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A methodology to assess energy-demand savings and cost-effectiveness of adaptation measures in educational buildings in the warm Mediterranean region

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A B S T R A C T

Educational building stock in Cyprus are a significant part of the public building stock, with these buildings leaning towards being less energy-efficient, especially in comparison to other public buildings. The energy and climate directives set by the European Union for 2050 call for changes in the building sector, particularly for existing public building stock. This study suggests a design approach and assessment for retrofitting scenarios, which meet energy demands for educational buildings in Cyprus, based on their long-term cost effectiveness. Adaptation measures refer to changes in the geometry, construction, and operation of buildings. The approach combines energy demand modelling through dynamic software simulation using Integrated Environmental Solutions (IES-VE) and retrofit options, ranked by life cycle costing analysis (LCCA). These options may have very different upfront costs, but also very different carbon implications, and they result in different life expectancy predictions. The research findings contributes to delivering novel knowledge in the rather limited literature regarding the implication of adaptation measures on energy performance of educational buildings in the Mediterranean region and especially in correlation to their life-cycle cost. The aim is to give the stakeholders as much information as possible regarding their interventions, so that they can make informed decisions. This information will then be used to develop a framework that may be used more extensively to support decision-making in retrofitting existing educational buildings for climate change resilience.

1. Introduction

Educational buildings require specially designed and controlled occupant comfort conditions since they are mostly occupied by people who spend a significant percentage of their daily time studying or supporting the development of students (teaching, support and grounds staff). Therefore, the need for optimal learning conditions is becoming crucial and should be as sustainable as possible while taking in consideration human physiology and the natural environment. A significant part of the existing public non-residential building stock in Cyprus are educational buildings which are currently characterized by poor energy performance and low comfort levels, since the majority them was constructed before the 2007 Minimum Energy Efficiency Requirements.

According to the new National Action Plan for 2021–2030 of the Climate and Energy Policy Framework, the objective is to implement important interventions in the residential and tertiary sector that aim to embed more efficient electrical appliances while improving buildings' energy efficiency. Specifically, the decisions of the European Council regarding the 2021–2030 Action Plan are based on three objectives at a EU level, i.e. (a) the reduction of at least 55% of greenhouse gases in comparison to the 1990 levels, (b) an improvement in energy efficiency of at least 32.5%, and (c) for renewable energy to reach a share of at least 32% (European Commission, 2019).

Additionally, the Recast Energy Performance of Buildings Directive (EPBD), demands that "the public sector in each Member State should lead the way in the field of energy performance of buildings" and that "buildings occupied by public authorities and buildings frequently visited by the public should set an example" (Official Journal of the European Union, 2010). Educational buildings in particular, can act as best-practices projects, where pupils can identify specific changes to the design and function of classrooms, therefore understanding how to be responsible users by adopting an operational behaviour that saves energy.

The use of targeted mild and passive measures aims to ameliorate the energy performance and overall comfort and well-being

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in public building classrooms throughout the entire year, for the benefit of the educational community. One of the major challenges to achieving nearly zero energy needs in existing buildings is the economic factor (Aste et al., 2016; Verbeeck and Hens, 2005; Sesana and Salvalai, 2013). High investment margins, long payback periods and perceived credit risk, are usually barriers to energy renovation strategies. The proof of the economic profit in energy retrofitting investments for existing buildings is still rather limited (Sesana and Salvalai, 2013; Menassa, 2011). Therefore, many consumers see the high operating cost and poor indoor environment as an acceptable way out rather than pursuing time-consuming, disruptive, and possibly risky retrofitting activities. Life cycle costing could be a significant tool for informing decision making in an investigation of the benefits and hazards of investments into the building retrofit sector.

Educational buildings comprise a significant portion of about 80% of the public non-residential building stock and in the case of Cyprus, the less-energy efficient category, as the majority of building area was built before 2007 and the introduction of energy performance requirements. The purpose of this study is to examine the impact of adaptation measures in energy performance and to assess their cost-effectiveness when applied in the educational buildings in Cyprus. This approach combines energy demand modelling through dynamic software simulation using Integrated Environmental Solutions (IES-VE) and retrofit option ranking with life cycle costing analysis (LCCA). These options may have very different upfront costs, but also very different carbon implications, and result in different life expectancy predictions. The examination of comfort conditions and energy performance of educational buildings in Cyprus and widely in the East Mediterranean region is rather limited. This study aims to add valuable knowledge in the existing literature and develop a methodology to assess the effectiveness of adaptation measures. Moreover, it quantifies the results of an applied example of an energy upgrade and evaluates them in terms of energy efficiency and life cycle cost. The aim is to provide the various stakeholders with as much information possible about their interventions, so that they can make informed decisions. This information will be used to develop a framework that could be used more extensively to support decision-making in retrofitting existing educational buildings for climate change resilience. The proposed methodology and results presented herein could be effectively employed in educational buildings of other countries which share similar typological characteristics and climatic conditions, as well as in other building types which have similar compositional, typological and construction characteristics. The proposed methodology and results can be used for the energy upgrade as well as in the design of new educational buildings.

2. Literature review

2.1. The concept of life cycle costing analysis

Over the last few years, Life Cycle Costing (LCC) has been gaining much attention in the construction sector. LCCA is a method to assess an economic condition by considering the total cost over the entirety of the operating life of an asset, including operating, maintenance, initial capital costs eventually evaluating the cost or benefit of its disposal at the end of its life (Flanagan et al., 1989). Therefore, LCCA can become a tool for decision-making helping someone to choose between alternative project proposals, designs, or building components (Kirk and Dell'Isola, 2002).

LCCA can be applied at any stage of the supply process and there are various different standards available to guide an LCCA (ISO 15686-5:2017, EN 15459-1:2017). These are differentiated in terms of cost categories and cost breakdown structures. The importance of using LCCA in the building sector is supported at a European regulatory level by Directive 2010/31/EU, which acknowledged that "Member States should calculate cost optimal levels of minimum energy performance requirements using a comparative methodology framework according to the consequent Commission Delegated Regulation and its Guidelines (Commission, 2012) based on EN 15459:2007" (the old version of EN15459-1:2017) (CEN (European Committee for Standardization), 2017a). "Cost optimal level means the energy performance level, which leads to the lowest cost during the estimated economic lifecycle, wherein the lowest cost is determined by considering energy-related investment costs, maintenance and operating costs including energy costs and savings" (Commission, 2012).

2.2. Previous studies using life cycle costing

Cost-optimal methodologies for assessing retrofitting practices in existing buildings have been introduced by several studies . Hamdy et al. (2013) developed a methodology to identify the most cost-optimal and best energy performance for nearly Zero Energy Buildings in the case of a single-family house in Finland. The study investigated different options in design characteristics of the building envelope, from heat recovery ventilation systems, to systems for heating/cooling, and even considering different sizes of thermal and photovoltaic solar systems, concluding that the cost-optimal energy performance level is between 93 and 103 kWh/m^2 based on environmentally friendly heating systems. Tagliabue et al. (2014) presented a cost-optimal methodology to identify the most optimal solution for replacing an oil boiler in an apartment in Milan, Italy between three technical systems. Ganiç and Yilmaz (2014) researched office buildings in Turkey using the global cost calculation periods.

Wang and Holmberg (2015) assessed the energy demand renovation scenarios of existing Swedish residential buildings in terms of their long-term cost effectiveness using LCCA. Hong et al. used LCC together with the environmental impact (LCCO$_2$) to assess retrofitting strategies in Chine, while Paiho et al. (2015) suggested a cost-optimal assessment methodology for retrofitting strategies of residential buildings in Russia extending the application of LCC to building district level. Tubelo et al. (2021) examined the cost-effectiveness of envelop design characteristics in affordable housing for single family in order to achieve thermal comfort. The study revealed that an increase of the cost by 12% and 9% can lead to 40%–45% improvement of thermal comfort conditions; while an increase of cost by 57% can lead to 73%–76% improvement of thermal comfort conditions. Jung et al. (2021) investigated integrated passive strategies of a multi-storey residential building in South Korea by suggesting a multi-objective optimization of the building. The study highlights that design factors are most likely to improve results, such as occupants and window-to wall ratio and airtightness, all of which improving economic feasibility, energy and environmental impact by 37%, 53%, and 40% respectively.

Zachariadis et al. (2018) used multiple indices to evaluate the cost-effectiveness of energy efficiency measures in residential buildings including: weighted effort in investment cost, nominal index of total investment, payback period, and net present value. The study determined that specific energy retrofitting options should be prioritized, such as, insulating roofs, installing heat pumps, and replacing lighting and equipment with more efficient alternatives, and then highlighted the weaknesses of current regulatory energy efficiency policies in Cyprus. Ziogou et al. (2017) investigated urban office buildings in Cyprus and the impact on the energy, environmental and economic performance of green roofs. The study revealed that primary energy consumption in heating and cooling operation was reduced by up to 25% and to 20% respectively, while the economic analysis showed that green roof technology is not effective yet in terms of cost to be used in the particular type of building, i.e. offices. Finally, Loukaidou et al. (2017) examined the cost-optimal analysis of building envelope characteristics in the climatic conditions of Cyprus to achieve zero energy buildings and found that the reference test-cell building performed significantly higher than the national minimum requirements in its cost-optimal energy performance levels.

3. Methodology

The study presented in this paper is part of a project (Heracleous and Michael, 2020, 2019; Michael and Heracleous, 2017; Heracleous and Michael, 2018; Heracleous et al., 2021) that aimed to assess the climate change resilience of educational buildings in Cyprus. The majority of educational buildings (with a percentage of 79% of the total floor area) were built before 2007 and the Minimum Energy Efficiency requirements. Indeed, nearly all educational buildings were built in the 1980s, as a result of increased investment in infrastructure following the Turkish invasion of 1974. Principally designed and constructed by a division of the Cyprus Ministry of Education and Culture, namely the Technical Services, during the 1980s and 90 s, these buildings are of standardized typologies and construction characteristics. This specific building stock shares is characterized by the repetition of design elements as well as spatial configurations. They are two-storey buildings, rarely three-storey, with an evident standardization in their design and construction. The layout of the functional spaces along open corridors is the most intense feature of the typological organization of the typical school buildings. These provisions are combined to create a system of linear building elements, with the existence of closed courtyards in the form of atriums, open courtyards on one or both sides and free elements. This system allows the building to be fully adapted to the available plot and favours additions to the building programme by expanding or adding new classrooms. However, the architectural design of the school building arises without substantial concerns regarding the climatically rational design, the topographical height differences, the appropriate building orientation and the arrangement of the openings in relation to the prevailing winds.

The methodology used in this study is constituted by two parts. The first part assesses the energy performance of the selected educational buildings over a typical meteorological year, whilst the second investigates the economic feasibility of passive design strategies for improving energy performance using LCCA.

3.1. Case study and climate

The case study chosen was the Archbishop Makarios III Secondary School in the urban area of Nicosia, Cyprus, as it was a representative sample of the investigated category. Cyprus has a typical Mediterranean climate, with hot dry summers (mid-May to mid-September) and relatively rainy and rather unpredictable winters (November to mid-March) (Table 1).

Table 1
Nicosia outdoor air temperature and monthly global horizontal radiation (Meteonorm Software).

	Monthly Global Horizontal Radiation (Wh/m^2)			Monthly Outdoor Air Temperature (°C)		
	Average	Min	Max	Average	Min	Max
January	107	0	626	11.5	2.8	19.8
February	141	0	725	11.7	3.4	21.1
March	193	0	848	14.4	5.7	24.4
April	238	0	931	17.6	9.1	27.8
May	276	0	1008	22.2	13.6	31.7
June	302	0	993	25.8	17.5	34.6
July	292	0	1048	28.6	21.2	37.6
August	292	0	978	28.5	21.7	35.3
September	225	0	916	25.4	15	33.9
October	174	0	830	22.4	13.6	31.9
November	127	0	685	17.1	8.4	27.1
December	102	0	558	13.2	5.2	22.3

Classrooms are mostly rectangular approximately measuring 7.00×8.00×3.20 m (W×L×H) (Fig. 1). The classrooms are connected with semi-open corridors (i.e., open-air covered spaces), arranged one next to the other, are 2 m wide, with some solar protection (Fig. 2). There are openings along the two long sides of each classroom, with a window-to-floor ratio being 25% and a window-to-wall ratio of 50% in the south and 17% in the north elevation, with no openings on the east and west elevations. The existence of clerestories instead of windows on sides not facing the courtyard contributes to this isolation even further, by ensuring every interruption of the visual connection of the school space with the wider built and natural environment. The north clerestories of the classroom are not shaded. On weekdays from 7:30 to 13:35, each classroom's occupancy rate reaches 20 students, with 3 small break-intervals (Heracleous et al., 2021). Table 2 summarizes the construction details of the said buildings. Typical school buildings have a load-bearing structure made of reinforced concrete like most building structures in Cyprus. The wall is filled with Cypriot conventional perforated bricks and have no thermal insulation in masonry or load-bearing elements, columns and beams. The openings are usually made of aluminium frames, less often with metal ones, while in all cases they have single pane of glass.

3.2. Software simulation

The cost-effectiveness of passive strategies and the energy performance of schools in Cyprus were evaluated using the dynamic thermal simulation IES-VE, and Integrated Environmental Solutions Limited (2019). The building envelope design, geometry and construction characteristics were modelled after the existing building. The on-site conditions were tracked through occupancy and operational schedules over each climatic period. The operating hours of the educational buildings were from 7:30 to 13:35, with windows being opened over the totality of occupied hours in the summer, in the winter only during the three 20-minute break-intervals and during the spring/autumn period from 9:00 to 13:35. The selected classroom stayed closed from 13:35 to 7:30, with no occupancy (Heracleous et al., 2021). Florescent lamp luminaires are used for lighting with maximum sensible gain of 10 W/m^2, and including 20 people, 78W/p of maximum sensible gain and 40W/p of maximum latent gain (EN 17772-1:2017) (CEN (European Committee for Standardization), 2017b). For the simulation, the software employed data downloaded from Meteonorm v.7.1.11 for the typical meteorological year (TMY).

Internal and external environmental conditions were monitored in order to validate the predictive consistency of the model. Detailed information regarding the calibration of the model has previously been published (Heracleous et al., 2021).

Generally, educational buildings in Cyprus could be considered as free-running buildings, as most of the time they are not supported by technical heating and cooling systems. The building is only supported by technical systems during the winter period, and for a limited period of the day (3 h). However, for the purposes of this study, and the evaluation of energy performance and LCC of educational buildings, technical systems are provided during the teaching period, in order to achieve the

Fig. 1. Views of the outside and inside of the Archbishop Makarios III Secondary School.

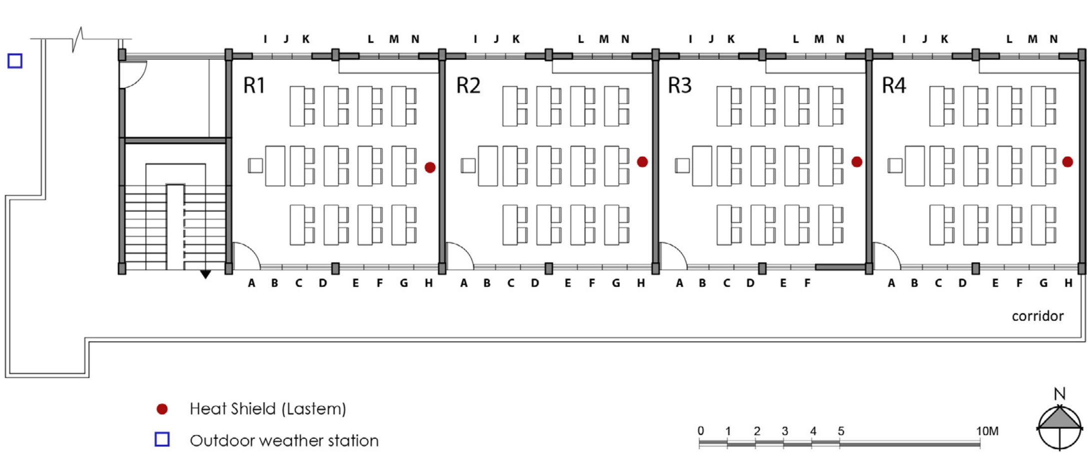

Fig. 2. Typical layout plans of a secondary school classroom in Cyprus. The openings in each classroom are marked with letters A to N, with the positions of the indoor and outdoor environmental recording equipment marked by coloured dots.

Table 2
Typical Cypriot school construction characteristics and materials.

Building Elements	Construction Detail	U-Value (W/m^2 K)	G-value	Effective Thermal Capacity (KJ/m^2 K)
External Wall	200 mm single brick layerand 20–25 mm plaster and paint with blush colour	1.4	–	120
Internal Wall	100 mm single brick layerand 20–25 mm plaster and paint with off-white colour	1.2	–	120
Roof	Concrete and asphalt layers of 5 mm in light grey colour	3.2	–	240
Ground Floor	Concrete slab and cement-basedsealed floor tiles in light grey colour	1.6	–	232
Window	6 mm single-glazed aluminium frame	6.0	0.8	–

required indoor thermal comfort. For heating systems, a diesel-heated boiler system with seasonal energy efficiency of 0.92 was used, which is the typical and most conventional system widely used in educational buildings in Cyprus. For cooling, based on the technical specifications provided by the Ministry of Education, Culture, Sports and Youth, in the case of the installation of air conditioning, this would be a wall-mounted, air-cooled, split type heat pump, with a minimum seasonal energy efficiency ratio (SEER) of 5.6. A system with seasonal energy efficiency ratio of 6 was selected for the needs of this study. Based on EN 15251:2007 (EN CEN, EN 15251:2007, 2007), the default design values of the indoor operative temperature in classrooms in Category II buildings with mechanical systems in winter and summer is 20 °C and 26 °C respectively. These set points were based on the aforementioned standard and were applied for the occupied time. Table 3 summarizes the operation characteristics of technical systems.

Table 3
Technical system operation.

Parameter	Operation	Reference
Operation period of technical systems	5 days per week from 07:30 to 13:35	With regards to local usage pattern
Heating period	October to April (15days of Christmas and 15days of Easter breaks excluded)	With regards to local climatic conditions
Temperature required during operation hours for the heating period	20 °C	EN 15251:2007, Category II
Cooling period	May to November	With regards to local climatic conditions
Temperature required during operation hours for the cooling period	26 °C	EN 15251:2007, Category II

3.3. Adaptation measures for energy performance and cost-effectiveness

There are many techniques which can be used to improve the thermal and energy performance of educational buildings such as the improvement of the thermal properties of the building envelope, the geometry of solar shading systems, operational behaviour (Philokyprou et al., 2014), as well as the integration of supporting technical systems i.e. mechanical ventilation with heat recovery (MVHR) (Table 4). The same techniques have been used in another study by the authors in order to evaluate their effectiveness in the reduction of degree hours under different climatic conditions (Heracleous et al., 2021). Specifically, Cases 1–4 examine the addition of a new layer of exterior insulation using a rockwool render system, Cases 5–8 evaluate the thermal performance of a new layer of extruded insulation added on the roof covered by paving slabs, Cases 9–11 consider a new layer of extruded insulation installed on the floor covered by screed and new final floor lined with ceramics, Cases 12–15 explore the replacement of the existing windows with relatively high-performance windows with an aluminium frame. All the abovementioned strategies aim to reduce the heat losses to the external environment over the heating period, while minimizing heat gains during the cooling period. Cases 16–18 suggest the increase of ventilation rates during the summertime (windows A, C, F, J, M i.e., a total size of 4.75 m^2). The characteristics of the Mediterranean climate make natural ventilation a particularly effective strategy for improving thermal comfort conditions, both during the summer season and on the hottest days of the intermediate seasons. Natural ventilation aims to remove heat from the human body (direct physiological effect), cool the indoor spaces, cool the structural elements of the building envelope (indirect physiological effect) as well as to improve indoor air quality. Utilizing natural ventilation to cool buildings requires a sufficient temperature difference between indoor and outdoor temperatures. Due to safety reasons associated with the openings of windows during the night time, a ventilator that closely imitates the window operation was selected based on the results of the simulation in the first stage. The ventilator that uses a fan for air extraction has an efficiency of 1000 l/s, i.e. 3600 m^3/h. Cases 19–21 see the addition of both fixed and movable shading devices to provide sun protection of glass surfaces in the south-orientated classrooms that receive extensive solar heat gains. Additionally, mechanical ventilation with heat recovery is introduced, to reduce heat losses through ventilation while exploiting heat recovery to decrease heating demands, as well as improving indoor air quality (Case 22). The efficiency of recovery was set to 70% and the air extraction efficiency set to 200 l/s. Initially, each parameter is examined individually, while keeping other components unchanged and then followed by the consideration of their combinations.

The combinations of retrofitting scenarios are based on the best performance of individual cases in terms of their cost-effectiveness and are categorized based on their installation difficulties into light, medium and advanced retrofitting. Specifically, light retrofitting involves retrofit options with a high impact on energy demand and easy installation, hence avoiding multiple visits and likely user intervention. Medium retrofitting approaches include options with a high impact on energy demand and medium difficulties to install. Advanced retrofitting refers to all the possible retrofitting options which include measures with both high and low impact on energy demand, regardless of construction difficulty, to achieve the biggest possible reduction in energy demand (Wang and Holmberg, 2015). The difficulty rate also suggests the smooth running of the schools throughout the academic year in terms of maintenance. Table 4 summarizes the simulated retrofitting scenarios cases (C), i.e., C1–C41.

3.4. Data analysis methodology

For the evaluation of educational buildings, the modelling is divided into two stages. The first stage considers the evaluation in their existing state (base case scenario), while the second phase considers the remodelled version of educational buildings that implements different retrofit alternatives in the current climatic conditions, with the provision of technical systems. IES-VE dynamic software was used to model the base case and each suggested scenario together with energy consumption in kWh/m^2/year and the calculated LCCA. The final simulation results are of the retrofitted educational buildings. The results are compared with the case before retrofitting in order to identify the potential for energy consumption decrease.

3.4.1. Energy evaluation

The energy efficiency of both the base case and the alternative scenarios was assessed based on the annual primary energy consumption per square meter of the building, as derived from IES-VE. The existing literature regarding energy analysis suggests the consideration of primary energy consumption instead of final energy consumption (CEN European Committee for Standardization), 2008; Thiede, 2012). This type of energy consumption considers the efficiency of the production, distribution and end-use of an energy source i.e., the overall efficiency of the energy production–consumption cycle. Consequently, the primary energy consumption values can be benchmarked directly with similar values for any kind of energy system (Solmes, 2009). The established national primary energy conversion factor of 2.7 for electricity and 1.1 for heating oil, were used to convert the electricity consumption and boiler consumption into primary energy consumption in Cyprus (Energy Service- Ministry of Energy Commerce and Industry, 2015). The national representative conversion emission factor of primary energy of electricity and heating oil is 0.794 and 0.266 of CO_2 per kWh, respectively.

3.4.2. Economic evaluation

A benchmarking mechanism based on cost optimization was introduced, with respect to Directive 2010/31/EU and European Regulation 244/2012/EU (Commission, 2012). This framework indicates that the examination of specific economic factors considering the long-term financial outlook such as life cycle cost analysis, should be used. In each case, both the base case and retrofit scenario were economically compared using the method of net present value (NPV). Life cycle cost represents the cumulative cost expressed in present value over the period of analysis (Wang and Holmberg, 2015).

The calculation of the global cost or LCCA needs for each retrofitting scenario, the initial investment, the sum of annual costs for every year (including running and replacement costs) together with the final value, with reference to the starting year (2020, for the current case study) of the calculation period. Based on the EU Delegated Regulation the global cost for macroeconomic calculation is defined as follows:

$$C_g(\tau) = c_I + \sum_j \left[\sum_{\iota=1}^{\tau} \left(C_{a,i}\,(j)\right) \times R_a\,(i) - V_{f,\tau}\,(j) \right] \quad (1)$$

Where τ is the calculation period; $C_g\ (\tau)$ the global cost over the calculation period (referring to the starting year); C_I stands for the initial investment costs for the energy efficiency measure or the set of measures j; $C_{a,i}\ (j)$ is the annual cost in the year I, for measure or the set of measures j (including running costs and replacement costs); $V_{f,\tau}\ (j)$ stands for the residual value of measure or set of measures j, at the end of the calculation period (discounted to the starting year); and $R_d\ (i)$ is the discount factor of the year.

Table 4
Retrofitting scenarios.

Refurbishment strategies						Cost	Retrofit option
				U value (W/m^2 K)	G-value		
Building envelope properties	New layer of exterior rockwool insulation on the walls (λ = 0,035 W/m K)	5 cm		0.43[a]	–	€43/m^2	C1
		8 cm		0.31	–	€47/m^2	C2
		10 cm		0.26	–	€50/m^2	C3
		15 cm		0.18	–	€55/m^2	C4
	New layer of extruded insulation on the roof (λ = 0,035 W/m K) covered by paving slabs	5 cm		0.53[a]	–	€36/m^2	C5
		10 cm		0.29	–	€41/m^2	C6
		15 cm		0.19	–	€46/m^2	C7
		20 cm		0.15	–	€51/m^2	C8
	New layer of extruded insulation on the floor (λ = 0,035 W/m K) covered by screed and new final floor	5 cm		0.50	–	€68/m^2	C9
		8 cm		0.35	–	€70/m^2	C10
		10 cm		0.29	–	€73/m^2	C11
	Replacement of existing windows with relatively high-performance glazing systems and window aluminium frames	double low-e glazing, standard frame	Frame Glaze Window	5.8 1.3 3.5[a]	– 0.7 –	€200/m^2	C12
		double low-e glazing, insulated thermal break frame No. 1	Frame Glaze Window	4.5 1.3 2.7[a]	– 0.6 –	€250/m^2	C13
		double low-e glazing, thermal break insulated frame No. 2	Frame Glaze Window	2.6 1.3 2.2	– 0.6 –	€300/m^2	C14
		triple glazing, insulated thermal break frame	Frame Glaze Window	2.6 1 1.3	– 0.5 –	€350/m^2	C15
Window operation	Increasing ventilation rate in summer	cross ventilation during daytime (07:30–13:30)				–	C16
		cross ventilation during daytime (07:30–13:30) and night-time (21:00–07:30) using ventilator with air extraction efficiency of 1000 l/s, i.e. 3600 m^3/h.				€1000/class	C17
		cross ventilation only during night-time (21:00-07:30) using ventilator with air extraction efficiency of 1000 l/s, i.e. 3600 m^3/h.				€1000/class	C18
Geometry	Shading devices	Increase overhang by 20cm				–	C19
		horizontal louvres 25-5-25-5-25-5 solar emissivity: 0.9				€ 1250/class	C20
		external movable horizontal louvres solar emissivity: 0.9 daytime/night-time resistance: 0.1 m^{2}k/W Transmission factor: 0° = 0.65, 15° = 0.40, 30° = 0.20, 45° = 0, 60° = 0, 75° = 0, 90° = 0, Operation: Winter: 18:00–07:00 Summer: 07:00–18:00				€ 2170/class	C21
Mechanical ventilation	Mechanical ventilation with heat recovery (MVHR) with 70% efficiency	8 l/s/person (or 200 l/s) Operation: Winter: 07:30–13:35 on Summer: 07:30–13:35 on, 00:00–07:30 and 13:35–24:00 on when outdoor air temperature is < 31 °C and outdoor relative humidity is <70%				€4000/class	C22
Combinations	Light	Roof ins.10 cm +MVHR		C6 + C22			C23
	Light	Roof ins.15 cm +MVHR		C7 + C22			C24
	Light	Roof ins.10 cm +MVHR+ Vent.		C6 + C22 + C17			C25
	Light	Roof ins.15 cm +MVHR+ Vent.		C7 + C22 + C17			C26
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 8 cm		C6 + C22 + C2			C27
	Medium	Roof ins.15 cm +MVHR+ Wall ins. 8 cm		C7 + C22 + C2			C28
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 10 cm		C6 + C22 + C3			C29
	Medium	Roof ins.15 cm +MVHR+ Wall ins. 10 cm		C7 + C22 + C3			C30
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 10 cm+ Vent.		C6 + C22 + C3 + C17			C31
	Medium	Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Vent.		C7 + C22 + C3 + C17			C32
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame		C6 + C22 + C3 + C14			C33
	Medium	Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame		C7 + C22 + C3 + C14			C34
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 8 cm + Double glazed low-e insulated frame+ Vent		C6 + C22 + C2 + C14 + C17			C35
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Vent		C6 + C22 + C3 + C14 + C17			C36
	Medium	Roof ins.15 cm +MVHR+ Wall ins. 8 cm + Double glazed low-e insulated frame+ Vent		C7 + C22 + C2 + C14 + C17			C37
	Medium	Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Vent		C7 + C22 + C3 + C14 + C17			C38
	Medium	Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Shading		C6 + C22 + C3 + C14 + C21			C39
	Advanced	Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame + Floor ins. 5cm		C6 + C22 + C3 + C14 + C9			C40
	Advanced	Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double-glazed low-e insulated frame + Floor ins. 5 cm + Shading + Vent.		C6 + C22 + C3 + C14 + C9 + C21 + C17			C41
	Advanced	Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double-glazed low-e insulated frame + Floor ins. 5 cm + Shading + Vent.		C7 + C22 + C3 + C14 + C9 + C21 + C17			C42

[a] It is noted that based on the updated regulation regarding the Minimum Energy Efficiency Requirements for a building (Law, KDP 121/2020), the specific intervention performs below the requirements.

The annual costs are the sum of maintenance costs, energy cost, operational costs and replacement cost. Moreover, the discount factor R_d considers the real interest rate (R_r, %) and the time of the considered cost. It can be calculated according to Eq. (2), where p stands for the number of years since the starting period.

$$R_d\,(i) = \left(\frac{1}{1+R_r}\right)^p \tag{2}$$

The calculation period of the global energy performance associated cost was set to 30 years according to European Standard EN 15459-1:2017 (CEN (European Committee for Standardization), 2017a), with the study referring to public buildings.

Table 5 summarizes the lifecycle of building components, and the annual preventive maintenance cost including operation, inspection, cleaning, adjustments, repairs, and consumable items as percentage factor (Mc) of the initial investment cost.

Table 5
Lifecycle of building components, annual maintenance, repair, operation and service factor of system components.

Component	Lifespan (p) – in (years)	Mc (%)	Reference
Wall finishes of thermal facade	15	0	Local market
Windows	30	1	Local market
Insulation	50	4	Ascione et al. (2015), Loukaidou et al. (2017)
Roofing-membrane	20	1	Wang and Holmberg (2015)
Roofing-tile	80	0	Wang and Holmberg (2015)
MVHR	20	0.40	EN 15459-1:2017 CEN (European Committee for Standardization) (2017a),
Filter material to be exchanged	1		Local market
Extractor fan	20	4	EN 15459-1:2017 CEN (European Committee for Standardization) (2017a)
External shutter fixed	30	4	Local market
External shutter automated	30	6	Local market
Electronics	20		

Table 6
Economic parameters for evaluating the global cost.

Calculation period (T)	30 years	EN 15459-1:2017
Real interest rate (Rr)	0	Bloomberg Markets
Discount rate (Rd)	0.28 (10 years)	Bloomberg Markets
	0.55 (15 years)	Bloomberg Markets
	0.84 (20 years)	Bloomberg Markets
	0.90 (25 years)	Bloomberg Markets
	1.08 (30 years)	Bloomberg Markets
Electricity cost	0.1689/ kWhe	Cyprus Energy
	2.20% increase per year	Regulatory Authority
Heating oil cost	0.069/ kWht	Retail Fuel Prices
	3.8% increase per year	Observatory

An additional maintenance cost was added annually for supervision and cleaning of the roof at 1% of the initial cost (i.e., 40 €/year), and for rubbing and varnishing of the floor at 2% of the initial cost (i.e., €50/year or €500/10 years). It is noteworthy that for the reference building, windows, wall, and roof maintenance is differentiated by considering its particular characteristics and age. Specifically, wall maintenance was set to 6 €/m^2 for refreshing the wall rendering every five years and roof maintenance was set to 11 €/m^2 for renewal of the roof membrane every 20 years. Windows maintenance includes lubrication of mechanisms with silicone spray and lubrication of sealing rubbers and that represents 2% of the initial cost (€100/year).

Table 6 indicates the real interest rate, discount rate and energy cost according to the guidelines of the Building Performance Institute Europe (Buildings Performance Institute Europe BPIE, 2013) and European regulation (CEN (European Committee for Standardization), 2017a). Heating oil and electricity costs for the starting year were obtained from the Retail Fuel Prices Observatory and Cyprus Energy Regulatory Authority, including regional and national taxes. The percentage of change of the electricity price as shown in the last 5 years, was observed with an average of 2.2% and was included for the future estimation of the price. The reduction of the electricity price due to the pandemic was neglected, as it is assumed that the energy price will rise again after the end of the pandemic. The percentage in the increase of heating oil prices worldwide was observed for the last 10 years with an average value of 3.8%, which was included for the future estimation of the oil price.

According to European Regulation 244/2012/EU (Commission, 2012), the period of calculations for public buildings has an impact on the residual value of a number of building elements at the end of the calculation period. Replacement costs are only considered for technical installations. The residual value is determined by means of a straight-line depreciation of the initial investment cost of the building element to the end of the calculation period, discounted at the beginning of the calculation period. The residual value was only considered for the paving slabs and technical systems respectively, with a depreciation factor of 10%, regarding the cost of materials.

3.4.3. Sensitivity analysis

The sensitivity analysis is extremely useful in efforts to understand the impact of a particular variable by evaluating some of the key parameters' robustness, such as the evolution of energy prices and discount rates. The sensitivity analysis should augment the understanding of influential factors in the system to support decision-making. While the selection of a cost-optimal refurbishment solution happens in the early stages of decision-making, the economic analysis is useful when future variables fluctuate, and it may also help in providing recommendations. This analysis can be used to assess the robustness of the optimal solution, under what occasion it might change and in which way. For this study, the sensitivity analysis considered different discount rates and energy prices for heating oil and electricity.

Currently there is low inflation and low interest rates with both the capital cost and the required return rate of investments falling in the general economy. A discount rate of 3% (in real terms) is suggested by European Regulations, which has been used for assessing retrofitting scenarios in existing and new buildings in many countries (Commission, 2012). Therefore, the first case in the sensitivity analysis assumes a discount rate of 3% throughout the whole calculation period.

Regarding the evolution of the energy price, an additional increase of 0.5% in the rate of increase per year is considered as a future projection for both electricity and heating oil prices (i.e., 2.7% increase of electricity and 4.3% increase of heating oil) for the first case. The second case examines a small decrease of 0.5% in the rate of increase of the energy price (i.e., increase of 1.7% of electricity and increase of 3.3% of heating oil).

Lastly, as schools are increasingly moving towards an all-day model, with other activities taking place during non-school hours, the sensitivity of the life cycle cost of the adaptation measures is investigated in order to find out if these measures are of further help to the utilization of school structures and/ or how they affect their life cycle. For that reason, the technical systems were activated during the afternoon between 14:45 and 17:45.

4. Results and discussion

Results were assessed according to the demands for energy for heating and cooling in the current climatic conditions. The analysis was conducted during the occupied hours i.e., 07:30–13:30, for both the ground floor, centre-section classroom and the first floor, centre-section classroom, both with south orientation. The analysis was only performed during the period that the educational buildings were operational, i.e., September to June, excluding the Christmas and Easter holidays.

4.1. Energy performance of existing educational buildings and life cycle cost analysis

The educational building under study exhibits higher needs for heating in comparison to cooling, throughout the period operation. This is attributed to the fact that school buildings remain

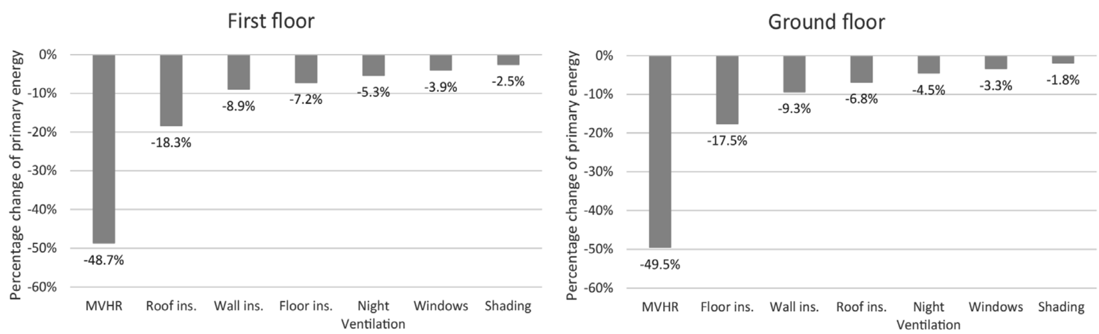

Fig. 3. The ranking of retrofitting options based on the total primary energy saving in the south-oriented classrooms of the first and ground floor.

closed during the summer period and the hours of operation are from 07:30 to 13:30, thereby avoiding the highest temperatures appearing around 15:00. The classroom on the first floor requires slightly higher energy compared to the ground floor classroom, as it has higher exposure to outside environmental conditions due to the roof. Specifically, the heating loads represent 73% and 79% of total energy loads for the classrooms on the first and ground floor, respectively, and the cooling loads represent 27% and 21% of total energy loads for the classrooms on the first and ground floor, respectively. The primary energy for heating the first floor classroom was 88% out of the total primary energy of 67.9 kWh/m^2/yr, whilst for cooling 12% of 9.4 kWh/m^2/yr, throughout the whole academic year. The primary energy for heating the classroom of the ground floor was 91% of the total primary energy of, 68.2 kWh/m^2/yr., while for cooling it was 9% of 6.9 kWh/m^2/yr, throughout the whole academic year. The lifecycle cost for 30 years for the classroom on the first and ground floor is €20,347 and €20,081 respectively.

4.2. Energy demand and retrofit ranking

The results showed that, providing a heat recovery ventilation unit has resulted in the highest energy-saving ranking at about 49% both for the first and ground floor classrooms. It should be noted that due to the peculiarity of the building, which is most often used in the winter when MVHR is much more effective, the heat recovery has the highest energy ranking. In a classroom that has its roof exposed to the external environment, the roof insulation is the second most important retrofitting option (18%); while in a classroom that is located on the ground floor, floor insulation is the second most important retrofitting option resulting in a reduction of 18%. Adding insulation on the wall also has high ranking, by minimizing the total primary energy by about 9%, while night ventilation lowers the total primary energy consumption by about 5%. Windows provide a reduction of primary energy by 3%–4%. Shading devices have little impact on the total energy savings calculated at 2%, as classrooms are south-facing, and the overhang created by the external corridor is considered adequate. Fig. 3 shows the ranking of individual retrofitting scenarios, based on the mean reduction of the consumption of total primary energy for the classrooms on the first and ground floor, while Fig. 4 shows the contribution of retrofitting scenarios for the reduction of consumption of primary energy for heating and cooling, separately.

Fig. 5 shows the primary energy heating and cooling consumption of individual retrofitting scenarios, while Fig. 6 shows the consumption of primary energy of heating and cooling of combined retrofitting scenarios during the academic period, in the south oriented classrooms of the first and ground floor. Considering that MVHR and roof insulation are the most effective solutions for reducing primary energy consumption, cases C23 and C24 address those retrofitting scenarios utilizing 10 cm and 15 cm thicknesses of roof insulation, achieving a total reduction of 62% and 62.5% respectively (from 77.2 kWh/m^2/yr. to 29.4 kWh/m^2/yr and 28.9 kWh/m^2/yr. respectively). While the combination of all passive strategies reduces the primary energy from 77.2 kWh/m^2/yr. to 17.6 kWh/m^2/yr., i.e., a reduction of 77.3%

4.3. Cost-effectiveness of retrofitting scenarios

The cost-effectiveness assessment of retrofitting scenarios presented below focuses on the south-oriented classrooms on the first floor (large windows on the south and small clerestories on the north). The particular classrooms were selected because based on the climatic conditions of the Mediterranean they exploit significant solar gains during the winter period and can easily be applied a shading system during the summer time to eliminate solar gains.

As shown above, the difference between the ground and first floor classrooms in primary energy consumption is not high and therefore the results can be generalized for the entire school building.

4.3.1. Individual retrofitting scenarios

The Wall retrofitting scenarios in Table 6 represent four cases based on four different thicknesses (5 cm to 15 cm) of a Rockwool render system, exhibiting different U-value and cost characteristics. As observed, all the cases provide lower LCC (ΔCg $= -0.2$–1.4%) for the 30 years of calculation in comparison to the reference building, making all the retrofitting options cost-effective. The higher the insulation, the higher the LCCA, ranging from €20,053 to €20,300. The reduction of primary energy utilization compared to the reference building is about 6–7 kWh/ m^2/yr., i.e., a 8%–9% reduction.

The Roof retrofitting scenarios show calculations for the four different thicknesses of insulation (5 cm to 20 cm) covered with paving slabs, exhibiting different U-value and cost characteristics. As illustrated in Table 7, cases of up to 15 cm insulation provide lower LCC (ΔCg $= -1.0$–3.7%) for the 30 years of calculations, in comparison to the reference building, and cases with improved wall systems make roof retrofitting options cost-effective. Despite of the initial investment cost being higher than the improved wall system cost, the energy savings are also higher. However, the case utilizing 20 cm roof insulation (C8) shows a higher LCC by 0.9% in comparison to the reference building. The thicker the insulation, the higher the LCCA ranging from €19,601 to €20,523. The reduction in consumption of primary energy in comparison to the reference building is about 13–14 kWh/m^2/yr., i.e., a 17%–19% reduction.

The installation of floor insulation, the replacement of existing single-glazed windows with high-performance glazing systems and improved window frames, the increase of ventilation rate

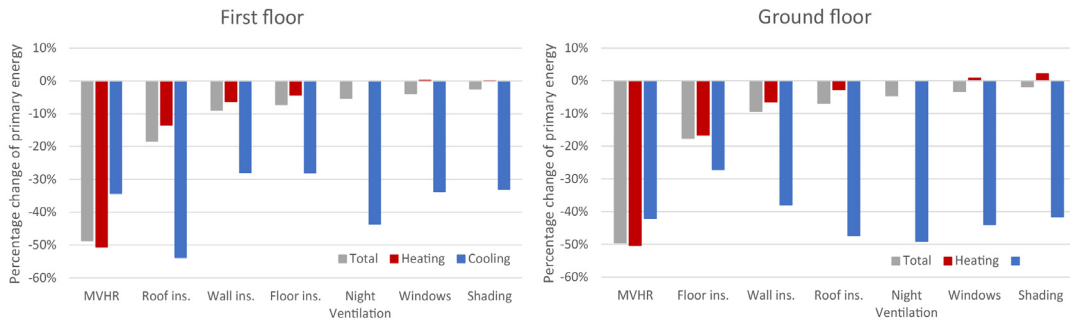

Fig. 4. The percentage change of the consumption of total primary, heating and cooling energy in the south-oriented classrooms of the first and ground floor.

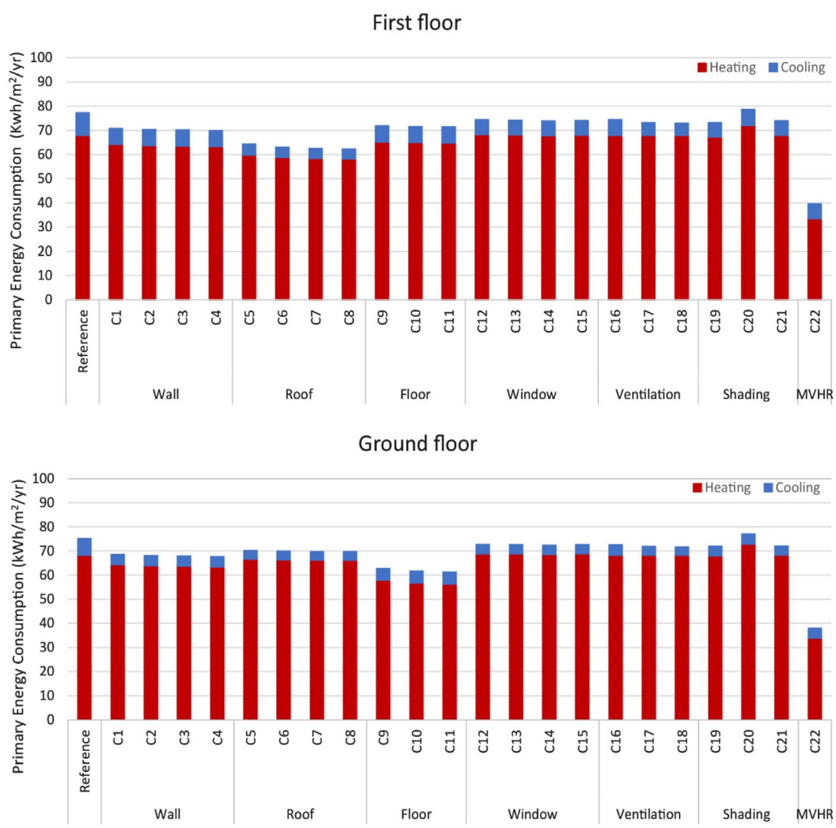

Fig. 5. Primary energy consumption of the individual retrofitting scenarios during the academic period in the south oriented classrooms of the first and ground floor.

during daytime and evening, as well as installed shading systems, provide higher global costs compared to the reference building and therefore are not considered significantly cost-effective solutions.

The MVHR retrofitting option is deemed important for both indoor conditions and air quality. The case of MVHR provides higher LCC for the 30 years of calculations compared to the reference building, i.e., €22,396 ($\Delta Cg = 10.1\%$). However, the reduction in primary energy consumption in comparison to the reference building is quite high at about 38 kWh/m^2/yr. i.e., a 49% reduction.

Fig. 7 illustrates the LCCA for the individual retrofitting approaches with different characteristics by comparing them with the reference building. As shown, the application of roof insulation has the lowest cost with a significant reduction in energy consumption in comparison to the reference building.

4.3.2. Combinations of retrofitting scenarios

After the examination of individual strategies, the final best retrofitting scenario for this building is defined using a combination of retrofitting solutions. To reduce the cases for whole building optimization, some aspects remain constant, by using the optimal case from previous examinations, especially for the interventions in construction. Specifically, the two best cases for wall and roof, as well as the best case of floor insulation, were investigated and combined with other strategies, setting up 20 scenarios. It must be noted that all combinations aimed to satisfy the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted since 2020. Combinations considered light, mild and advanced retrofitting scenarios, based on their ability to reduce the energy consumption, and to gauge difficulty of application.

All cases include MVHR, as it is important for both air quality and also for the thermal and the energy performance in school buildings. The MVHR decreases heat loss from ventilation significantly during winter and hours of discomfort, since it provides

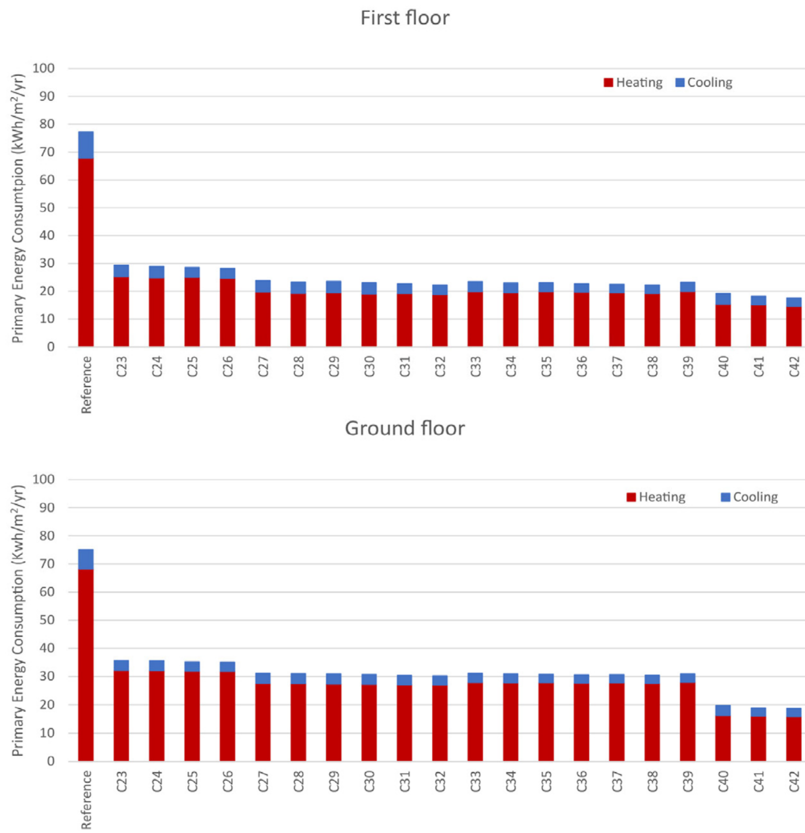

Fig. 6. Primary energy consumption of the combined retrofitting scenarios during the academic period in the south oriented classrooms of the first and ground floor.

Table 7
Energy performance, CO_2 emissions and LCCA of individual retrofitting strategies for the south-oriented classroom in the first floor.

Component	Scenarios	Annual Heating Load (MWh)	Annual Cooling Load (MWh)	Annual final cons. (kWh/m^2/y)	Annual primary energy (kWh/m^2/y)	Total CO_2 Emissions (kgCO_2/m^2/y)	Investment cost (€)	LCCA (€)
	Ref.	3.18	1.17	65.17	77.24	25.49	–	20,347
Wall	C1	3.00	0.84	60.78	70.83	22.39	1,391	20,053
	C2	2.98	0.84	60.37	70.41	22.29	1,521	20,111
	C3	2.97	0.84	60.22	70.24	22.25	1,619	20,180
	C4	2.96	0.84	59.98	69.98	22.19	1,782	20,300
Roof	C5	2.80	0.57	56.01	64.32	19.52	3,024	19,601
	C6	2.75	0.54	55.01	63.08	19.06	3,444	19,807
	C7	2.73	0.53	54.61	62.58	18.88	3,864	20,147
	C8	2.72	0.52	54.39	62.30	18.78	4,284	20,523
Floor	C9	3.05	0.84	61.75	71.90	22.67	3,808	23,334
	C10	3.04	0.84	61.50	71.65	22.62	3,920	23,402
	C11	3.03	0.84	61.40	71.54	22.60	4,088	23,552
Window	C12	3.20	0.78	64.35	74.50	23.13	3,320	21,938
	C13	3.19	0.77	64.16	74.25	23.02	4,150	22,729
	C14	3.17	0.77	63.91	73.97	22.95	4,980	23,512
	C15	3.18	0.76	64.09	74.12	22.95	5,810	24,371
Ventilation	C17	3.18	0.67	63.70	73.26	22.33	1,000	22,556
	C18	3.18	0.64	63.62	73.04	22.16	1,000	22,528
Shading	C20	3.38	0.82	67.98	78.69	24.42	1,250	23,102
	C21	3.18	0.76	63.99	73.99	22.89	2,175	25,910
MVHR	C22	1.57	0.77	32.73	39.65	13.80	4,000	22,396

controlled ventilation and ensures the required air exchange to maintain indoor air quality. In the summer period, it removes the warm air to the outside, thereby cooling the building envelope. Additionally, during the Global Covid-19 pandemic, the need for healthy educational buildings has become central to both global and local efforts to control the spread of the virus, making the provision of fresh air throughout the entire academic year not only an ideal situation to achieve in the future, but a fundamental necessity for the present day.

Scenarios C23–C24 combined, are the most effective cases in terms of energy saving, i.e., MVHR and roof insulation 10 cm and 15 cm thick. As observed, with an increase of 10% and 17% of the LCC in comparison to the reference building, the primary energy consumption is reduced by 47–48 kWh/m^2/yr, respectively. The LCC is €22,413 and €23,849 respectively (Table 8).

Table 8
Energy performance, CO_2 emissions and LCCA of combined retrofitting strategies.

Strategy Combination	Scenarios	Annual Heating Load (MWh)	Annual Cooling Load (MWh)	Annual final cons. (kWh/m^2/yr)	Annual primary energy (kWh/m^2/yr)	Total CO_2 Emissions kgCO_2/m^2/y	Investment cost (€)	LCCA (€)
	Ref.	3.18	1.17	65.17	77.24	25.49	–	20,347
Roof10 cm +MVHR	C23	1.18	0.51	24.49	29.38	9.99	7,444	22,413
Roof15 cm +MVHR	C24	1.17	0.50	24.12	28.93	9.82	7,864	23,849
Roof10 cm +MVHR+ Vent	C25	1.17	0.45	24.07	28.61	9.51	8,444	25,050
Roof15 cm +MVHR+ Vent	C26	1.15	0.44	23.71	28.17	9.35	8,864	25,398
Roof10 cm +MVHR+ Wall8cm	C27	0.92	0.51	19.47	23.86	8.53	8,965	23,389
Roof15 cm +MVHR+ Wall8cm	C28	0.90	0.50	19.02	23.31	8.33	9,385	23,719
Roof10 cm +MVHR+ Wall10cm	C29	0.91	0.51	19.23	23.60	8.46	9,063	22,352
Roof 15cm+MVHR+ Wall10cm	C30	0.89	0.50	18.77	23.03	8.25	9,483	22,681
Roof10 cm +MVHR+ Wall10cm+Vent	C31	0.90	0.45	18.80	22.80	7.96	10,063	24,987
Roof15 cm +MVHR+ Wall10cm+Vent	C32	0.88	0.44	18.35	22.26	7.77	10,483	25,318
Roof10 cm +MVHR+ Wall10cm+Window	C33	0.93	0.45	19.42	23.52	8.18	14,043	25,975
Roof15 cm +MVHR+ Wall10cm+Window	C34	0.91	0.44	18.97	22.96	7.97	14,463	26,306
Roof10 cm +MVHR+ Wall8cm+Wind.+Vent	C35	0.93	0.39	19.26	23.05	7.80	14,945	28,565
Roof10 cm +MVHR+ Wall10cm+Wind.+Vent	C36	0.92	0.39	19.01	22.78	7.72	15,043	28,617
Roof15 cm +MVHR+ Wall8cm+Wind.+Vent	C37	0.91	3.07	26.83	44.13	24.77	15,365	28,899
Roof15 cm +MVHR+ Wall10cm+Wind.+Vent	C38	0.90	0.38	18.57	22.24	7.53	15,463	28,951
Roof10 cm +MVHR+ Wall10cm+Window+ Shading	C39	0.93	0.41	19.33	23.22	7.92	16,218	31,606
Roof10 cm +MVHR+ Wall10cm+Window+ Floor5cm	C40	0.72	0.48	15.39	19.21	7.14	17,851	29,909
Roof 10cm+MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent	C41	0.71	0.38	14.89	18.17	6.43	21,026	37,325
Roof15 cm +MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent	C42	0.68	0.36	14.38	17.56	6.22	21,446	37,465

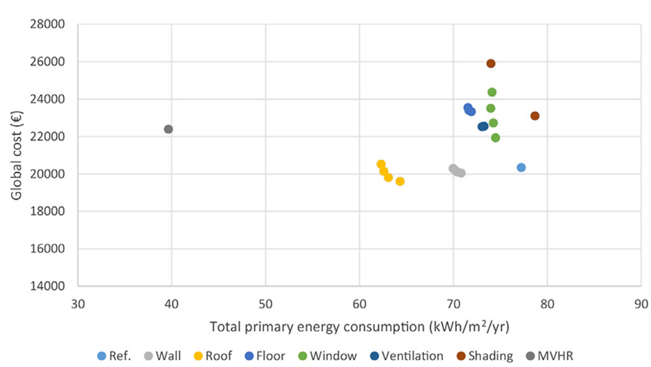

Fig. 7. Cost optimality study-comparison for different individual retrofitting scenarios.

Scenarios C27–C30 investigate the two best scenarios for wall and roof insulation in terms of the LCC, and indicate which case provides the best LCC when it is combined with the MVHR. The best-case scenario is the one with the 10 cm insulation on the roof and the 10 cm insulation on the wall, in combination with the MVHR (C29), giving the lowest LCC at €22,352. The results show that primary energy consumption is reduced by 54 kWh/m^2/year (69% reduction) for a 10% increase in LCC when compared to the reference building. Despite the investment cost being higher in comparison to the aforementioned cases, the reduction in primary energy consumption offsets this difference. Moreover, as the numbers indicate, a 10 cm wall insulation works better in terms of lowering the LCC and resulting in higher energy saving compared to the wall with 8 cm insulation. Additionally, the difference between 10 cm and 15 cm of insulation on the roof has a minor difference regarding the LCC (i.e., 1% difference) and therefore the best in terms of performance (i.e., 15 cm insulation) can be used. However, for each combination the analysis presents data for both cases to have a better overview of the performance of each scenario.

Scenarios C31–C32 include additional ventilation to the scenarios C29–C30, to identify whether greater ventilation has a higher impact on a better insulated building envelope. Again, the energy performance of these scenarios is only 1% lower compared to the C29–C30 scenarios. The LCC is about 23%–24% higher than the reference building ranging from €24,987 to €25,318, with a total reduction of primary energy of about 54–55 kWh/m^2/year.

Scenarios C33–C34 include improved windows to the ones in scenarios C29–C30, in order to achieve an optimally insulated building envelope, and to avoid condensation. To be compatible with the Law and the minimum requirements set therein, a double low-e with insulated frame window system was selected for analysis. With an increase of 28%–29% of the LCC (€25,975 - €26,306) when compared to the reference building, the reduction in primary energy consumption is minor compared to scenarios C29–C30 that do not include window replacement, i.e., only 0.2 kWh/m^2/year compared to C29–C30. Again, the combinations showed that windows are not a cost-effective solution.

Scenarios C41–C42 combine all the possible retrofit solutions, with different roof insulation, to achieve the maximum energy performance; and to identify the impact on the LCC. The results showed an increase in the LCC by about 83%–84% compared to the

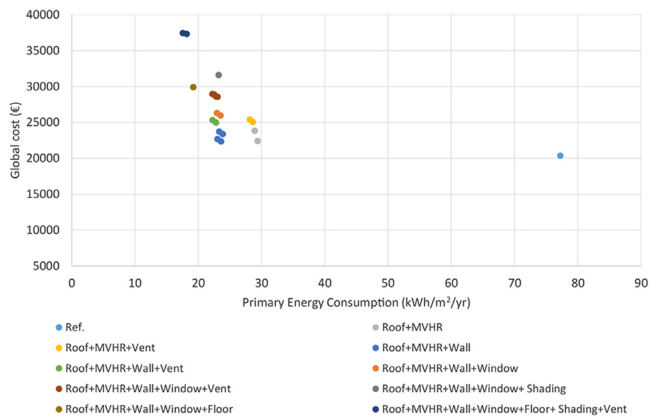

Fig. 8. Cost optimality study-comparison for different combined retrofitting scenarios.

reference building, i.e., €37,325 and €37,465; with a reduction in primary energy consumption by 59–60 kWh/m^2/year. This shows that the advanced retrofitting scenario is not a cost-effective solution for the improvement of energy performance in the case study for an educational building.

Fig. 8 illustrates the LCCA of combined retrofit approaches, for each different characteristic by comparing them with the reference building. As shown, the application of roof insulation in combination with the addition of MVHR and wall insulation has the lowest cost, with a significant reduction in consumption of energy in comparison to the building of reference. The aim of this graph is to help formulate some suggestions to select appropriate retrofitting approaches for educational buildings.

The LCCA is an important tool to support policymakers' decision-making efforts for energy upgrade. The significance of LCCA is also highlighted in the research undertaken by Belany et al. (2021), which established LCCA in lighting retrofitting for the improvement in energy of buildings. The study revealed that LCCA is a well-suited tool for the estimation of the future development in energy consumption and it can offer reasonably accurate results before the implementation of the investment itself. LCCA can help with decision making to ensure the best refurbishment solutions. Similar conclusions were presented in the study conducted by She et al. (2021), who investigated the cost and energy life cycles in zero-energy buildings by a multi-objective optimization.

4.4. Sensitivity analysis

The sensitivity analysis considered different values of discount rates and energy prices to identify the robustness of key input parameters, which can help the development of recommendations for decision makers. Additionally, the life cycle cost of adaptation measures was examined applying an all-day use scenario (assuming use of the school building for auxiliary activities outside of the educational day), to identify how the scheduling of a building's premises affects the results.

4.4.1. Discount rate at 3%

The sensitivity analysis has shown that the higher discount rate of 3% throughout the entire calculation period led to a decrease of the global cost, with reference to both the reference building and the proposed retrofitting options, increasing the risk of failure of cost-effectiveness of adaptation measures. The results for a higher discount rate agree with the research of Ascione et al. (2015) who state that a higher discount rate leads to the improvement of the cost curve; given that the global cost is lowered, however, this means a higher risk when undertaking retrofit improvements. For the present study, all the individual strategies result in higher global costs in comparison to the reference building. The global cost of the reference building was €14,246 while the global cost of the most cost-effective strategy C29 was about 30% higher compared to the reference building, i.e., €18,522 (Fig. 9).

4.4.2. Increase in the rate of increase of energy price

Variation in the energy price affected the results of the LCC. This is in accord with the study of Ganiç and Yilmaz (2014) who found that energy price is one of the main factors that influence global costs in energy retrofitting investments. A higher increase in the price of energy supports even further the selection of the most optimal environmental solutions that have lower energy demands. The increase of the price of energy leads to a higher LCC for the building in reference and a reduction in LCC for the retrofitting interventions and it can have major repercussions on the global cost, also considering the overall energy costs. This is in accord with the study undertaken by R. Amstalden and Imboden (2007)] which found that a higher energy price makes energy-efficient retrofitting scenarios an attractive investment opportunity. The LCC of C29 is 6% higher (i.e., €22,666) than the reference building (i.e., €21,390) but results in a reduction in primary energy consumption of 69% in comparison to the reference building. The second lowest LCC was the scenario where MVHR, 15 cm of insulation on the roof and 10 cm of insulation on the wall were applied (i.e., C30). The LCC of C30 was higher by only 7% compared to the reference building (Fig. 10). The sensitivity analysis shows that the higher the increase of energy price the lower the negative difference is in the LCC compared to the reference building.

4.4.3. Decrease in the rate of increase of energy price

A lower increase of energy price reduced the LCC of the reference building, as well as that of the retrofit interventions. As the rate of increase of energy price is decreased, the interventions result in a smaller cost, as the overall energy cost is decreased. This is in accord with the research conducted by R. Amstalden and Imboden (2007) who stated that for low energy price, the potential of energy efficient retrofitting strategies is relatively small. The LCC of the reference building is €19,399 (Fig. 11). In terms of the combinations, the lowest LCC compared to the reference building was provided again by case C29, where MVHR in combination with 10 cm of insulation on the roof and 10 cm of insulation on the wall were applied, with an increase of LCC at 14%, i.e., €22,067.

4.4.4. Extension of school curriculum during the afternoon

The sensitivity analysis on extending the school day has shown that adaptation measures are shown to be even more effective, especially when the curriculum is extended in the afternoon, as the difference in the LCC compared to the reference building is minimized. This is an important decision-making element that emphasizes the need for energy upgrades so that school buildings are habitable throughout the day. Specifically, this scenario (C29) reduces the primary energy demand by 69% with a small increase of global cost by 4%, i.e., €22,063 compared to the €21,917 of the reference building. The alternative to installation of 15 cm of insulation on the roof instead of 10 cm is also considered a cost-effective strategy as the difference in the LCC is minor (only 1% compared to the aforementioned scenario, i.e. €23,208) minimizing the energy request by 70% (Fig. 12). When considering future energy price increases, LCC of C29 (under an extended curriculum) results in a performance similar to that of the reference building.

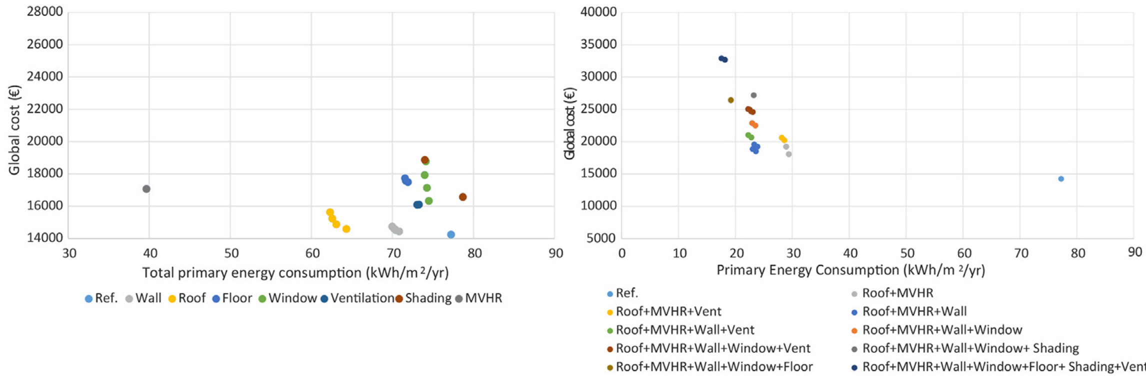

Fig. 9. Comparison of cost optimality study for different individual and combined retrofitting scenarios for a fixed discount rate of 3%.

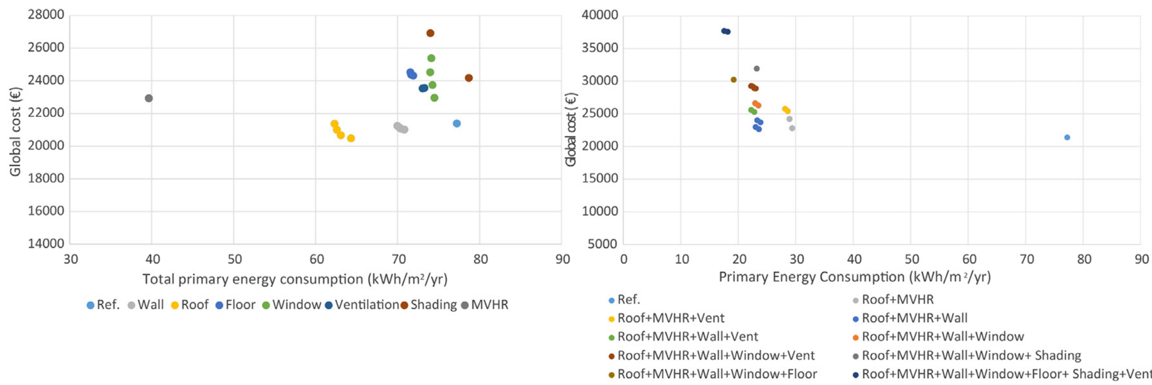

Fig. 10. Cost optimality study-comparison for different individual retrofitting scenarios for an additional increase of 0.5% in the rate of increase on the energy price.

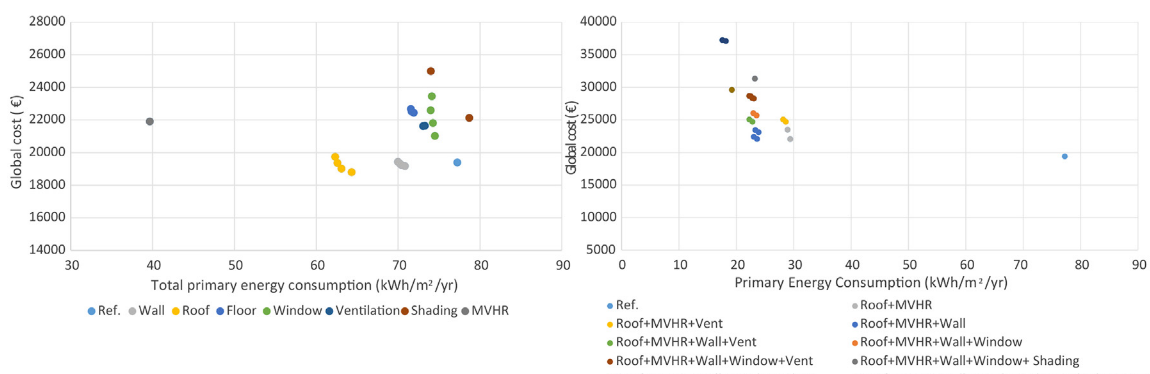

Fig. 11. Cost optimality study-comparison for different individual and combined retrofitting scenarios for a decrease of 0.5% in the rate of increase of the energy price.

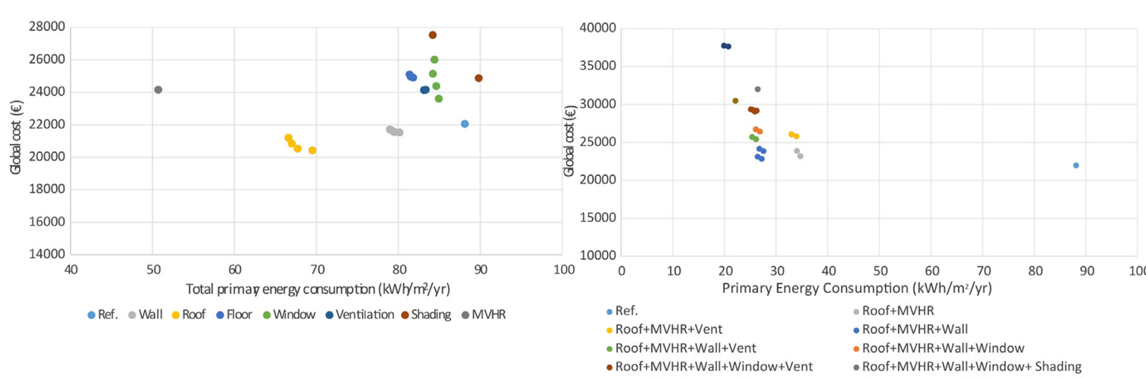

Fig. 12. Cost optimality study-comparison for different individual and combined retrofitting scenarios for occupied hours 07:30–13:35 and 14:45–18:00..

The results presented above highlight that the choice of input parameters is very important, and the use of the LCC methodology can be a valuable tool for delivering sustainability, provided it is expertly applied. This is in line with the research of Kurnitski et al. (2011) who state that results of the cost optimal analysis were sensitive to the rate of discount and the appreciation of energy prices. Moreover, based on the study of Ganiç and Yilmaz (2014) every step in the cost analysis needs to be analysed at the national level.

5. Conclusions

This paper aims to provide a holistic solution for designing energy retrofitting proposals for educational buildings in Cyprus, capable of integrating suitable standards and methodologies. The aim was to inform decision-making and support policymakers to identify poor energy performance in educational buildings, and determine whether lowering energy demand and associated greenhouse emissions in these buildings was possible and/or economically feasible. More precisely, the research assessed the effectiveness of different retrofitting measures and evaluated their effect on the energy performance of educational buildings. Using an IES-VE calibrated dynamic thermal simulation model, the impact of minimizing LCC (specifically reducing the need for energy consumption) was examined through the geometry of the building, the construction, and the operation. The approach combined modelling energy demand and the ranking of retrofitting options with LCCA. Moreover, the study identified the influence of different values of key factors such as the discount rate, energy cost and considerations for different hours of operation for educational buildings in Cyprus. The main findings of the study are listed below:

- Based on energy ranking, the most effective strategy for reducing energy use was installing mechanical ventilation, with a heat-recovery feature, achieving a decrease of primary energy consumption by 49%; followed by the installation of insulation on the roof, with a primary energy reduction of 18%; and the installation of insulation on the wall with a primary energy consumption reduction of 9%. Based on the LCCA, the strategies outlined above are considered as the most cost-effective solutions.
- Increasing ventilation rates up to 1000l/s overnight, replacing the windows with more technologically efficient solutions, and additional shading devices on the south-oriented classrooms have a low effect on the energy performance of educational buildings.
- Combined retrofitting scenarios achieved energy demand savings of between 62%–77% in the educational building under study, depending on the retrofitting scenario. More specifically, 10 cm of insulation on the roof and walls combined with MVHR (medium retrofitting scenario) reduced energy consumption by 69%, with a small increase of the global cost by 10% in a real interest rate. However, the retrofitting scenario that incorporated all the possible combined measures does not produce higher economic profits in the long-term, as it may well increase the LCC by 84%.
- The sensitivity analysis regarding the increase of the discount rate to 3% has shown that the retrofitting measures have a higher risk, as the difference of LCCA in relation to the reference building becomes higher. Overall energy costs have the biggest impact on LCC. The sensitivity analysis revealed that the optimal energy and environmentally-concerned solutions are the most cost-optimal solutions as well.
- The sensitivity analysis regarding the duration of school hours has shown that adaptation measures are considered even more effective when the hours are extended during the afternoon, as the difference in the LCCA compared to the reference building is minimized. Moreover, considering a further increase of energy prices in the future, LCC is almost the same with the reference building for an extended school hourly programme.

In conclusion, the results underline that the selection of the parameters of input is highly significant. The aim of this study is to add valuable knowledge in the field of energy upgrades of educational buildings in Cyprus quantifying the effectiveness of measures in terms of energy efficiency and life cycle cost. The implementation of cost-optimal methodologies can support policymakers' decision-making efforts, allowing them to identify and plan for the sustainable retrofitting of buildings, as demonstrated by this case study which has applied the methodology to educational buildings in Cyprus. The results of the present study can be used for the energy upgrade of educational buildings that share the same typological and climatic characteristics as well as in the design of new buildings. Finally, the recommendations from this study include a pilot framework for future ministry-based analysis and on-site implementations.

CRediT authorship contribution statement

C. Heracleous: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **A. Michael:** Writing – review & editing, Supervision. **A. Savvides:** Writing – review & editing, Supervision. **C. Hayles:** Writing – review & editing, Supervision.

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.

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