€/year]		292	302	305
Electric Energy				
Consumption [kWh/year]	28,203	13,672	13,045	13,045
Cost [€/year]	7615	3691	3522	3522
Cost per apartment [€/year]	423	205	196	196
Savings [€/year]		218	227	227
Total Saving per apartment [€/year]		510	529	533

primary energy consumption and cost are reported; in addition, assuming equal energy consumption per each apartment, the annual saving per each housing unit is determined.

The total energy savings are remarkable when comparing the solutions investigated with the building in its current status. On the other hand, the energy savings become smaller when comparing the coat insulation with the respect to the ventilated façade: the total saving per housing unit is 20 €/year.

For the NPV estimation, a capital cost per each housing unit for the coat insulation and the ventilated façade equal to 10,500 (114 €/m^2) Euro and 14,000 (153 €/m^2) Euro respectively is considered. The net present value trend is displayed in Fig. 14. Constant energy requirements are the main assumption of this calculation; in addition, no tax reliefs for the improvement of the energy efficiency in buildings granted by the Italian legislation are considered. Under this hypothesis, it can be observed that the longest payback concerns case#3, i.e. 27 years; the payback of the coat insulation technologies lies between the twentieth and twenty first year due to the smallest initial investment and having remarkable savings every year.

4. Conclusions

In this paper, the energy savings due to the thermal performance improvement of a residential building external walls have been evaluated. The coat insulation and the ventilated façade have been investigated as possible solutions for increasing the building envelope energy efficiency and their performance has been numerically calculated.

The numerical analysis has combined two different approaches: the global heat transfer coefficients of the considered configurations are determined by means of the computational fluid dynamics modeling and implemented into a lumped and distributed model developed using the Modelica language.

The CFD model accounts for the full 3D-geometry of the building, the walls thickness and the windows and the materials thermal properties. The Multiband thermal radiation Model was adopted in order to calculate the radiative heat transfer that is dependent on wavelength. The thermal performance of the proposed solutions are estimated in two reference days: January the 15th 2021 and June the 21st 2021. The numerical results demonstrated that the global heat transfer coefficients of the two proposed technologies were lower during the summer and winter simulations: differences of 1.6 W/m^2K and 0.6 W/m^2K were calculated during the summer and winter day respectively.

Finally, the results of the CFD analysis were employed in the 0D/1D in order to estimate the primary energy consumption over the entire year.

The numerical analysis demonstrated that both the analyzed solutions enabled to save remarkable amount of fuel and of electric energy for the heating and cooling systems, i.e. approximately the 37% and 51% respectively. The coat insulation and the ventilated façade demonstrated similar benefits in terms of annual energy saving but a remarkable difference can be noticed for the initial capital cost; therefore, the coat insulation resulted to be the best technology for improving the thermal performance of reference building. The payback was calculated between the twentieth and twenty first year without taking into account any financial support.

Finally, this study developed a tailored combined methodology to evaluate the energy and cost savings due to the improvement of the thermal insulation of external walls in a building located in Cesena. The CFD methodology carried out to determine the global heat transfer coefficients of the different scenarios analyzed is tailored for a specific building and requires effort to replicate the study on a different technology. Future works will deal with the improvement of the DoE analysis to define correlations for the ventilated façade and the coat insulation technologies to be included in the lumped and distributed parameter approach without the need of a preliminary CFD simulation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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