E3S Web of Conferences **523**, 01007 (2024) https://doi.org/10.1051/e3sconf/202452301007
53rd AiCARR International Conference

Retrofitting historical buildings with innovative techniques: double-skin façade and skylights for courtyard buildings

Giuseppe Aruta[1]*, *Fabrizio* Ascione[1], *Nicola* Bianco[1], *Anna* Iaccheo[2], *Teresa* Iovane[1], and *Margherita* Mastellone[3]

[1]Università degli Studi di Napoli Federico II, Department of Industrial Engineering (DII), Italy
[2]Università degli Studi di Napoli Federico II, M. Sc. Engineer, freelance, Italy
[3]Università degli Studi di Napoli Federico II, Department of Architecture (DIARC), Italy

Abstract. Historical buildings hold significant cultural values but often face challenges in meeting modern sustainability and functionality standards. The aim of this study is to enhance the energy efficiency, occupant comfort and resilience of the heritage stock while preserving its historical significance, by assessing the application of innovative retrofitting techniques, such as double-skin façades and wide skylights for the courtyards' covering. The first part delves into the concept of retrofitting and the importance of preserving historical architecture, especially in Italy, whose historical centers represent a unique example to be preserved and prepared for future sustainability challenges. The second part focuses on the use of double-skin façades and glazed covers for courtyards, in the retrofitting process, to study the influence that they have on the whole building. It discusses how these techniques can be adapted to suit the unique characteristics of courtyard buildings, balancing modern needs with heritage conservation. A repeatable case study is examined to showcase the successful implementation of these techniques in historical courtyard buildings and to illustrate the practicality of retrofitting solutions while respecting the historical context and architectural integrity of the structures. This research seeks to encourage architects, preservationists, and stakeholders to embrace these innovative techniques for the revitalization of our architectural heritage.

Keywords: historical building, double-skin façades, skylights, courtyard buildings, energy retrofit.

1 Introduction

Buildings are known to be responsible for around 40% of energy use and 36% of greenhouse gas (GHG, or CO_2) emissions in Europe [1]. Improving building energy efficiency is essential to meeting long-term climate goals and reducing human environmental impact on the world. There are difficulties in reducing CO_2 emissions and energy consumption because more than

* Corresponding author: giuseppe.aruta2@unina.it

75% of the building stock in Europe was built before to the introduction of energy efficiency laws. This suggests that in addition to focusing on the construction of new buildings, which ensures reduced energy use, it is also essential to encourage and carry out the refurbishment of old structures in order to mitigate the building sector's impact on CO_2 emissions [2]. The buildings constructed in Italy prior to 1960, which constitute a criticism, account for about 42% of the country's entire architectural heritage [3]. This stock also requires policies aimed at improving structural performance beyond energy efficiency, in the same way as the post-World War II reinforced concrete buildings that, as it is well-known, even show the same several issues. In particular, a large number of these structures are structurally inadequate, frequently not meeting safety standards for vertical loads and not being built to resist seismic activity. Many of these structures have exceeded their useful life cycle according to current regulations [4], making it necessary to carefully evaluate their condition and possible improvement measures. The seismic vulnerability of such buildings is particularly relevant in some European regions, including Italy, Greece and Turkey, and this concern is expected to grow due to new seismic zones and extractive activities, such as fracking [5]. Therefore, the restoration and structural improvement of these buildings have become crucial to ensure the safety and sustainability of urban areas affected by such problems. In this scenario, the need to intervene clearly emerges to address the performance and structural deficiencies of post-World War II buildings and to reduce the current unsustainable energy waste through redevelopment operations. The studies conducted revealed that, when dealing with historic buildings suffering from structural problems, the option of renovation proves preferable to demolition. In this regard, it is interesting to observe that, if it is now recognized that the construction sector significantly impacts the environment at every stage of the life cycle (from initial design, to procurement of raw materials, to construction, operation and maintenance up to decommissioning, demolition and disposal), the phases that produce the highest quantities of waste are precisely those of demolition and reconstruction [6]. The waste generated by the reconstruction and therefore by the demolition of buildings and other infrastructures is approximately one third of the waste produced within the European Union (it is estimated, for the construction phase alone, the average production of approximately 15-20 m^3 of waste per 100 m^2 of surface - approximately 100-150 kg/m^2 [6]. These data clearly highlight the need to study alternative solutions to demolition and reconstruction for the recovery of existing buildings. Some episodes such as the collapse of an industrial warehouse with photovoltaic panels installed in Emilia-Romagna following the 2012 earthquake have highlighted the fallacy of separately addressing problems related to energy efficiency, structural stability and the architectural appearance of buildings. Therefore, a holistic approach that simultaneously considers energy efficiency, structural stability and architectural appearance is essential to ensure sustainable and long-lasting results in building management. Figure 1, even in an extreme synthesis, resumes three different approaches to "revitalize" a building, comparing them from different point of views, e.g., environmental impact and useful life of the building, i.e., demolition-reconstruction interventions, energy requalification and engineered double-skin, by exploiting new envelope chances provided by structural exoskeletons. The scheme highlights that only through integrated structural and energy redevelopment solutions on existing buildings it is possible to reduce the environmental impact, in terms of the production of new materials and waste disposal and relaunch the useful life of existing buildings (now exhausted) by another 50 years. The use of external additional structures (typically made in metallic frames and matrices) commonly called exoskeletons has been considered one of the possible alternatives to be used for seismic retrofitting of existing buildings. The use of this intervention strategy is very topical not only because it is the only one that can be implemented safely without interrupting the use of the building, but also because it can be effectively adopted in cases where an integrated retrofit can be carried out (formal, energetic and functional) of the entire construction.

 https://doi.org/10.1051/e3sconf/202452301007

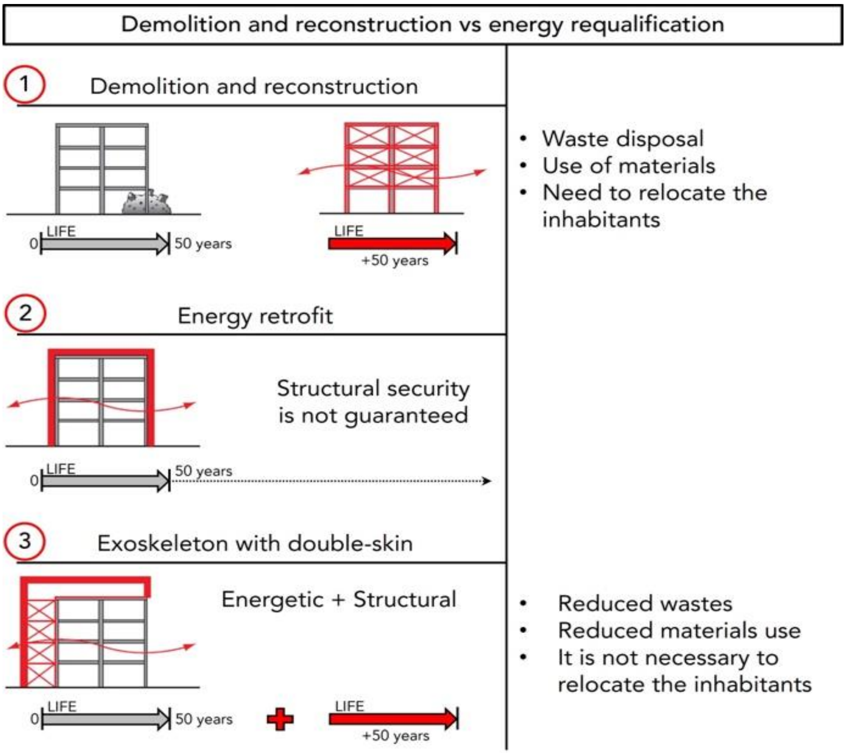

Fig. 1. Demolition and reconstruction vs energy requalification. Comparison, from different point of view of the possible measures

Applied to buildings, it translates into an independent volumetric expansion, defined by a structure on autonomous foundations, to be juxtaposed with the fronts, where it can accommodate new spaces and act as a support for a new customizable envelope and any new elevations of the building. The levels on which it intervenes are: structural, as a system for static and seismic consolidation; energy (thermal insulation, solar greenhouses or ventilated facades), as a device for reducing consumption and environmental impact and increasing living comfort; typological, in terms of an opportunity to reorganize and redesign housing cuts; functional, as an opportunity to insert new vertical and horizontal connectives; architectural, for the technological rethinking of the interfaces between inside and outside. If configured correctly, the multifunctional exoskeleton has all the potential to evolve into extremely specific solutions to meet needs in any context, showing considerable application flexibility. In this paper, one point of view will be analyzed: the opportunity of installing a second skin to the building.

One of the most promising applications is the creation of double-skin façade (DSF), which boast significant energy advantages. This innovative architectural solution not only contributes to the aesthetics and functionality of buildings, but also offers an environmentally friendly solution to improve energy efficiency and environmental comfort. A DSF, thanks to the cavity created with its installation, ensures that the internal environment is no longer subject to direct heat exchanges with the external one (see Figure 2). This results in less heat loss during the winter periods [9]. However, at the same time, overheating could occur during the summer period, with negative consequences for the demand for energy for cooling [10]. In fact, without adequate and sufficient ventilation, greenhouse effects can cause an increase in temperature in the cavity, causing heat transfer into the occupied spaces. The main factors promoting air movement in buildings with DSF are the movement of the surrounding wind

and the pressure difference due to thermal buoyancy that occurs in the cavity. The thermal chimney phenomenon inside the DSF occurs due to the density difference between the warmer air inside the cavity and the colder air outside [11]. One of the solutions proposed to deal with the increase in energy demand for cooling in this technology is the shading system. Pomponi et al. [12] have investigated many DSF systems in temperate climates. Overall, this system achieved a reduction in energy consumption of 90% for heating and 30% for cooling. In courtyard buildings, it is interesting also to study what the effect skylights application to the courtyards could be (see Figure 3). Not many researchers to date have been interested in the impact this technology can have on buildings of this type. Aldawoud and Clark [13] analyzed and then compared the energy performance between a courtyard, with the same geometric proportion, and a central atrium. Throughout the world, courtyard buildings are a significant form of vernacular architecture that may be found in many different temperature zones. Often, in cold climates and to improve thermal performance, courtyards may have skylights, that open to the sky, creating buffer zones for better managing ventilation, lighting and thermal flows. Wang et al. [14] examined the effects of these technologies as well as the enhancement that glass-covered courtyards have on building energy efficiency. The findings demonstrated that, without altering the original envelope construction, closed roof courtyards may lower their yearly total energy consumption up to around 20%.
In this paper, with reference to a Mediterranean climate, thermal performance of double-skin façades and large skylights for courtyards are investigated, in order to understand the beneficial effects in winter and, on the same, the possible adverse performance during the warm season. The aim is to understand possibility of exploiting responsive components (i.e., seasonal variation of air changes and sunshade), instead of traditional insulation measures. Therefore, the goal is to use skylights and double-skin façades to reduce, and in some cases eliminate, the phenomena of overheating by getting savings.

Fig. 2. Example of a DSF application (Berlin, Germany)

Fig. 3. Example of skylights application to create an atrium (Berlin, Germany)

The suggested actions are examined on an actual residential building in Naples, a city with a Mediterranean climate. The impacts on the energy demanded for space heating and cooling are examined. Alternatives are suggested in order to optimize energy savings, and several scenarios are examined, with brief notes about the technical and economic feasibility.

2 Case study

The historic building choose as case study is located in Naples, along the city's picturesque seafront. This architecture, made of tuff, has a trapezoidal shape. The building is inserted in a densely built urban context; it is free to the South, while it is surrounded by several buildings in all other directions, which imply a shading effect on the building. The south-facing side is 47.5 m long, while the east, north and west facades are 31.6 m, 46.4 m and 41.5 m long, respectively. The building has 5 floors, with a total height of 26 m. The ground floor has a height of 7 m, the first floor is 5.5 m, and the remaining floors are of 4.5 m each. There is an open internal courtyard, rectangular in shape, whose wall lengths are respectively starting from the South and proceeding counterclockwise of 21 m, 11.5 m, 21 m and 11.5 m. The total area of the building is 5617 m^2, comprehensive of all the space conditioned area. Figure 4 shows different views of the investigated historical building and of the urban context where it is located. With reference to the transparent envelope, the building has windows and doors consisting of single glass (U_g = 5.67 W/(m^2K)) and of wood frame (U_f = 2.2 W/(m^2K)), with a reliable and has a U_w = 4.90 W/(m^2K). Regarding the opaque envelope:

- the external vertical walls are composed of 3 cm of plaster, three blocks of 40 cm of tuff (ρ = 2300 kg/m^3) and 5 cm of plaster, with a U-value equal to 1.04 W/(m^2K);
- the roof is made up of 3 cm of plaster, one 20 cm block of wood to approximate the presence of the beams, one 20 cm block of tuff and 2 cm of flooring, for a total transmittance U-value equal to 0.605 W/(m^2K).

Fig. 4. Historical building subject of the case study. 1) Southeast view of the building; 2) South view of the building; 3) Top view of Via Caracciolo where the building is located

Subsequently, the internal loads, i.e., lights, equipments, and the building occupancy rate are defined. Operating hours are planned based on typical and conventional profiles for residential buildings. In particular, the maximum use of the building, e.g., the maximum occupancy and the greatest use of devices such as lights and equipment, occurs during the morning hours, before work, and in the evening, when returning home. The occupancy rate is set to 0.04 person/m^2. The control of artificial lighting is based on the control of natural light: artificial lighting integrates natural light to achieve a lighting level of 150÷300 lux (average ≈ 200 lux). About the equipment, a power density of 4 W/m^2 is defined. The microclimatic control, of every apartment, is obtained through a conventional natural gas boiler by supplying hot water to the radiators inside each space. The efficiency of the combustion generator is 0.85. Instead, low-efficiency electric DX split systems—air-to-air and in-room models—with a nominal energy efficiency ratio (EER) of 2.8 are used to meet the cooling request.

3 Materials and methods

Masonry structures, such as the one under examination, have also demonstrated structural criticalities in addition to reinforced concrete structures, particularly when exposed to seismic activity. In addition, this building typology also offers limits related to historicity and the difficulties of interfering with the more traditional energy retrofit interventions, e.g., external insulation, in addition to these crucial structural issues.

Due to these critical issues, action must be taken on these buildings, and one option to examine is adding a reinforcing framework, or structural exoskeleton, to allow the building to continue operating throughout the intervention. Both the utilization of these structures for retrofitting existing buildings [15] and their seismic performances have been studied in the literature [16]. Double-skin façades technology lends itself to being integrated with exterior exoskeletons by coating them with a glazing system, in anticipation of their widespread use as a structural reinforcement system. The advantages of this intervention would therefore be structural, artistically, protective against external factors, and energetic.

Therefore, the study's suggested retrofit methods include installing skylights to cover the courtyard and a double-skin façade to conceal an exoskeleton framework. To evaluate the energy benefits, achieved with the proposed measures, the building is modeled in the "as is" state using DesignBuilder® (v 6.1.8) [17], one of the graphical interfaces of EnergyPlus (v 8.9.0) [18]. In this software, the building's occupancy rate, the installed micro-climatic control systems, interior loads (lights and equipment), and all the other thermophysical characteristics of the building envelope have been defined, starting from typical values form other calibrated energy models. Since the building is almost surrounded by other edifices, the urban context has also been recreated (although in a simplified way), and it is crucial to take into account the shadowing effect that is created [19]. The building's energy consumption is then examined, directly using the EnergyPlus dynamic energy modeling capability. More in details, once created the physical model, a dynamic energy simulation is carried out with EnergyPlus. All told, relevant parameters for running the simulation, simulation parameters and boundary conditions are listed in Table 1.

The heating period starts on 15 November and ends on 31 March, with a maximum activation time of 10 h per day, according to the classification of the Italian territory provided by the Italian Decree D.P.R. 412/93 [20]. Primary energy conversion factors equal to 1.95 and 1.05 are used for electricity and natural gas, respectively [21]. The primary energy consumption (PEC) value for heating is obtained as a function of the whole heating system efficiency (boiler, regulation, losses and so on), while the PEC value for cooling is calculated as a function of the energy efficiency ratio (EER) imposed to the cooling system. The considered specific cost, to calculate the running cost (RC) are, respectively, for the natural gas c_{ng} = 0.0981 €/ kWh$_p$ [22], while for the electric energy c_{el} = 0.3115 €/kWh$_{el}$ [23]. The costs considered for natural gas and electricity, i.e., c_{ng} and c_{el} refer to those reported by Eurostat today (January 2024) and referred to the first half of 2022. At this point, once the case study is characterized, it is possible to move on to the definition of the retrofit measures proposed. Specifically, the examined scenarios are three:

- scenario 1, which considers a double-skin façade on the South wall;
- scenario 2, which considers the application of skylights on the courtyard;
- scenario 3, which considers both the retrofit measures of scenario 1 and 2.

To be able to estimate the best one among the scenarios examined, analyzing the individual citizen perspective, different economic metrics are introduced: simple pay-back (SPB), discounted pay-back (DPB), and net present value (NPV). The NPV is evaluated at 10, 20, 30, 40, and 50 years, by considering a 3% discount rate, as reported by the European Union [24].

Table 1. Simulation parameters and boundary conditions used for the simulations

Simulation Parameters	
Solution Algorithm	Conduction Transfer function
Surface Convection Algorithm - inside	TARP
Surface Convection Algorithm - outside	DOE-2
Number of timestep per hour	4
Boundary Conditions	
Weather Data	NAPLES – ITA IWEC Data – 162890
Heating setpoint	20°C
Cooling setpoint	26°C

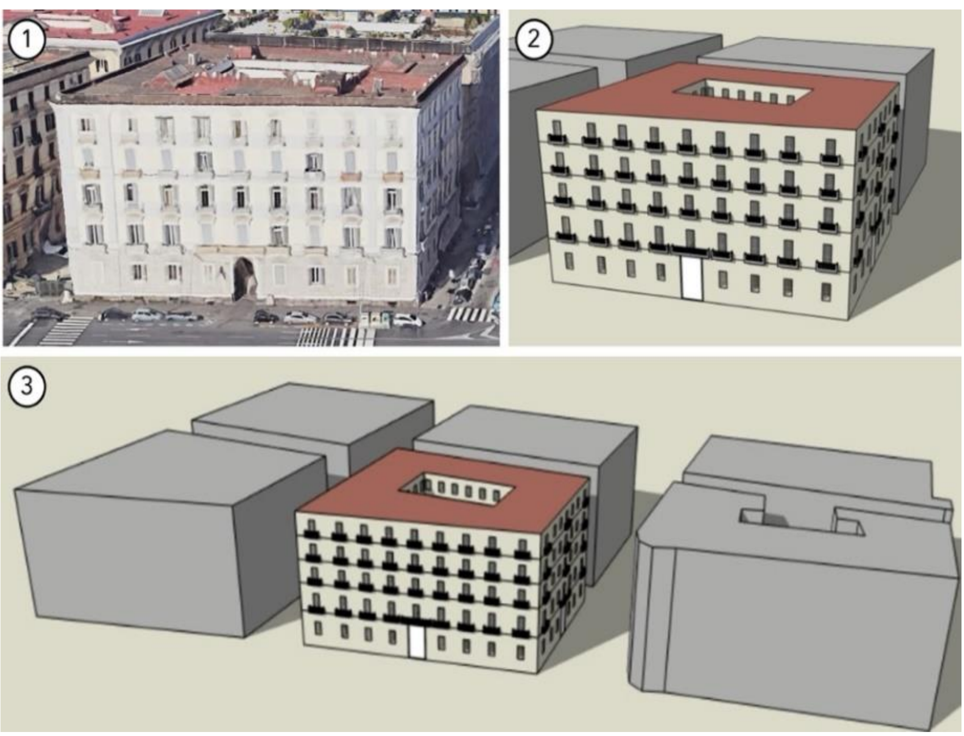

Fig. 5. Historical building model. 1) South view of the building; 2) South view of the building model; 3) Top view of the model and of the surrounding buildings

4 Results and discussions

The space heating and cooling system's PEC for the state “as is” building (see Figure 5 for the building model) are as follows, both in terms of absolute energy consumed and per m^2 in relation to the total floor area:

- PEC for space heating (PEC_h): 236’747 kWh_p/year or 42.1 $kWh_p/(m^2year)$;
- PEC for space cooling (PEC_c): 121’448 kWh_p/year or 21.6 $kWh_p/(m^2year)$;
- PEC for interior lighting: 63’327 kWh_p/year or 11.1 $kWh_p/(m^2year)$;
- PEC for equipment: 167’929 kWh_p/year or 29.9 $kWh_p/(m^2year)$.

Starting from these energy demands, the following sub-sections will show effects, potentiality, and limitations of the presented energy efficiency measures for the building envelope.

4.1 Scenario 1: double-skin façade

The first investigated energy efficiency measure consists of the application of a double-skin façade (DSF). It represents both a structural and energy intervention, with several positive advantages.

In this paper, only the energy behaviour is investigated. The application of a double-skin façade lies in the addition of a second, external, and completely glazed, envelope to the building existing, which becomes an internal layer. An air cavity is created between these two layers, and this involves that the indoor conditioned environments – in contact with such air cavity – are no longer directly exposed to the outside environment and so to the heat transfer with it (see Figure 6). Because of the solar radiation, the air temperature inside the cavity increases compared to that of the outdoor environment, and this represents a positive effect in the winter season, while a negative and overheating effect is expected in the summer season. DSF is a highly engineered envelope technology, requiring deep knowledge of heat transfer, by considering both direct effects and reverse ones. Such almost all bio-climatic techs aimed at improving the winter thermal performance, present a high risk of summer failure to be deeply taken into account. Such technologies exploit the greenhouse effects due to the selective behaviour of glasses, with respect to visible, solar and infrared radiation. Therefore, for this application, once verified the suitability of this technology, with respect to common ones (e.g., thermal insulation, absorptive coatings, etc.), the system should be optimized, through a deep sensitivity study. It means that several models should be tested, by varying, for example, the spectral characteristics of the glass, the number of glazed systems, the portion and the characteristics of blades and blinds, position, and dimension of openings and so on. Finally, here only a preliminary study to highlight the advantages (if any) is done. Then, a deepening optimization (position, dimension, materials, management of screen, kind of glass, thermochromic, photochromic, electrochromic, etc.), also by considering the availability on the market, is anyway mandatory. Obviously the use of a second skin, even if transparent and especially if screened during certain hours of the day, can lead to an increase in energy demand for lighting (second glass, frame, screens which, even when deactivated, over the course of the day, however, they reduce the net incoming radiation), and therefore it is essential to consider this issue, again with a view to optimizing this technology.

In this study, the DSF is applied only to the South façade of the building. The depth of the cavity is 1 m (to completely include the balconies, see Figure 2) and the external surface is equipped with a laminated low-e single glaze with a thermal transmittance of 5.3W/(m^{2}K). The cavity is completely closed and not ventilated. The results achieved through this energy retrofit intervention are:

- a reduction in primary energy demand of about 8.4% for space heating;
- an increase in primary energy demand of about 2.9% for space cooling.

As previously discussed, these are expected results with a completely closed DSF façade. To mitigate the negative effect of the cooling energy demand, the cavity is made naturally ventilated, and external shading devices are implemented. The shading systems, positioned externally, are activated only in the summer season for a threshold of solar radiation equal to or higher than 120 W/m². Natural ventilation can also be very useful in some months of the winter season, in fact by opening the cavities, it is possible to use the greenhouse effect to preheat the air. This advantage could occur in the months of February and March where solar radiation, being the maximum hours of sun available, can maximize this effect. With this further intervention, the primary energy demand reduces of about 8.4% and 14% for space heating and cooling, respectively. Therefore, thanks to the natural ventilation and the adoption of external shading systems during the summer season, it is possible to nullify the negative effect – the increase in cooling energy demand – obtaining an energy benefit. In order to deepen the study of this intervention and the effects connected to it, a comparison is made with thermal insulation. In detail, the Soth façade is energy renovated with the addition of 8 cm of expanded polystyrene respecting the limit in terms of thermal transmittance value for the external vertical walls.
The investigated building is located in Naples, and thus according to the division of the Italian territory, it belongs to the climate zone C, for which the U-value should be 0.34 W/(m²K). The thermal insulation of the South wall involves a reduction of about 3.5% and 5.1% for, respectively, space heating and cooling energy demand. Table 2 resumes the results of the comparison between the base case, the DSF (considering the different operating conditions) and the wall insulation. Table II highlights a greater energy benefit obtainable through the DSF, which exploits and interacts with the external environment, compared to a more conventional one, the thermal insulation, which instead blocks the interactions. By incorporating the environment, double-skin façades actively regulate temperature through features such as passive solar heating and natural ventilation, reducing the dependence on energy-intensive insulation systems. Integrating environmental factors into building design aligns with sustainable energy practices, utilizing sunlight and natural airflow to enhance energy efficiency and reduce the environmental impact associated with conventional insulation methods.

Fig. 6. DSF building model

Table 2. Space heating and cooling PEC comparison for scenario 1

	PEC_h	ΔPEC_h	PEC_c	ΔPEC_c
	[$kWh_p/(m^2y)$]	[%]	[$kWh_p/(m^2y)$]	[%]
Base case	42.1	/	21.6	/
Closed DSF	38.6	-8.4	22.2	+2.9
Ventilated DSF with shadings *(in summer)*	38.6	-8.4	18.6	-14.0
Thermal insulation *(for comparison)*	40.7	-3.5	20.5	-5.1

4.2 Scenario 2: skylights

The second investigated energy efficiency measure consists of using skylights as coverage of the inner courtyard (see Figure 7 for the skylights building model).
In this case, the objective is to reduce energy needs in winter, guaranteeing greater stability to the internal temperature of the building. At the same time, it is necessary to study what happens in the summer season to avoid a greater cooling demand linked to overheating of this new internal area. The intervention therefore concerns the courtyard for a glass surface of 11.3 x 20.75 m^2 with clear single panes of transmittance equal to 5.67 W/(m^2K). To study the conditions established within this new zone, i.e., the atrium of the building, a plot is carried out, taking some days of the month of January as an example of the air temperatures both inside this new environment and external, i.e., outdoor air temperatures (see Figure 8). It is possible to notice how globally there is a significant increase in temperature compared to the case without skylights, where the temperature of this environment coincides with the external one. This improvement is then reflected in the global improvement in heating performances which sees a reduction in primary energy demand by 12%. The situation is instead the opposite in the summer season, where the heat accumulated within this environment, due to solar radiation, creates an increase in PEC_c equal to 4.1%. By inserting a shading system, active in the summer season, it is possible to mitigate this effect, even providing an overall cooling need reduction of 0.9%. This is the net result of contrasting effects, and thus a slight overheating related to the limited (but present) greenhouse effect and the significant impact of the added shading on the courtyard fenestrations. Table 3 resumes the results for this scenario.

Fig. 7. Skylights building model

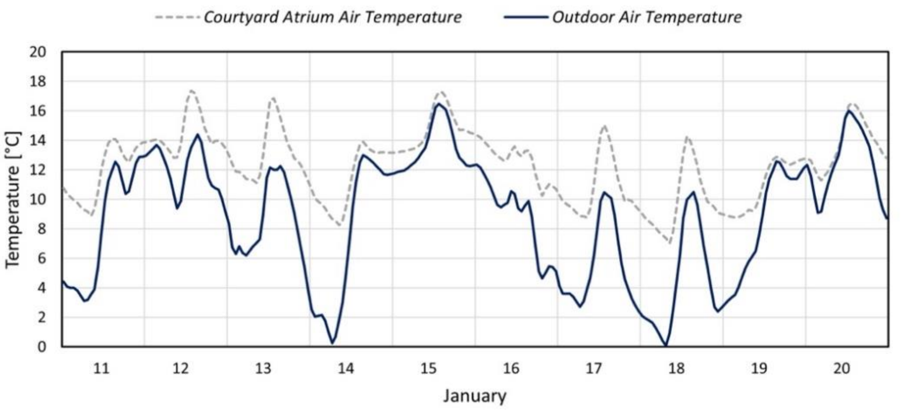

Fig. 8. Comparison between courtyard atrium and outdoor air temperatures for 10 January days

Table 3. Space heating and cooling PEC comparison for scenario 2

	PEC$_h$	**ΔPEC$_h$**	**PEC$_c$**	**ΔPEC$_c$**
	[kWh$_p$/(m^{2}y)]	[%]	[kWh$_p$/(m^{2}y)]	[%]
Base case	42.1	/	21.6	/
Skylights	37.0	-12.2	22.5	+4.1
Skylights with shadings *(in summer)*	37.0	-12.2	21.4	-0.9

4.3 Scenario 3: DSF and skylights

In the last scenario, DSF and skylights are combined (see Figure 9) to evaluate the building energy performance. The best configurations for DSF and skylight are adopted, i.e., a naturally ventilated DSF, with shading devices adopted for both. The results achieved through this energy retrofit intervention are:

- a reduction in primary energy demand of about 21.5% for space heating;
- a reduction in primary energy demand of about 12.9% for space cooling.

It is therefore interesting to note how through these two interventions it is possible to revalue the present historical heritage. For research purposes, the same intervention is carried out by replacing the already proposed laminated glasses (which is the one widely applied for this type of intervention) with double low-emissivity glasses, resulting in a further improvement in the winter season and a slight worsening in the summer one, i.e., primary energy reduction by 26.3% and 12.4%, respectively.

Along with the energy analysis of the results, it is essential to conduct also an economic one to study which scenario is most cost-effective. After a market analysis, investment costs (IC), for the retrofit measures, are identified (see Table 4). In the first scenario an 85% incentive is contemplated, which refers to the Sismabonus, currently present in Italy, and intended for those who carry out interventions for the adoption of anti-seismic measures on buildings. In this scenario the exoskeleton cost is not considered. The 50% incentive refers to the Ecobonus which focuses on interventions aimed at improving the energy efficiency of buildings, such as window replacements.

The feasibility of these interventions, however, requires strong incentives, as can be seen from Table 5 (the reported economic results refer to the laminated glasses); in fact, the payback times, considering a discount rate of 3%, are around 40 years. However, interventions such as the DSF have multiple uses which are not limited to improving the energy conditions of the building but also the structural ones, extending its life and justifying its outlay. Same for the application of skylights, in fact by making the atrium area closed to the outside it is also possible to redevelop the latter for common uses, increasing the useful volume of the building, creating a further possibility.

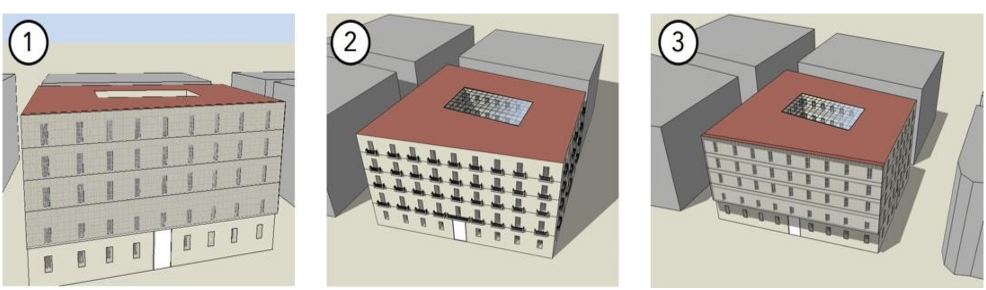

Fig. 9. Scenario 3 model: DSF and skylights. 1) DSF; 2) skylights; 3) DSF and skylights

Table 4. PEC saving, RC saving and IC for each scenario considered

Scenario	IC		Incentive	$IC_{incentivized}$	ΔPEC	ΔRC
	[€/m^2]	[k€]	[%]	[k€]	[kWh_p/y]	[€/y]
1	900	812	85	122	36570	4620
2	600	140	50	70	30904	3161
3	600 ÷ 900	952	50 ÷ 85	192	68799	7856

Table 5. Incentivized SPB, DPB and NPVs for each scenario considered

Scenario	SPB	DPB	NPV_{10}	NPV_{20}	NPV_{30}	NPV_{40}	NPV_{50}
	[y]	[y]	[€]	[€]	[€]	[€]	[€]
1	26.4	53	-82433	-53112	-31294	-15060	-2980
2	22.2	37	-43068	-23004	-8075	+3033	+11299
3	24.4	45	-124860	-74999	-37898	-10291	+10251

5 Conclusions

The integration of double-skin façades and skylights emerges as a sensitive and strategic approach for enhancing the sustainability of historical courtyard buildings. Preservation of architectural heritage requires a delicate balance between modern energy efficiency standards and the conservation of historical aesthetics. The double-skin façade, with its discreet yet effective thermal performance, enables the reduction of energy consumption without compromising the visual integrity of the building's façade.
Simultaneously, well-designed skylights contribute to the illumination of internal spaces, respecting the historical context while providing occupants with a connection to the sky above. The judicious use of these technologies not only addresses the pressing need for sustainable practices but also ensures that historical buildings continue to stand as vibrant, functional spaces adapted to contemporary environmental demands. By embracing these design solutions, it is possible to contribute to the longevity of historical buildings, ensuring their continued relevance in a modern, environmentally conscious context. The adoption of double-skin façades and skylights may be:

- more acceptable for preservation aims compared to traditional insulation;
- may be integrated in seismic and structural interventions;
- could provide significant energy improvements of the buildings.

Finally, by improving the responsive behavior, even in Mediterranean and warm climates such technologies could be applied for integrated retrofitting of historical buildings, where the past and present coexist seamlessly.
Under the feasibility point of view, results do not show encouraging paybacks but, given the decarbonization targets and the constraints of heritage buildings, evaluations concerning the mere economical convenience require a dedicated deepening.

References

1. Energy Efficiency (2022).
2. European Commission, “Energy efficiency in buildings,” (2020).
3. CRESME. Il recupero e la riqualificazione energetica del patrimonio edilizio: una stima dell’impatto delle misure di incentivazione, (2018).
4. Allocation Impact Report Italy, (2023).

5. P. La Greca, G. Margani, Seismic and Energy Renovation Measures for Sustainable Cities: A Critical Analysis of the Italian Scenario. Sustainability, **10**, 254 (2018).
6. EU Construction & Demolition Waste Management Protocol, (2016).
7. P. Foraboschi, E. Giani, Esoscheletri: miglioramento sismico e rigenerazione architettonica: seconda parte. Structural. **215**, 1-19 (2018).
8. A. Marini, C. Passoni, A. Belleri, F. Feroldi, M. Preti, G. Metelli, P. Riva, E. Giuriani, G. Plizzari, Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept. European Journal of Environmental and Civil Engineering, **26:7**, 2475-2495 (2017).
9. G. Aruta, F. Ascione, N. Bianco, T. Iovane, G.M. Mauro, A responsive double-skin façade for the retrofit of existing buildings: Analysis on an office building in a Mediterranean climate. Energy and Buildings, **284**, 112850 (2023).
10. E. Gratia, A. De Herde, Are energy consumptions decreased with the addition of a double-skin?. Energy and Buildings, **5**, 605-619 (2007).
11. A. De Gracia, A. Castell, L. Navarro, E. Orò, L. F. Cabeza, Numerical modelling of ventilated facades: A review. Ren. and Sustainable Energy Reviews, **22**, 539-549 (2013).
12. F. Pomponi, P. A. E. Piroozfar, R. Southall, P. Ashton, E. R. P. Farr, Energy performance of Double-Skin Façades in temperate climates: A systematic review and meta-analysis. Renewable and Sustainable Energy Reviews, **54**, 1525-1536 (2016).
13. A. Aldawoud, R. Clark, Comparative analysis of energy performance between courtyard and atrium in buildings. Energy and Buildings, 40(3), 209-214 (2008).
14. B. Wen, Q. Yang, F. Xu, J. Zhou, R. Zhang, Phenomenon of courtyards being roofed and its significance for building energy efficiency. Energy and Buildings, **295**, 113282 (2023).
15. R. Buda, C. Bedon, R. Pucinotti, Retrofit of Existing Reinforced Concrete (RC) Buildings: Steel vs. RC Exoskeletons. Applied Sciences, **57**, 104904 (2022).
16. A. Reggio, L. Restuccia, L. Martelli, G.A. Ferro, Seismic performance of exoskeleton structures. Engineering Structures. 198, 109459 (2019).
17. DesignBuilder (v. 6.1.8). Available online at: https://designbuilder.co.uk//software
18. EnergyPlus (v. 8.9.0). Available online at: https://energyplus.net
19. F. Ascione, N. Bianco, T. Iovane, M. Mastellone, G.M. Mauro, Is it fundamental to model the inter-building effect for reliable building energy simulations? Interaction with shading systems. Building and Environment, **183**, 107161 (2020).
20. D.P.R. (Decree of the President of the Republic) 26 agosto 1993 n. 412. [in Italian]
21. Italian Government, Decreto interministeriale 26 giugno 2015. Annex 1
22. Eurostat, "Natural gas price statistics". 2022.
23. Eurostat, "Electricity price statistics". 2022.
24. EC 2012/C. 2012. Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating.

Acknowledgements

This research was funded by Italian PRIN 2022, Italian Government, project entitled HERITAGE – Holistic Energy Renovation and adaptive reuse of historical buildings and sites for an Inclusive, resilienT, and Globally sustainable built Environment, n. 20223M4R8B.