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Energy Performance Simulation of "Constantin Xenakis Art Gallery"

ARISTOTLE UNIVERSITY OF THESSALONIKI

TRANSPORT SYSTEMS RESEARCH GROUP

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Contents

1. Introduction

The work object of deliverable D 4.4.3a, is to perform a detailed energy simulation in a museum case study in the city of Serres in Greece and to evaluate the energy performance of the building after its renovation towards nearly zero energy consumption (NZEB – consumption of primary energy below 60 kWh/m2). The building that was chosen, dates back to the Ottoman period, is located in a former military camp at the southeast area of the city of Serres at climate zone C, and after its restoration and renovation is transformed into a Thematic Museum which hosts the modern art collection of Constantin Xenakis.

The energy performance simulation of the Contemporary Museum 'Art Gallery "Contantin Xenakis" was carried out with the help of two collaborating energy simulation tools, EnergyPlus and DesignBuilder. DesignBuilder is a software with a friendly graphical interface which allows the visualization of complex three dimension building models, while possessing a comprehensive data input layout. It's an integrated building simulation software for energy performance, which is built upon the simulation engine of EnergyPlus, while incorporating all its capabilities.

Due to its unique structural design and its energy consumption diversities between its internal spaces, the museum was separated into three distinct conditioned thermal zones, according to the same operational schedules, same HVAC systems and interior conditions such as temperature set-points etc. The simulation was performed with four time steps per hour, evaluating the energy consumption of the base building and the proposed energy improvement scenarios.

The input data for the museum was extracted through architectural plans, electromechanical data, information provided by the technical supervisor team and building construction team, while following the Greek regulation (KENAK) and its technical guidelines when the data was insufficient (TOTEE 20701-1/2017) simulating the building's real energy consumption.

All input data that was imported into the simulation software is listed in tables, along with schematics and figures, and the energy simulation performance of the Art Museum C. Xenakis is documented in net and source energy for better understanding and evaluation.

Structure of the deliverable "D 4.4.3a"

Chapter 1: In the first chapter, general information about the project is provided, along with general information about the deliverable content.
Chapter 2: In the second chapter, general information about the Museum C. Xenakis is provided which includes topographic features (location, site plans), geometric features (construction details, building plans), weather data and HVAC system characteristics.
Chapter 3: In the third chapter, information about the two energy simulation tools that were utilized in this project, is provided. Also, in this section, the methodology that was followed is described and the data that was input in the simulation engine is presented.
Chapter 4: In fourth chapter, the building's energy performance simulation is conducted and the results are presented in tables and graphs.
Chapter 5: In the final chapter, a brief review of the deliverable is made and a final evaluation of the project is carried out.

2. Case Study – Art Museum Constantin Xenakis

2.1 Location

The renovated building which now hosts the modern art collection of Constantin Xenakis, was originally constructed at the beginning of the 20th century during the Ottoman era with eclecticism as architectural approach, rendering it, according to Greek legislation, as a traditional preserved edifice, prohibiting that way any alteration of its external features.

The C. Xenakis Museum is located in a former military camp at the southeast area of the city of Serres, with 41,09^0 latitude and 23,55^0 longitude, completely exposed to the outside environmental conditions, with the dense tree planting as the only natural barrier for the wind and sun. The tall trees provide a natural shading throughout the year, allowing only a small portion of the solar energy to reach the facades of the building.

There are two entrances in the site where the Museum is located, one in the north west side and the other one in the south west. The building was constructed in a ground surface with a slight slope (~2%) oriented from North to South and the main entrance is located to the north east side of the building. The location of the C. Xenakis Museum is presented in figures 2.1 and 2.2.

Figure 2.1 – Location of the C. Xenakis Museum *[Source: Electronic services of National Land Registration of Greece. Internet page: gis.ktimanet.gr, aerial photographs of years 2015-2016.]*

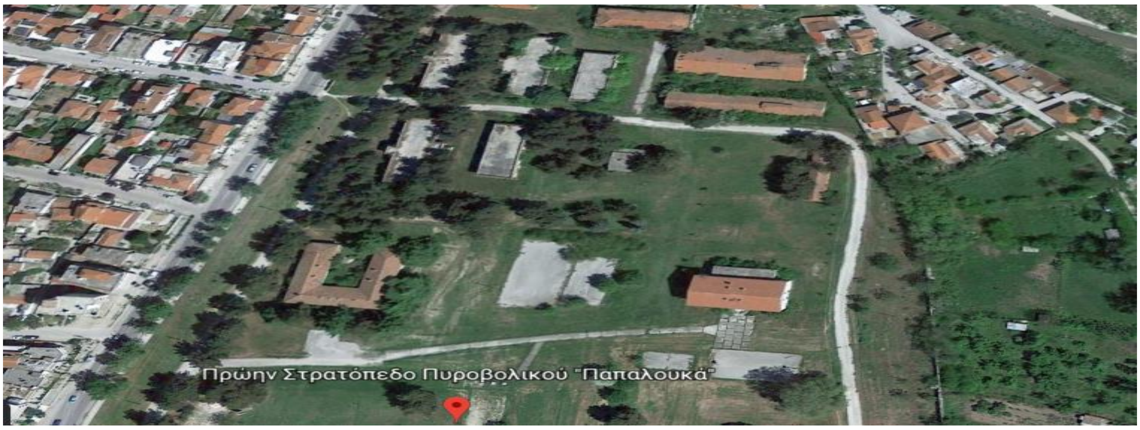

Figure 2.2 – Location of the C. Xenakis Museum of year 2022. *[Source:* https://www.google.com/maps/place/Πρώην Στρατόπεδο Πυροβολικού "Παπαλουκά"]

2.2 Climatic data

The C. Xenakis Museum is located at the southeast area of the city of Serres, which belongs in Climate Zone C out of the 4 distinctive Climate Zones (A, B, C or D) according to the Greek regulation. The climatic data for that area is summarized in the table 2.1, while the following diagrams 2.1 – 2.6 present the annual weather conditions. More specifically,

- the average annual site outdoor air dry bulb temperature is 15,24 ^oC, the minimum average value of months is 3,51 ^oC on January and the maximum average value of months is 26,96 ^oC on July,
- the maximum site outdoor air dry bulb value of temperature of each month ranges between 16,70 ^oC and 39,50 ^oC. The highest value (39,50 ^oC) is recorded on July, and the lowest value (16,70 ^oC) is recorded on January.
- the minimum site outdoor air dry bulb value of temperature of each month ranges between -7,70 ^oC and 16,20 ^oC. The lowest value (-7,70 ^oC) is recorded on January, and the highest value (16,20 ^oC) is recorded on August.
- the site's average annual wind speed is 1,87 m/s, while the maximum of moths is observed on March at 2,20 m/s, and the minimum of months at 1,59 m/s on October.
- the average diffuse solar radiation rate per area for the site is 73,96 W/m^2, the maximum of months is 109,48 W/m^2 on June and the minimum is 33,37 W/m^2 on December.
- the average direct solar radiation rate per area is 186,87 W/m^2, the maximum of months is 282,58 W/m^2 on July and the minimum is 102,41 W/m^2 on December.

Table 2.1 Geographical and climatic data C. Xenakis Museum

Latitude	41,09°
Longitude	23,55°
Elevation above sea level (m)	51
Standard pressure at elevation (Pa)	100714
Average annual site dry bulb temperature (^oC)	15,24
Maximum annual site dry bulb temperature (^oC)	39,50
Minimum annual site dry bulb temperature (^oC)	-7,70
Average annual site wind speed (w/s)	1,87
Average annual site diffuse solar radiation (W/m^2)	73,96
Average annual site direct solar radiation (W/m^2)	186,87

**The climate data that were used in the simulations of the C. Xenakis Museum were created using the meteorological data of Meteonorm software which contain climatological data of every location on the globe. The climatological data of the location of Serres were processed and imported into the simulation software DesignBuilder.*

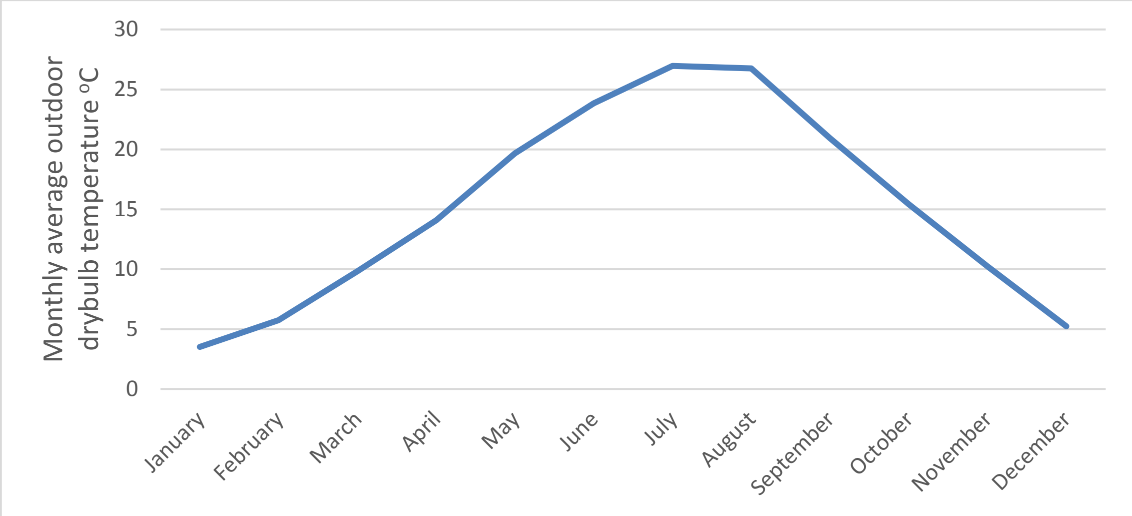

Diagram 2.1 – Monthly site average outdoor drybulb temperature °C of C. Xenakis Museum

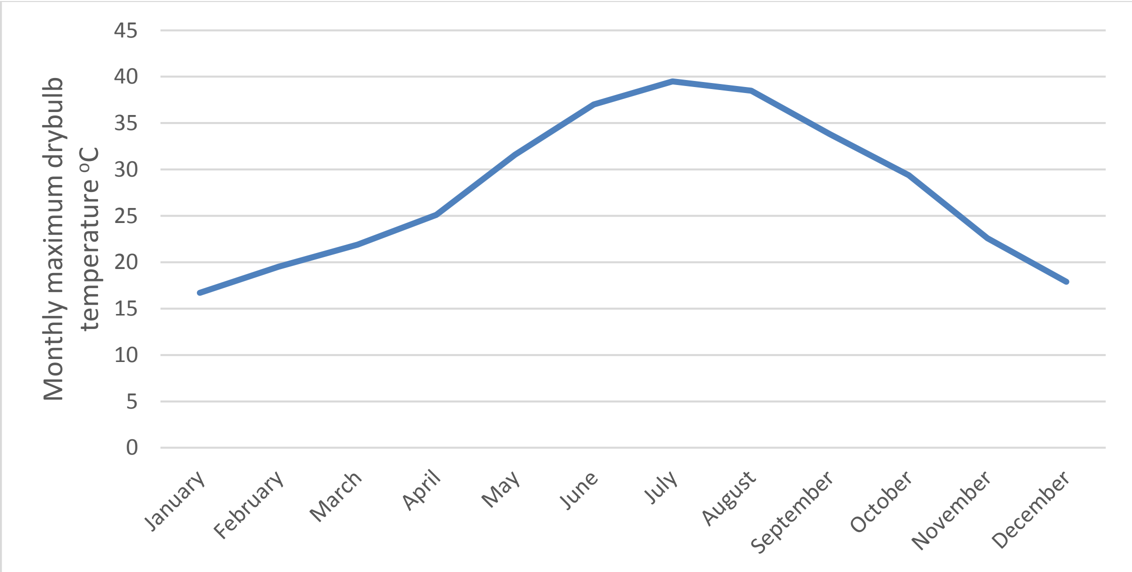

Diagram 2.2 – Monthly site maximum outdoor drybulb temperature °C of C. Xenakis Museum

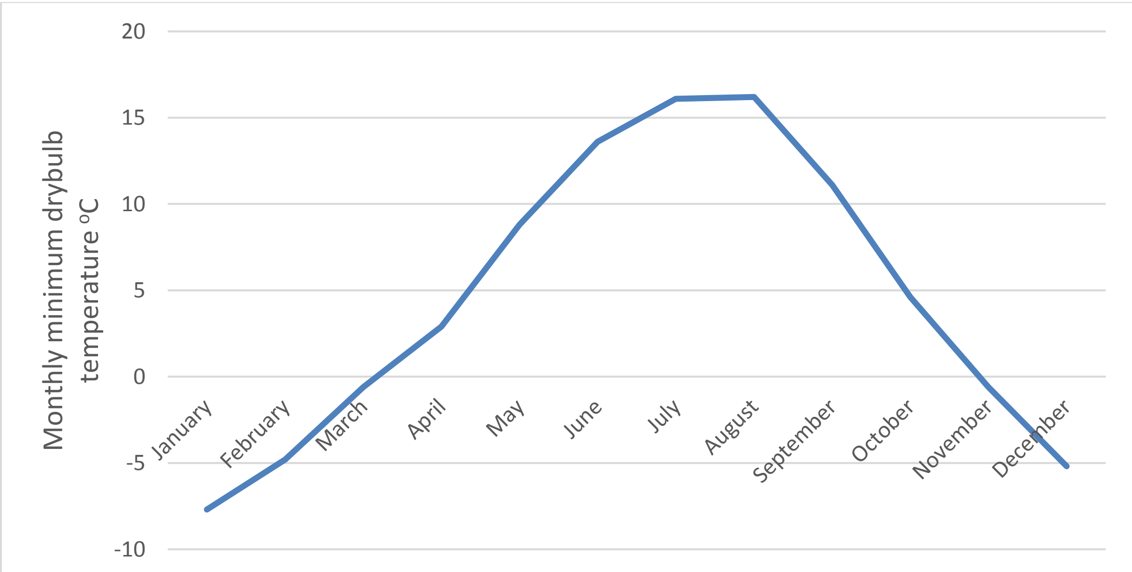

Diagram 2.3 – Monthly site minimum outdoor drybulb temperature °C of C. Xenakis Museum

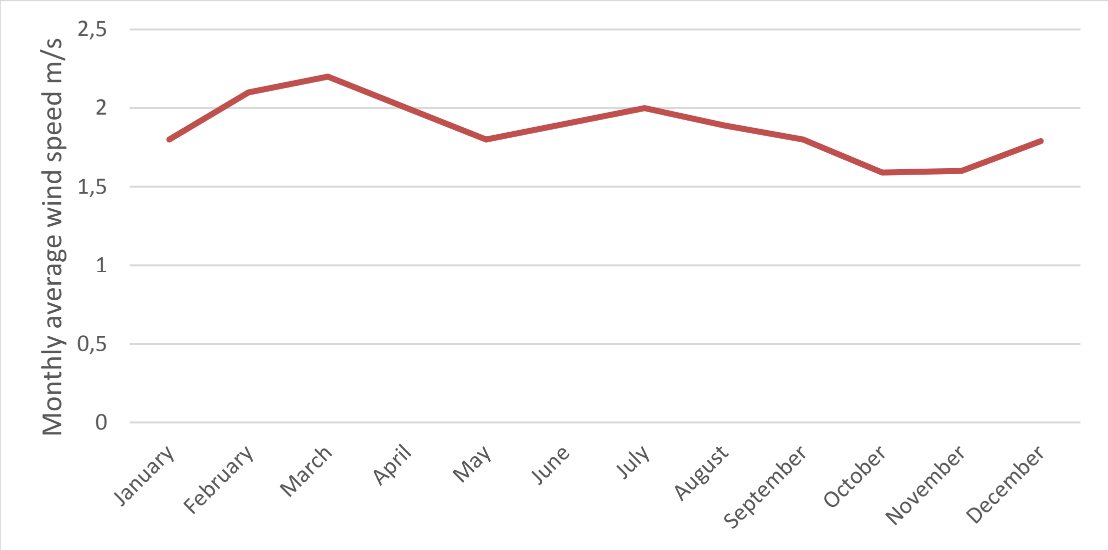

Diagram 2.4 – Monthly site average wind speed of C. Xenakis Museum

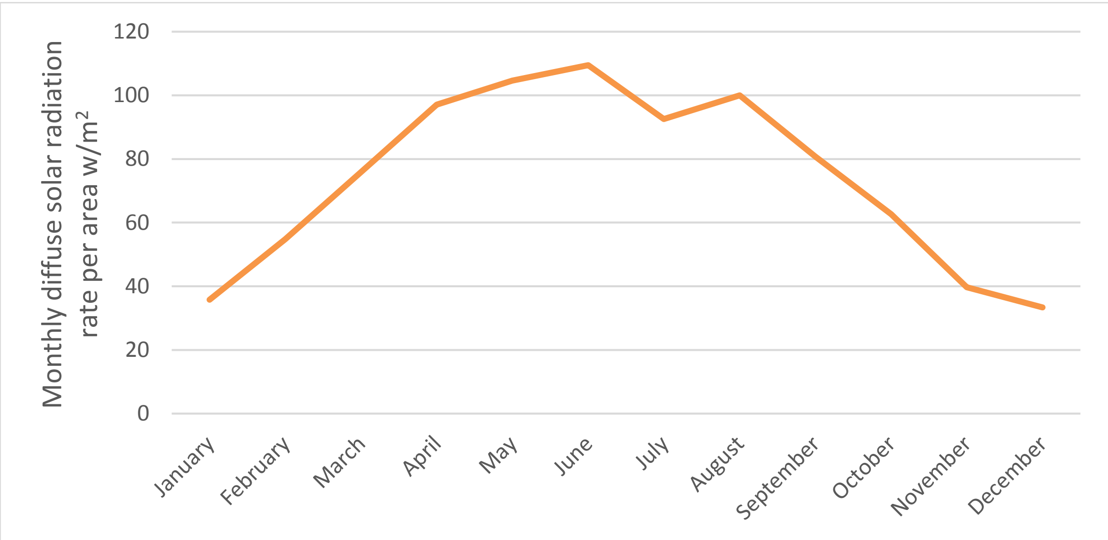

Diagram 2.5 – Monthly site diffuse solar radiation rate per area W/m^2 of C. Xenakis Museum

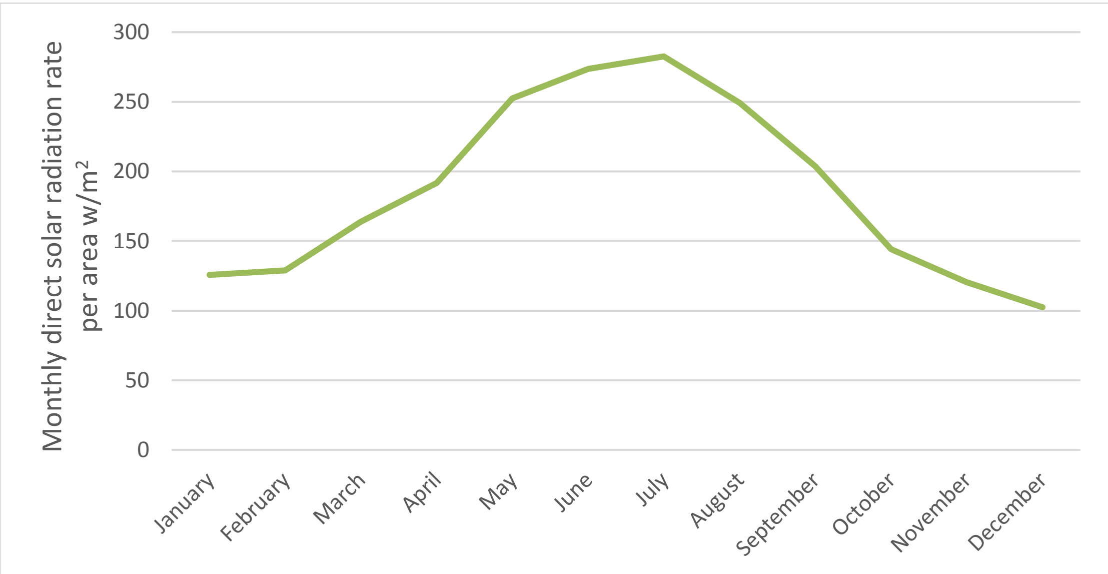

Diagram 2.6 – Monthly site direct solar radiation rate per area W/m^2 of C. Xenakis Museum

2.3 General information of Museum C. Xenakis

2.3.1 Building description – Site area – Plans

The C .Xenakis Museum is part of a total group of eleven buildings in the military compound of "Papaloukas" in Serres. The total site area is around 124.000 m^2 which is intended for reconstruction and redevelopment and is easily accessible from its two entrances at the north west side and south west. At the west side, it borders the old ring road of Serres, at north side a residential area the while at the east and south side there are unconstructed areas.

Figure 2.3 – Site plan of C. Xenakis Museum

The total area of the building is 651,91 m^2 and the total height of the examined conditioned area (from the outside layer of ground floor till the outside layer of the roof) is 4,85 m. The total volume amounts to 3.176,77 m3.

It is a single floor building with a slab roof, upon a ground surface with a minor slope of around 2%, and its two elongated sides are orientated in 25^0 from true North.

Figure 2.4 – Orientation of C. Xenakis Museum from true North

It is composed of one rectangular shaped main body of 568,30 m^2 and its two smaller side projections in the north east and north west side of the building accounting for 68,30 m^2 and 15,40 m^2 respectively.

In the following figures 2.5 – 2.9, the floor plan of the Museum and its facades of all its sides can be found.

The Museum will operate 6 days per week for 5 hours and will able to accommodate more than thirty visitors for two to five hours per day. Also, the Museum C. Xenakis will remain available for the public and will be able to host educational programs for schools or visitors for six days per week throughout the year.

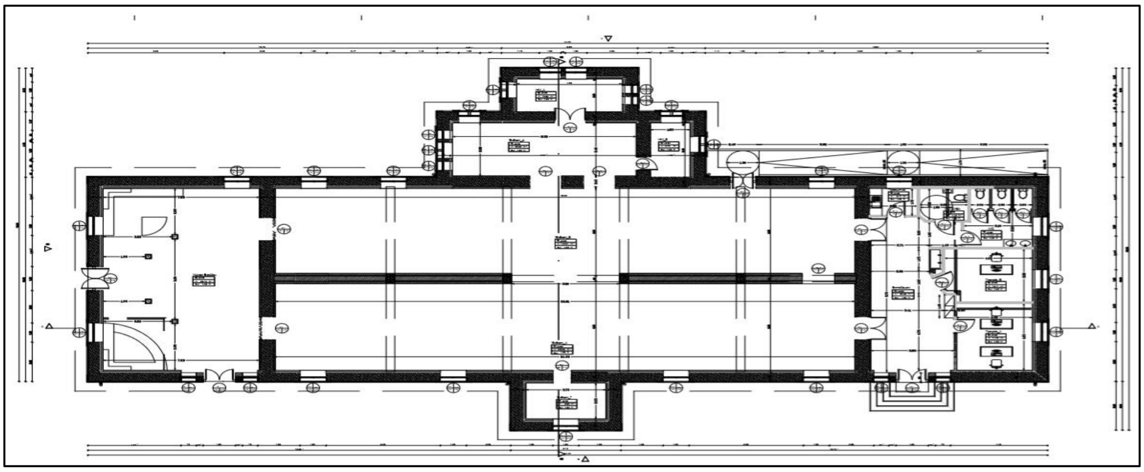

Figure 2.5 – Floor plan of Museum C. Xenakis

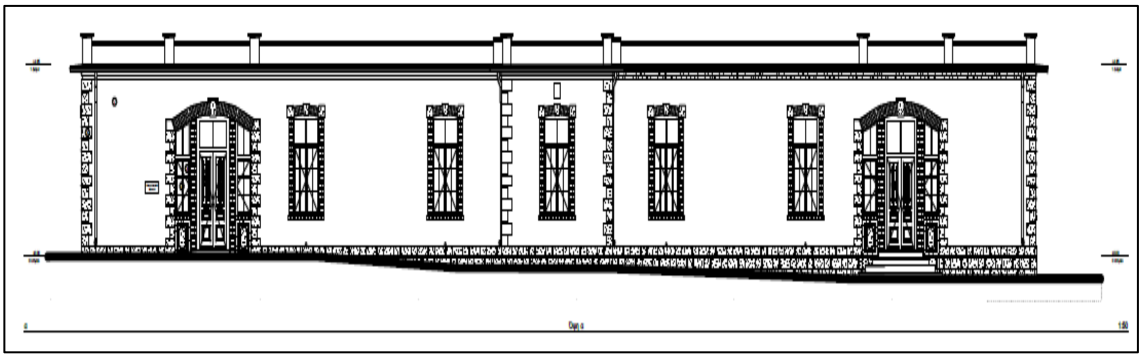

Figure 2.6 – North West façade (Façade A) of Museum C. Xenakis

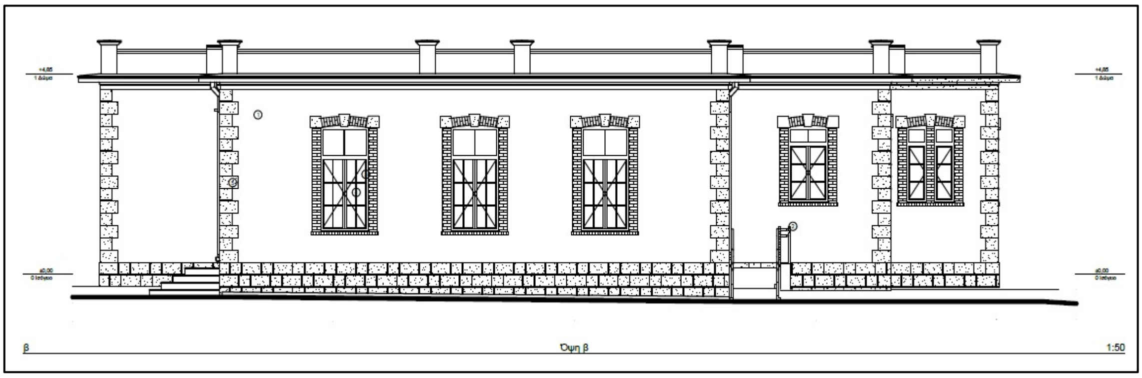

Figure 2.7 – South West façade (Façade B) of Museum C. Xenakis

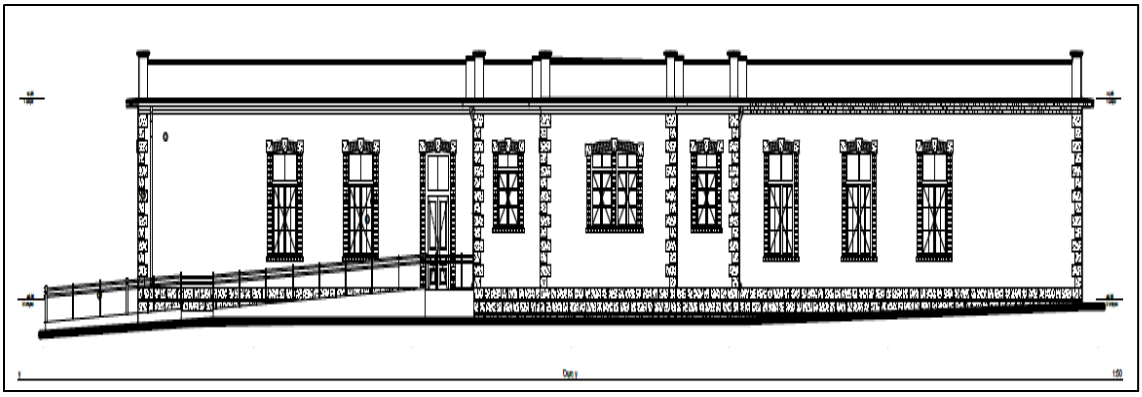

Figure 2.8 – South East façade (Façade C) of Museum C. Xenakis

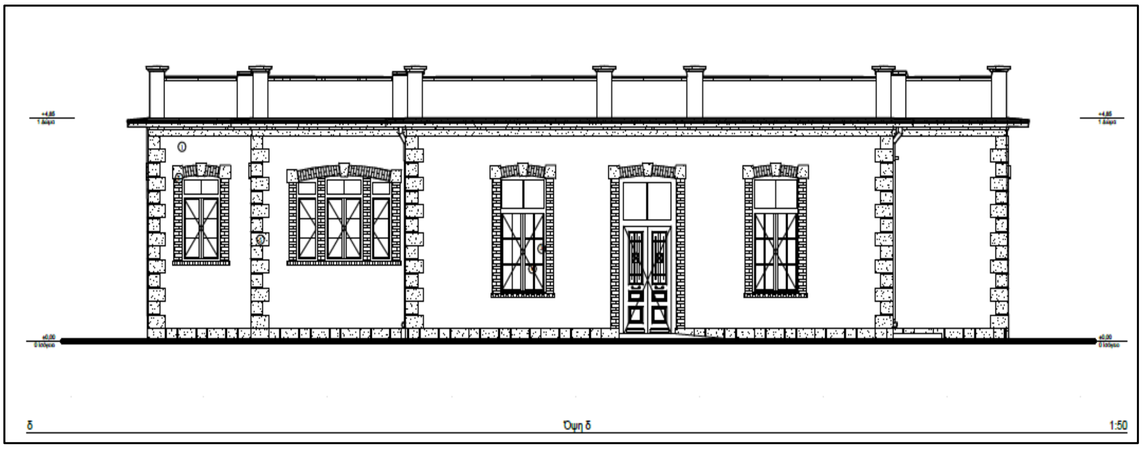

Figure 2.9 – North East façade (Façade D) of Museum C. Xenakis

The table 2.2 summarizes the Museum's total floor area and volume.

Table 2.2 – Floor area and volume of Museum C. Xenakis

Floor	Area, m²	Floor Height, m	Volume, m³
Floor area of Museum C. Xenakis	651,91	4,85	3.176,76
Conditioned Spaces	651,91		3.176,76
Unconditioned Spaces	0		0

2.3.2 Construction details

The exterior wall of the Museum was constructed with limestone covered by an outer and an inner mortar coating. During the renovation, due to the prohibitions of the Greek legislation about traditional buildings, the outer coating of the building was carefully repaired and restored, while a layer of an 8 cm insulation of mineral wool (MW) was added to the interior of the building's walls. The insulation was covered by a gypsum plasterboard which was rendered with a pasty mixture, colored according to museum's standards. The total thermal transmittance (U-Value) of the exterior wall after the renovation is 0,336 W/m^{2}K, satisfying the threshold limits (U-value 0,45 W/m^{2}K) for external walls of new Greek regulation (KENAK) for renovated buildings.

The roof of the Museum was a Zoellner type flat roof covered by cement-sand mortar and old asphaltic membrane at the outer side, which were removed during the renovation of the building. A perlite concrete layer was added above the Zoellner slab, and was covered by a waterproof asphaltic membrane. At the inner side of the roof, a metallic grid with a layer of cement-sand mortar was applied to strengthen the slab, while a layer of a 10 cm of extruded polystyrene (XPS) was added for insulating purposes. The thermal transmittance (U-Value) of the roof after the renovation is 0,240 W/m^{2}K, satisfying the threshold limits (U-Value 0,40 W/m^{2}K) for roofs of new Greek regulation (KENAK) for renovated buildings.

The floor of the Museum was a reinforced concrete slab covered by an inner mortar coating. After the renovation, a layer of cement sand mortar, a 5 cm insulation of extruded polystyrene (XPS) were added to the interior of the building, covered by marble tiles. The thermal transmittance (U-Value) of the ground floor after the renovation is 0,543 W/m^{2}K, satisfying the threshold limits (U-Value 0,75 W/m^{2}K) for ground floors of new Greek regulation (KENAK) for renovated buildings.

Initially, the building had single glazed windows, with old wooden frame. After the renovation, the windows were replaced with double glazed 4mm-16mm with argon 90%-4mm with Low-E coating, maintaining the wooden material for the frames due to the prohibitions of the Greek legislation about traditional buildings. The thermal transmittance (U-Value) of the openings after the renovation is 1,30 W/m^{2}K, satisfying the threshold limits (U-Value 2,80 W/m^{2}K) for openings of new Greek regulation (KENAK) for renovated buildings.

Table 2.3 – Construction details of Museum C. Xenakis

	Construction details (layers)	(U-Value)
Exterior wall	• Cement-sand mortar coating • Limestone • MineralWool (MW) • Gypsum board • Pasty finish render	0,336
Flat roof	• Waterproof asphaltic membrane • Perlite concrete • Zoellner type slab (Reinforced concrete with brickwork) • Cement-sand mortar coating • Extruded polystyrene (XPS)	0,240

Ground floor	• Unreinforced concrete or lightly reinforced • Extruded polystyrene (XPS) • Cement sand mortar • Marble tiles	0,543
Openings(windows/doors)	• Wooden flamed, double glazed 4mm-16mm argon 90%-4mm with Low-E coating • Light transmission: 61% • Total solar transmission: 37%	1,300

**In the Appendix 1 of the deliverable, the calculations of U-Value of the construction elements are presented.*

2.3.3 Lighting

The Museum C. Xenakis has 146 anti-glare LED Gu10 lights 7,5 W, distributed throughout the spaces of the building (exhibition room, offices, entrance, educational room and auxiliary spaces) separated in three types: surface mount, recessed and suspended. The total power density of the install capacity is measured at 1,1 kW and operate according to the time schedule of the museum. In the table 2.4, the lightning elements of the museum are presented.

Table 2.4 – Lighting elements of Museum C. Xenakis

Lamp Type	No of Lamps	Hours of Operation	Installed Capacity (kW)
Surface mount anti-glare Led Gu10 7,5W	120	5 hours	0,90
Recessed anti-glare Led Gu10 7,5W	18	5 hours	0,14
Suspended anti-glare Led Gu10 7,5W	8	5 hours	0,06
Total Led Lights	146	5 hours	1,1

2.3.4 HVAC systems

The building initially didn't have any heating, cooling or ventilation equipment so after the renovation, new highly efficient HVAC systems were installed to the Museum. A Ground Source Heat Pump (GSHP), also known as geothermal heat pump, was chosen to cover the heating and cooling needs of the Museum C. Xenakis, and two similar heat recovery units with cross-flow heat exchanger were installed for mechanical ventilation.

Due to the fact that the surrounding area of the museum was sufficient enough to accommodate a ground source heat pump, a slinky type, horizontal closed loop system was installed. The horizontal closed loop system consists of a pipe network with dedicated fluid circulation loop, buried in the soil, in order to exchange energy through the undisturbed temperatures of the ground according to the depth. At the north east side of the Museum C. Xenakis, occupying as less space as able, 35 trenches, at 1,2 m depth, were created to install the loop. The total length of the loop with the trenches is around 8.750 m.

2.3.4.1 Heating System

The Ground Source Heat Pump has heating capacity 58 kWth (58.220 W) with high COP at 3.8 and is able to meet the needs of the spaces of the Museum C. Xenakis for heating, providing hot water at 50 ^{o}C. The hot water loop consists of a two pipe system (supply and return), distributed from the heating collector to Fan Coils Units (FCU) located in each space of the Museum, three of which are installed in the floor of the educational room and auxiliary spaces, two are installed in the floor in the offices and four are installed in the interior roof in the exhibition room, presented at table 2.5.

2.3.4.2 Cooling System

The Ground Source Heat Pump is also operating to cover the required cooling loads of the building. The cooling capacity of the heat pump is 52 kWco (52.608 W) with high EER at 4.8 and is able to provide cold water at 7 ^{o}C. The chilled water loop includes a two pipe system of supply and return which provides chilled water to cooling coils inside the Fan Coil Units (FCU). The cooling collector distributes the cold water to all the terminal units in each space of the Museum, presented at table 2.5.

Table 2.5 – Terminal Units (FCU) of Museum C. Xenakis

Location	Number	Type	Air Flow	Cooling Capacity	Heating Capacity
			(m^3/h)	Kw	kw
Office	2	Floor FCU	550	3,2	4.2
Public rooms (educational room, entrance and auxiliary spaces)	3	Floor FCU	550	3,2	4.2
Exhibition room	4	Roof FCU	2.400	10,0	14,0

2.3.4.3 Mechanical Ventilation

For mechanical ventilation, two heat recovery units with cross-flow heat exchanger were installed with motor power 0,676 kW, each proving 2.000 m^3/h of fresh air, covering the ventilation requirements of the exhibition area of the museum. A supply ductwork begins from each air – air heat exchanger which is connected to the terminal units inside the exhibition room (FCUs located at the interior of the roof) for the distribution of the air while the air is extracted out of the space though a return ductwork. During this circulation, the two air flows of different temperatures pass through the heat exchanger, transferring heat between the fresh incoming air and the exhausted air, resulting to high energy saving.

3. Energy performance simulation methodology and inputs

3.1 Energy performance simulation tools

3.1.1 Energy Plus

The software that was used for the energy simulations for the Museum C. Xenakis is Energy Plus. Energy Plus is an integrated building energy simulation software which was developed by the U.S. Department of Energy (DOE) in collaboration with National Renewable Energy Laboratory (NREL) and other national and private research institutions, and is widely used by design engineers, researchers, architects and energy modelers (EnergyPlus™). It is a free energy simulation tool which underwent a series of updates since its initial creation and incorporates the capabilities of its predecessors BLAST and DOE-2. During the development of the software, Energy Plus has been tested through various standard methods in order to strengthen its validity. The tests focused on three major categories, analytical tests including HVAC and building fabric tests (ASHRAE), comparative tests (ANSI/ASHRAE, IEA SCH, BESTest) and release and executable tests (BESTest) (Castell A.,Solé C., 2015).

Figure 3.1 – Energy Plus software [Source: Energy Plus internet site, www.energyplus.net]

Energy Plus is a complete energy simulation and thermal analysis tool for building envelope characteristics, real climate data, HVAC systems, shading, physical and artificial lighting, equipment, moisture and water use, and is able to conduct simulations at user defined time-steps of even less than an hour (Castell A.,Solé C., 2015).

The software allows a detailed definition of building geometry model, considering calculations for construction details (external and internal building elements, windows, ground domain, structure arrangement) while three-dimensional shading components (external and local) are taking into account, including calculations for daylight control, interior illuminance, glazing and solar penetration (Md. Faruque Hossain, 2019). Furthermore, the user is able to create and insert their own weather data in the software for a much more precise energy simulation of the building's location. The weather file proving the geographic location of the examined area, is able to determine the sun's position throughout the year and can contain annual data for dry and wet bulb temperatures, wind speed, air humidity, etc. along with sky modeling for solar radiation calculations (Corrado V., Enrico Fabrizio E., 2019).

Amongst its other capabilities, Energy Plus incorporates a heat air balance solution method taking into account the radiant and convective effects that generate temperatures in the interior and exterior surfaces of the building's envelope. Also, the software, includes a heat and mass transfer model, that is able to simulate the movement of the air between the thermal zones (Chowdhury A. A. et al., 2016).

One of the main strengths of the Energy Plus software is the highly sophisticated simulation of the HVAC systems. Heating, cooling and ventilation systems can be designed in simple or detailed way. The main components of the HVAC systems are: hot and chilled water loops, air loops, condenser loops, solar loops, domestic hot water loops, zone controls, and terminal units. Each loop is created with supply (boiler, chillers, cooling towers, water heaters) and demand nodes (hot and chilled water coils) which are connected to the installed terminal units (convectors, FCUs, AHUs, etc.). The user is able to insert a large number of input data including performance curves, capacities, flow rates etc (EnergyPlus™).

3.1.2 DesignBuilder

Even though Energy Plus is one of the most complete, available for use, software for energy simulation, it still remains without a graphical interface. For that reason, many third parties created user friendly interfaces in order to allow a much easier building structure design and simplified data input, such as the DesignBuilder.

Figure 3.2 – DesignBuilder software [Source: DesignBuiler internet site, https://designbuilder.co.uk/]

DesignBuilder is an easy to use software which combines a friendly graphical interface for complex three dimension building models along with a comprehensive data input layout. Users are able to design highly detailed building compounds with their boundary conditions rapidly, while navigating through its tabs to insert data easily and accurately. Its main strength it's the visualization of all the applied data in the model: the building structure and the site as a whole, the shading compounds,the construction elements, the climate data, the HVAC systems and its connections, the operating schedules, setpoints etc.

DesignBuilder is built upon the Energy Plus simulation engine and it updates according to latest versions. So, it's an integrated building simulation software for energy performance, taking into account all parameters which are incorporated in Energy Plus such as building envelope, climate data, HVAC systems, mechanical and natural ventilation, activity schedules, setpoint temperatures, heat gains and losses, internal loads, miscellaneous equipment, etc. while providing visualization and simplicity to the model (DesignBuilder).

The software that was used for the model design and data input for the Museum C. Xenakis is the DesingBuilder.

3.2 Building geometry construction – Thermal zone separation

In order to design the building's geometry in the DesignBuilder software, it was important to determine the thermal zones. According to the Greek regulation and its Technical Guidelines (TOTEE 20701-1/2017), it is important to separate the building into different thermal zones when the following conditions are met

- There are zones with different use, operation characteristics or operation conditions (temperature, humidity, fresh air, etc.)
- There are zones in the building which are conditioned by different HVAC system due their different interior conditions.
- There are zones which demonstrate large amounts of energy transfer (solar gains, thermal losses) in comparison with the other sides of the building such as south oriented zones.
- The temperatures setpoint in the zones differ by more than 4 ^oC in comparison with the other sides of the building.
- There are zones where the mechanical ventilation system provides less fresh air than the 80% of the total area of the zone.

According to the aforementioned suggestions, and due to its unique structural design, the Museum C. Xenakis, was separated into three different conditioned thermal zones which demonstrate distinct use and activity schedules, HVAC systems and temperature setpoints. The conditioned zones are: 1) Public Spaces (Educational room, entrance and auxiliary spaces), 2) Exhibition room, and 3) Office. Inside the building, there is an unconditioned area of around 60 m^3 were the mechanical equipment is located, which was included the Exhibition room thermal zone, according to the Greek regulation and its Technical Guidelines (TOTEE 20701-1/2017), spaces with volume less than 10% of the total volume of the building can be integrated into other zones.

The figures 3.3 and 3.4 present the design of geometry of the building compound of the Museum C. Xenakis and its site in DesignBuilder software.

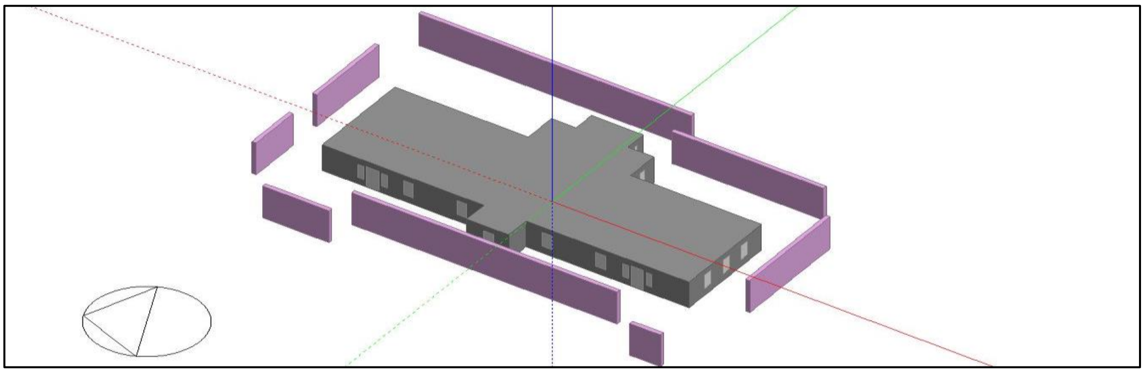

Figure 3.3 – South West side of the Museum C. Xenakis

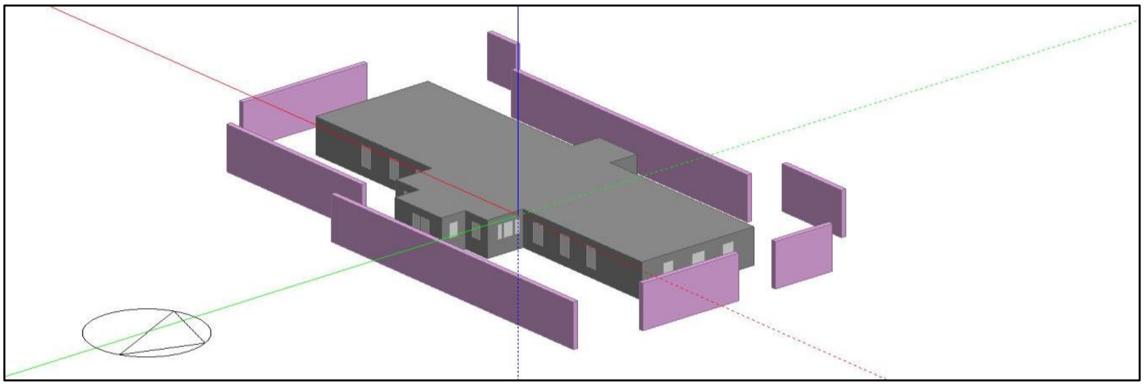

Figure 3.4 – North East side of the Museum C. Xenakis

The table 3.1 demonstrates all the conditioned thermal zones of the building along with all the areas and volumes, facades and window openings and the figures 3.5 – 3.12 illustrate the separation of the thermal zones (each color represents a different thermal zone).

Table 3.1 – Conditioned and unconditioned thermal zones of Museum C. Xenakis with areas and volumes, facades and window openings

	Area [m2]	Volume [m3]	Opening Area [m2]
Public Spaces	178,16	864,05	38,75
Exhibition room	436,23	2115,73	46,63
Office	37,52	181,99	6,24
Total	651,91	3161,77	91,62
Conditioned Total	651,91	3161,77	91,62
Unconditioned Total	0	0	0

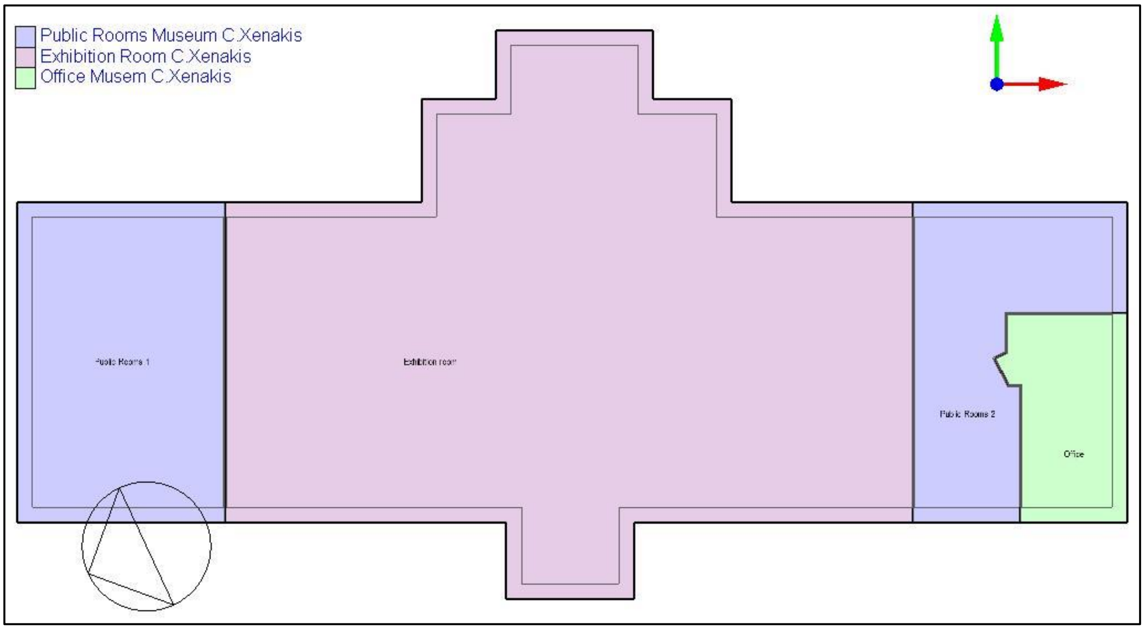

Figure 3.5 – Plan of Museum C. Xenakis – Thermal Zone Separation

3.3 Construction elements of the building envelope

The data of each component of every layer of all the construction elements (exterior wall, flat roof, ground floor and openings) was imported to the DesignBuilder software. The imported data includes the thickness of every layer, its position (outermost or innermost) to the element and its thermal properties (thermal conductivity, density and specific heat), important for heat transfer and thermal transmittance (U-Value) calculations.

The construction element of the exterior wall of the Museum C. Xenakis consists of five layers from outermost to innermost: 5 cm cement-sand mortar coating, 60 cm limestone, 8 cm MineralWool (MW), 2 cm Gypsum board and 1 cm pasty finish render.

The calculated total thermal transmittance (U-Value) of the exterior wall after the renovation is 0,336 W/m^{2}K.

The construction element of the flat roof of the Museum C. Xenakis consists of five layers from outermost to innermost: 4 mm waterproof asphaltic membrane, 8 cm perlite concrete, 30 cm Zoellner type slab (Reinforced concrete with brickwork), 3 cm cement-sand mortar coating, 10 cm extruded polystyrene (XPS). The calculated total thermal transmittance (U-Value) of the flat roof after the renovation is 0,240 W/m^{2}K.

The construction element of the ground floor of the Museum C. Xenakis consists of four layers from outermost to innermost: 15 cm unreinforced concrete or lightly reinforced, 5 cm extruded polystyrene (XPS), 8 cm cement-sand mortar, 3 cm marble tiles. The calculated total thermal transmittance (U-Value) of the flat roof after the renovation is 0,543 W/m^{2}K.

The windows are wooden framed double glazed 4mm-16mm with argon 90%-4mm with Low-E coating, adequate airtightness, light transmission 61%, and total solar transmission (SHGC) 37%. The total thermal transmittance (U-Value) of the openings is 1,30 W/m^{2}K.

Table 2.3 – Construction details of Museum C. Xenakis

	Construction details (layers)	**(U-Value)**
Exterior wall	• Cement-sand mortar coating • Limestone • MineralWool (MW) • Gypsum board • Pasty finish render	0,336
Flat roof	• Waterproof asphaltic membrane • Perlite concrete • Zoellner type slab (Reinforced concrete with brickwork) • Cement-sand mortar coating • Extruded polystyrene (XPS)	0,240
Ground floor	• Unreinforced concrete or lightly reinforced • Extruded polystyrene (XPS) • Cement sand mortar • Marble tiles	0,543
Openings(windows/doors)	• Wooden flamed, double glazed 4mm-16mm argon 90%-4mm with Low-E coating • Light transmission: 61% • Total solar transmission: 37%	1,300

In the Appendix 1 of the deliverable, the calculations of U-Value of the construction elements are presented.

3.4 Building’s hours of operation

The operation hours of the building will be the same for all the thermal zones. Even though, there are different thermal zones such as office and exhibition room which operate following different time schedules according to the Greek regulation and its

Technical Guidelines (TOTEE 20701-1/2017), the workday schedule for the Museum C. Xenakis will be the same. The building will operate at the same hours: 5 hours per day and 6 days per week. The table 3.3 demonstrates the workday schedule for all the thermal zones within the Museum C. Xenakis.

Table 3.3 – Operation hours for all conditioned thermal zones of Museum C. Xenakis

	Hours per day	Days per weak	Months per year
Museum C. Xenakis	5	6	12

3.5 Occupancy – Internal gain from occupants – Clothing and activity rate

According to estimations, the Museum will be able to host more than thirty visitors for two to five hours per day per week. Also, the Museum C Xenakis will remain available for the public and will be able to host educational programs for schools or visitors for six days per week throughout the year. The occupancy schedule was created taking into account the presence factor and the frequency of the external visits according to those estimations for the thermal zones of Exhibition room and public spaces.

The office's thermal zone will be occupied by one employer who, amongst other responsibilities, will welcome the visitors to the facilities and guide them through the exhibits. The working profile of the occupant and the occupancy schedule of the office's thermal zone was created taking into consideration all the parameters of the workday schedule of the museum.

Also, the metabolic rate of the occupants, along with their clothing for both the heating and cooling period was taken into account during the input of the data to the simulation software. The table 3.4 presents the number of the occupants per area according to the estimations for all the conditioned thermal zones of the model, the percentage of their presence in the zone, and their metabolic rate.

Table 3.4 – Number of occupants per area, factor of presence and metabolic rate

Thermal Zone	Number of occupants per area (occupants/m2)	Presence Factor	Metabolic rate, (W/person)
Public spaces	0,43	0,25	90
Exhibition room	0,43	0,25	90
Office	0,03	0,25	80

3.6 Shading and lighting

The C. Xenakis Museum is part of a total group of eleven buildings in the military compound of "Papaloukas" in Serres, at a total site area around 124.000 m^2. The surroundings of the museum are covered with tall trees which provide shading throughout the year and their dense foliage allows only a small portion of the solar radiation to reach the exterior walls of the building (Fig. 3.13, 3.14).

The windows of the museum are equipped with external wooden shades (panes) as a means of protection from the sun which remain closed at the exhibition room to prevent any unwanted solar radiation from entering the interior of the space. Also, in order the exhibits to be further protected, shades (drapes) are placed in the interior side of the windows which are covered with an extra anti-glare coating with 99% protection from UV radiation, 0,5 shading coefficient, light reflection 32% and light transmission 22%.

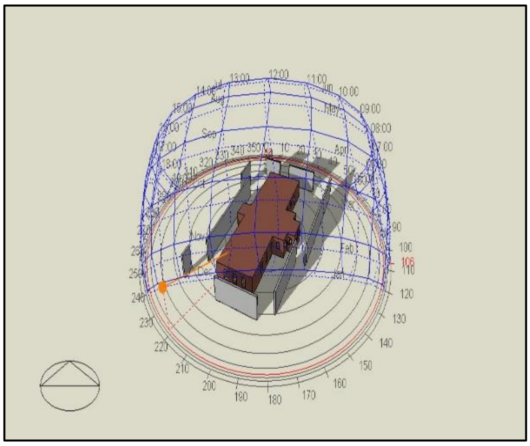

Figure 3.13 – 1 January (Coldest day of the year according to the weather data)

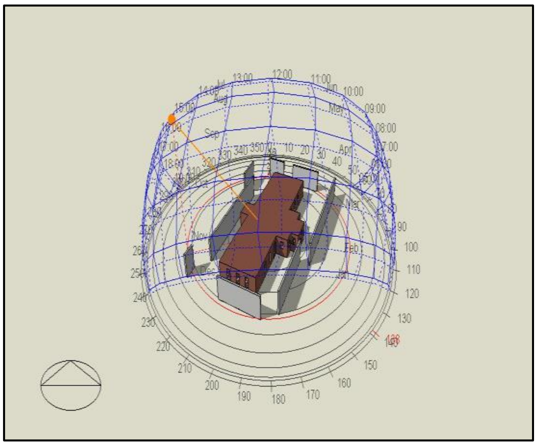

Figure 3.14 – 24 July (Hottest day of the year according to the weather data)

The Museum C. Xenakis has 146 anti-glare LED Gu10 lights 7,5 W, distributed throughout the spaces of the building (Exhibition room, offices, entrance, educational room and auxiliary spaces) separated in three types: surface mount, recessed and suspended. The total power density of the install capacity is measured at 1,1 kW and following the time schedule of the museum. In the table 2.4, the lightning elements of the museum are presented.

Table 2.4 – Lighting elements of Museum C. Xenakis

Lamp Type	No of Lamps	Hours of Operation	Installed Capacity (kW)
Surface mount anti-glare Led Gu10 7,5W	120	5 hours	0,90
Recessed anti-glare Led Gu10 7,5W	18	5 hours	0,14
Suspended anti-glare Led Gu10 7,5W	8	5 hours	0,06
Total Led Lights	146	5 hours	1,1

Table 3.6 – Hours of operation of lighting and target illuminance of all the conditioned thermal zones

Thermal Zone	Hours per day	Days per weak	Months per year	Target illuminance, (lux)
Public spaces	5	6	12	100
Exhibition room	5	6	12	200
Office	5	6	12	500

3.7 Temperature setpoints and operation schedules

In order to provide thermal comfort for the occupants in each thermal zone, is important for setpoint temperatures to be defined. The setpoint temperatures for heating and cooling periods were determined according to the Greek Technical Guidelines (TOTEE 20701-1/2017). The table 3.7 demonstrates the input data for setpoint temperatures.

Table 3.7 – Temperature setpoints and Operation schedules of all conditioned thermal zones

Thermal Zone	Heating period, (°C)	Cooling period, (°C)
Public spaces	18	26
Exhibition room	20	23
Office	20	26

The heating and cooling set-point temperatures are achieved with the installed Ground Source Heat Pump. The heating system of the Museum C. Xenakis is operating from the 15st of October until 30th of April, while the cooling system is operating from the 1th of June till 31th of August.

3.8 HVAC Systems

At the renovated Museum C. Xenakis, a Ground Source Heat Pump (GSHP) was installed to cover the heating and cooling needs. The system consists of one main Hot Water Loop and one main Chiller Water Loop which are connected to the heating and cooling collector in the storage room respectively, and through a two pipe network of supply and return, it is distributed in the terminal units (FCUs) at each space of the museum.

The Ground Source Heat Pump (GSHP) was installed at the north east side of the building in order to take advantage of the unused area of the site. The system is a slinky type, horizontal closed loop, which was buried at 1,2 m in the ground, inside of 35 trenches of around 8.750 m length total. According to data from the Hellenic National Meteorological Service the yearly mean temperature for the ground at depth 1,0 m was 16,4 ^{o}C. Propylene glycol at 20% is used for antifreeze protection. The whole pipe network is adequately insulated and the temperature operating range of the system is -6 ^{o}C for heating and +49 ^{o}C for cooling. The system is stored in the equipment room inside the museum along with circulator pumps, the buffer tank, the expansion tank and the heating and cooling collector.

Two heat recovery units with cross-flow heat exchanger were installed in the building to cover the needs for ventilation while saving energy through heat recovery. The air loop of the system consists of a fresh air supply ductwork which is connected to the Fan Coil Units (FCUs) and a return ductwork of exhausted air.

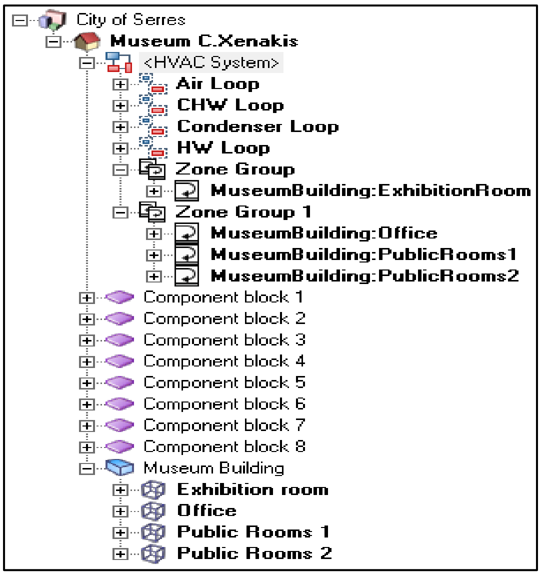

Figure 3.15 – HVAC systems and zones of Museum C. Xenakis

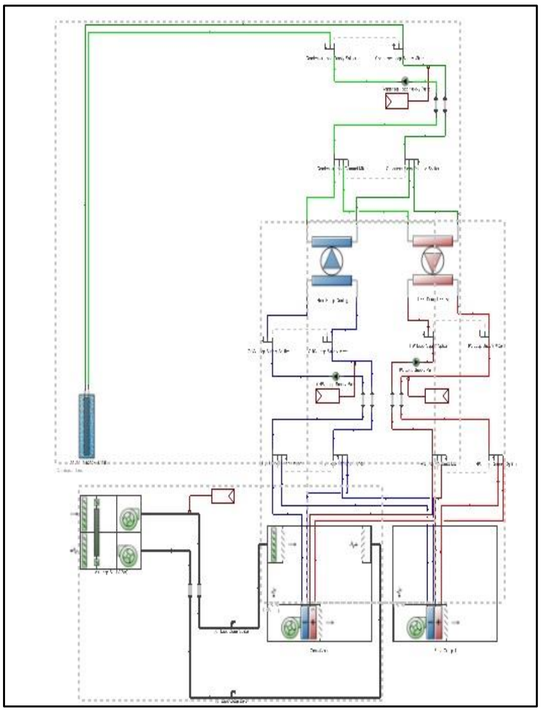

Figure 3.16 – Schematic of the complete HVAC system of Museum C. Xenakis

The figure 3.15 illustrates the connections and loops of all the HVAC systems of Museum C. Xenakis and the figure 3.16 illustrates the complete HVAC systems' schematic.

3.8.1 Heating Systems

The Ground Source Heat Pump has heating capacity 58 kWth (58.220 W) with high COP at 3.8 and is able to meet the needs of the spaces of the Museum C. Xenakis for heating, providing hot water at 50 ^{o}C through a two pipe hot water loop (supply and return), which is connected to the terminal units of each thermal zone (FCUs).

The heating systems are operating from the 15st of October until the 30th of April, and the set-point temperature of each thermal zone were defined (Offices: 26 ^{o}C, Exhibition room: 23 ^{o}C, Public Spaces (Entrance, auxiliary rooms and education room): 26 ^{o}C). The figure 3.17 presents the source of the heating system (GSHP), the two pipe hot water loop with supply and demand, and the thermal zones along with their terminal units (FCUs).

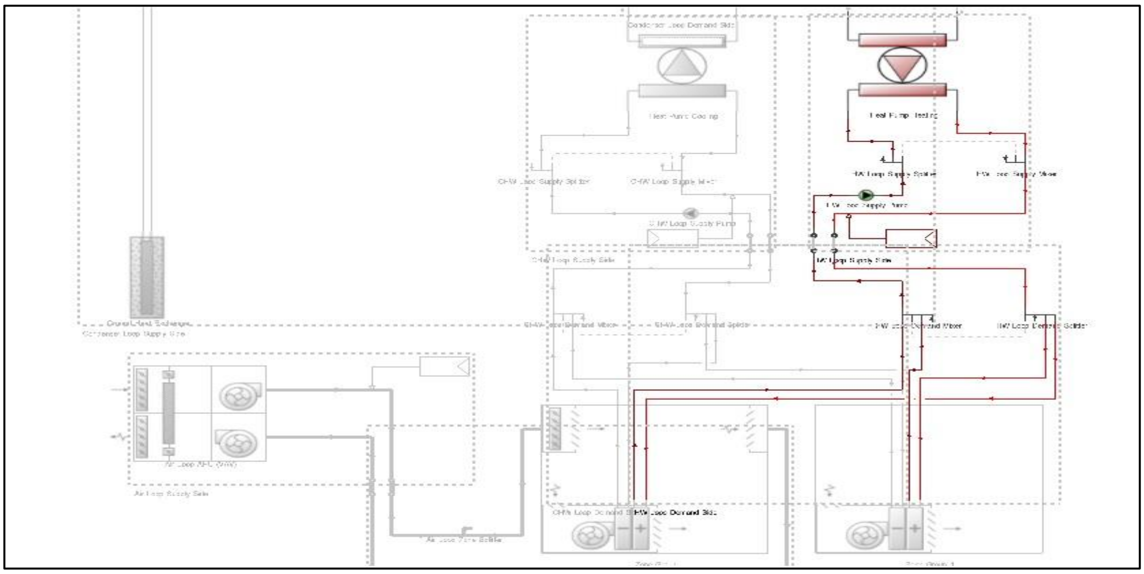

Figure 3.17 – Schematic of the Heating systems – Hot water loops of Museum C. Xenakis

3.8.2 Cooling Systems

The Ground Source Heat Pump has cooling capacity 52 kWco (52.608 W) with high EER at 4.8 and is able to meet the needs of the spaces of the Museum C. Xenakis for cooling, providing cold water at 7 ^{o}C through a two pipe chilled water loop (supply and return), which is connected to the terminal units of each thermal zone.

The cooling system is operating at the period of 1st of June till 31th of August, and the set-point temperatures of each thermal zone were defined (Offices: 20 ^{o}C, Exhibition room: 20 ^{o}C, Public Spaces (entrance, auxiliary rooms and education room): 18 ^{o}C). The figure 3.18 illustrates the source of the cooling system (GSHP), the two pipe chilled water loop with supply and demand, and the pipe connection with the cooling coils inside the Fan Coils Units (FCUs) and the thermal zones along with the terminal units.

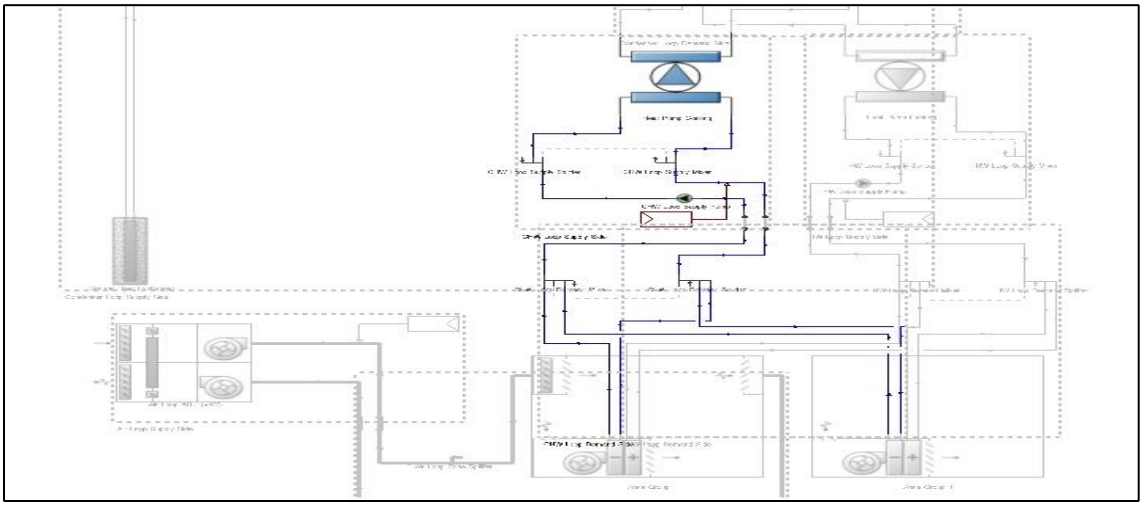

Figure 3.18 – Schematic of the Cooling system – Chilled water loop of Museum C. Xenakis

3.8.3 Air handling units (AHUs) – Ventilation

The mechanical ventilation equipment of the C. Xenakis Museum consists of two heat recovery units with cross-flow heat exchanger with motor power 0,676 kW, each proving 2.000 m^3/h of fresh air to the space. They are operating without recirculation, covering the ventilation requirements of the exhibition area of the museum, following the working profile of the occupants of the thermal zone.

The Air Loop of the heat recovery unit consists of the supply and return ductwork. The intake fresh air is supplied through an insulated ductwork to the roof FCUs at the exhibition room, while the exhausted air is extracted out of the room through the return ductwork. The two air flows with different temperature meet at the heat exchanger transferring heat to each other, resulting to saving energy.

The figures illustrate the mechanical ventilation equipment which includes the air distribution unit, the supply fan, the ductwork, the zone extract fan and the air loop extract fan.

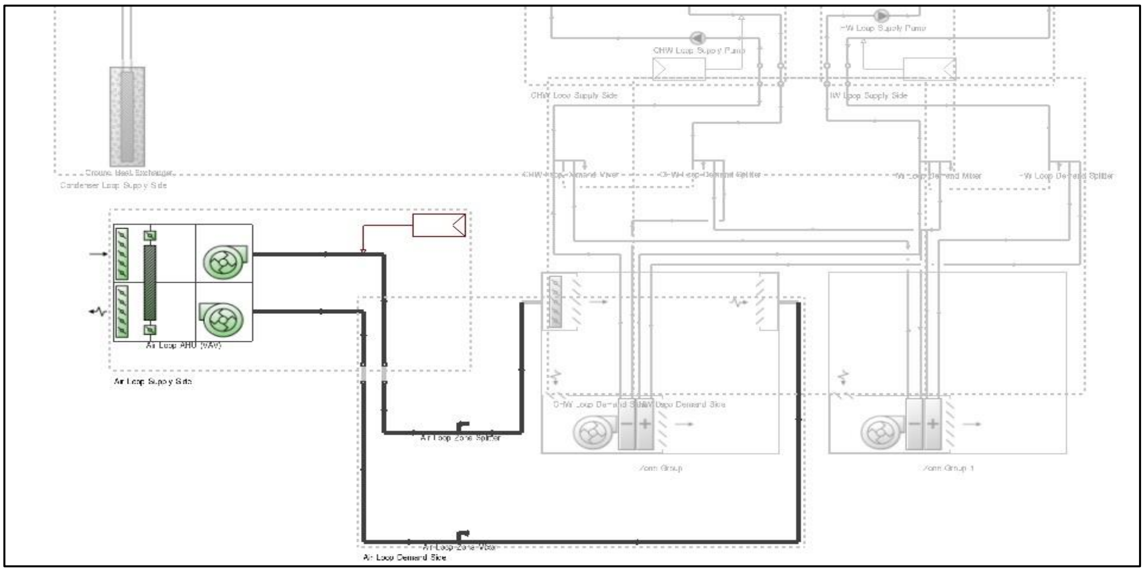

Figure 3.20 – Schematic of mechanical ventilation of Museum C. Xenakis

5. Energy performance simulation

After the gathering of all the available information and data, an accurate building model was designed into the energy simulation software DesingBuilder. The site of the building contains the location's climate characteristics, illustrating the objects in the surroundings. The model was formed using the imported floor plan of the building, following the exact real building's geometry and features, taking into consideration the complexity of its zones and systems. The museum consists of three different thermal zones, including the public rooms, the exhibition room and the office. Material properties about all the layers of the construction elements of the building were input into the model, based on the available data.

After the construction of the building model, occupancy schedules, activity profiles, lighting and equipment specifications were imported into the software. For the museums' occupancy and working patterns, a rather consistent estimation was conducted throughout the week.

The building is heated and cooled with a high efficiency closed loop, horizontal, slinky type, ground source heat pump, according to the defined heating and cooling thermostat controls of each thermal zone. Furhermore, the building is mechanically ventilated with a heat recovery unit with cross flow heat exchanger, assisting in energy saving.

After the simulation, the energy performance of the building was conducted, and results about its energy consumption were extracted.

5.1 Results of simulation of Museum C. Xenakis

In the following tables 5.2, 5.3 the monthly and yearly results about the net and primary energy consumption for the building are presented. Furthermore, there are detailed diagrams and tables which illustrate the energy consumption per conditioned area and the energy consumption separated per category (heating, cooling, etc.), showing their percentages out of the total energy consumption.

According to the Greek regulation(KENAK) and its Technical Guidelines, the conversion from net to primary energy is 2,9 for electricity.

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The total net energy consumption of electricity of the museum which corresponds to heating, cooling, ventilation, lighting, and equipment, is presented in the table 5.1 and is 11.448,25 kWh while the total primary energy is 33.199,93 kWh. The total net energy consumption per area is 17,56 kWh/m^2 and the primary energy consumption is 50,93 kWh/m^2.

The diagram 5.1 presents the percentages of each consumption per category. The heating consumption is 35% of the total source consumption, the cooling electricity is 22%, the fans is 22%, the interior lighting is 9%, and the interior equipment is 12%.

The diagram 5.2 presents the total primary energy consumption of each category per area. The heating consumption is 18,13 kWh/m^2, the cooling is kWh/m^2, the consumption of fans is 11,06 kWh/m^2, the consumption of lighting is 4,48 kWh/m^2 and the consumption of equipment is 6,00 kWh/m^2.

Table 5.1 – Total net and primary energy consumption per category of Museum C. Xenakis

TOTAL ENERGY CONSUMPTION				
	NET Energy Consumption		**PRIMARY** Energy Consumption	
	kWh	kWh/m2	kWh	kWh/m2
Total electricity	11.448,25	17,56	33.199,93	50,93
TOTAL ENERGY CONSUMPTION PER CATEGORY				
	NET Energy Consumption		**PRIMARY** Energy Consumption	
	kWh	kWh/m2	kWh	kWh/m2
Heating	4.074,60	6,25	11.816,34	18,13
Cooling	2.531,03	3,88	7.339,99	11,26
Fans	2.486,16	3,81	7.209,86	11,06
Interior Lighting	1.008,11	1,55	2.923,52	4,48
Interior Equipment	1.348,35	2,07	3.910,22	6,00
TOTAL	11.448,25	17,56	33.199,93	50,93

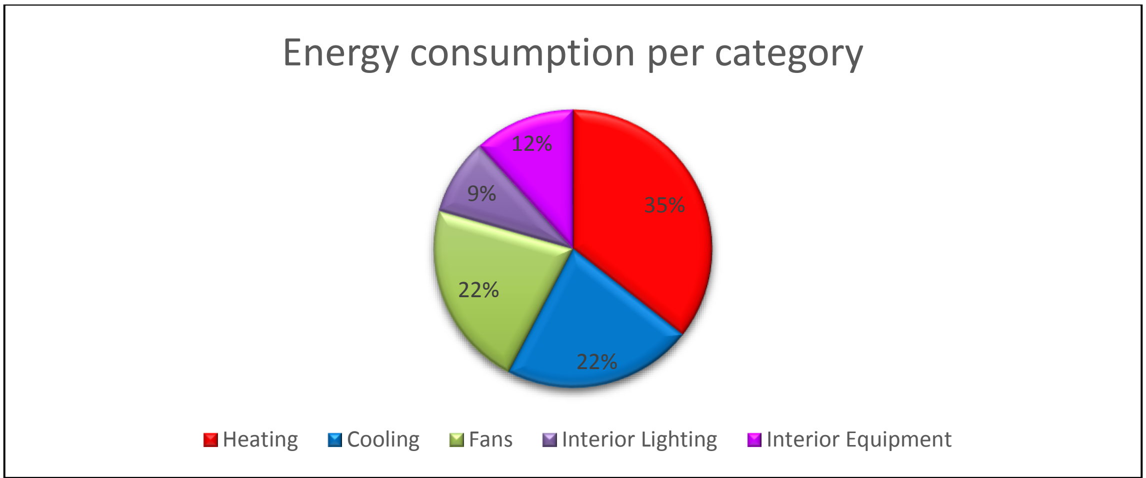

Diagram 5.1 – Percentages of primary energy per category of Museum C. Xenakis

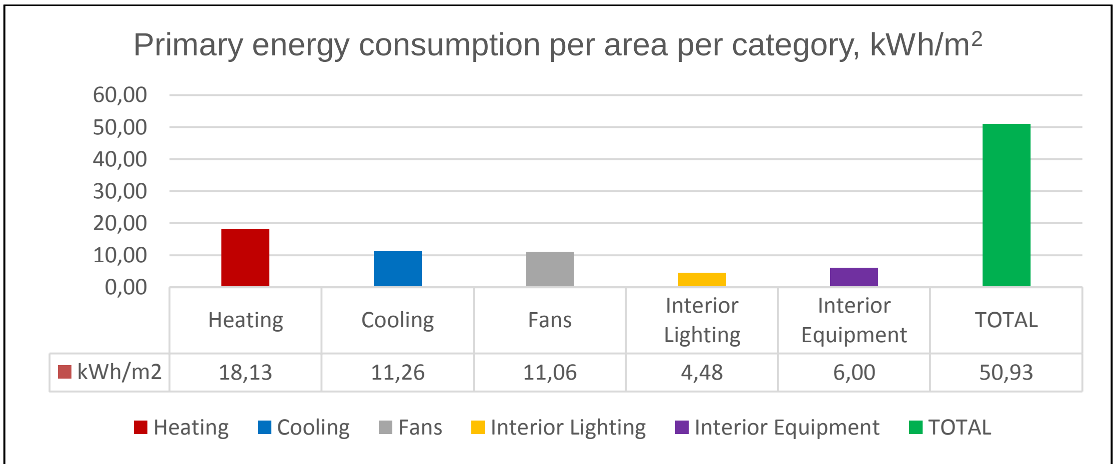

Diagram 5.2 – Primary energy consumption per area per category of Museum C. Xenakis

The monthly net and primary energy consumption in kWh and kWh/m^2 is presented in the table 5.2.

The highest energy consumption of the building is observed at August with 1.421,61 kWh net energy or 4.122,67 kWh primary energy, while the lowest energy consumption is observed at October with 582,30 kWh net energy or 1.688,67 kWh primary energy.

Table 5.2 – Monthly net and primary energy consumption of Museum C. Xenakis

TOTAL MONTHLY ENERGY CONSUMPTION				
	NET Energy Consumption		Primary Energy Consumption	
	kWh	kWh/m^2	kWh	kWh/m^2
January	1.293,03	1,98	3.749,79	5,75
February	1.068,91	1,64	3.099,84	4,76
March	895,47	1,37	2.596,86	3,98
April	616,56	0,95	1.788,02	2,74
May	630,03	0,97	1.827,09	2,80
June	1.085,07	1,66	3.146,70	4,83
July	1.313,83	2,02	3.810,11	5,84
August	1.421,61	2,18	4.122,67	6,32
September	629,82	0,97	1.826,48	2,80
October	582,30	0,89	1.688,67	2,59
November	807,11	1,24	2.340,62	3,59
December	1.104,51	1,69	3.203,08	4,91
Annual Sum	11.448,25	17,56	33.199,93	50,93
Minimum of Months	582,30	0,89	1.688,67	2,59
Maximum of Months	1.421,61	2,18	4.122,67	6,32

The distribution of primary energy consumption in kWh/m^2 in all the different categories of the building is presented in table 5.3.

The highest monthly primary energy consumption of the building for heating is observed at January with 4,29 kWh/m^2 and for cooling at August with 4,35 kWh/m^2. The highest total monthly primary energy consumption of the building is observed at August with 6,32 kWh/m^2, while the lowest primary energy consumption is observed at October with 2,59 kWh/m^2.

Table 5.3 – Monthly primary energy consumption per category of Museum C. Xenakis in kWh/m^2

TOTAL MONTHLY ENERGY CONSUMPTION PER AREA PER CATEGORY						
kWh/m^2						
	Heating	Cooling	Fans	Interior Lighting	Interior Equipment	Total monthly Electricity
January	4,29	0,00	0,59	0,37	0,50	5,75
February	3,40	0,00	0,55	0,34	0,46	4,76
March	2,46	0,00	0,61	0,39	0,52	3,98
April	1,34	0,00	0,57	0,36	0,48	2,74
May	0,00	0,00	1,90	0,39	0,52	2,80
June	0,00	2,95	1,01	0,37	0,50	4,83
July	0,00	3,97	1,01	0,37	0,50	5,84
August	0,00	4,35	1,07	0,39	0,52	6,32
September	0,00	0,00	1,93	0,37	0,50	2,80
October	1,06	0,00	0,66	0,37	0,50	2,59
November	2,13	0,00	0,59	0,37	0,50	3,59
December	3,45	0,00	0,59	0,37	0,50	4,91
Annual Sum	18,13	11,26	11,06	4,48	6,00	50,93

The total monthly primary energy consumption in kWh/m^2 is presented in the diagram 5.3 while the distribution of primary energy consumption in kWh/m^2 in all the different categories of the building is presented in diagram 5.4.

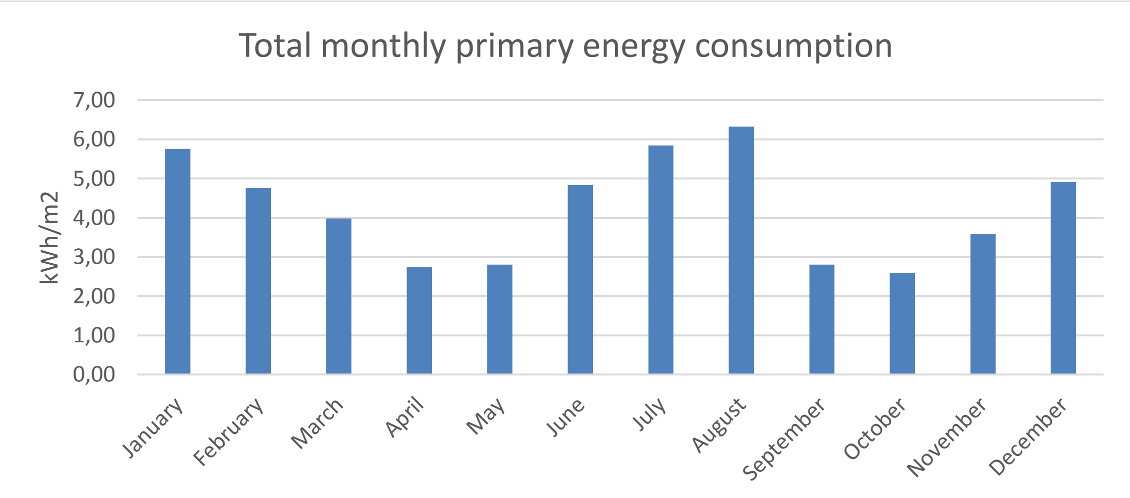

Diagram 5.3 – Total monthly primary energy consumption of Museum C. Xenakis

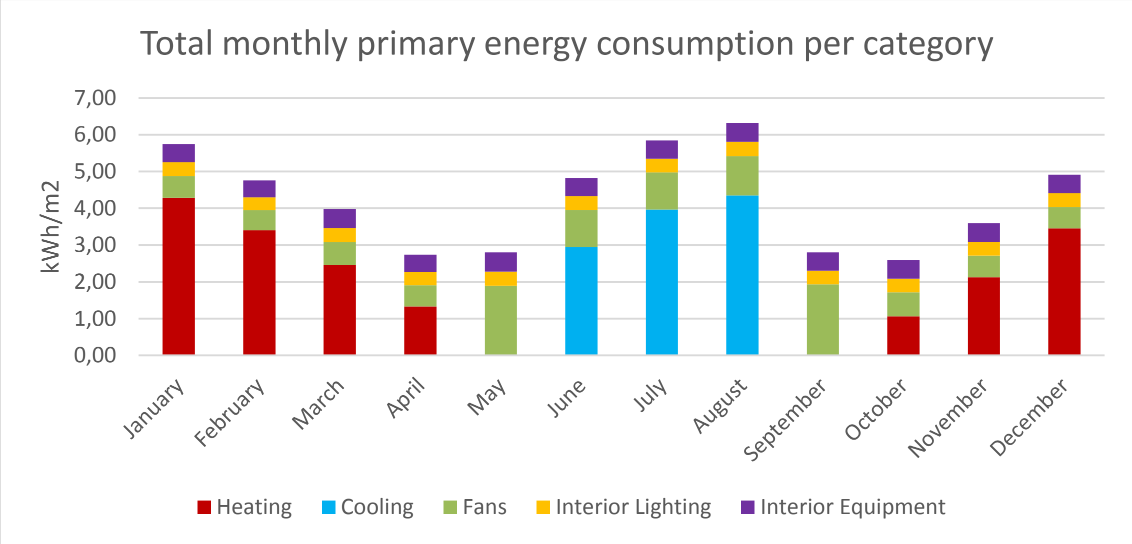

Diagram 5.4 – Total monthly primary energy consumption per category of Museum C. Xenakis

6. Conclusion

The aim of this deliverable, is to calculate the energy consumption of a renovated building museum and through an energy simulation software, to evaluate its energy performance towards a "nearly" zero energy consumption building (NZEB - consumption of primary energy <60 kWh / m^2).

The case study building of this deliverable was an old building which is considered "listed" due to its unique specifications, with restrictions by the Greek legislation for any intervention to its facades. It was chosen for renovation, in order to host the contemporary art collection of "Constantin Xenakis", and is located at an area of the city of Serres, which is called "Area of cultural activities and recreation parks", at the former military compound of "Papaloukas", renamed now into "Thematic Park Konstantinos Karamanlis".

The Museum C. Xenakis constructed during the Ottoman era, with eclecticism as architectural approach, is a single floor building with a slab roof, upon a ground surface surrounded by trees, and its two elongated sides are orientated in 25^0 from true North. Its total surface is 651,91 m^2 and its total height along with ground and roof slab is 4,85m.

The building initially had no insulation in any of it surfaces, with decorative elements at its corners and the perimeter of the windows and doors. The exterior wall was limestone with thickness 60 cm, the roof was a Zoellner type slab, and the ground floor was unreinforced concrete with cement sand mortar. The openings of the building were wooden framed, single glass with wooden panes.

In order to reduce the thermal losses and to improve the energy performance of the building, insulation is added in all of its surfaces (8 cm insulation layer of MineralWool placed at the internal side of the exterior walls, 10 cm insulation layer of Extruded Polystyrene with waterproof membrane at the exterior side of the roof, 5 cm insulation layer of Extruded Polystyrene) and the old openings are replaced with new with low thermal transmittance U-Value (double glazed, with low-e coating at the glass and argon). The openings and panes are constructed from wood exactly as the former ones. Furthermore, shades (drapes) are placed in the interior side of the windows which are covered with an extra anti-glare coating to provide additional protection from the sun.

Also, it was important to install a system driven by renewable energy sources (RES). Due to the restrictions for listed buildings, along with the availability of sufficient land at the surrounding area, the option of Geothermal Energy was preferred**.** A high efficient slinky type, horizontal closed loop, geothermal heat pump system was chosen, available for heating and cooling. The system is buried at 1,2 m in the ground, inside of 35 trenches, amounting of 8.750 m length total.

The heating capacity of the geothermal heat pump is 58 kWth with COP at 3.8, providing hot water at 50 ^oC through a two pipe hot water loop (supply and return) while the cooling capacity is 52 kWco with EER at 4.8, providing cold water at 7 ^oC through a two pipe chilled water loop (supply and return). The terminal units of the system are Fan Coil Units (FCUs) located at the roof at the exhibition room and at the floor at all the other places of the museum. The mechanical ventilation system consists of a heat recovery unti with cross flow heat exchanger for energy saving and the air is distributed through a supply and extract ductwork.

The building was simulated in the energy performance simulation tool DesignBuilder which incorporates the EnergyPlus engine and was separated into thermal zones, spaces with the same use, electromechanical equipment and operation schedules. The Museum C. Xenakis was separated into three thermal zones according to their occupancy profiles, operation characteristics, heating and cooling demands. The thermal zones are: Thermal Zone 1: Entrance and educational room, Thermal Zone 2: Exhibition room, Thermal Zone 3: Office and all the available data was input into the energy performance simulation software DesignBuilder to calculate the energy consumption of the building.

After the energy improvement interventions and the installation of the geothermal heat pump, including the energy consumption of the interior lighting and equipment the total net energy consumption of electricity of the museum which corresponds to all the categories (heating, cooling, ventilation, lighting, and equipment), is 11.448,25 kWh while the total primary energy is 33.199,93 kWh. The total net energy consumption per area is 17,56 kWh/m^2 and the primary energy consumption is 50,93 kWh/m^2.

Through the suggested interventions and the energy improvement installations, a low energy consumption building was designed, able to achieve the goal of a “nearly” zero energy consumption building (consumption of primary energy <60 kWh / m^2).

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APPENDIX 1

U Factor Calculation for Exterior Wall					
Number of layers	**Construction layers (outermost to innermost)**	**Density, P**	**Thickness, d**	**Conductivity, λ**	**Thermal Resistance, (R-Value)**
		kg/m³	**m**	**W/(mK)**	**(m²K)/W**
1	Cement-sand mortar coating	1800	0,050	0,870	0,057
2	Limestone	2200	0,600	1,700	0,353
3	MineralWool (MW)	80	0,080	0,035	2,286
4	Gypsum board	700	0,020	0,210	0,095
5	Pasty finish render	1820	0,010	0,700	0,014
Total thickness of the construction element (Σd), m			0,760	RΛ	2,806
Internal Surface Resistance, (m²K)/W				Ri	0,130
External Surface Resistance, (m²K)/W				Ra	0,040
Total Thermal Resistance, (m²K)/W				Rtotal	2,976
Thermal Transmittance (U-Value), W/(m²K)				**U**	0,336

U Factor Calculation for Flat Roof					
Number of layers	**Construction layers (outermost to innermost)**	**Density, P**	**Thickness, d**	**Conductivity, λ**	**Thermal Resistance, (R-Value)**
		kg/m³	**m**	**W/(mK)**	**(m²K)/W**
1	Waterproof asphaltic membrane	1100	0,004	0,230	0,017
2	Perlite concrete	450	0,080	0,140	0,571
3	Zoellner type slab (Reinforced concrete with brickwork)	2240	0,300	0,658	0,456
4	Cement-sand mortar coating	1800	0,030	0,870	0,034
5	Extruded polystyrene (XPS)	40	0,100	0,034	2,941
Total thickness of the construction element (Σd), m			0,514	RΛ	4,020
Internal Surface Resistance, (m²K)/W				Ri	0,10
External Surface Resistance, (m²K)/W				Ra	0,04
Total Thermal Resistance, (m²K)/W				Rtotal	4,160
Thermal Transmittance (U-Value), W/(m²K)				**U**	0,240

U Factor Calculation for Ground Floor					
Number of layers	**Construction layers (outermost to innermost)**	**Density, P**	**Thickness, d**	**Conductivity, λ**	**Thermal Resistance, (R-Value)**
		kg/m³	**m**	**W/(mK)**	**(m²K)/W**
1	Unreinforced concrete or lightly reinforced	2200	0,150	1,650	0,091
2	Extruded polystyrene (XPS)	40	0,050	0,033	1,515
3	Cement sand mortar	2000	0,080	1,400	0,057
4	Marble tiles	2800	0,030	3,500	0,009
Total thickness of the construction element (Σd), m			0,310	RΛ	1,672
Internal Surface Resistance, (m²K)/W				Ri	0,17
External Surface Resistance, (m²K)/W				Ra	0,00
Total Thermal Resistance, (m²K)/W				Rtotal	1,842
Thermal Transmittance (U-Value), W/(m²K)				**U**	0,543

Art Gallery 'Constantin Xenakis' Monitoring Report

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Contents

Abstract

Measuring equipment was installed at the Art Gallery ‘Constantin Xenakis‘, located at the city of Serres (Greece), to monitor indoor thermal and ambient conditions. The instrumentation included air temperature and humidity sensors, installed at two locations inside the building and a micro-meteo station installed outdoors, on the roof of the building. They are a wireless instrumentation and thus the data can be transmitted wireless at remote distance but also manually collected. The instrumentation was installed at the building on the 23rd of March 2022.

Executive summary

The thermal conditions inside the Art Galley ‘Constantin Xenakis’, located at the city of Serres (Greece), are being monitored with 2 wireless sensors located inside the building and a micro-meteo station located outdoors, on the top of the roof. Thermal monitoring of the building started on the 23rd of March 2022.

1. Introduction

In order to monitor the real thermal conditions inside the building after the energy upgrade interventions that were performed at the Art Gallery ‘Constantin Xenakis‘ building (Figure 1) and to identify possible sectors which can be improved (HVAC systems, etc.), a monitoring programme of indoor thermal and ambient conditions was implemented. The monitoring programme at the Art Gallery ‘Constantin Xenakis’ includes outdoor air temperature, relative humidity, wind speed and wind direction measurements and indoor measurements of air temperature and relative humidity.

Figure 1. The Art Gallery ‘Constantin Xenakis’ building (A. Dimoudi photo archive)

2. Installation of measurement instruments

2.1 Selection of measurement points

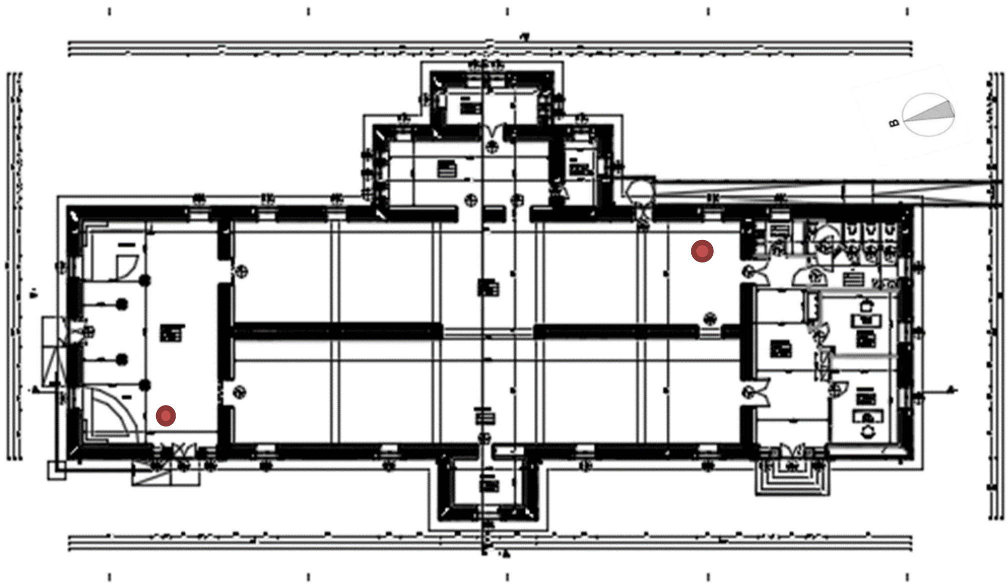


Figure 2. Plan of the Art Gallery 'Constantin Xenakis' building with location of monitoring instrumentation (red circles)

The indoor thermal conditions are being monitored at two locations: one sensor was located at the entrance lobby, at the NE side of the building and a second sensor was located at the opposite side of the building, at the SW side, inside the exhibition space (Figure 2). This selection made in order to measure the worst-case scenario of indoor air temperature and relative humidity values both on winter and summer periods respectively. A micro-meteo station, was located on the roof of the building, above the main entrance, to monitor the outdoor, ambient conditions.

2.2 Measurement Instruments

The outdoor measurement instrument, shown in figure 3, consists of sensors for measurement of:

- Air Temperature,
- Relative Humidity,
- Wind Speed and
- Wind Direction

connected to:

- one (1) wireless outdoor data logger.

Figure 3. *Outdoor weather station*

The main technical features of the meteo station are:

- Record up to 58,000 samples
- Temperature range: -40 to + 150 ^{0}C
- Humidity measuring range: 0 to 100 %RH
- Velocity measuring range: 1 to 75 m/s
- Velocity direction measuring range: 0^0 to 360^0

The indoor thermal conditions, shown in figure 4, consists of sensors for measurement of:

- Air Temperature,
- Relative Humidity,

each one connected to:

- one (1) wireless data logger.

Figure 5 shows the installation of the sensors in the interior of the building.

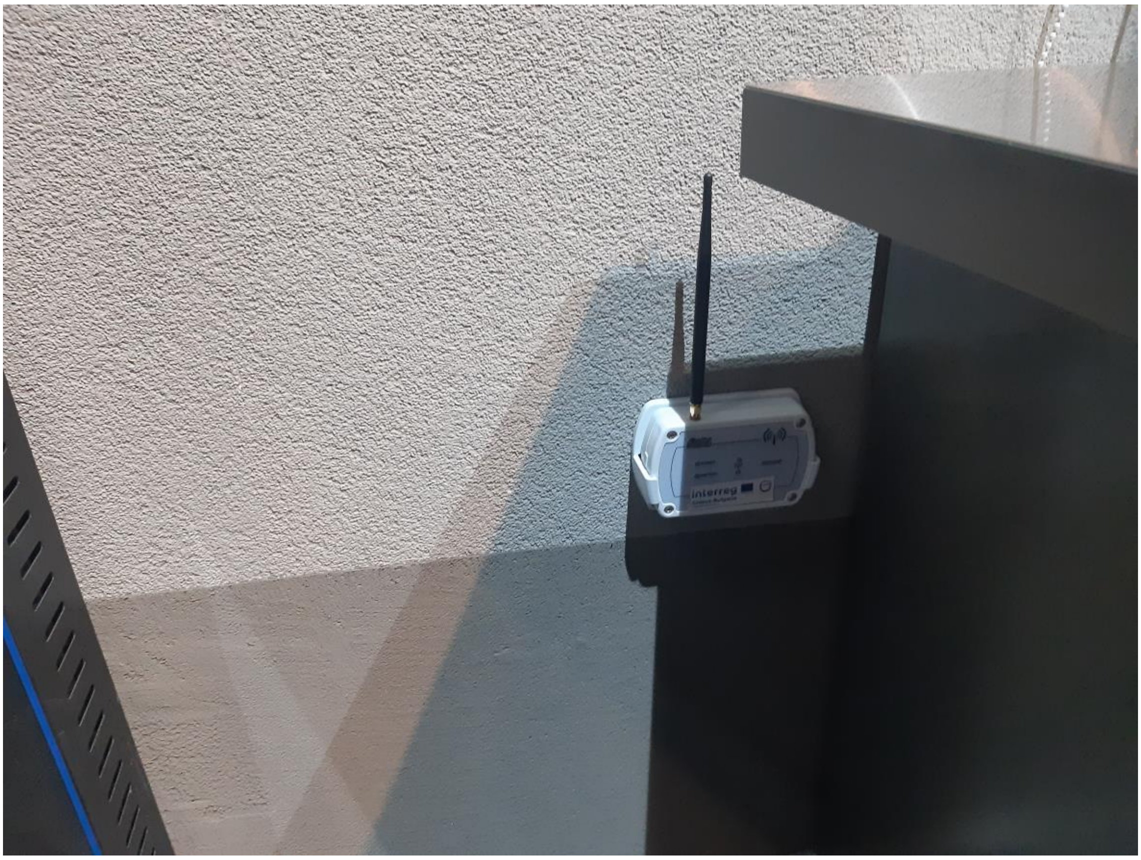
a)


Delta OHM
HD35EDG
LOG
2022/08/02
08:55
Relative humidity
52.2 %
Temp 25.8 °C
Dew point 15.3 °C
PVP 17.36 hPa
PING
ENTER
MENU
FUNC
Interreg
Greece-Bulgaria

b)

c)

d)



e)

f)

Figure 4. Indoor air temperature and humidity measuring instrument and wireless data logger

a, b: Entrance Lobby c, d: Exhibition Space

e, f: Wireless data logger

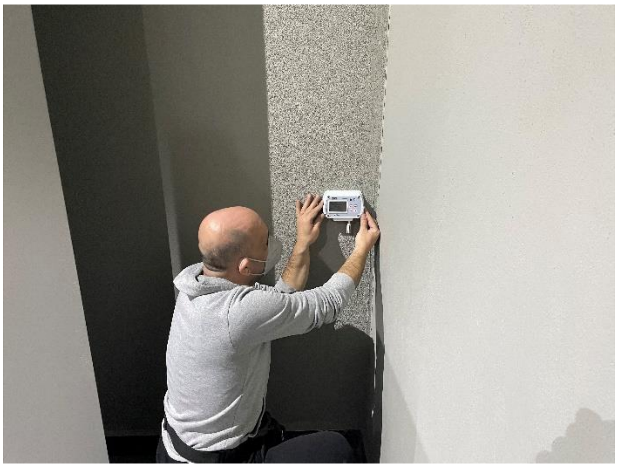


Figure 5. Installation of indoor instruments at the Art Gallery building

The main features of the indoor integrated data logger with air temperature and humidity sensor are:

- Record up to 24,000 samples
- It has a graphic display
- Air temperature range: -40 to + 105 ^{0}C
- Air humidity ratio measuring range: 0 to 100 %RH

Figure 6 shows the topology that was implemented for the connection of the instruments. One (1) Base unit is used for interconnection between computers and USB + Wi-Fi data logger. The Wi-Fi interface is used for connecting to the wireless LAN (LAN) either to connect the ETHERNET environment to a LAN cable.

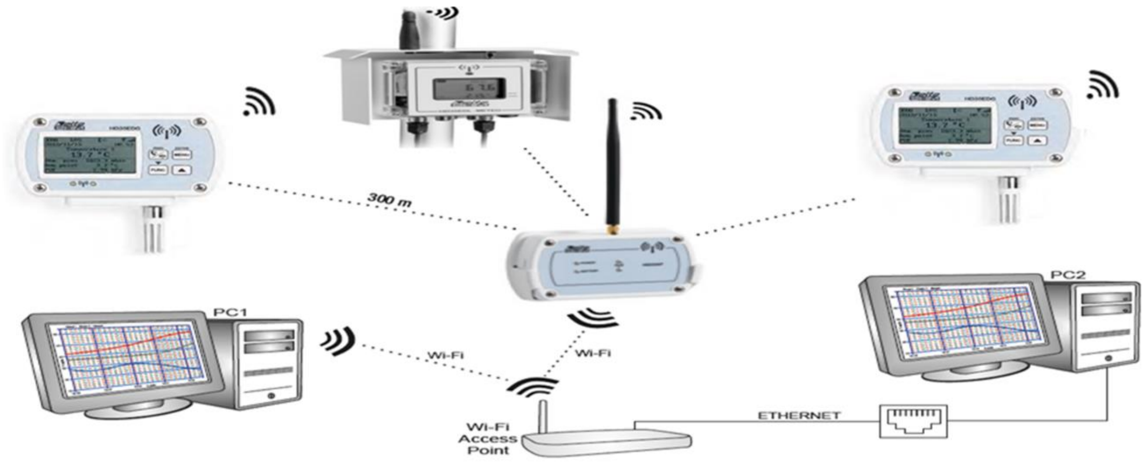


Figure 6. Measurements instruments connection topology

3. Monitoring Results

Figures 5 and 6 illustrate the results of the first monitoring period, from 23rd of March to the first days of April respectively.

Figure 5 illustrates the mean hourly values of air temperature and relative humidity at the exterior of the building and the two measuring locations inside the building, for the period 23rd to 31st of March.

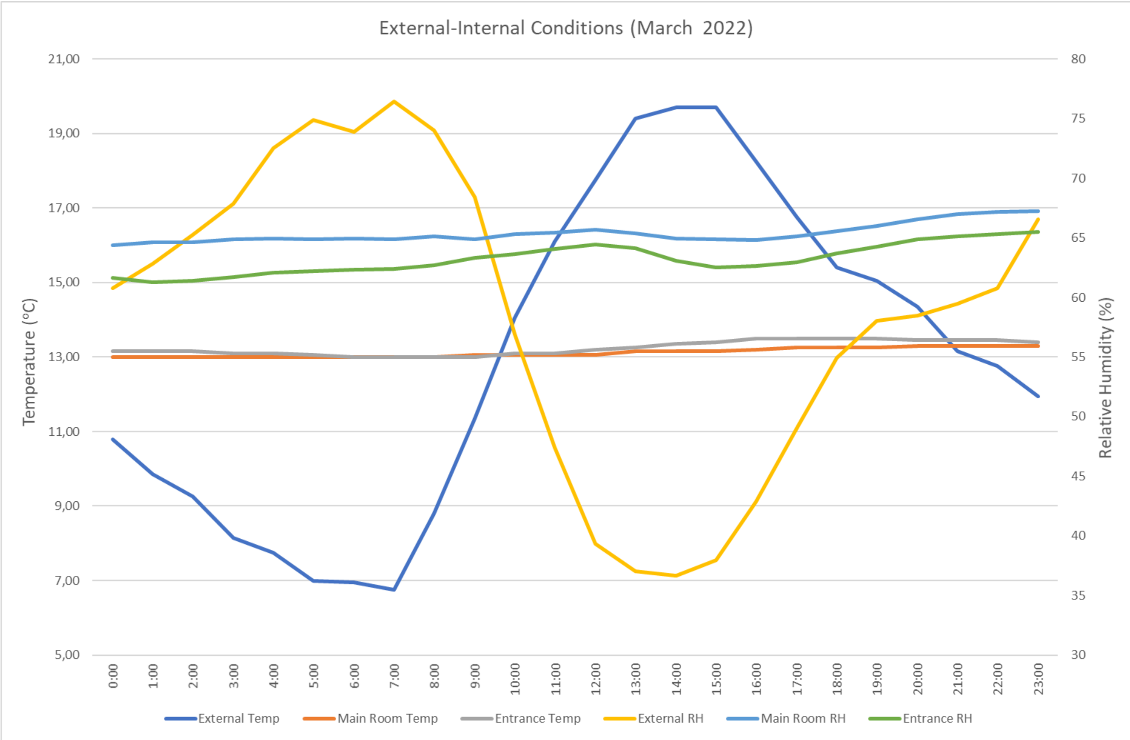


Figure 5. Mean hourly values of outdoor and indoor air temperature and relative humidity, in the Art Gallery 'Constantin Xenakis' (Serres, Greece), in March 2022

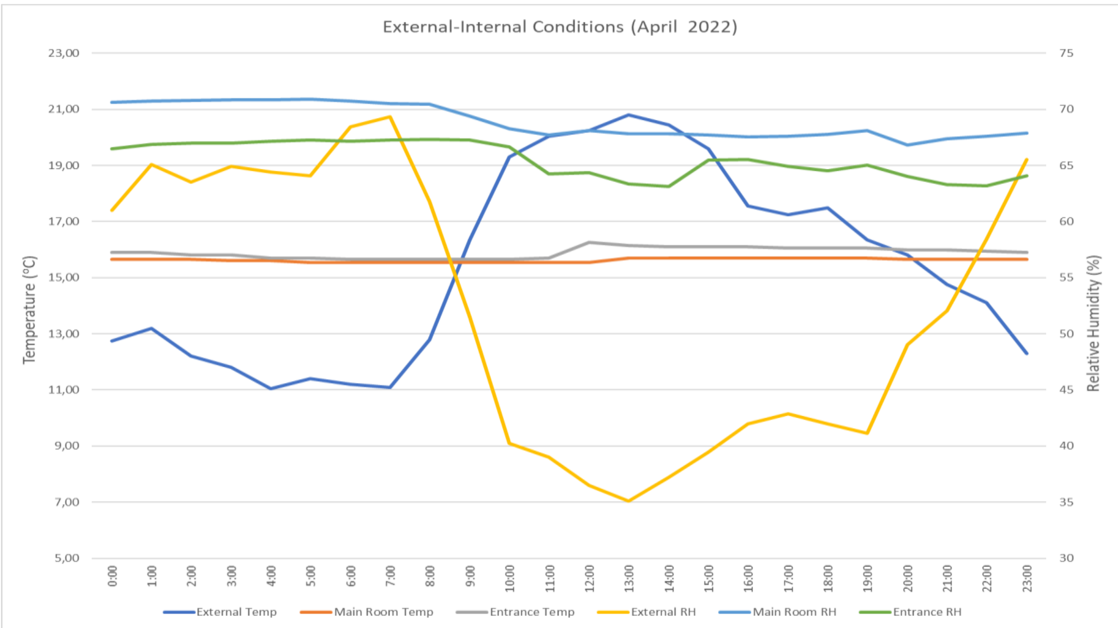


Figure 6. Mean hourly values of outdoor and indoor air temperature and relative humidity, in the Art Gallery 'Constantin Xenakis' (Serres, Greece), in April 2022

As showed in the figures 5 and 6, the most important finding is the stability of the internal air temperature and relative humidity despite the major variations of external conditions. It should be mentioned that during the first monitoring period of the building, the air conditioning system was not operating and thus, the interior thermal conditions reflect the contribution of the building envelope as reaction to external, ambient conditions. This result indicates that the main energy efficiency interventions at building's envelope (i.e. building's envelope thermal insulation, windows with high thermal characteristics) are successful.

Interreg
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European Regional Development Fund

Art Gallery Operational Guide (EN)

ARISTOTLE UNIVERSITY OF THESSALONIKI

TRANSPORT SYSTEMS RESEARCH GROUP

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Contents

Abstract

The ‘Art Gallery Operation Guide’ summarizes the main recommendations for the rational use and operation of the energy systems in the Art Gallery building: heating, cooling, lighting and equipment. It is a short, illustrated guidebook, for exhibition at the Art Galley Reception and Workshop room, adding also the environmental vision at the educational programme of the Art Gallery.

Executive summary

The aim of the ‘Art Galley Operation Guide’ is to give the basic instructions for the operation of the building, ensuring thermal comfort conditions in its interior but also restricting energy waste. It is a short, illustrated guidebook addressed at the users of the building. It summarizes the main recommendations for the rational use and operation of the energy systems in the Art Gallery building: heating, cooling, lighting and equipment

Guide of Operation of Arts Gallery Building

1. Space Thermostat Control

NOTE

Heating season:

When the Art Gallery is closed thermostat must be set at 17 °C.

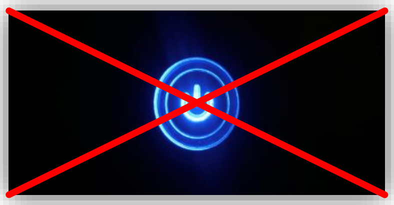
Heating Season: 18 °C

Cooling Season: 26 °C

2. Electrical Devices Switch Off

All electrical pieces of equipment such as display devices (projectors) must be in the off-mode from central switch.

Stand-by mode must be avoided.



NOTE:

In case there are many electrical devices in the building, it is recommended to connect them via multi-socket systems to switch off simultaneously from plug.

3. Artificial Lighting Control

Switch of artificial lights when leaving a space.

NOTE

Movement sensors installation to automatically control switch off/on space artificial lights, especially in service spaces such as bathrooms (WC), etc.

4. Space Ventilation

When feasible, spaces must be adequately ventilated.

NOTE

Cooling Season:

Natural ventilation must take place early in the morning and prior Art Gallery visitors' opening schedule or in the afternoon about its visitors' closing schedule.

NOTE

Heating Season:

Natural ventilation must take place during noon time if feasible.

ATTENTION!!!

Natural ventilation always take place with heating-cooling systems switched off.

5. Solar Radiation – Space Shading

During the heating period, variable shading devices such as stories and louvres must be wide open, especially those attached in south facing openings (in case daylight is allowed in exhibits space).

During the ooling period, care must be taken in managing variable shading devices to avoid transmission of intense solar radiation within indoor spaces.

6. Inspection of Building Envelope and E/M Equipment

Visual inspection of building façades to identify degraded areas (cracks in render, moisture accumulation, mold, etc.) and scheduled inspection of all E/M equipment with special attention to HVAC.

7. Readings on Monitoring Equipment

Surveillance of air temperature and relative humidity readings and recordings.

Desired conditions during **winter** season:

Air temperature range from 20 to 22 ^{o}C and air relative humidity range between 35 to 40%.

Desired conditions during **summer** season:

Air temperature range from 26 to 27 ^{o}C and air relative humidity range between 50 to 60%.

Description of Measuring Instrumentation

The Project is co-funded by the European Regional Development Fund and by national funds of the countries participating in the Interreg V-A "Greece-Bulgaria 2014-2020" Cooperation Programme.

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Contents

Abstract

This report describes the measuring equipment that was obtained with funds of the 'CULTURE DIPOLE' project, in the frame of the Interreg V-A 'Greece – Bulgaria 2014-2020' Cooperation Programme. The instrumentation includes wireless air temperature and humidity sensors, for indoor and outdoor measurements with integrated data loggers, a waterproof shield for the outdoor sensor and a wind speed sensor. It is a wireless instrumentation and the data can be transmitted wireless at remote distance but also manually collected.

Executive summary

The instrumentation acquired for monitoring the thermal conditions in the Art Gallery 'Constantin Xenakis' are described in this report. The instrumentation includes integrated data loggers and sensors for air temperature, air humidity and wind speed that can transmit data wireless.

1. Instrumentation catalogue

No	Model	Manufacturer	Description	Pieces No
1	HD 35EDG 1N TVI	Delta Ohm	Wireless air temperature and humidity data logger with LCD Display	1
2	HD35EDM TCE option X	Delta Ohm	Wireless, Waterproof data logger with LCD display + External antenna + HD32MT4.6 solar shield + HD2003.77/40 clamping	1
3	HP3517 E TC1 5	Delta Ohm	Combined probes for temperature and relative humidity	1
4	HD54.3	Delta Ohm	Wind speed cup	1

2. Instrumentation technical specifications

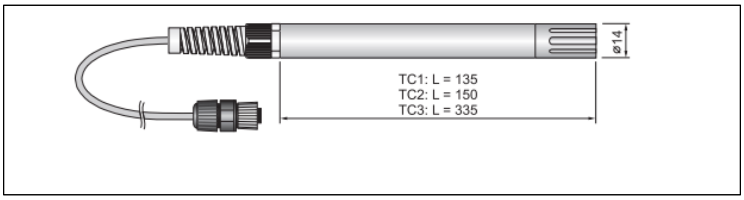
2.1 HD 35ED 1N TVI Wireless air temperature and humidity data logger with LCD Display (DELTA-OHM)

Storing Capacity	24.000 samples
Type of Sensor	Sensor integrated in humidity module
R.H. sensor measurement range	0…100 %RH
Temperature sensor measurement range	-40…+105 °C
Data logger operating conditions	Temperature: -20…+70 ^{0}C Humidity: 0….85 %RH
Other calculations	TD: dew point TW: wet bulb temperature AH: absolute humidity MR: mixing ratio PVP: partial vapour pressure
Power supply	Non-rechargeable lithium-thionyl-chloride (Li-SOCl2) 3.6V internal battery (Typical duration 2 years with 30΄΄ sample intervals)
Mounting	Wall support HD35.03

2.2 HD35EDMTC Wireless, Waterproof data logger with LCD display (DELTA-OHM)

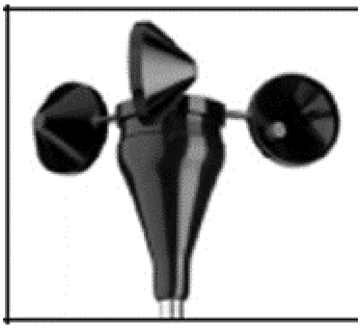
- Temperature, humidity, atmospheric pressure, solar radiation, rainfall quantity, wind speed and direction wireless data logger.
- IP 67 waterproof housing. Custom LCD display.
- It stores the measures in its internal memory (from 28,000 to 58,000 samples depending on the number of inputs used) and transmits the logged data to the base unit automatically at regular intervals or upon request.
- Five inputs with M12 connector: for the HP3517TC... temperature and relative humidity combined sensor, for the pyranometer, for the rain gauge, for the HP54.3 cup anemometer and for the HP54.D wind vane.
- Calculated quantities: dew point, daily solar radiation in Wh/m^2 (Wh = Watt hour), rainfall rate in mm/h, Wind Chill, Wind Gust, dominant wind direction. Acoustic alarm with internal buzzer. Con⇒ guration via HD35AP S software.
- Powered by the internal battery.
- Installation: wall mount or ⇒ xing to a 40 mm diameter mast through the clamping HD2003.77/40.
- Protection shield against solar radiations HD32MT4.6 for outdoor installation.
- External antenna for outdoor installation.
- Measurements range:
  - Humidity Measuring range : 0…100% RH
  - Temperature Measuring range : -40…+105 °C
  - Wind speed Measuring range : 1…65 m/s
  - Wind direction Measuring range : 0…359.9°
  - Atm. Pressure Measuring range : 300…1100 hPa
  - Solar radiation Measuring range : 0…2000 W/m2
- Data logger operating conditions: Temperature: -20…+700C , Humidity: 0….85%RH
- Power supply: Non-rechargeable lithium-thionyl-chloride (Li-SOCl2 BAT-2013DB) 3.6V internal battery (Typical duration 4 years with 30´´ sample intervals)

2.3 HP3517 E TC1 5 Combined probes for temperature and relative humidity (DELTA-OHM)



R.H. Sensor	Capacitive
Temperature sensor	Pt100 1/3 DIN
R.H. sensor measurement range	0…100 %RH
Temperature sensor measurement range	-40…+150 °C (HP3517ETC1 5 with Pt100 sensor)
R.H. sensor operating temperature	-40…+150 °C with option E
Accuracy	± 1.8 %RH (0…85 %RH) / ± 2.5 %RH (85…100 %RH) T=15…35 °C ± (2 + 1.5% measure)% @ T=remaining range
Cable length	5 meters
Connection	8-pole M12 female connector

2.4 HD54.3 Wind speed cup (DELTA-OHM)



Passive cup anemometer	3 cups
Measuring range	1…75 m/s
Operating conditions	Temperature: -45…+60 °C Humidity: 0…100% RH
Output signal	Sine wave with linear frequency depending on wind speed, typical peak-to-peak amplitude 12 V @ 60 Hz.
Cable length	5 meters (CPM12AA4.5)
Height assembled	81 mm

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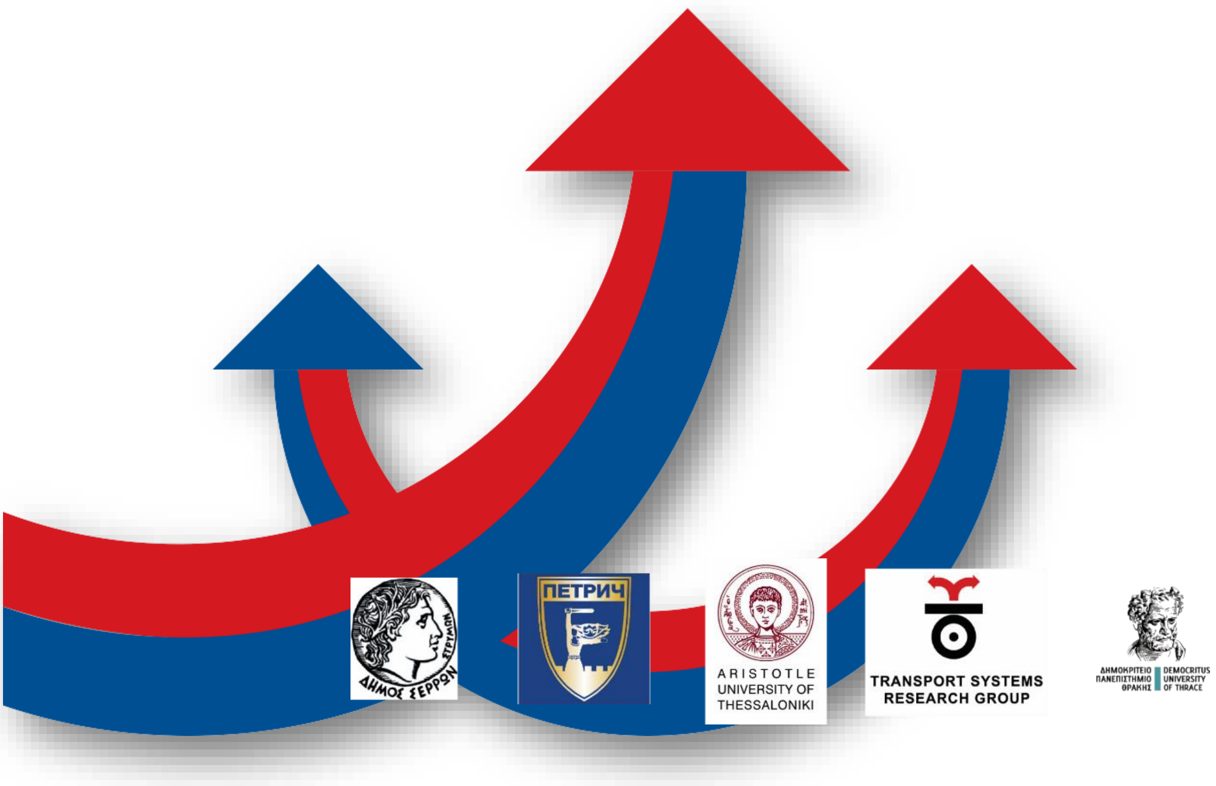
cultural DIPOLE

NEARLY ZERO ENERGY MUSEUMS HANDBOOK



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DISCLAIMER

The sole responsibility for the content of this publication lies with the authors. The views expressed in this publication do not necessarily reflect the views of the European Union, the participating countries, the Managing Authority and the involved project beneficiaries: Municipality of Serres, Municipality of Petrich, AUTh, DUTh.

Contents

Thermal Comfort in Museum Buildings

Athena Kantzioura

1. Introduction

The European Directive on Energy Efficiency in Buildings (Directive 2018/844/EU) introduced the need to construct new buildings according to Near Zero Energy Buildings (NZEB). In contemporary cities most of the building stock has been constructed before the introductions of NZEB. So, there is a challenge in existing buildings, both scientific and technical, to minimize energy consumption while at the same time production is increased. The challenge is even more demanding in the case of historic buildings due to their cultural value and local national regulations (Ascione et al, 2015).

ISO 50001, is commonly used in Europe. It focuses on improving the energy performance of buildings including energy efficiency, use and consumption and establishes an energy management system in existing buildings.

Another point of view of the procedure to obtain NZEB appears in the standard ISO 50001:2011, which defines how to achieve net zero energy buildings.

Moreover, the indoor climate conditions in a building is highlighted as an important factor as people increase their time spent in closed spaces. The microclimate inside the building depends on various factors. The most important ones are air's temperature, humidity, air velocity and surface temperature of obstacles. The combination of these factors indicates the level of users' thermal comfort/discomfort (Nakielska and Pawłowski, 2020).

In museums there is a trifold goal. It is essential to achieve energy savings, thermal comfort conditions and to preserve the exhibits, too. This is due to the sensitivity of the materials of exhibits, which are exposed to indoor environmental conditions.

2. Renovation of Museum Buildings

On 19th century, museums were important part of the urban structure that met social needs and functions. Nowadays the role of the museums expands to areas such as the conservation and transmission of knowledge (Isaac, 2013), (Saraoui et al, 2018).

The museums in historic buildings can become paradigms of sustainable development if their revitalization, energy and architectural upgrading maintain their cultural value (Costanzo et al, 2006), (Berg et al, 2017), (Magrini et al, 2016).

Architectural renovation and re-use of existing and historic building nowadays is a widespread need in countries where there is plenty of buildings and structures of high cultural and artistic value. In particular, the conversion of historic buildings into community structures and facilities (Pisselo et al, 2016), (Oliveira et al, 2017) with public function is increasingly frequent and encouraged by local municipalities.

The microclimate within such historic buildings represents a major problem (Cabeza et al, 2018), especially for the preservation of art works and collections, which are often inside such buildings (Vecco, 2010). Regarding the conservation of art works, the indoor environmental conditions are very important. The air temperature (˚C), the relative humidity (%), the illumination level (lux), and the pollutants concentration (ppm) are the main factors responsible determining the proper indoor conditions for preservation of cultural heritage works (Schieweck et al, 2007), (Andretta et al, 2016). Values outside the accepted range of those factors alternate the artwork materials, accelerate the chemical degradation rate and challenge chemical damage (corruption, oxidation) (Pavlogeorgatos, 2003), (Ankersmit, 2005), (Pigliautile et al, 2019).

3. Thermal Comfort

According to ASHRAE Standard (2010), «Thermal comfort is a state of mind that expresses satisfaction with the surrounding thermal condition». However, the conditions needed to obtain thermal comfort are not the same for everyone. There are six main factors that must be considered when determining thermal comfort (Table 1) (Millatina and Syafii, 2021):

Table 1: Factors affect the thermal comfort

No	Variable	Definition	Unit
1	Metabolic rate (metabolic rate)	Rate of transformation of chemical energy into heat and mechanical work by metabolic activity in an organism, usually expressed in units of unit area of the total body surface	metric
2	Clothing insulation	is resistance to heat transfer caused by clothing suits	clo
3 4	Air temperature Radiant temperature	temperature in the surrounding environment uniform surface temperature of an imaginary black enclosure, where the user will exchange the same amount of radiant heat as in the actual nonuniform space	Celcius Celcius
5	Air speed	the rate of movement of air at a point, regardless of its direction	m/s
6	Humidity	the ratio of the partial pressure of water vapor in the air with the saturation pressure of water vapor at the same temperature and total pressure.	%

Different thermal comfort models have developed over the last years (Doornbos, 2016). A very widespread thermal comfort indicator is the Predicted Mean Vote (PMV), which was proposed by Fanger (1970) (Fanger, 1970). PMV is a common model which displays the thermal sensation on a 7-point scale. It is ranging from -3 to 3, where the -3 presents the state very cold, the 0 is natural and the 3 is very hot.

According to ASHRAE (2009) «The PMV is the imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at the specified activity».
PMV considers six different parameters, which are divided in two categories. The first category is the environmental variables such as the air temperature, the air velocity, the mean radiant temperature and the relative humidity. The second category is the personal variables including variables such as the metabolism and clothing insulation (Taleghami et al, 2013).
The PMV has a strong relation with the Predicted Percentage of Dissatisfied (PPD), which predicts the percentage of occupants being dissatisfied with the thermal conditions inside a building. These indexes reflect the heat exchange balance for an average person based on uniform environmental parameters, such as activity intensity and clothing level of insulation. The model aims for constant indoor climate conditions without permissible fluctuations (Kramer et al, 2018).
Another used model to define the thermal comfort conditions is the adaptive model (Humphreys et al, 2013). The adaptive model describes the «strong relationship between the thermal comfort and the mean temperature inside a building». The ASHRAE developed an adaptive comfort model based on collected data in different climatic zones (De Dear et al, 1998). The results concluded that the different thermal experiences of the occupants, the different clothing, the availability to control the indoor conditions and the occupant expectations affect their thermal responses. These outcomes guided us to the initial adaptive standard «ANSI/ASHRAE 55-2004R Thermal environmental conditions for human occupancy» (Doornbos, 2016).
The adaptive process takes into consideration the pattern of outside weather conditions, the seasonal variations of environmental conditions, the exposure to them, the human adaptability and the human expectations (Kramer et al, 2018). So, the outdoor weather conditions are usually the main input to adaptive models, which predicts a set of comfort temperatures or ranges of thermal comfort out of monthly mean outdoor temperatures (Doornbos, 2016).
The adaptive thermal comfort approach and the possibility of widening temperature bandwidths regarding collection preservation, may result in optimal thermal comfort conditions and improve the building's energy behaviour (Kramer, 2018).

3.1 Thermal comfort standards in museums

The requirements for indoor air quality for general purpose premises such as apartments, offices are defined by appropriate standards. In special purpose facilities, e.g. museums, the determination of desired or even necessary parameters of indoor environment is difficult and ambiguous (Gaoming et al, 2010).
Standards, e.g. EN-ISO 7730 and ASHRAE Standard 55, prescribing thermal comfort requirements are mainly based on research in office environments (Kramer et al, 2018).
However, comparing a visitor in a museum to an employee into an office, there are significant differences.

1. The average time people spent in a museum is about 70.7 minutes, while office employees are mostly at work for 8 hours a day, 5 days a week (Jeong and Lee, 2006).
2. The activity level of a visitor in a museum (walk) is about 1.5 met while office workers are seated (activity level=1.0met).
3. A museum visitor is spending quality relaxed time during his visit, while an office worker can be under stress and pressure during his work.
4. In a museum the main reason that can dissatisfy the visitors are things related to the exhibits such as the method of exhibition, the visual and locomotor accessibility, the illumination and rest areas, while the employees are more sensitive to the indoor conditions (Jeong and Lee, 2006).

The indoor environmental factors in a museum must within a specific range of value to ensure ideal conditions and to protect the objects from degradation due to external parameters and also create comfortable indoor environment for staff and visitors.
In countries with large numbers of historic monuments, there are regulations which determine the optimum environmental factors (Gennusaet al, 2008), (Pavlogeratos, 2003). Some guidance regarding the environmental conditions can be found in ASHRAE publications (ASHRAE, 2007), (Harriman et al, 2008). The threats can be removed by a combination of means, such as the use of appropriate technical solutions. The dehumidification or humidification of museum rooms, the heating, cooling and air-conditioning of exhibition halls are some practices in order to accomplish appropriate conditions of indoor microclimate in museums.

3.2 Degradation and indoor conditions

The parameters of Tair and RH can cause degradation to the exhibitions. According to Martens (Martens, 2012) there are the following three types: the biological, the chemical and the mechanical degradation. The first one accounts for fungi, the second is the chemical process an object is subjected to and the last causes materials to change shape and form through shrinking or expanding.
Those three degradation mechanisms are widely mentioned in literature and risk assessment methodologies are provided in several works (Schito and Testi, 2017), (Huijbregts et al, 2012), (Silva, 2014), (Schito et al, 2018).
However, making the indoor climate suitable for the preservation of objects is difficult because every collection consists of different materials. The mainly factors which influence the indoor microclimate of a museum are described bellow:

Air relative humidity (RH, %)

In museums, the RH is an important microclimate parameter, because a big variety of exhibits' materials may degrade. The main reason is the air moisture absorption or desorption from the elements. The most sensitive materials in these processes are organic materials (e.g. paper, fabric, wood, bones, horns etc.). An additional aggravating factor associated with the level of humidity is the large fluctuations of it, which can cause permanent damage to some of the exhibits. Specifically, low levels of relative humidity result into making the materials more fragile, breakable or stiff, while high levels cause decline of material flexibility, deformation of elements, lower mechanical resistance and higher sensitivity to fungi and bacteria development. Consequently, it is possible to have paint decay, metallic corrosion, cracking and clouding of glass and other types of degradation (Nakielska and Pawłowski, 2020).

Air temperature (Tair, ºC)

Air temperature affects the configuration of the microclimate conditions in a museum. Air temperature in combination with the relative humidity affect the collection of exhibits, while at the same time it remains an important factor of the thermal comfort conditions, too. The appropriate selection air conditioning and ventilation systems is crucial for the temperature, as those systems have to react to the variable inner and outer conditions.

Regarding the optimum inner climate conditions for different kinds of exhibits there are recommendations from the European Federation of HVAC National Association. Table 2 presents the values of Tair and RH for some items and materials. The problems that could be caused by an inappropriate combination of air temperature and relative humidity would have consequences of degradation in the museum exhibitions. A combination high temperature and low air relative humidity can cause materials to dry, lose their flexibility and ultimately create cracks. This is applicable to materials such as leather, parchment, paper and glues. On the other hand, a combination of both high temperature and high air relative humidity can cause microbial development and a suitable environment for insects and rodents. Temperatures below 10°C along with high air relative humidity and poor circulation will inevitably lead to moistness and microbial development.

Table 2: Recommended values of Tair and RH, REHVA project

Item/Material	Air Relative Humidity (%)	Air Temperature (ºC)
Iron armour, weapon	<40	
Bones, ivory	45-64	19-24
Bronze	<55	
Pater	50-60	19-24
Anatomic collection	40-60	19-24
Minerals collection, stone, marble	45-60	<30
Leather, hode, parchment	50-60	
Botanical collection (including herbs)	40-60	
Oriental lacquer	50-60	19-24
Wood	40-65	19-24
Painting on wood, polychrome wood	45-65	19-24
Books, manuscripts	50-60	19-24
Ethnographic materials	40-60	19-24
Organic materials (generally)	50-65	19-24
Plastics	30-50	
Polished metals and alloy brass, silver, tin, lead, copper	<45	
Gold	<45	
Papyrus	35-40	19-24
Fur and leather	45-60	15-21
Paintings on canvas	35-50	19-24
China, ceramics*, stoneware, earthen goods *for some kinds of ceramic made in a lower temperature, the RH has to be <45%	20-60	

Air pollution

The air pollution parameter is also a significant factor in the indoor climate of a museum. The degradation risks connected with the air quality and the concentration of some gas contamination can cause irreversible changes in the museum collections (Nakielska and Pawłowski, 2020).

Lighting

The influence of lighting depends on the length of time the objects will be exposed and the elements which the materials are made of. In fact, light has oxidative properties throughout the whole wave length spectrum, which results in colour changes to the materials and other distortions such as fragmentation, brittleness and other. To protect the exhibits from lighting, the windows should be equipped with the UV filters or foils ensuring that light rays do not land directly on objects. At the museum halls, the lighting should be kept at f 50–200 lux, depending on the type of the building. In warehouses 150 lux is ideal. The light sources should not emit light in the UV spectrum otherwise lighting fittings should be equipped with UV and IR filters (Nakielska and Pawłowski, 2020).

3.3 Assessment of artwork risk

In many studies, two methods are used for artwork maintenance and preservation. The first one is solely based on the curators’ experience and the guidelines suggesting temperature and relative humidity setpoints for different artwork typologies (Schito and Testi, 2017). The second one evaluates the risk via correlations formulated for each degradation case.

The Michalski (Michalki, 2002) use the lifetime multiplier (LM) as a key indicator for artwork risk assessment of chemical nature. This index compares the effects of actual microclimate to the effects of a benchmark microclimate (i.e., 20 °C and 50% for Tair and RH set-points, for artworks of organic nature). The LM equation, at time is:

$$LMi = \left(\frac{RHref}{RHi}\right)^{1.3} exp\left[\left(\frac{Eo}{R}\right)\left(\frac{1}{Ti + 273.15} - \frac{1}{Tref}\right)\right]$$

Where:

RHref=50% and Tref=293.15 K for benchmark microclimate values,

R= 8.314 J/mol K (ideal gas constant),

RHi (%) actual value of relative humidity,

Ti [°C]) actual value of temperature,

Ea (J/mol) activation energy, obtained experimentally, characterizing the artwork typology in scrutiny (values of this parameter for different materials can be found in **Error! Reference source not found.**, 0, 0).

When LM is higher than one, current microclimate reduces chemical risks with respect to benchmark microclimate (Schito et al, 2018).

4. Indoor climate museums

The standard values for indoor environmental parameters of buildings where artworks are preserved have been tested in field studies in order to achieve the best conditions for thermal comfort of visitors and artwork preservation (Pigliautile et al, 2019).

The standard EN 15757 analyses how the microclimate of heritage buildings can be controlled, to achieve an integration under the conditions of sustainable development.

The ASHRAE introduced guidelines for museums with respect to indoor conditions. Table 3 presents the different classes where AA is the strictest one (Doornbos, 2016).

The table depicts different climate classes ranging from class AA (precision control) to class D (relaxed control) (Michalski, 2007). Every class corresponds to a specific description of the corresponding risk to a collection. For example, the class AA yields no risk of mechanical damage to most artefacts and paintings, while the class A yields only a small risk to highly vulnerable objects. Classes AA, A and even B are presented as ‘precision control’, but with different relaxations (Kramer et al, 2016).

Table 3: Environmental guidelines for museums (ASHRAE)

Class of control	Short-term fluctuations and space gradients	Seasonal adjustments in system set points
AA	±5%RH, ±2°C	RH no change, Up 5°C and down 5°C
A	±5%RH, ±2°C	Up 10% RH and down 10% RH, up 5°C and down 10°C
A	±10%RH, ±2°C	RH no change, Up 5°C and down 10°C
B	±10%RH, ±5°C	Up 10% RH and down 10% RH, up 10°C and low as necessary to maintain RH control
C	Within range 25-75% RH year-around, rarely over 30°C, usually below 25°C	
D	Reliably below 75% RH	

It is very difficult to decide which climate class fits best to a specific situation, especially when museums are housed in historic buildings. The hypothesis that the strictest indoor climate class (AA), will be the overall optimum solution does not always correspond to reality. Configuring the climate inside the museum according to a strict climate class, may result into considerable energy consumption which could be otherwise be avoided. Moreover, historical buildings could suffer from long standing conditions like moisture and vapour condensation during winter (Brown ad Rose, 1996). Also, relative studied have sown that the desired strict indoor climate in most historical buildings are practically unachievable, even for the most sophisticated HVAC systems (Kramer et al, 2016), (Martens, 2012).

Moreover, even if such a strict climate control was feasible, there is no evidence that this would result to a more effective protection of exhibits.

So, nowadays there are notions to shift from strict conditioning to loosen ones. This policy aims to decrease energy costs and to increase the sustainability of the museum buildings Dardes and Staniforth, 2015).

Recent studies have found that a wider Tair and RHair fluctuations than expected do not affect most of the exhibits (Lukomski, 2012). For example, Martens (2012) conducted a large-scale experimental study including 21 museums in the Netherlands. They used damage functions for biological, chemical and mechanical degradation to assess collections' degradation risks. The study concluded that collection risk on lower level of indoor microclimate control was not necessarily larger compared to museums with a high level of indoor climate control.

A standard set-point in museums for the whole year was not proven to be the best choice. On the contrary, the controlled seasonal fluctuations are more effective in collection's protection and energy efficiency (Kramer et al, 2015). The ASHRAE (2011) identifies classes for the climate in museums, galleries, and libraries, up to the strictest class (AA) and specifies short fluctuations of ±2°C with additional seasonal set-point adjustments of ±5°C. For loan exhibitions with a starting-point of 21°C, this results in a range of 14–18°C in winter and 24–28°C in summer (Kramer et al, 2018a).

Some studies indicate that a proper determination of T and RH can improve the energy efficiency up to 75% (Ascione et al, 2018), ensure thermal comfort conditions without increase the risks for exhibits. For example, changing the temperature setpoint during the seasons allows an energy saving up to 13% and stricter control of indoor microclimate only during winter (museum in Belgium) (Ascione et al, 2017) had good results for both artworks and visitors' thermal comfort.

Hence, further research is necessary about acceptable temperatures regarding thermal comfort within museums.

5. Conclusion

A museum construction and/or rehabilitate to improve energy efficiency and thermal comfort conditions is a complex process.

The museum halls ask for a thoughtful selection of the natural and artificial material's characteristics influencing the building itself, the collections displayed, the comfort of visitors and the energy saving.

The internal microclimate conditions affect the collections, so an appropriate heating and ventilation system is important to protect the exhibits and to insure comfortable thermal conditions for the visitors along with energy savings.

Taking into account energy saving policies in buildings and especially in museums, it is important to adopt methods for energy efficiency, thermal comfort and artwork preservation. This strategy applied in museums, especially when they are hosted in historic buildings, can showcase them as cultural centres and examples of sustainable development.

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RES Systems (Geothermal energy, Solar heating & cooling, PV, Biomass)

Stamatis Zoras

1. Introduction

Climate is defined as the set of various environmental elements (such as temperature, humidity, speed, direction and composition of air). Climate is divided into outdoor and indoor climate. Outdoor is defined as the climate of the free (open) environment from walls. Indoor climate is defined as the climate of a confined environment within walls (Sellountos, 2002).
The factors that affect the climate of a building are presented in Fig. 1.

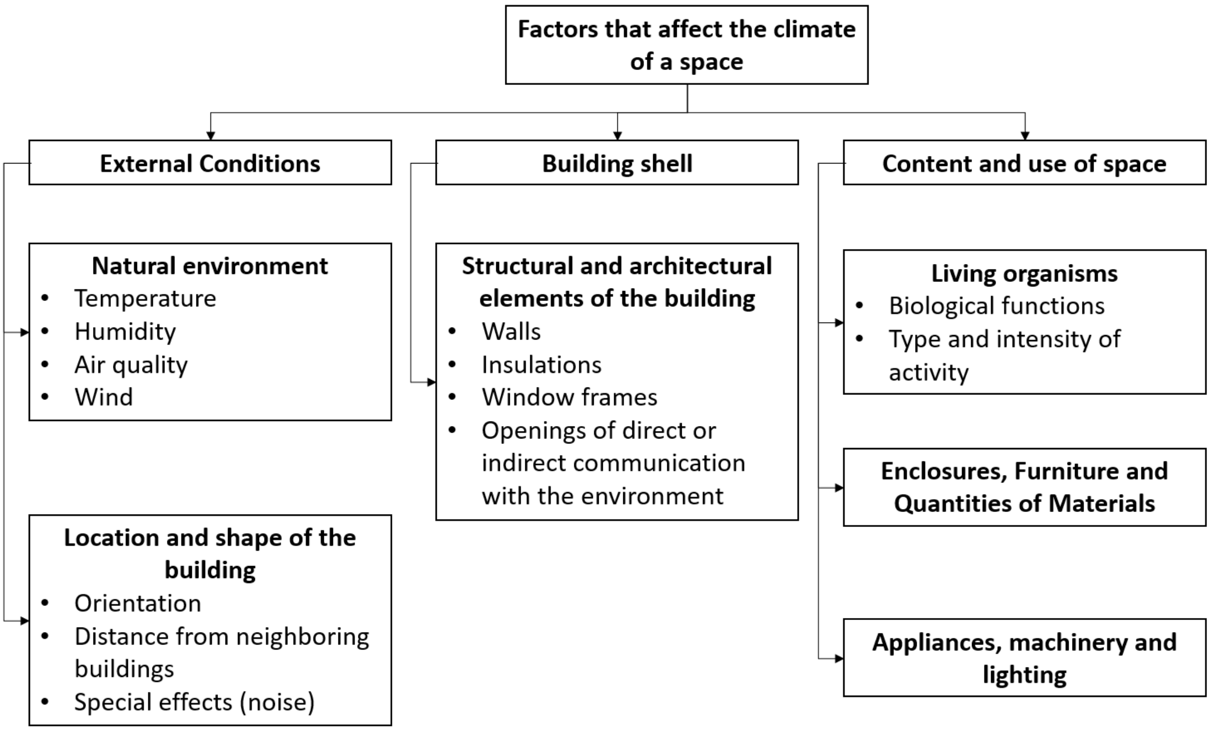


Figure 1: Factors that affect the climate of a building (Sellountos, 2002)

The 'ideal' human comfort conditions developed through statistically proven preferences of people and depend on the type of building (houses, hospitals, museum, cinemas, industrial buildings, etc.). Various tables and diagrams, such as Yaglow or ASHRAE diagrams, are used to determine desired human comfort conditions (see Fig. 2).

Various automated heating and air conditioning systems (direct or indirect) are used to achieve the ideal human comfort conditions. The main feature of direct heating systems including open fireplaces, etc., is the fact that the heat generation system is located inside the room spaces that are being heated, while indirect heating systems (e.g. geothermal source, solar panel, etc.) are located outside of indoor spaces that are being heated, and they heat a heat carrier (e.g. water, air), which is led to the heated rooms, using heat exchangers (via conduction, convection, radiation).

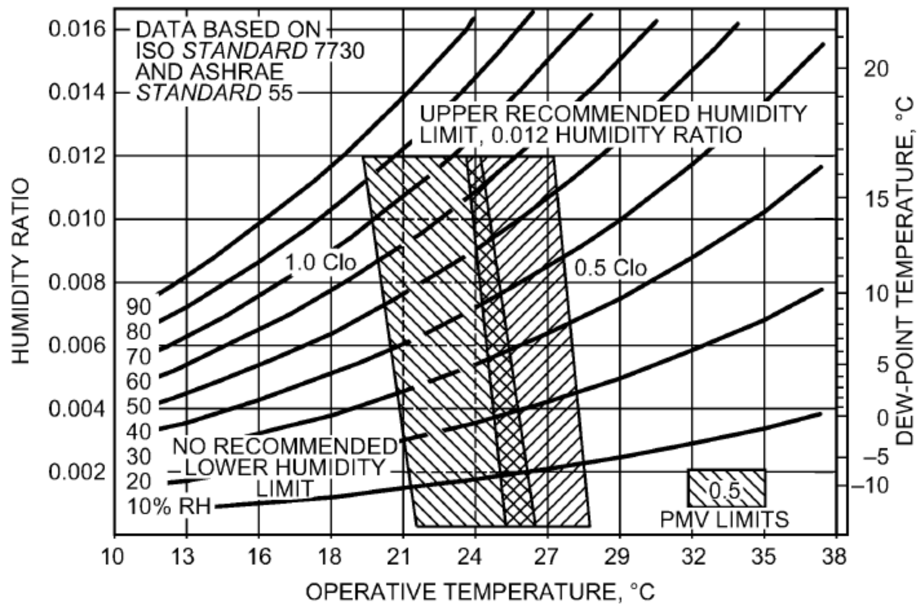


Figure 2: ASHRAE Summer and Winter Comfort Zones [Acceptable ranges of operative temperature and humidity with air speed ≤ 0.2 m/s for people wearing 1.0 and 0.5 clothing during primarily sedentary activity (≤1.1 met)] (ASHRAE, 2017).

In recent years, there is a great interest in renewable energy (RES). RES is defined as *'energy from renewable non-mineral sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, tidal, wave and other forms of ocean energy, hydroelectric, energy from biomass, energy from gases released in landfills, from gases produced in wastewater treatment plants and biogas'* (EC, 2018).

2. Geothermal Systems in Buildings

Geothermal energy is defined as *'energy stored in the form of heat under the earth soil's surface'* (T.O.T.E.E.20701-8, 2021). Shallow or normal geothermal systems are *'the systems that utilize the heat of geological formations and surface or groundwater'* (T.O.T.E.E.20701-8, 2021). Geothermal pumps are used for heating and/or cooling a building and/or producing hot water in boilers. The fitting depends on the temperature of the available fluid. There are different types of heat pumps depending on the agent material that is pumped and circulated in the circuit and depending on the agent that is discharged into the environment: air-air, air-water,

water-water, water-air and ground-air. In Greece, the types of air-air and air-water are those commonly used (Sellountos, 2002).

2.1 Calculation of thermal and cooling loads for the dimensioning a geothermal pump

Prior to the calculation of thermal needs, the thermal insulation of the building must be checked to verify weather it meets the requirements of the Greek regulation of thermal insulation. Thermal needs depend on the properties of the building (e.g. masonry, construction materials, size, openings, ventilation, etc.). The total thermal needs of the building result from the sum of the thermal needs of the individual spaces. The design of the installation must cover the losses of the building even at the lowest possible temperatures. The actual heat loss of a building is less than the heat generated by the installation. The thermal needs of a building are the maximum heat losses. The methodology for calculating heat loss is based on laws of heat transfer. Heat losses include thermal permeability losses from structural elements (walls, openings, ceilings), incremental losses and ventilation losses.

As in the calculation of thermal loads, the calculation of cooling loads is performed in each area of the building, with a similar methodology. The total cooling load of each room consists of the perceived load (which changes the room temperature) and the latency (which changes the humidity of the room). This load varies for each period of the day, with a maximum value which depends on the orientation of the space and the use. Cooling loads depend on the thermal permeability losses of the structural elements, the ventilation losses (real and latent) and the thermal gains (radiation, people, appliances, lighting, etc.). The calculation of refrigerant loads is based on Carrier methodology with ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) psychrometric diagrams (ASHRAE, 1992).

The annual heating and cooling needs are also calculated so the total losses of the building correspond to the minimum power of the heat pump. The cooling power is calculated accordingly. For the dimensioning of the geothermal systems, the geothermal pump is initially selected according to the calculation of the thermal and cooling loads (it is the same for the horizontal and vertical system) and the inlet-outlet temperatures. The unit includes various other components such as heat exchangers, circulator, expansion tank, etc.

The coefficient of performance COP is the degree of energy efficiency of the heat pumps. COP is calculated from the ratio of the heat transferred (Q) to the electricity consumed (W), (see Eq. 1).

$$COP = Q/W \tag{1}$$

A heat pump that delivers 4000 watts and consumes 1000 watts has COP 4 (=4000/1000).

In 2013, the seasonal coefficient SCOP (Seasonal Coefficient Of Performance) was introduced and it measures energy efficiency during the winter season (for heating) and during the summer season (for cooling).

There are two main categories of geothermal heat pumps: open loop systems, see Fig. 3, and closed loop systems, see Fig. 4.

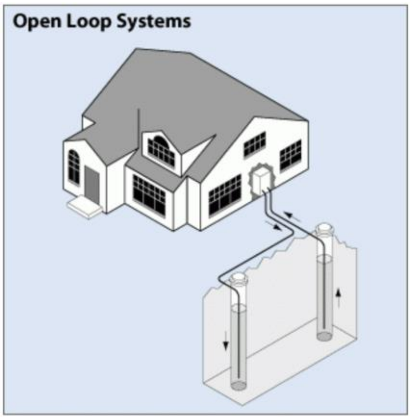
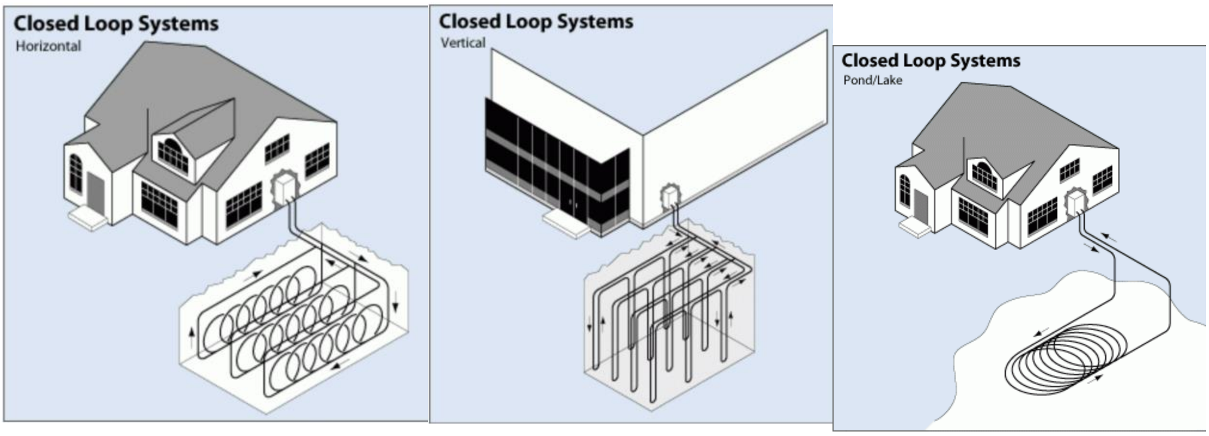


Figure 3: Geothermal open loop system



a. b. c.

Figure 4: Geothermal closed loop systems

3. Photovoltaic Systems in Buildings

There are two categories of solar energy systems: *passive solar systems* and *active solar systems*. Passive solar systems mainly concern the structural elements of buildings that utilize the physical laws of heat transfer. Active solar systems, especially photovoltaics, convert solar energy into electricity using Photovoltaic (PV) cells, through photoconductivity (Duffie et al., 2020). Photovoltaic systems are used to generate electricity by utilizing solar energy, to cover part or the total of electrical charge.

There are *small movable PV* and *automatic PV* systems. The utilization of solar radiation to produce electricity with the use of batteries for the possibility of autonomous operation rank the PV is the most suitable technology for energy generation applications in buildings of isolated areas.

An autonomous PV system can meet the electricity needs for domestic use, with the correct calculation of the electricity needed for storage (Karaisas, 2014). There are different types of PV systems that can be installed in a building depending on the use and the available area. In a building it is allowed to install a PV on the roof, on the chamber and on a terrace canopy.

In most cases of electrification, more than one PV panel is required, properly connected (in series, in parallel, or mixed connection), see Fig. 5.

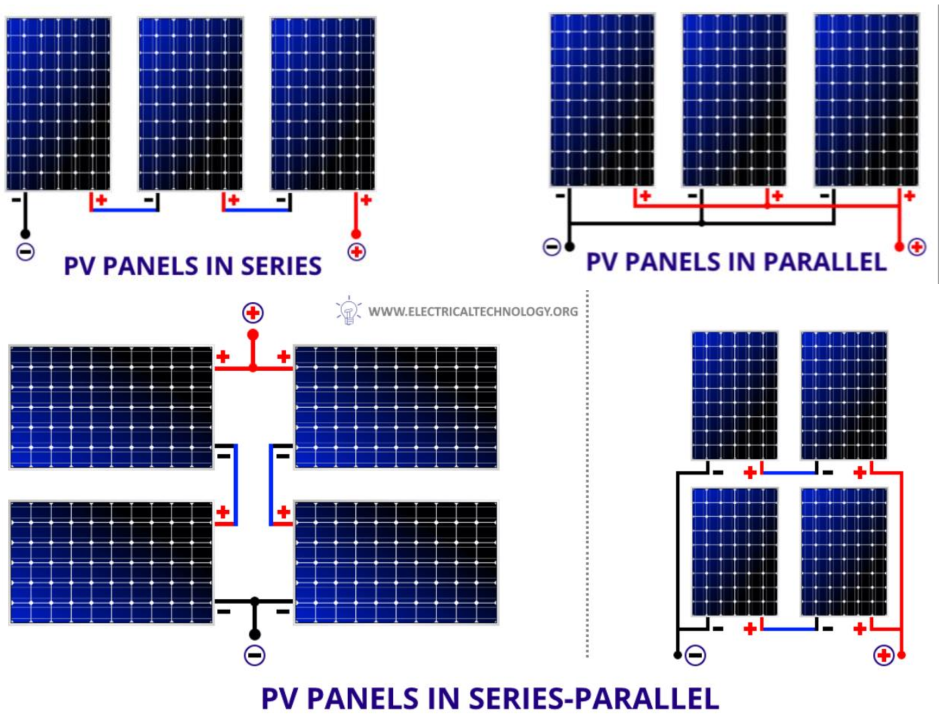


Figure 5: PV in series, in parallel and series-parallel (mixed) connection (electrical technology, 2020)

- *PV panels in series*
  The panels must have the same short-circuit current (I_{SK}) and the same maximum current (I_m). Series connection is used when is required greater voltage than the voltage of a frame.
  The total voltage of the array is equal to the sum of the voltages of the n frames: $V_{OC} = V_{OC1} + V_{OC2} + ... + V_{OCv}$ (open circuit voltage), $V_m = V_{m1} + V_{m2} + ... + V_{mv}$ (maximum power voltage) (Karaisas, 2014), see Fig. 6a.
- *PV panels in parallel*
  The frames should have the same open circuit voltage (V_{oc}). Parallel connection is used when is required higher current than the current of a frame. The total current will be equal to the sum of the currents in each frame: $I_{SC} = I_{SC1} + I_{SC2} + ... + I_{SCv}$ (short circuit intensity), $I_m = I_{m1} + I_{m2} + ... + I_{mv}$ (maximum power intensity) (Karaisas, 2014), see Fig. 6b.
- *PV panels in serries-parallel (mixed) connection*
  Serries-parallel connection is a combination of connection in series and parallel in order to increase the voltage and increase the current at the same time (Karaisas, 2014), see Fig. 6c.

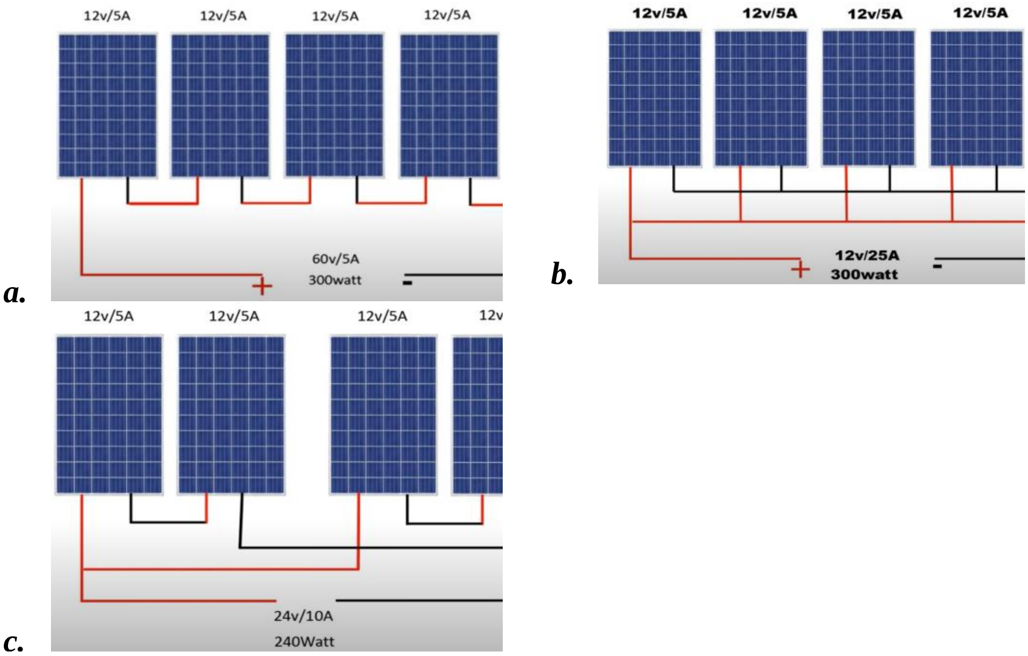


Figure 6: Examples of PV connection. **a.** PV in series, **b.** PV in parallel and, **c.** PV in series-parallel (mixed) connection (QUIRCTECH, 2022)

The necessary parameters for the design and dimensioning of the PV system are recorded: specification data and building data such as PV system performance, PV panel surface, installation location parameters, orientation and PV slope.

PV systems calculations required knowledge of metrology and solar radiation measurements. The PV installation is done with South orientation and with a slope towards the horizontal level. The solar radiation in terms of the horizontal level, for differing locations, for each month, is given by specific tables. For each month and each zone there is an angle of PV inclination where the total energy is maximum.

The main factors that affect the photovoltaic electricity calculations are the average daily solar energy, the efficiency of the PV module, the coefficient of correction of efficiency due to temperature, the packing coefficient of the array, the coefficient of pollution and the total surface modulus.

There are different types of PV panels depending on raw material used in solar cells. Silicon PV panels dominate, as silicon is the second most abundant material in earth after oxygen, is environmentally friendly, easily formed (melts) and is suitable for harsh environmental conditions: its electrical properties are maintained up to 125 ^{o}C (T.O.T.E.E.20701-8, 2021). The energy efficiencies of silicon PV differ depending on the technology (monocrystalline or polycrystalline: 12-22% and amorphous silicon PV thin film 7- 11%) (NREL, 2020). Fig. 7 shows different types of PV crystals.

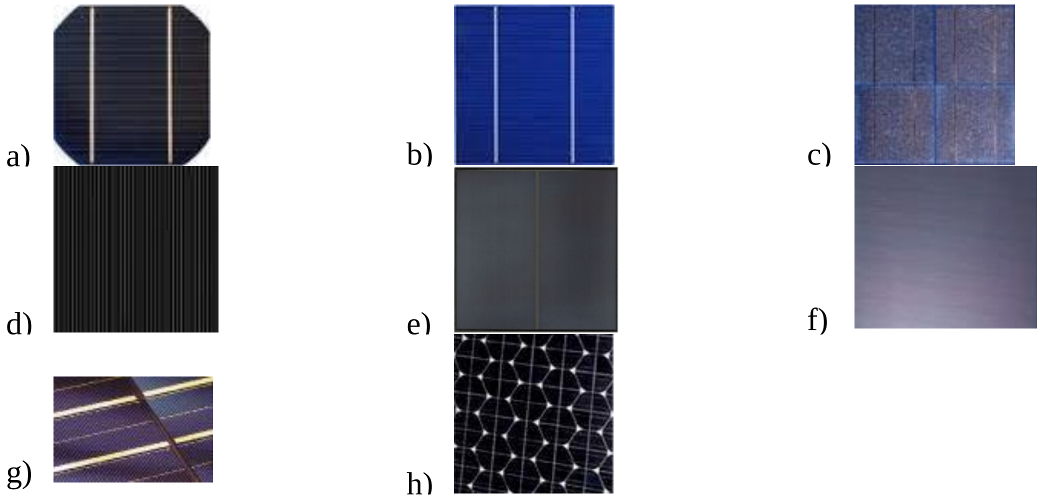


Figure 7: PV elements of crystalline silicon (a-c): a. Monocrystalline Silicon Elements (sc-Si), **b.** Polycrystalline Silicon Elements (mc-Si), **c.** Silicon Film (Ribbon-Si). **PV thin film elements (Thin Film) (d-g): d.** Copper biselinoid (CIS, CIGS), **e**. Amorphous Silicon (a-Si), **f.** Cadmium Telluride (CdTe), Gallium Arsenic (GaAs). **Other technologies of PV materials (h):** h. Hybrid photovoltaic (HIT), as well as various types of nanocrystalline photovoltaic cells (nc-Si) (Duffie et al., 2020; Selasenergy, 2021)

There are various types of batteries that are used in PV systems, such as lead ($Pb-H_2SO_4$), nickel-cadmium (Ni-Cd), zinc-bromine (Zn-Br), zinc-chlorine (Zn-Cl) etc. The energy stored in a accumulator is calculated by Eq. 2 (Wh).

$$E\kappa = \beta * Q * U_\beta * h_a \quad (2)$$

where β is the discharge depth of the accumulator, Q is the capacity of the accumulator (Ah), U_β is the discharge voltage of the accumulator (V), and h_a is the efficiency degree of the accumulator (usually the value 0.85 is used).

The connection of the accumulators can be:

- *In series* (where the total voltage $U_{tot} = U_1 + U_2 + ... + U_v$ and the total nominal capacitance of the array is equal to $Q_{tot} = Q_1 = Q_2 = ... = Q_v$ and the total intensity is equal with $I_{tot} = I_1 = I_2 = ... = I_v$) or
- *In parallel* (where the total nominal voltage of the array is equal to $U_{tot} = U_1 + U_2 + ... + U_v$, with the total nominal intensity equal to $I_{tot} = I_1 + I_2 + ... + I_v$ and the total nominal capacitance of the array equal to $Q_{tot} = Q_1 + Q_2 + ... + Q_v$) or
- *In series-parallel (high intensity and large capacity).*

Depending on the type of photovoltaic, the appropriate *converter* is used: DC-DC (for conversion of direct voltage to direct, smaller or larger, in order to reduce losses in the transmission line), DC-AC inverter (conversion of direct current to alternating current, for house or industrial use), DC-AC network cover the needs of PV power of low, medium or high power) etc.

4. Solar Thermal Systems in Buildings

Solar thermal (ST) systems utilize solar radiation directly to generate heat, or indirectly to generate electricity, using solar panels of superheated fluid with a steam turbine. ST systems are included in renewable energy system (RES) technologies (European Directive 2018/2001/EU). The installation of solar thermal systems in a new building introduced by law 3851/2010. In new buildings, solar thermal systems have the potential of becoming mandatory to cover part of the needs for domestic hot water (DHW) using ST, with a minimum percentage of the solar thermal share of 60% (annual basis).

ST systems are divided into *passive solar systems* (solar panels that utilize solar energy without consuming any other form of energy), such as solar panels for natural hot water circulation and *active solar systems* (where in addition to solar energy, they used devices that consume other forms of conventional energy (circulators, solenoid valves, etc.).

Accelerated circulation solar panels are the most well-known solar thermal systems. Those are divided in two categories: *flat solar panels* (for fluid temperatures from 40 to 150 ^{o}C) and *concentrator solar panels with mirrors* (for temperatures above 150 ^{o}C, superheated fluid).

Solar flat water or air collectors are used in buildings for DHW production and heating and/or cooling (Solar Combi System).

The heat generated from the absorption surface of solar radiation of ST is transferred to the fluid circulating below the absorption surface through a tube (coil). Hot water is used either directly (open circuit) or using a heat exchanger (closed circuit). ST systems are accompanied by a *hot water storage tank*.

Flat solar panels are classified according to the protective transparent cover they have (glass, plastic, vacuum, without cover, etc.) and according to the painting method of collector surface:

- *Solar panels without transparent cover* (constitute a more economically viable solution, up to 30 ^{o}C, pool water heating, but not suitable for low temperature areas),
- *Solar panels with single transparent cover* (constitute the most common DHW technology in buildings, 40-60 ^{o}C),
- *Solar panels with double transparent cover* (fluid temperature up to 80 ^{o}C, suitable for low temperature areas for DHW production and heating),
- *Solar panels with selective pigment* (titanium, increased absorption coefficient 95%, suitable for DHW production, heating and cooling and/or in combination with desalination units).
- *Solar vacuum collectors* (suitable for requirements from 80-150 ^{o}C such industrial applications, cooling with absorption).

The technical characteristics of a ST system affect the ability to utilize solar energy on the surface as well as thermal losses. Technical characteristics that affect the performance of solar panels are the thermal efficiency coefficient (FR) of the solar system, the transmittance coefficient (t) of the transparent cover of the solar system, the absorption coefficient (α) of the solar radiation of the absorber, and the coefficient of thermal losses (UL) of the solar system (T.O.T.E.E.20701-8, 2021).

The instantaneous degree of efficiency η for a given intensity of solar radiation on the surface of the collector is calculated by Eq. 3.

$$\eta = Q/A_C * G_T = F_R * (\tau * a)_n - (F_R * U_L * (T_i - T_a))/G_T \quad (3)$$

where $F_R * (\tau * a)_n$ is the coefficient of thermal gain (ικανότητα αξιοποίησης ηλιακής ενέργειας) (ability to utilize solar energy) of the solar collector,, $F_R * U_L$ (W/m^{2}K) the coefficient of heat loss,, T_i the temperature of the solar collector (°C), T_a outdoor air temperature (°C), and G_T (W/m^2) the intensity of the incident solar radiation (T.O.T.E.E.20701-8, 2021).

The degree of efficiency as a function of the proportion of the difference between ST temperature and the temperature of ambient air, to the intensity of solar radiation is shown in Fig. 8.

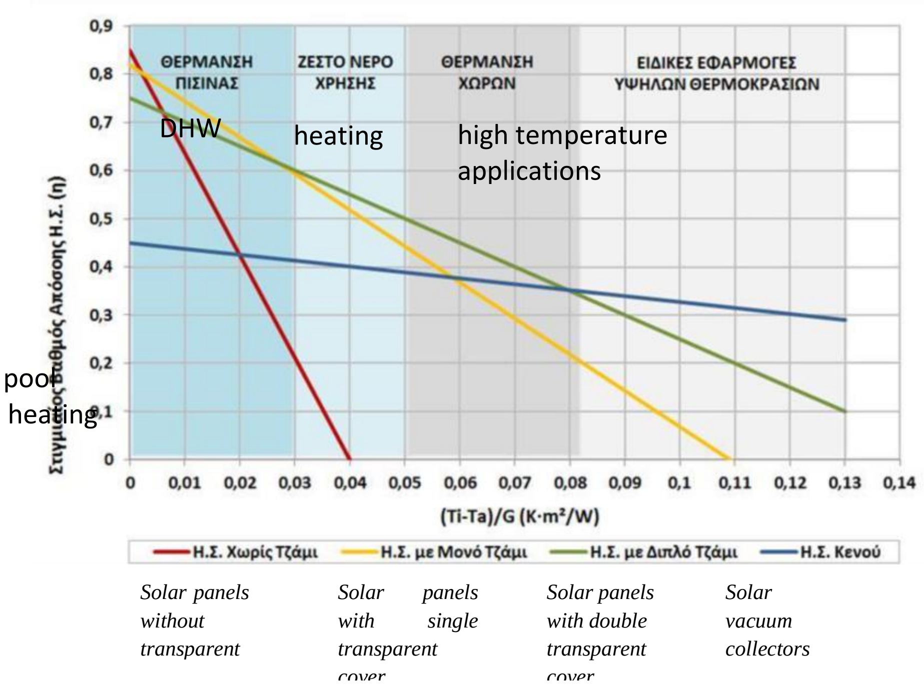


Figure 8: Instantaneous efficiency performance of solar panels (T.O.T.E.E.20701-8, 2021)

The location of the solar panels plays an important role in maximizing the use of solar radiation, as the position of the sun changes during the day. The solar panels in the northern hemisphere receive the maximum possible solar energy in the case of the south orientation, azimuth angle 0°.

If it is required to install solar panels in different orientation (e.g. sloping roof), it is important to increase the collector area or to change the slope to balance the decreased efficiency).

Hot water storage systems constitute the main parts of ST systems. They are divided in local or central and are classified according to the existence or non-existence of heat exchanger and the way of their installation (T.O.T.E.E.20701-8, 2021):

- *Heaters without heat exchanger* (used in open circuit installations),

- *Heaters with heat exchanger* (most ST systems use boiler with heat exchangers, closed circulation systems, for DHW, heating etc.),
- *Dual energy heaters* (combines the use of two energy sources, solar and electric-resistance),
- *Triple energy heaters* (combines the use of three energy sources, solar, electric and energy of a third conventional system, e.g. boiler, used for DHW and heating of a building),
- *Horizontal or vertical layout heaters* (vertical layout systems are more efficient for water circulation natural water heating systems, but in most cases horizontal layout systems are used, as the total height of the installation is lower).

The heat loss coefficient H_{st} (W/K) of the storage tank is calculated by Eq. 4.

$$H_{st} = S/(T_{set} - 20) \tag{4}$$

where S (W) are the losses of the storage container and T_{set} (°C) the adjustment temperature of the container provided by the manufacturer.

The dimensioning a ST system depends mainly on the technical characteristics and the climatic conditions of the area. The capacity of the heater depends on the surface (m^2) of the collecting surface, the solar energy, the rate and the hours of use of the DHW.
Various complex techniques such as analytical simulations and various approximate calculations such as the *f-chart method* on a monthly or annual basis are used to dimension the solar thermal systems.

4.1 DHW and heating of a building – f chart method

The coverage rate f of the monthly thermal load is calculated by Eq. 5 (T.O.T.E.E.20701-8, 2021).

$$f = 1.029 * Y - 0.065 * X - 0.245 * Y^2 + 0.0018 * X^2 + 0.0215 * Y^3 \tag{5}$$

where X (0<X<18) the amount of energy losses to the total thermal load of the month, Eq. 6 (T.O.T.E.E.20701-8, 2021).

$$X = F_R U_L * (FR'/FR) * (T_{ref} - \bar{T}_{air}) * \Delta t * K_2 * K_3 * (A_C/L) \tag{6}$$

and Y (0<Y<3) is the amount of energy that can utilize towards the total thermal load of the month, Eq. 7 (T.O.T.E.E.20701-8, 2021).

$$Y = F_R * (\tau\alpha)_n * (FR'/FR) * ((\tau\alpha')/(\tau\alpha)_n) * \bar{H}_T * K_4 * (A_C/L)$$
(7)

where FR'/FR is the correction factor of collector, $F_R U_L$ (W/m²/K) total heat loss factor (given by the manufacturer), $F_R * (\tau\alpha)_n$ solar energy utilization by the collector (given by the manufacturer), T_{ref} is the reference temperature (100 °C), $\bar{T}_{air}$ the average monthly air temperature (T.O.T.E.E.20701-3, 2010), Δt the time period of the month (sec), $\bar{H}_T$ the average monthly solar radiation (J/m²/mo) which falls on the surface of the solar panel (T.O.T.E.E. 20701-3), $(\tau\alpha')/(\tau\alpha)_n$ correction factor for the collector slope (EN 15316-4-3), K_2 the tank capacity correction factor $K_2=(M/75)^{-0,25}$ where M the volume of the tank (lt/m^2), K_3 the hot water correction factor $K_3 = 11.6 + 1.18 * T_w + 3.86 * T_m - 2.32 * \overline{T}_a/(100 - \overline{T}_a)$ where T_w is the desired temperature of DHW, T_m the average network temperature and $\overline{T}_a$ he average monthly air temperature (T.O.T.E.E.-20701-3), K_4 is the correction factor for the load heat exchanger (usually takes the value1), A_C is the surface of the solar panel (m^2).

The average monthly thermal load for the supply of DHW (Q_{dhw}) or/and heating (Q_h) in Joule is calculated by Eq. 8 (T.O.T.E.E.20701-8, 2021).

$$Q = Q_{dhw} + Q_h + Q_{d,ls} + Q_{st,ls} \qquad (8)$$

The load for the domestic hot water Q_{dhw} is calculated by Eq. 9 (T.O.T.E.E.20701-8, 2021).

$$Q_{dhw} = N * V_w * \rho * c_P * (T_w - T_m) \qquad (9)$$

where N is the number of days of each month, Vw is the average daily consumption of DHW (L/d), as defined in (T.O.T.E.E.20701-1, 2017), usually 50 L/(d per), ρ the density of water, (1 kg/L), c_p the specific heat of water (4190 J/kgK), T_w the desired temperature of DHW(45 °C) daily DHW consumption and, T_m the network water temperature (T.O.T.E.E.20701-3, 2010) for specific climatic zones of Greece.

The heating load of a space Q_h is calculated from Eq. 10 (T.O.T.E.E.20701-8, 2021).

$$Q_h = (U_m * A) * HDD_x * 24\ hours/day * 3600\ J/Wh \qquad (10)$$

where $(U_m * A)$ in W/K is the product of the average coefficient of thermal permeability U_m (W/m^2K) on the surface of the building A (m^2), HDD_x (Kd) are the heating days of the base month x temperature X °C (usually 18 °C for domestic use) (T.O.T.E.E.20701-3, 2010).

The heat losses $Q_{d,ls}$ of the distribution network for each month are calculated from the sum of the heat losses of the individual branches of the distribution network, on the number of N (d) days of operation of the network per month and the operating hours per day t (h/d). The losses of the individual branches / sections (i) are calculated from the linear heat transfer $\psi_{d,i}$ (W/m/K), the length of the network L (m), the temperature difference between the transit space Tα (°C) and the temperature of the distribution mean T_i (°C) in section i of network, Eq. 11 (T.O.T.E.E.20701-8, 2021).

$$Q_{d,ls} = \sum[\psi_{d,i} * \Lambda * (T_\iota - T_\alpha)] * N * \tau\ hours/day * 3600\ J/Wh$$

(11)

where the linear heat transfer $\psi_{d,i}$ for each branch / section of the distribution network $\psi_{d,i} = \pi/\frac{1}{2*\lambda} * \ln\left(\frac{D}{d_a}\right) + \frac{1}{h_a*D}$ where λ (W/m/K) is the thermal conductivity of the insulation, D (m) is the outer diameter of the branch pipe with the insulation, d_α (m) is the outer diameter of the branch pipe and h_α ($W/m^2/K$) the heat transfer coefficient outside the insulated pipe (T.O.T.E.E.20701-1, 2017).

So, the heat losses $Q_{st,ls}$ (σε kWh) τ of the storage system are calculated by Eq.. 12 (T.O.T.E.E.20701-8, 2021).

$$Q_{st,ls} = H_{st} * (T_{st} - T_\alpha) * t \qquad (12)$$

where H_{st} (W/K) is the heat loss coefficient of the storage vessel, T_{st} (°C) is the temperature of the water in the storage vessel, Tα (°C) is the temperature of the space where the storage vessel is located and t (h) is the operating time of the storage tank.

The average monthly load Q(i) covered by the solar thermal system is calculated by Eq. 13 (T.O.T.E.E.20701-8, 2021).

$$\mathrm{Q(i)} = L(i) * f(i) \tag{13}$$

where f is the percentage of cargo coverage for each month (i) of the year.

The annual load covered by the collector is calculated from the sum of the individual monthly loads, Eq. 14 (T.O.T.E.E.20701-8, 2021).

$$\mathrm{Q(i)} = \sum_{\iota=1\div12} L(i) * f(i) \tag{14}$$

In any case, the energy consumption of the auxiliary systems (e.g. circulators) must be taken into account.
In Greece, 1 m^2 of flat simple solar collector is usually installed for each person (of the house) to cover the needs of 50 lt for DHW, while for heating corresponds to 1 m^2 of flat simple solar collector for about 600 kcal/h (700 W) (TEE, 2011), while the optimal ratio for Southern Europe is 75 lt per m^2 of collecting area (Duffie et al., 2020).

5. Biomass Systems in Buildings

Biomass is defined as ‘the biodegradable fraction of products, wastes and residues of organic origin from agriculture, including plant and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as biodegradable of industrial and municipal waste and scrap, of biological origin’ (EC, 2018).
Direct combustion is one of the oldest ways of utilizing biomass for electricity production and heat production. In addition to energy plants, agricultural residues can be used as solid biofuels as they have high calorific value (much higher than lignite) and almost zero ash content (much lower than lignite) (Vasileiadou et al., 2020; 2022).
Combustion stoves, open or closed fireplaces can supply a central heating system using radiators and a water exchanger, through which the hot water circulates and supplies the distribution network of the central heating system and an expansion tank.
The thermal efficiency of modern biomass boilers (50-500 kW), see Fig. 9, is greater than 85% while the thermal efficiency of traditional fireplaces and energy fireplaces does not exceed 25% and 50%, respectively (TEE, 2011).
For the production of electricity from biomass, mainly cogeneration systems of electricity and heat (CHP) with standard steam turbine technology are used. CHP systems with internal combustion engines have a high degree of efficiency. CHP systems have a capacity of up to 2 MW, so they are considered suitable to meet energy needs in buildings such as museums, hospitals, businesses, etc. (TEE, 2011).

Figure 9: Biomass boiler (agroenergy, 2022)

Large installations require a fuel storage and transport device (see Fig. 10).

Figure 10: Storage and transport of biomass fuel at the refueling point (TEE, 2011)

6. Good Museum Practices

Table of good museum practices considering RES and HVAC exploitation for power generation and energy saving.

MUSEUM	**Approach**	**DETAILS**

Museum of Cycladic Art, Greece	Good practice waste recycle	**Green Museum.** A strategic goal of the Museum of Cycladic Art is to reduce its energy footprint and educate the public on environmental issues. In 2019, together with WWF Hellas, the Museum created Cycladopolis, an educational game for children over 6 years old, which circulated in schools in Greece and abroad through the Museum's Museum Kit on Cycladic culture. The main goal of Cycladopolis is for students to understand the value of nature for life on our planet and learn about biodiversity in the Cyclades and the concept of sustainable development through fun games and riddles. ✓ The Museum develops educational programmes to raise children's awareness of environmental issues. ✓ The Museum recycles waste and uses LED lamps for 80% of the lighting. ✓ The Cycladic Shop uses only paper bags. ✓ The Cycladic Café uses biodegradable straws. ✓ The solvents and plastic bags used for cleaning are biodegradable. ✓ Recycled paper is used for most purposes (photocopies, napkins, etc.).
The Stavros Niarchos Foundation Cultural Center (SNFCC), Greece	Solar	Stavros Niarchos Foundation Cultural Center (SNFCC) has received a Platinum level LEED certification, the highest possible rating for environmentally conscious and sustainable buildings. The SNFCC is the first cultural project of such scale to earn the LEED Platinum Certification in Europe and Greece. The SNFCC, designed by the Renzo Piano Building Workshop, is a project that includes the construction and complete outfitting of new facilities for the **National Library of Greece** and the **Greek National Opera** as well as the creation of the 210,000 m² Stavros Niarchos Park. The commitment and determination to establish a paradigm of environmental stewardship and innovative sustainable design and building practices are manifested in all aspects of the design and construction of the project; from the Stavros Niarchos Park that also functions as a **green roof,** to the Canal and to the **innovative**

		state-of-the-art photovoltaic canopy. One of the emblematic design features of the project is the energy roof, one of the largest in Europe, towering over the Greek National Opera building. The **roof, made of photovoltaic panels**, is an innovative construction and engineering achievement, contributing to the goal of drastically reducing CO2 emissions, as well as to the daily energy requirements of buildings. Furthermore, the **Canal** together with the Stavros Niarchos Park, create a favorable **microclimate,** and contribute to the flood protection not only of the SNFCC, but of the surrounding communities as well.
Natural History Museum, Alexandroupoli, Greece-Under development	Geothermal	Horizon 2020 – Development of geothermal heat exchange pumps for heating and cooling
The historic Academy of Athens (1926), Greece. The building was initially used to house the Numismatic Museum in 1890, and in 1914 the Byzantine Museum and the State Archives. Finally, on 24 March 1926, the building was handed over to the newly established Academy of Athens-Under development	Geothermal & Solar	The historic Academy of Athens (1926), the highest research establishment in the country, one of the capital's most recognisable landmarks, will become a leading zero energy building by tapping heat 100 meters below the surface of the earth. The 130-year-old building located on Panepistimiou Avenue will go green through the use of **geothermal energy and solar panels,** according to the Academy's general secretary Christos Zerefos. It is the first time that geothermal power, which draws energy from deep within the earth's core, will be used by a main building in central Athens. Drilling for the first well at a depth of 100 meters has already been completed with drilling on another 17 wells expected soon, Zeferos told state news agency ANA-MPA. Liquid filled pipes running down the well **will help cool the building in summer and warm it up in winter with the help of pumps**, controlling its temperature throughout the year.

		The building was designed as part of an architectural "trilogy" in 1859 by the Danish architect Theophil Hansen, along with the University and the National Library. The building was initially used to house the Numismatic Museum in 1890, and in 1914 the Byzantine Museum and the State Archives. Finally, on 24 March 1926, the building was handed over to the newly established Academy of Athens. It is considered to be the most important work of Hansen, and is regarded by some experts as the most beautiful neoclassic building worldwide.
20 monasteries in Mount Athos, Greece-Under development	Solar	The community of 20 monasteries in Mount Athos **will cover most of its energy needs with solar panels** with the help of the Greek government. The project is aimed at boosting the level of self-sustainability and reducing pollution and greenhouse gas emissions. The Centre for the Preservation of Athonite Heritage (KEDAK), one of the public agencies responsible for conservation in Mount Athos, **gave a green light for the construction of 21 photovoltaic systems** in the autonomous region. A recent study on the utilization of renewable energy sources revealed the community of 20 monasteries on the peninsula can cover 75% of the energy needs with the project. The installation of solar power units will reduce greenhouse gas emissions and air and noise pollution and enable the monasteries to address the gradual increase in energy demand, the statement adds. KEDAK noted that there would be less dust as fuel is currently transported on the dirt road network in the area.
ELEPAP Historical Building, in Pangrati, Greece-Under development	Solar	Aiming to combine sustainable development and the company's green footprint with social initiatives and organisations, doValue Greece **chose to finance the acquisition and installation of solar panels at the historical building of ELEPAP in Pangrati.** ELEPAP (Rehabilitation for the Disabled) is the oldest non-profit organisation in Greece, providing rehabilitation services to children since 1937. The

		goal is to ensure the energy autonomy of the building, which is ever so important given the global energy crisis, while drastically reducing the cost of electricity and protecting the environment through clean energy production and use. The **solar panel installation project** at ELEPAP will have a huge impact in terms of saving energy and reducing fixed expenses. The profits gained from the implementation of this project will be used on rehabilitation treatments for the brave kids with disabilities of ELEPAP. We support the great effort of ELEPAP to offer ever more Life Steps to more than 1,000 infants, children and adults with disabilities all over Greece.
The museum of Delphi is situated on the side of Mount Parnassos, Greece	Heat pumps	Total floor area 2 500 m², The original **air-conditioning system was replaced with a new system that incorporates a heat recovery unit.** All standard luminaires were replaced with highly energy-efficient luminaires. Daylight compensation is applied through the BMS. For acoustic reasons, all suspended ceilings were replaced with new ones, made from recycled glass fibre, that also maintain the desired light reflectivity. In order to enhance the thermal comfort levels, while minimising the use of air-conditioning, ceiling fans were installed in the main exhibition areas. With the use of ceiling fans, the cooling set point can be increased from 26°C to 29°C, thereby reducing air-conditioning running hours. The advanced BMS controls all building services, air-conditioning, heat recovery, demand control ventilation, ceiling fans, lighting and shading devices. The implemented energy measures result in excellent energy and environmental building performance and ensure an A energy rating according to the EPBD. Key points concerning the design The museum of Delphi is an exemplar low energy building museum with good visual and thermal comfort due to an energy efficient HVAC system equipped with heat recovery and demand control ventilation in

		conjunction with the use of ceiling fans and the correct distribution of daylight.
The Smithsonian National Museum of the American Indian, Washington D.C., USA	Solar HVAC	High standards achieved for exterior and interior building management Extensive use of native vegetation within the museum's landscape Indoor environmental air quality, Water-efficient and sustainable landscape, **Onsite and offsite use of renewable energy,** Recycling and waste management
The Field Museum, Chicago, USA	Solar HVAC	In 2013, The Field Museum worked with Smart Energy Design Assistance Center (SEDAC), an applied research program at the University of Illinois at Urbana-Champaign supported by the Illinois Department of Commerce and Economic Opportunity (DCEO) Illinois Energy Now program, to conduct an energy audit and identify opportunities for energy efficiency savings and reducing the building's energy footprint. Air Conditioning **The Museum utilizes a chiller/thermal storage system, which keeps the building's climate cool in the warmer months and ensures proper humidity for the collections year round.** The system works by producing ice during evening hours when citywide demand for energy is lower. The ice is placed in thermal storage containers, and water flow introduced. Air is blown around the containers and then circulated through the building during the day. This reduces the Museum's impact on the region's grid system and prevents brownouts, as air conditioning usage is highest during mid-day. **Solar Power** **The Museum has a 99.4 Kilowatt photovoltaic**

		solar array on its roof. An average residential solar array is between 2 and 4 Kilowatts, so the Museum's is pretty substantial. In fact, when it was installed in 2002, it was the largest solar array in Illinois. You can see The Field Museum's solar array producing electricity in real-time. For more information, there is an article in "Energy Seeds," a blog maintained by the Illinois Clean Energy Foundation.
The California Academy of Sciences, San Francisco, USA	Solar	Living Roof on which 6 inches of soil insulates the building, prevents storm water runoff, and provides a home for local birds, butterflies and native plants. The Living Roof is also surrounded by a solar canopy comprised of 6**0,000 photovoltaic cells which supply 213,000 kWh of energy annually, cutting greenhouse gas emissions by 405,000 pounds.** As for the interior, the building was designed with energy efficient floor-to-ceiling glass panels which not only reduce heat absorption and minimize the amount of energy needed to cool the space, but also permit the entrance of natural sunlight.
The Prado Museum, Madrid, Spain	Solar	A roof which generates solar energy will be a major feature of Lord Norman Foster's renovation of a 17th century building to extend Madrid's famous Prado museum.
The Museum of Tomorrow, Rio de Janeiro, Brazil	Solar HVAC	The Museum do Amanhã (Museum of Tomorrow) opened in 2015 and was designed with sustainability at the forefront. It features solar panels that move with the sun as well as an air conditioning system that uses water from nearby Guanabara Bay, cleaning it and returning it to its source in the process. It also collects and reuses rainwater. The museum saves around 9.6 million litres of water and 2,400 megawatt-hours of electricity per year.

The Museum of Liverpool, Liverpool, UK	‘Trigeneration’ heating, cooling and electric system	Energy efficiency played a huge role in the building’s design, which includes the use of a ‘trigeneration’ system to create heat, electricity and cooling in one integrated process as a way of reducing carbon emissions. The integrated process reduces carbon emissions by 884 tons a year—“equivalent to the environmental benefit of 88,400 trees”— allowing for extreme energy efficiency.
The Exploratorium, San Francisco, USA	Solar	The Exploratorium's goal is to achieve net-zero energy operation and become the largest museum in the U.S to do so. one of the largest on a cultural institution in the world, and the only one helping a museum achieve **net-zero energy** goal! Our SunPower **solar power system uses 5,874 solar panels** and takes up 78,712 sq. ft. of roof space. That’s 1.36 football fields, or over 28 tennis courts! We harvest over 2 million kWh per year from the sun. Over the 30-year life of our SunPower solar system, we’ll avoid creating 49,109 tons of carbon dioxide emissions. All that CO2 is equivalent to removing 9,540 cars on California’s highways for one year. Our building’s **HVAC system circulates bay water through two titanium heat exchangers**, saving us water and energy. The bay water fluctuates between 50°F and 66°F seasonally and is used as a heat source and heat sink to efficiently produce hot and chilled water for the building’s radiant slab. This also eliminates the need for cooling towers. Using bay water to heat and cool the building eliminates the need for evaporative cooling towers for heat rejection. This saves us an annual 2 Million gallons of water (just over 3 Olympic size swimming pools), which would otherwise be lost to evaporation. Rainwater falling onto the Exploratorium’s roof is captured and stored in two cisterns, holding around 23,000 gallons at a time (that’s 368,000 glasses of water). It’s then filtered and used for flushing toilets. All other roof runoff is filtered before being returned to the bay, reducing pollutants in our stormwater runoff.

Grand Rapids Art Museum, Grand Rapids, USA	Green HVAC	The museum stores and recycles all rain water and snow for toilets, plant irrigation, pool and water wall, **Three 12 foot energy recovery wheel (ERWs) [are an integral part of heating, ventilation and air conditioning (HVAC)],** Earth tube air preconditioning system, Heat recovery ventilator. Efficient HVAC equipment, Advanced control system (occupancy and CO2 sensor), Super insulated envelope
The Natural History Museum, London, UK	Solar	**Museum to go carbon neutral by 2035.** More than 300 solar panels were installed, providing a total system capacity of 88kWp, capable of generating up to 75,835kWh a year, enough to meet the entire building's annual electricity needs and potentially saving the Museum £9,100 per year. It also saves more than 21 tonnes of carbon dioxide emissions per year, which is equivalent to planting 10,514 trees. .The Natural History Museum (NHM) has become the world's first museum to set a science-based carbon reduction target, developed in line with the Paris Agreement, an international treaty on climate change adopted in 2015. The target represents a 60 percent reduction in NHM's carbon emissions by 2031 compared to 2015.
Natural History Museum of Utah, Salt Lake City, USA	Solar	The museum holds over 1.2 million objects, over a site of 163,000 square feet. 1,400 solar panels which will ultimately provide 25 percent of the museum's total energy power.As for current operating practices, the building uses two 10,000-gallon cisterns on the roof to collect rain water which is used to irrigate the whole site. The exhibits also use motion censored lighting to ensure that no unnecessary energy is spent and the outdoor lighting has achieved LEED "dark sky" requirements meaning they won't contribute to light pollution. Rainwater is also collected from the roof to irrigate the entire site. During the construction process, over 75% of the waste generated was recycled. This includes wood, metal, concrete, plastic and cardboard, as well as office supplies. In addition, the project restored surrounding areas to their natural state after construction, replanting native vegetation.

Terra – The Sustainability Pavilion, Dubai, UAE	Solar	Renewable energy systems with a combined total capacity of 5.5 megawatts on all permanent building projects across the Expo site. That's enough energy to go approximately 180,000 round trips from Downtown Dubai to the Corniche in Abu Dhabi! Terra - The Sustainability Pavilion aims to be LEED Platinum certified and has 12,000 sqm of photovoltaic panels across its roof and energy trees.
MuSe, Trento, Italy	Solar and geothermal	the MUSE as a system for the completely **renewable energy supply, taking advantage of photovoltaic, solar panels and geothermal probes.** The cistern system for rainwater recovery can achieve water savings five times larger than other similar buildings. The materials used in the interior spaces have been chosen taking into account the performance of comfort and health, while the openings were related with the landscape, also favoring the entry of natural light. Other key features are the optimization of the management of waste resulting from the construction, which were almost completely recycled, and the completely underground parking.
The Markham Museum	Geothermal	the Markham Museum met LEED Gold qualification by meeting a number of standards, including: Alternate Transportation, Reflective Roof Water Reduction, Construction Materials, Mechanical Systems, Healthy Workplace. Mechanical Systems The Markham Museum Collections Building incorporated a **Geothermal Heat Exchange System**. This system uses a CFC/HCFC free refrigerant that is pumped through a series of pipes 110m below ground. Once preheated by the earth, the refrigerant is used to preheat the high efficiency water boilers used to supply hot water to the building's heating coils and heat pumps.

Denver Museum of Nature & Science	District heating and air conditioning	Denver Museum of Nature & Science is planning to install a heat pump system that utilizes the city's municipal water system. The **heating and air conditioning in the new wing of the Denver Museum if Nature & Science will run on an unusual, subterranean heat source: the recycled wastewater rushing through the pipes below**. The museum could have proposed a standard ground-source heat pump system, one that taps into geothermal sources by drilling and installing numerous shallow wells over a large area, to provide a heat and cooling resource for the units. But instead, they're planning to install an **open-loop system that uses water circulating within the city's municipal water system**. This project, which received $2.6 million in funds from the Recovery Act, should reduce energy expenses significantly while providing information to support similar implementations in other locations. The [new wing] will meet the LEED platinum specifications and use 50 percent less energy than a typical building of its kind. Our ultimate goal is to create a Zero Energy Building, where we produce more energy that we consume. These energy efficient practices could save the museum up to $7 million over the next 20 years.
the National Museum of African American History and Culture (NMAAHC)	Solar	100-kW solar array NMAAHC , efficient infrastructure
The Toledo Museum	Solar & micro-turbines	The latest addition to the Museum's green arsenal is a **brand new 360kW solar canopy** installed over a large portion of the newly renovated main parking lot. The canopy nearly doubles the amount of renewable energy produced by the existing **200 kW solar array** on the roof of the main Museum. On a sunny day it is estimated that 50% of the electrical demand for the 250,000 sq. ft. building is provided by the sun. **Four micro-turbines** were installed in the power plant in 2004. They were joined by two more micro-turbines and chillers in the Glass Pavilion's power plant in

		2012. These generators are about the size of a refrigerator and burn natural gas. They produce **65 kW** of electricity apiece and have been a cornerstone of the Museum's energy saving efforts. With micro-turbine technology in place, the Museum has been able to generate 15 percent of its own electrical power, reducing its dependence on the electrical grid. Micro-turbines have many advantages, including: Pollute less than conventional systems,Increased efficiency so they use less fuel, Few moving parts (without oil lubricants), Burn a variety of fuels, Durable and reliable (run 24/7), Immediate energy production, Require little maintenance, Create large amounts of energy in a small amount of space, Work alone or in groups for capacity and redundancy, Can generate electricity if the power grid fails.
Chungnam Art Museum in Naepo, South Korea.	Solar	Design plans include multiple solar panel arrays over the parking-lot seating areas and additional south-facing solar panels. **Zero Net Energy performance:** multiple solar panel arrays over the parking-lot seating areas and additional south-facing solar panels on the building's roof.
The New England Regional Art Museum in Armidale	Solar	**One of the largest solar power arrays on any regional gallery in the country.** The **240 panels** installed on the roof of NERAM will provide up to 88 Kwh to offset the power used by the facility's lights, air-conditioning and other systems potentially saving thousands of dollars in operational costs each month.
The Parisian Quai Brainly Museum – Paris, France	RES	Firstly, one of the significant green features is the stunning 800mq vertical garden. And, by itself, the **green wall is said to improve the air quality and also reduce thermal dispersion during both winter and summer**. The museum also consists of a **renewable energy system** that is based on **solar** and **geothermal energy**.
Palazzo Gallenga Stuart in Italy	geothermal	Active geothermal system with cool tiles with appearance of traditional historic tile. Innovative cool tiles lead to 14% cooling energy savings. Geothermal energy system lead to about 65% energy savings

Australian National Maritime Museum	Solar	Lightweight solar panels power (A 235 kW array of 812 panels) up Maritime Museum. $6.6 million investment into Sunman Energy Co Ltd – parent to Energus – to develop "eArche", the new lightweight, Flexible solar panel technology, made from a polymer composite material. The array will now reduce the Museum's electricity consumption by approximately 25 per cent.
The Museum of the American Revolution, Philadelphia	RES	Highlights of the Museum's efforts include: More than 80 percent of lighting is LED, which saves energy and cuts maintenance costs A green roof covers 50 percent of the building A stormwater retention system recycles as much as 18,000 gallons of water a day Approximately 70 percent of the electricity used by the Museum comes from **green energy** Approximately 80 percent of cleaning products used by the Museum are eco-friendly
Canada including the Canadian Museum of Nature in Ottawa, Manitoba Hydro Place,Winnipeg, Canada	Geothermal system	Manitoba Hydro Place also has the largest **closed loop geothermal system** in the province. 280 boreholes, each 150 mm (6") in diameter, penetrate the site 125 metres (400 ft.) underground, circulating glycol which is cooled in the summer and heated in the winter by the ground source heat exchanger. Depending on the season, a **24 metre tall waterfall** feature in each of the atria humidifies or dehumidifies the incoming air. During colder temperatures, recovered heat from exhaust air, and passive solar radiant energy are used to warm the fresh air. The 22-storey building achieved LEED Platinum in 2012. One of its notable features is that compared to the average office building, the Manitoba Hydro Place uses 70% less energy, saving $500,000 every year. Its HVAC system takes full advantage of raised access flooring.
Hotel Industrial, Paris (France)- historical building	Solar	Integrated Photovoltaic system on historical buildings
Tourist office, city of Alès (France)- historical building	Solar	Integrated Photovoltaic system on historical buildings

Sala "Nervi", Vatican City (Italy)- historical building	Solar	Integrated Photovoltaic system on historical buildings
Reichstags building- historical building	Solar	Integrated Photovoltaic system on historical buildings
Anatta House, Monte Verità Ascona, (1904) ; Man etti Hous e, Bironico, Monte Ceneri, (1600); Hôtel de La Sage, Avolène, Vallese, (1890)- Switzerland (historic buildings)-Case Studies	Solar	Integrated energy retrofitting methodology for historic buildings: Case Studies. Three case studies - Anatta House, Monte Verità Ascona, (1904) ; Man etti Hous e, Bironico, Monte Ceneri, (1600); Hôtel de La Sage, Avolène, Vallese, (1890), heritage buildings in Switzerland, have been examined, making it possible to define a series of solutions aimed mainly at improving the energy features of the building and the level of comfort inside (analyzed within the EnBau research project).
Blenheim Palace	Solar	Blenheim Palace is in the vanguard of a revolution among large landed estates. It is pushing forward a series of goals which will see the UNESCO World Heritage Site become carbon negative by 2025. Further targets include having 50% of visitors arriving in a carbon-friendly way by 2025, generating double the energy it produces now, reducing the carbon footprint of its current buildings by 25%, and constructing all new buildings to EPC Grade A rating.
Vatican (historic building)	Solar	Vatican City may be the smallest sovereign state in the world, but it is also one of the greenest. It has long been an exemplar for tackling climate change through its approach to renewable energy. Thanks to a unique **photovoltaic plant installed on the roof of the Vatican Audience Hall, the Papal State has been producing 300 MWh of solar energy every year since its installation in 2008.** The project was planned and managed by BayWa r.e. with the PV modules, inverters and its installation donated by solar technology provider, SolarWorld. A total of 2,394 PV modules were installed on the 2,134 m2 roof of the Nervi Hall.

The Sheikh Zayed Desert Learning Center SZDLC (museum and research centre)	Solar thermal cooling system (solar heat driven cooling technology)	In the HVAC design concept the thermal activation of building element to extract heat from the building was considered and finally implemented in the construction phase. The cold water production systems are coupled to thermally activated building elements, i.e. cold water flows through pipes integrated in the building‘s floors, walls and ceilings. The set-point of 16 degree Celsius is supplied by the **solar absorption chilled water system** and maintained by th e primary conventional chiller. The return temperature of the concrete core activation system is fairly constant over the year, showing that the system is supplying a base cooling load for the Sheikh Zayed Desert Learning Centre. The base load of the CCA is between 200 and 300 kWth. Simulation results support that the As-Designed model consumes 36.2% less primary energy than the Baseline model. This project demonstrates once again that a solar thermal cooling system needs monitoring and adjustments during start-up phase in order to reach the planned performance. This project proofs that an intelligent mix of natural based architectural design, innovative technologies and the local use of renewable energy sources reduces the environmental impact and life-cycle costs significantly in desert locations too.
Miami Science Museum	Solar	The world-class science museum features 250,000ft^2 . The green roof of the building is equipped with a rainwater-reclamation system that irrigates its indigenous plants, edible gardens and green walls. Solar photovoltaic panels generate on-site power for the complex.

Pérez Art Museum Miami (PAMM)	Heat pumps	Pérez Art Museum Miami (PAMM) received a LEED Gold Rating (2015) for its innovative and sustainable design, use of local and recycled materials, and location with access to public transportation. The building was designed to function with as small of a carbon footprint as possible PAMM's innovative design uses cutting-edge technology from around the world. The museum was the first in the U.S. to use Cobiax voided slab technology, a system that incorporates 100% recycled plastic with rebar into concrete slabs, which not only allows for expansive galleries with fewer support columns, but efficiently reduces approximately 35% of the amount of concrete used. **PAMM is cooled by a state-of-the-art Plenum system that recirculates air through ducts in the building's floors, rather than ceilings, saving energy and improving efficiency.** The museum is elevated above sea level, which not only puts the waterfront museum at a safe floodplain in the event of a hurricane, but also takes advantage of optimum breeze patterns off the bay, lowering the temperature of the museum's indoor and outdoor spaces by as much as 10 degrees, year-round. The overhanding canopy shades the museum from South Florida's intense sunlight, and PAMM's signature hanging gardens create a microclimate throughout the terrace that filters sunlight and cools outdoor display areas. A solar study was done to optimize shading and window positioning to take advantage of the climate for maximizing visitor comfort and energy efficiency. The facility features 200,000 square feet of indoor and outdoor program.
Science Museum in London and Locomotion in County Durham	Solar	Total energy use today is 43% less than it was in 2001 and 25% less than in 2011/12. This reduction has been achieved despite growth in the Science Museum Group (partly through new museums joining) that equates to a 24% increase in floor area. Since 2016 we have purchased all electricity for our museums from renewable sources while energy

		efficiencies and renewable electricity procurement have led to a 69% emissions' reduction against a 2011/12 baseline. Actions that have contributed to the reduction in energy use include LED lighting, plant replacement and embracing passive design such as harnessing natural light and passive cooling. In addition, we have **solar panels at both the Science Museum in London and Locomotion in County Durham**
Explora, nonprofit children's museum, Rome	Solar	For Explora, attention to environmental sustainability is a fundamental aspect. In fact, two photovoltaic systems in the museum produce 40 thousand kWh of clean electricity every year

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Museum Lighting design: A short overview.

Aris Tsangrassoulis

1 Introduction

The lighting design in the museum environment is catalytic in creating the right atmosphere, influencing visitors' visual appreciation of it. Lighting is part of the environmental stimuli that visitors receive and affect their preferences for a particular environment. An important work is that of Kaplan & Kaplan (1988) which can be applied in the case of lighting. According to it, the preference is influenced by:

1) The innate tendency we have to understand our environment. Images that we already have in our memory are compared to the image presented in front of us. If common features are recognized, an intimacy is created, a feeling of comfort.

2) The need to engage / explore an interesting environment. It can be enhanced by the complexity of this environment as well as by the sense of the unknown that invites us to interpret it.

2 Lighting design parameters

The parameters used by Kaplan & Kaplan are twofold: coherence and complexity. Coherence is related to the ability to interpret an environment while complexity is related to our desire to participate actively. An additional feature of modern museums is the exhibition of a large number of exhibits, thus greatly increasing the visual information received -and not easily interpreted- by visitors. This results in a phenomenon called "museum fatigue" (Bitgood, 2009). The proper design of the lighting system can help in the visual separation of the exhibits, thus reducing the intensity of this phenomenon.

In museums, however, in addition to the formation of interactive experiences, the need for protection of exhibits also needs to be considered. The lighting that impinges on the exhibit along with other factors, such as e.g. is the temperature / humidity etc. can cause damage to a wide variety of materials. This damage is cumulative and irreversible. It may be due to photochemical alterations due to ultraviolet radiation or thermophysical ones due to absorption of infrared radiation. It is obvious that the effect of lighting is significant in the exhibits. Due to its cumulative action, we do not need to know only the illuminance on a surface / object but the total exposure over a period of time (eg the hours of annual operation). The exposure is calculated by multiplying illuminance with the exposure time (lxh). The museum exhibits are divided into four categories according to their sensitivity and for each category a maximum illuminance as well as the yearly exposure to light are defined. According to the CIE 157: 2004 and the European technical specifications CEN / TS 16163 these categories are:

a. materials that are not sensitive to light (most metals, stone, most glasses, ceramics, enamel, and most minerals)
b. low sensitivity materials such as e.g. most oil paints, fresco, wood, horn bone and some plastics,
c. medium-sensitive materials such as most textiles, watercolors, prints, manuscripts, botanical exhibits and finally
d. highly sensitive materials e.g. silk, graphic arts, photographic material). The table below shows the lighting and exposure intensity limits for the different material categories.

Table 1: Maximum illuminance and exposure on exhibits with various sensitivities according to CIE 157: 2004.

Material light sensitivity	Maximum illuminance(lx)	Light exposure (lux *h/year)
Not sensitive to light	-	-
Low sensitivity	200	600000
Medium sensitivity	50	150000
Highly sensitive materials	50	15000

An important design parameter is also the "content" of lighting in ultraviolet UV radiation which is measured in μW / lm. Ideal values for the selection of light sources concerning UV radiation content is on the range between 0-10μW / lm with an absolute upper limit of 75μW / lm (ISO 11799: 2015). Typical values of UV output for various light sources are presented in the table below.

Table 2: Typical UV output of various light sources (μW / lm).

Light source	UV output [μW/lm]
Daylight	400 (sun) -1500 (blue sky)
Halogen lamp	40-200
Fluorescent lamp	30-150
Metal Halide lamp	160-700
LED	<5

Daylight shows a high UV output especially when diffuse light from the north part of the sky is used. It is therefore necessary to use glazing capable to absorb a large percentage of this harmful for the exhibits radiation. Glass manufacturers can provide this info in the form of :

- Ultraviolet transmittance (T_{uv} in wavelength range between 300-380 nm)
- Damage Weighted Transmission, (T_{dw}) which is a parameter related to the fading of surfaces/colors. The lack of glazing leads to a value of $T_{dw} = 1$. Obviously, a lower value means less effect on the exhibits. This parameter also can consider the effect of part of the visible spectrum (T_{dw-K} (Krochmann Damage Function, 300-500 nm) and T_{dw-ISO} (300-700 nm)).

The effect of ultraviolet radiation on colors is described using the spectral damage function D (λ) as shown in (Kaplan and Kaplan, 1988), (ISO 9050:2003):

$$D_{(\lambda)}=e^{(-0.0115*(\lambda-300))} \qquad (1)$$

where λ is the wavelength. This function has its maximum value of one (1) at 300 nm. Multiplying this function for each wavelength by the ultraviolet radiation intensity (mW / m^2) on the exhibit and then integrating in the range 300-400 nm, the weighted absolute UV intensity that an object is receiving from its environment is calculated.
From the above it is evident that the use of daylight in exhibit rooms is a significant design problem especially when exhibits very sensitive to light are present. Ceiling openings or skylights are commonly used to create illuminance both horizontally and vertically. The presence of solar patches gives a dynamic feature to the space if permitted. In general, daylight is used as diffuse lighting.

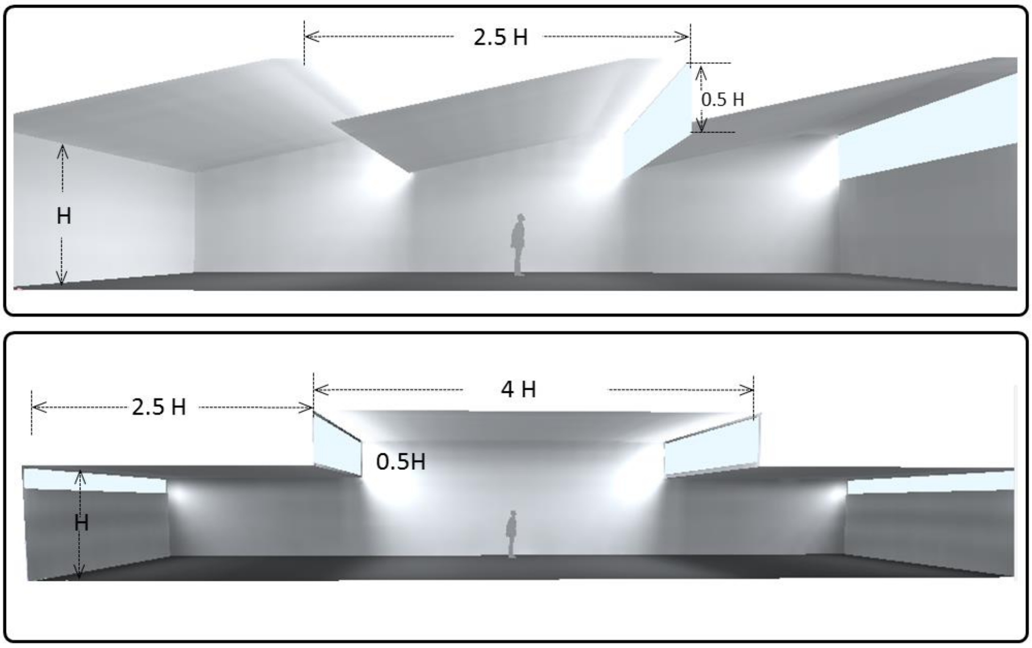

Figure 1: Clerestory openings sizing rules [Tsangrassoulis, 2015)]

3 Lighting systems design

In addition to the aforementioned requirements, there are some parameters that have to be taken into account during the design phase of a lighting system:

1. The illuminance levels and the luminance distribution on the various surfaces. The lighting levels proposed for corridors, foyers, etc. and the exhibit areas are quite different and therefore a different design approach will obviously has to be followed. The luminance distribution in the exhibition spaces is used to create the appropriate ambiance for the display of the exhibits. Using a strong luminance contrast between the exhibit and the surrounding surfaces, a dramatic presentation is created. This can be achieved either by increasing the illuminance on the exhibit or by modifying the reflectance of the surrounding surfaces. With luminance contrast 2:1 the luminance difference is just perceptible, while a ratio 30:1 is used for a dramatic display.

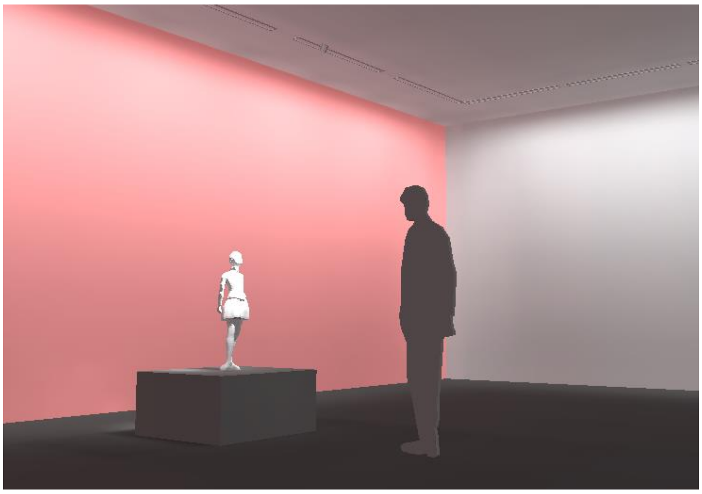

Figure 2: Luminance contrast between the exhibit and the surrounding surfaces.

High Dynamic Range photography can also be used to estimate the luminance distribution in a museum interior. Along with the camera a luminance meter is also needed to measure the luminance at a point. The photo can then be edited to capture the luminance distribution. This presented in the following figure.

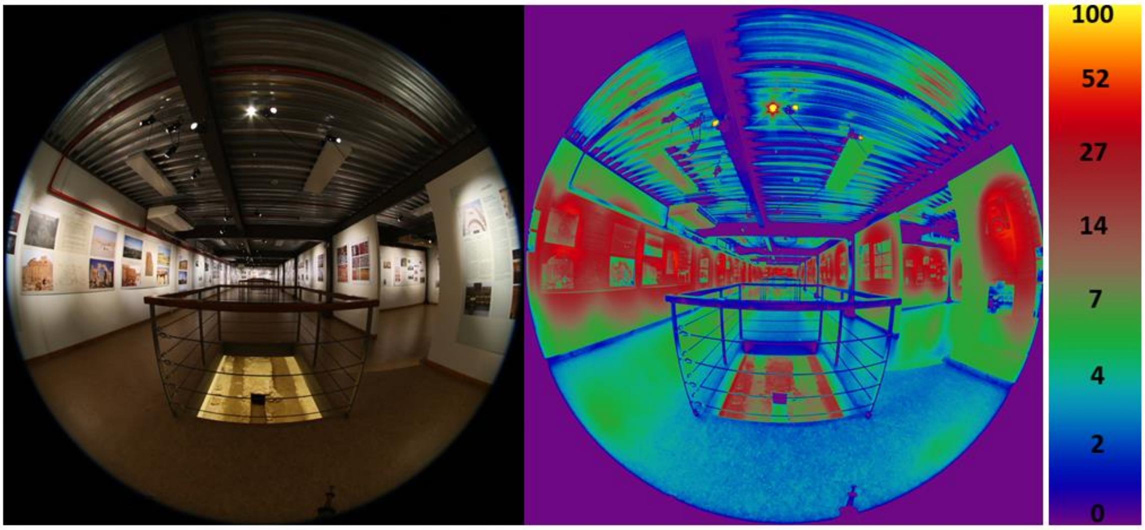

Figure 3: Luminace distribution with HDR photography.

2. Visual adaptation. Because, in museums, the required light intensity is rather low, the proposed lighting analysis should examine all techniques available for the proper adaptation of the human eye to these lower levels. The designer should have taken into account other parameters as well such as the movement of the visitors from space to space, especially when large differences in illuminance is proposed. What is particularly interesting is the connection of the subjective stimulus (illumination) with its objective measurement. In the case of lighting, it is the connection of brightness (B) with the luminance (L). The relation that connects them is $B \sim L^{0.33}$ (Stevens, 1970)

This practically means that if the brightness needs to be doubled then the luminance must be increased sevenfold!

3. Glare. Discomfort glare is caused either due to the existence of a high luminance lamp/luminaire in the field of view or by their reflections in the showcases or in the transparent covers of the exhibits. The solution to this problem is achieved by selecting suitable luminaires, their proper placement and the use of anti-reflective glass.

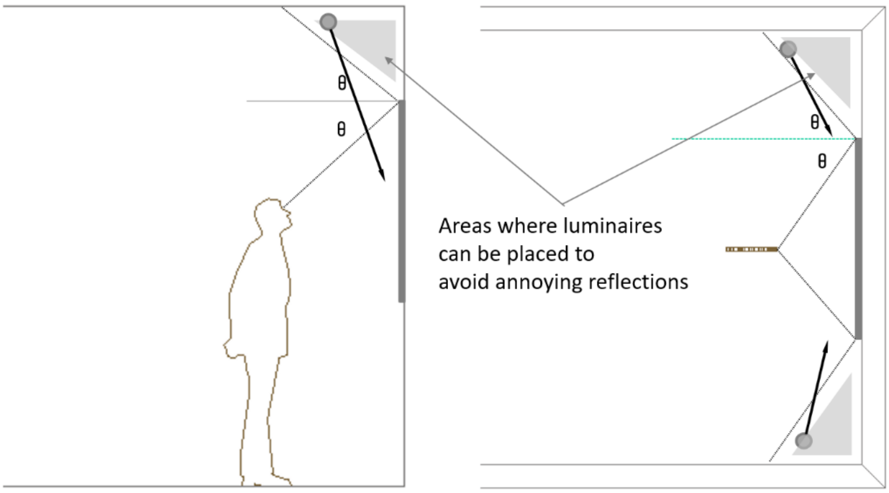

Figure 4: Practical method to avoid unwanted reflections on a painting.

4. Use light sources with the correlated color temperature (CCT) and very good color rendering index (CRI). The CCT is the temperature of a black body which at a certain temperature emits light which is chromatically similar to the light from the source being examined (of the same luminance). CCT is an indicator of the spectral distribution of radiation. According to EN 12464-1: 2011 ()light sources in terms of color temperature are classified as warm when CCT <3300 ^{0}K, neutral when 3300 0K <= CCT < 5300 ^{0}K and cold when CCT> 5300 ^{0}K. The Color Rendering Index (CRI) is used as a measure of the fidelity of colors (ie, how they actually look) relative to how they look when illuminated by a standard light source. The maximum value is 100. The comparison of light sources based on this indicator should be performed provided that they have the same CCT. Halogen lamps have a CRI close to 100 and LEDs can achieve values better the 90 and, in some cases, better that 95.
5. Three-dimensional modelling of exhibits / highlighting texture. A common way of highlighting the texture is to aim the exhibit at a steep angle (0-20 degrees from the vertical) while for 3D modelling the angle can be increased up to 30 degrees (IES RP-30-96 (R2008)).

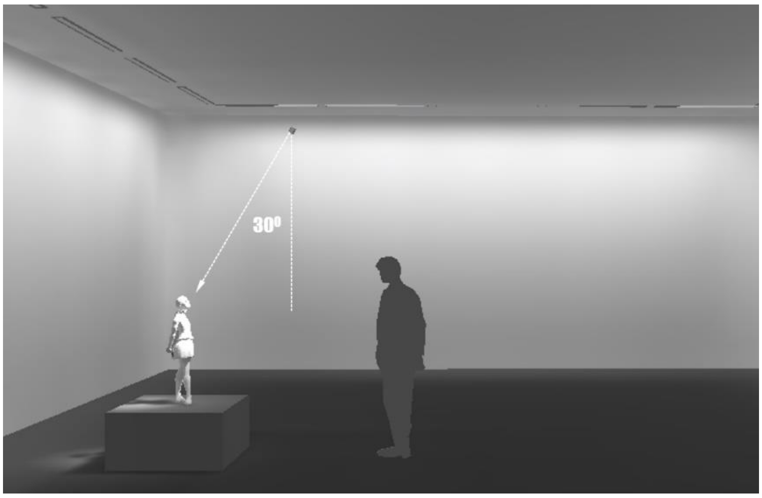

Figure 5: 3D modelling technique.

6. Maintenance. Easy access to luminaires for changing or modifying their position/aiming significantly reduces maintenance costs

Directional lighting is the most common lighting type used in museums. Luminaires with limited light beam (spots) can support this concept. The size of their light beam is defined by the beam angle. Angles up to 20 degrees correspond to a narrow beam spot while angles >50 degrees to Very Wide Flood. The beam angle depends on the light source but also on the reflector or the lens of the luminaire. There are also mechanical ways to adjust the light beam to be limited to the boundaries of the exhibit. The beam angle is the angle from the aiming axis of the luminaire in which the luminous intensity is 50% of the maximum value.

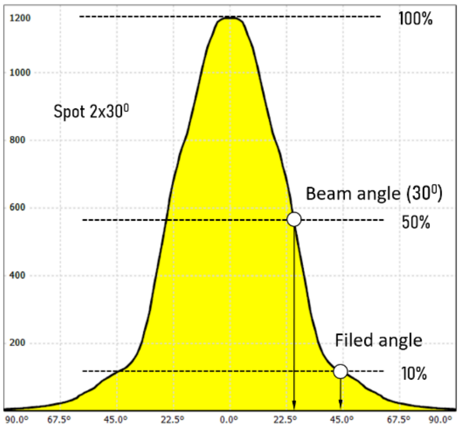

Figure 6: Definition of the beam and field angles of a spot.

Another type of luminaire used to uniformly illuminate vertical surfaces is the wall washer. These owe this property to its asymmetric luminous intensity distribution. A few years ago, the use of halogen spot was one of the main light sources due to its small size and excellent color performance. Today the use of LED sources is increasing since their light beam can be easily designed and the color rendering index can be > 90 as already mentioned. Of course, in this case there is the additional advantage of reduced energy consumption. Because museum temporary exhibitions have various requirements, the lighting system must be easily adapted to these. The most common solution is to use track lighting rails on which the luminaires can be placed. This solution offers a considerable flexibility as both the position and the aiming of the luminaires can be changed easily.

In his important paper Thomas Schielke(2020) describes six ways in which works of art can be illuminated

1. Placement of works of art in a space that prevail diffuse lighting. The works are distinguished due to the use of e.g., white colored surfaces. This idea, ie the use of a white space without special decoration appeared in 1927 and was adopted as a special museum aesthetic after its use in an exhibition in MoMA during 30s (www.intypes.cornell.edu). In this case diffuse lighting plays the main role and can be achieved either using daylighting or wall washer luminaires.

Figure 7: Diffuse lighting.

2. Subtle highlighting of exhibits. A combination of diffuse lighting and highlighting is used with the help of spots without strong contrasts.

Figure 8: Subtle highlighting.

3. Dramatic highlighting with the creation of intense luminance contrasts. The space is under-illuminated while the luminaires focus on the area of the exhibits using narrow beams.

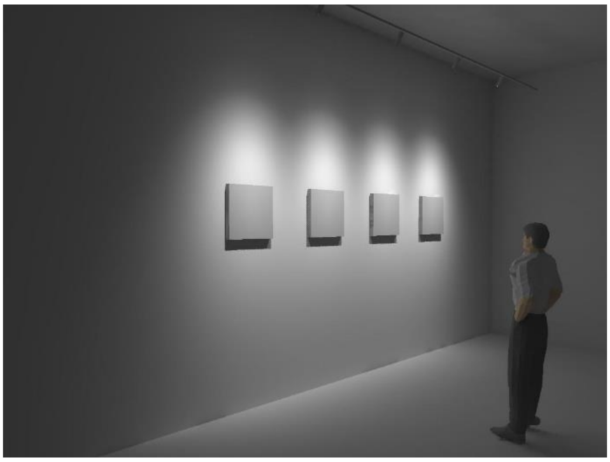

Figure 9: Dramatic hightlighting.

4. «Disappearance» of space. Only exhibits with minimal diffuse general lighting are illuminated. This is achieved by using luminaires whose light beam can be adjusted in such a way that only the surface of the works is illuminated. The impression is that the exhibits (usually paintings, drawings) are illuminated by some internal source. An additional strategy is used to intensify this concept. The exhibits (mainly paintings) are surrounded by a slightly larger surface of very absorbent material to completely eliminate the small light patches that are formed outside the boundary of the exhibit.

Figure 10: Very strong highlighting with minimal general diffuse lighting.

5. Hyperrealism. Lighting different areas of the exhibit. This differentiation can be done either by varying the intensity, beam shape or the light color.
6. Lighting is not only used to highlight the exhibit but also for other purposes (eg entertainment). For example, diffused colored lighting can be used.

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Acoustics

Stamatis Zoras

1. Principles of Building Acoustics

Building acoustics is the science of controlling noise in buildings, including the minimisation of noise transmission from one space to another and the control of noise levels and characteristics within a space.

Noise can be defined as sound that is undesirable, but this can be subjective and depends on the reactions of the individual. When a noise is troublesome, it can reduce comfort and efficiency. If a person is subjected to noise for long periods, it can result in physical discomfort or mental distress. A noisy neighbour environment can be one of the main problems experienced in public buildings and residential housing. It has been estimated that up to 4 million people in Britain have their lives disturbed by noisy neighbours, sometimes with tragic consequences. The best defence against noise is to ensure that proper precautions are taken at the design stage and during construction of the building. The correct acoustic climate must be provided in each space and noise transmission levels should be compatible with usage. Retrofitted remedial measures taken after occupation can be expensive and inconvenient.

Ideally, the sound insulation requirements of the building should take into account both internal and external sound transmission. The term 'building acoustics' embraces sound insulation and sound absorption. These two functions are distinct and should not be confused.

1.1 Sound insulation

Sound insulation is the term describing the reduction of sound that passes between two spaces separated by a dividing element. In transmitting between two spaces, the sound energy may pass through the dividing element (direct transmission) and through the surrounding structure (indirect or flanking transmission). In designing for sound insulation, it is important to consider both methods of transmission. The walls or floors, which flank the dividing element, constitute the main paths for flanking transmission, but this can also occur at windows, heating or ventilation ducts, doorways, etc.

The acoustic environment of the room and / or the building and the ability to reduce or eliminate air paths in the vicinity of the sound reducing element, e.g. doorsets, glazing, suspended ceiling cavities, ductwork, etc, will have a significant effect on its performance. For these reasons it is unlikely that figures quoted from laboratory test conditions will be achieved in practice. When the background noise is low, consideration may have to be given to a superior standard of sound insulation performance in conjunction with the adjoining flanking conditions. In any existing

sound insulation problem, it is essential to identify the weakest parts of the composite construction.
The Building Regulation requirements regarding the sound insulation of walls and partitions only relate to the transmission of airborne sounds. These include speech, musical instruments, loudspeakers and other sounds that originate in the air. In most cases, floors must also resist the transmission of impact sounds, such as heavy footsteps and the movement of heavy objects.

1.2 Indirect paths (flanking transmission)

Flanking sound is defined as sound from a source room that is not transmitted via the separating building element. It is transmitted indirectly via paths such as windows, external walls and internal corridors. It is imperative that flanking transmission is considered at the design stage and construction detailing is specified so as to eliminate or at least to minimise any downgrading of the acoustic performance. The sound insulation values quoted in system performance tables are laboratory values and the practicalities of construction will mean that acoustic performances measured in the laboratory will be difficult to achieve on site. See Figure 1.
One of the main reasons for this difference is the loss of acoustic performance via flanking transmission paths. Good detailing at the design stage will minimise this effect and optimise the overall levels of acoustic privacy achieved.
Design advice on flanking details must be followed to maximise the possibility of achieving the specified acoustic performance. It is imperative that the design advice is followed, otherwise site sound insulation values may not meet the minimum standards required by Building Regulations and expensive remedial treatment will be required.
Small openings such as gaps, cracks or holes will conduct airborne sounds and can significantly reduce the sound insulation of a construction. For optimum sound insulation a construction must be airtight. Most gaps can be sealed at the finishing stage using Gyproc Soundcoat Plus, Thistle plaster or Gyproc jointing compounds. Small gaps or air paths can be sealed with Gyproc Sealant. At the base of the partition, gaps will occur, particularly when boards are lifted tight to the ceiling.

1.3 Deflection head details – acoustic performance

Deflection heads, by definition, must be able to move and, therefore, achieving an airtight seal is very difficult without incorporating sophisticated components and techniques. Air leakage at the partition heads will have a detrimental effect on acoustic performance of any partition. For example, result in an insulation ability loss of around 4 dB to 5 dB due to air leakage, in addition to that lost due to flanking transmission (Figure 2).
Where acoustic performance is a key consideration, steps can be taken to minimise this loss of performance. Other factors, such as flanking transmission through the structural soffit, can significantly affect the overall level of sound insulation. Therefore, to optimise sound insulation performance, other measures may need to be taken.

A suspended ceiling installed on both sides of the partition may provide a similar cloaking effect to that of steel angles. CasoLine MF incorporating imperforate plasterboard can deliver a similar reduction in air leakage at the partition head. A tight fit between the ceiling perimeter and the surface of the partition lining board is important, although mechanically fixed perimeters are not essential. Ceilings with recessed light fittings may be less effective and if these cannot be sealed in some way, the installation of cloaking angles at the partition head should be considered. A suspended ceiling may also reduce the level of sound flanking transmission via the soffit.

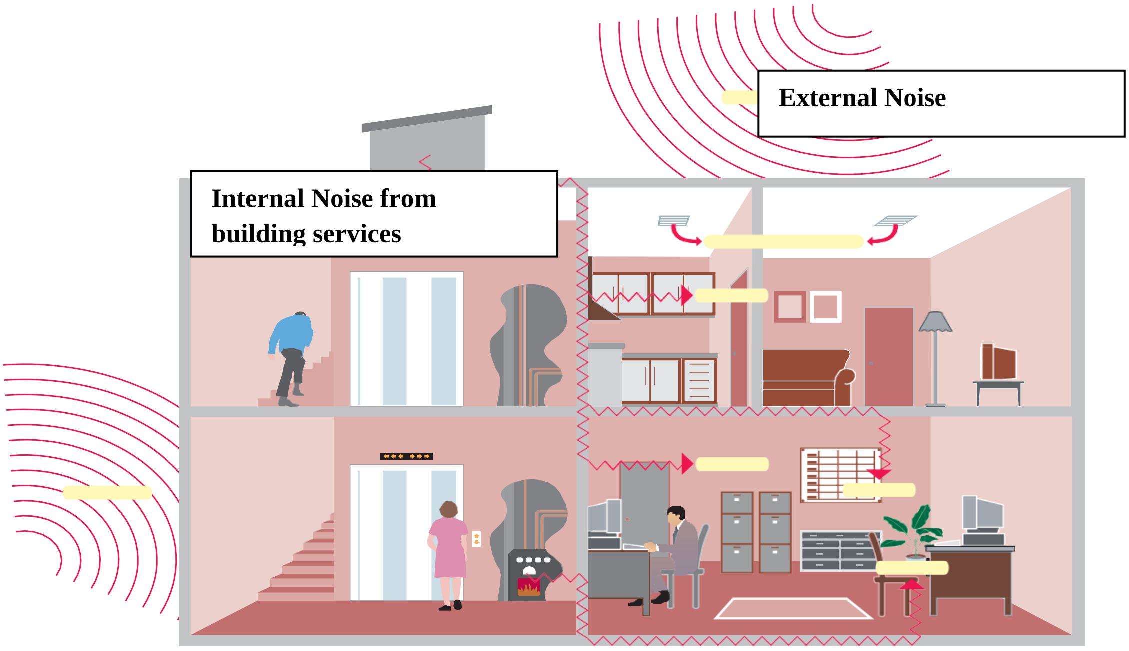


Figure 1: Internal and External Noise

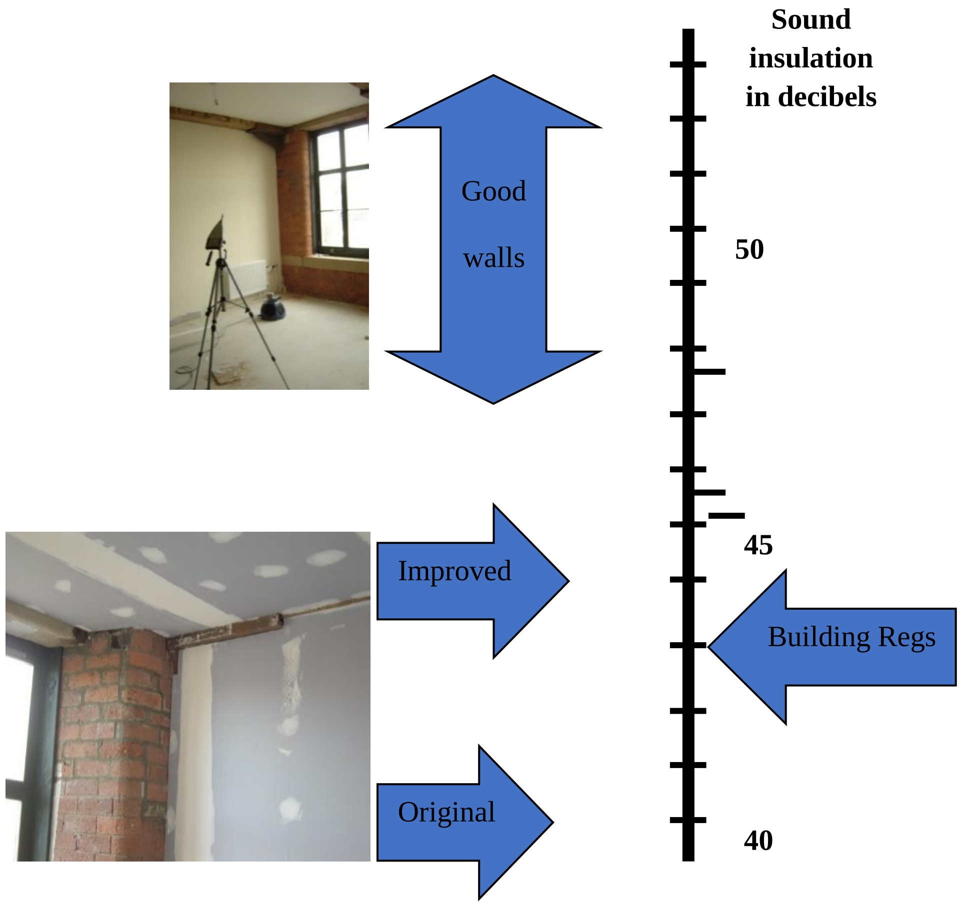


Figure 2: Detrimental effect on acoustic performance from air leakage

1.4 Partition to structural steelwork junctions

When designing the layout of rooms requiring separation by sound insulating walls abutting structural steelwork, consideration should be given to the potential loss of sound insulation performance through the steelwork. Although these details refer to structural steel column abutments, similar principles apply when abutting structural steel beams. We recommend that these details are checked by an Acoustic Consultant, in particular the performance via the flanking structure.

1.5 Sound by-passing a partition via the void above a suspended ceiling

This is a common source of sound transmission particularly where the ceiling is porous to sound. Where sound insulation is important, partitions should, wherever possible, continue through the ceiling to the structural soffit and be sealed at the perimeter junctions. Sound can easily travel through a perforated tile or lightweight suspended ceiling and over the top of a partition where it abuts the underside of the suspended ceiling. Gyproc plasterboard suspended ceilings offer better insulation where partitions must stop at ceiling level to provide a continuous plenum, and in this instance an option is to include a cavity barrier above the ceiling line.

1.6 Composite construction

A common mistake made when designing a building is to specify a high performance element and then incorporate a lower performing element within it, e.g. a door within a partition. Where the difference between insulation is relatively small (7 dB or less) there needs to be a comparatively large area of the lower insulation element before the overall sound insulation is significantly affected. A greater difference in sound insulation between the two elements normally results in a greater reduction of overall sound insulation performance.

Composite calculation chart can be used to calculate the net mean sound insulation of composite partitions, e.g. a window in a partition. The correct mean sound insulation value for each part of the partition must be known in order to calculate the difference. This difference, read off on the curved line against the appropriate ratios on the vertical scale, gives the loss of insulation in dB on the horizontal scale. This figure is subtracted from the value of the part with the higher resistance to obtain the net sound insulation of the partition. Similarly, the effect of gaps or holes in a partition are treated by giving a sound insulation value of 0 dB to the aperture.

Table 1 shows the acoustic effect on a range of partitions when various types of door are installed. It can be seen that if a poor performance door is included in a partition, it does not matter if the wall achieves 25 dB or 50 dB sound insulation as the net performance will never be better than 27 dB. The lowest performing element will always dominate the overall performance.

Table 1: Effect of including various door types within a partition system

Door construction	**Mean sound insulation of partition alone (dB)**					
	25	**30**	**35**	**40**	**45**	**50**
	Mean sound insulation of partition with doorways accounting for 7% of area (dB)					
Any door with large gaps around the edge	23	25	27	27	27	27
Light door with edge sealing	24	28	30	32	32	32
Heavy door with edge sealing	25	29	33	35	37	37
Double doors with a sound lock	25	30	35	40	44	49

1.7 Acoustic privacy

Two main factors affect the level of acoustic privacy achieved when designing a building:

• The sound insulation performance of the structure separating the two spaces.

• The ambient background noise present within the listening room.

The ambient background noise level can be a useful tool when designing buildings, as it is possible to mask speech from an adjacent space and hence provide enhanced speech confidentiality. There are a number of commercially available systems for achieving this and the technique is referred to as acoustic perfume. It is, however, more common to treat the problem by specifying appropriate levels of sound insulation. A guide to sound insulation levels is given in Table 2.

Table 2: Guide to sound insulation levels for speech privacy

Sound insulation between rooms R_w	Speech privacy
25 dB	Normal speech can be overheard
30 dB	Loud speech can be heard clearly
35 dB	Loud speech can be distinguished under normal conditions
40 dB	Loud speech can be heard but not distinguished
45 dB	Loud speech can be heard faintly but not distinguished
> 50 dB	Loud speech can only be heard with great difficulty

Acoustic privacy issues are dealt with in detail for healthcare and educational environments within EN ISO 11654.

1.8 Ambient noise levels

Along with acoustic privacy, the level of sound energy acceptable within a room should be assessed as regards intrusive noise levels and the level of potential noise likely to be generated within the room itself. For this purpose there are a number of methods, including the Noise Rating (NR) system. This rating quantifies the level of noise present within a space taking into account break-in of noise from the adjacent areas and also the background noise present within the space from ventilation or other building services. Table 3 gives the recommended maximum noise within different activity spaces using NR criteria.

Table 3: Recommended maximum noise rating for various types of room function

Situation	NR criteria (dB)
Sound studios	15
Concert halls, large theatres, opera houses	20
Large auditoria, large conference rooms, TV studios, hospital wards, private bedrooms, music practice rooms	25
Libraries, hotel rooms, courtrooms, churches, cinemas, medium-sized conference rooms	30
Classrooms, small conference rooms, open-plan offices, restaurants, public rooms, operating theatres, nightclubs	35
Sports halls, swimming pools, cafeteria, large shops circulation areas	40
Workshops, commercial kitchens, factory interiors	45

The factors that affect the ambient noise level of a space are:

• The level of external noise.
• The level of sound insulation designed into the surrounding structure.
• The amount and type of sound absorbing surfaces within the room.
• The noise generated by building services. Where control of ambient noise is critical, advice should be sought from an acoustic consultant.

1.9 Sound insulating dry linings

In designing for sound insulation, care should be taken to ensure that flanking transmission via the associated structure does not downgrade the performance of the partition or wall to a level below that required in use. This applies especially when a lightweight partition or wall is constructed in a masonry building. Care should therefore be taken to ensure the associated structure is able to achieve the level of sound insulation required. The performance of sound resisting floors of timber joist or lightweight concrete construction, supported on or flanked by conventionally finished masonry walls, can be adversely affected by flanking transmission in the walls. This effect can be significantly reduced by the application of Gyproc TriLine or a GypLyner wall lining system, to the flanking walls. Lining treatments can also be beneficial in refurbishment work when applied to flanking walls to a new or existing sound resisting wall (Fig 3).

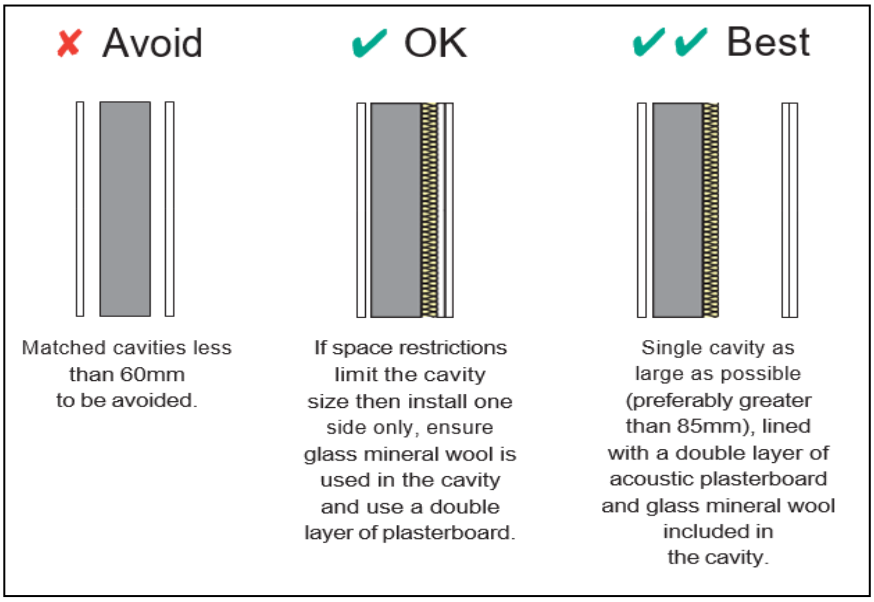
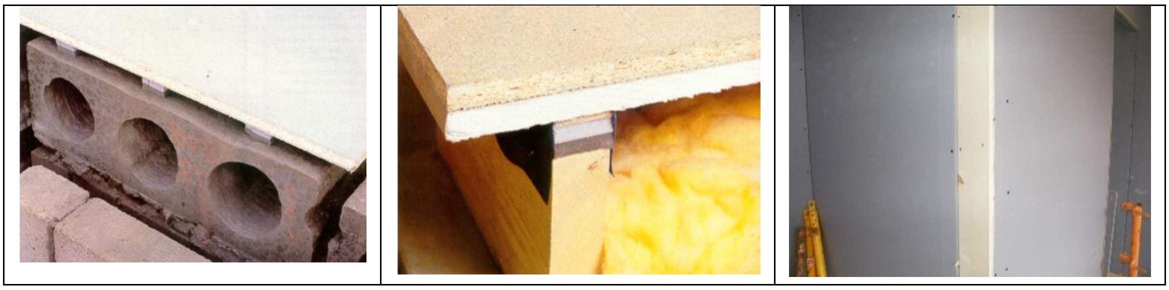


Figure 3: Benefits of lining treatments

2. Sound absorption

Sound absorption is the term given to the loss of sound energy on interaction with a surface. Sound absorbent surfaces are used to provide the correct acoustic environment within a room or space. The choice of material will be influenced by its acoustic efficiency, appearance, durability and fire protection. By converting some of the sound energy into heat, sound absorbing materials will also help sound insulation because less noise will be transmitted to other rooms. However, this reduction in noise is very small when compared with the potential reduction due to sound insulation. Sound absorption is therefore never a substitute for adequate sound insulation.



2.1 Reverberant energy

Reverberation is the persistence of sound in a particular space after the original sound is removed. A reverberation, or reverb, is created when a sound is produced in an enclosed space causing a large number of echoes to build up and then slowly decay as the sound is absorbed by the walls, ceilings, floor and air. The length of this sound decay is known as reverberation time and can be controlled using sound absorbing materials. The appropriate reverberation time for a space will be dependent on the size and function of the space. Some typical reverberation times are given in Table 4.

Table 4: Typical reverberation times

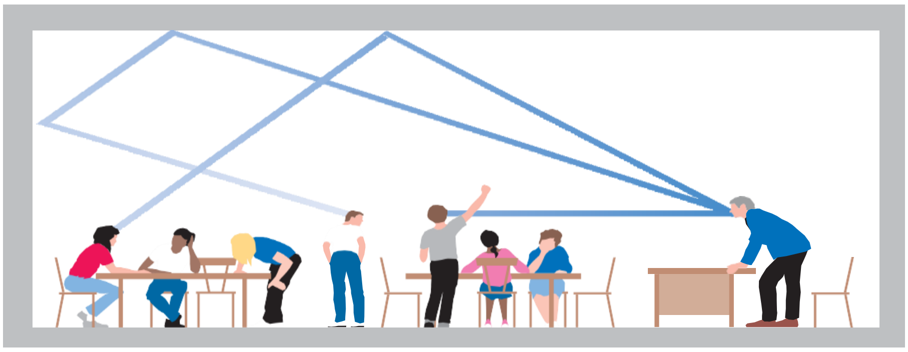
Type of room / activity	Reverberation time (mid frequency)
Swimming pool	<2.0 seconds
Dance studio	<1.2 seconds
Large lecture theatre	<1.0 seconds
Small lecture room	<0.8 seconds
Primary school playroom	<0.6 seconds
Classroom for hearing impaired	<0.4 seconds

- Rooms for speech should have an RT less than 1s (<0.8s required for school classrooms)
- For music the RT should be longer (depends on the type)
- Long RTs reduce speech intelligibility
- Very short RTs stop sound propagation around the room

2.2 Speech clarity

Speech clarity (intelligibility) is now recognised as essential in helping audience pupils in an confined environment to achieve their full potential. Research has shown that audience who cannot understand clearly what the speaker is saying have a tendency to 'switch off'. In a typical indoor space with the speaker at one end, sound reaches the visitors both directly from the speaker and via reflections from the ceiling, walls and floor (Figure 4).

Reverberation time alone cannot be relied upon to deliver a suitable environment for good speech intelligibility. In any situation where speech communication is critical, e.g. conference room, lecture theatre or classroom, it is necessary to design the space appropriately using a mixture of sound reflective and sound absorbing surfaces.



2.3 Sound absorption rating methods

The following ratings are calculated in accordance with EN ISO 11654: 1997.

Sound Absorption Coefficient, αs

Individual sound absorption figures quoted in third octave frequency bands are used within advanced modelling techniques to accurately predict the acoustic characteristics of a space. The coefficient ranges from 0 (total reflection) through to 1 (total absorption).

Practical Sound Absorption Coefficient, αp

A convenient octave-based expression of the sound absorption coefficient, commonly used by acoustic consultants when performing calculations of reverberation times within a building space.

Sound Absorption Rating, αw

A single figure rating used to describe the performance of a material. The single figure rating can have a modifier added to indicate if the spectral shape is dominated by a particular frequency range:

- L - absorption is predominantly in the low frequency region.
- M - absorption is predominantly in the mid frequency region.
- H - absorption is predominantly in the high frequency region.

The absence of a letter following the rating indicates that the absorber has no distinct area of sound absorption and has an essentially flat spectral shape. The values ascribed to the different classes are given in Table 7.

Table 7: Absorption classes

Sound absorption class	aw
A	0.90, 0.95, 1.00
B	0.80, 0.85
C	0.60, 0.65, 0.70, 0.75
D	0.30, 0.35, 0.40, 0.45, 0.50, 0.55
E	0.15, 0.20, 0.25
Unclassified	0.00, 0.05, 0.10

3. Large Structure Sound and Vibration Absorption

Concrete structural columns and beams of the frame had to be isolated from the vibrations that cause structure borne noise in the indoor environment. Museums are a certain category of buildings impacted by structure borne sound travelling through steel beams and the concrete foundations. The illustration below shows the incorporation of helical steel springs with a natural frequency of 3 - 5Hz to isolate the indoor space from outside heavy disturbances.

4. Examples of Museum Acoustic Design

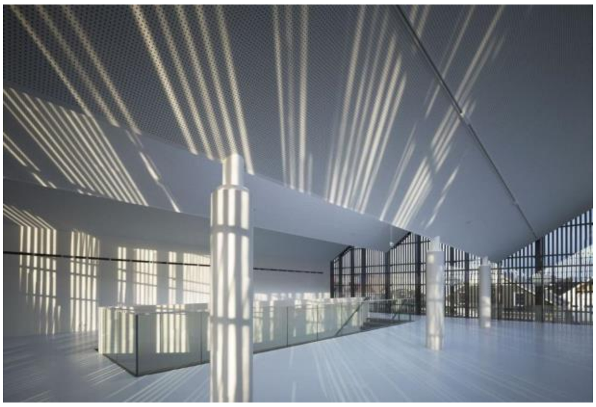
Generally, design of acoustics in museums and galleries is largely influenced by the natural lighting techniques by increased reflective surfaces and suspended ceilings with mounted light reflectors (see pictures below). Therefore, attempting to improve natural lighting, simultaneously, reverberation times are increased to >1 s. Use of heavy weight materials in walls’ of Greek museums such as marbles reduce the transmission of external noise but on the contrary employment of glazing surfaces reduce noise reduction ability. Use of suspended ceilings together with plasterboard surfaces improve noise protection whereas depending on the outdoor, mainly, transport facilities mounting of sound and vibration absorbers should further improve structure noise protection.

Beyeler Buseum, Switzerland

Menil Collection, Houston, USA

Mudam - Musée d’Art Moderne, Luxembourg

Cultural Arts Museum, Athens, Greece



Kaap Skil, Maritime and Beachcombers’ Museum, Texel, Netherlands

Delphi Museum, Delphi, Greece

Archaeological Museum, Thessaloniki

Archaeological Museum of Athens, Greece, Greece

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Building acoustics — Estimation of acoustic performance of buildings from the performance of elements. ISO 12354:2017

Acoustics — Sound absorbers for use in buildings — Rating of sound absorption. ISO 11654:1997: Reviewed 2018

Energy Performance Simulation of "Constantin Xenakis Museum" with DesignBuilder software

Pasxalis Vavalos, Argiro Dimoudi, Stamatis Zoras

1. Introduction

The aim of this work is to perform a detailed energy simulation in a museum case study in the city of Serres in Greece and to evaluate the energy performance of the building after its renovation towards nearly zero energy consumption (NZEB – consumption of primary energy below 60 kWh/m2). The building that was chosen, dates back to the Ottoman period, is located in a former military camp at the southeast area of the city of Serres at climate zone C, and after its restoration and renovation is transformed into a Thematic Museum which hosts the modern art collection of Constantin Xenakis.

The energy performance simulation of the contemporary art Museum "Contantin Xenakis" was carried out with the help of two collaborating energy simulation tools, EnergyPlus and DesignBuilder. DesignBuilder is a software with a friendly graphical interface which allows the visualization of complex three dimension building models, while possessing a comprehensive data input layout. It's an integrated building simulation software for energy performance, which is built upon the simulation engine of EnergyPlus, while incorporating all its capabilities.

Due to its unique structural design and its energy consumption diversities between its internal spaces, the museum was separated into three distinct conditioned thermal zones, according to the same operational schedules, same HVAC systems and interior conditions such as temperature setpoints etc. The simulation was performed with four time steps per hour, evaluating the energy consumption of the base building and the proposed energy improvement scenarios.

The input data for the museum was extracted through architectural plans, electromechanical data, information provided by the technical supervisor team and building construction team, while following the Greek regulation (KENAK) and its technical guidelines when the data was insufficient (TOTEE 20701-1/2017) simulating the building's real energy consumption.

All input data that was imported into the simulation software is listed in tables, along with schematics and figures, and the energy simulation performance of the Art Museum C.Xenakis is documented in net and source energy for better understanding and evaluation.

2. Case Study – Art Museum Constantin Xenakis

2.1 Location

The renovated building which now hosts the modern art collection of Constantin Xenakis, was originally constructed at the beginning of the 20th century during the Ottoman era with eclecticism as architectural approach, rendering it, according to Greek legislation, as a traditional preserved edifice, prohibiting that way any alteration of its external features.

The C. Xenakis Museum is located in a former military camp at the southeast area of the city of Serres, with $41{,}09^0$ latitude and $23{,}55^0$ longitude, completely exposed to the outside environmental conditions, with the dense tree planting as the only natural barrier for the wind and sun. The tall trees provide a natural shading throughout the year, allowing only a small portion of the solar energy to reach the facades of the building.

There are two entrances in the site where the Museum is located, one in the north west side and the other one in the south west. The building was constructed in a ground surface with a slight slope (~2%) oriented from North to South and the main entrance is located to the north east side of the building. The location of the C. Xenakis Museum is presented in Figures 1 and 2.

Figure 1: Location of the C.Xenakis Museum *[Source: Electronic services of National Land Registration of Greece. Internet page: gis.ktimanet.gr, aerial photographs of years 2015-2016.]*

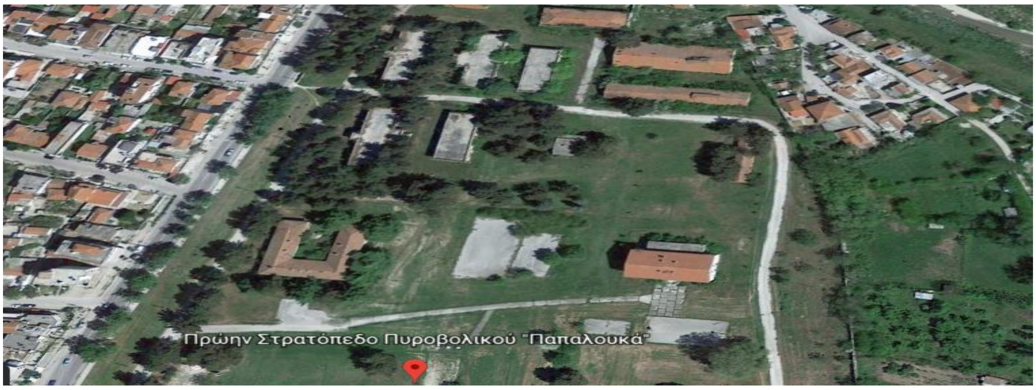

Figure 2: Location of the C.Xenakis Museum of year 2022. *[Source:* https://www.google.com/maps/place/Πρώην Στρατόπεδο Πυροβολικού "Παπαλουκά"]

2.2 Climatic data

The C. Xenakis Museum is located at the southeast area of the city of Serres, which belongs in Climate Zone C out of the 4 distinctive Climate Zones (A, B, C or D) according to the Greek regulation. The climatic data for that area is summarized in the Table 1, while the following Diagrams 1 – 6 present the annual weather conditions. More specifically,

- the average annual site outdoor air dry bulb temperature is 15,24 ^oC, the minimum average value of months is 3,51 ^oC on January and the maximum average value of months is 26,96 ^oC on July,
- the maximum site outdoor air dry bulb value of temperature of each month ranges between 16,70 ^oC and 39,50 ^oC. The highest value (39,50 ^oC) is recorded on July, and the lowest value (16,70 ^oC) is recorded on January.
- the minimum site outdoor air dry bulb value of temperature of each month ranges between -7,70 ^oC and 16,20 ^oC. The lowest value (-7,70 ^oC) is recorded on January, and the highest value (16,20 ^oC) is recorded on August.
- the site's average annual wind speed is 1,87 m/s, while the maximum of moths is observed on March at 2,20 m/s, and the minimum of months at 1,59 m/s on October.
- the average diffuse solar radiation rate per area for the site is 73,96 W/m^2, the maximum of months is 109,48 W/m^2 on June and the minimum is 33,37 W/m^2 on December.
- the average direct solar radiation rate per area is 186,87 W/m^2, the maximum of months is 282,58 W/m^2 on July and the minimum is 102,41 W/m^2 on December.

Table 1: Geographical and climatic data C. Xenakis Museum

Latitude	**41,09°**
Longitude	23,55°
Elevation above sea level (m)	51
Standard pressure at elevation (Pa)	100714

Average annual site dry bulb temperature (°C)	15,24
Maximum annual site dry bulb temperature (°C)	39,50
Minimum annual site dry bulb temperature (°C)	-7,70
Average annual site wind speed (w/s)	1,87
Average annual site diffuse solar radiation (W/m²)	73,96
Average annual site direct solar radiation (W/m²)	186,87

**The climate data that were used in the simulations of the C. Xenakis Museum were created using the meteorological data of Meteonorm software which contain climatological data of every location on the globe. The climatological data of the location of Serres were processed and imported into the simulation software DesignBuilder.*

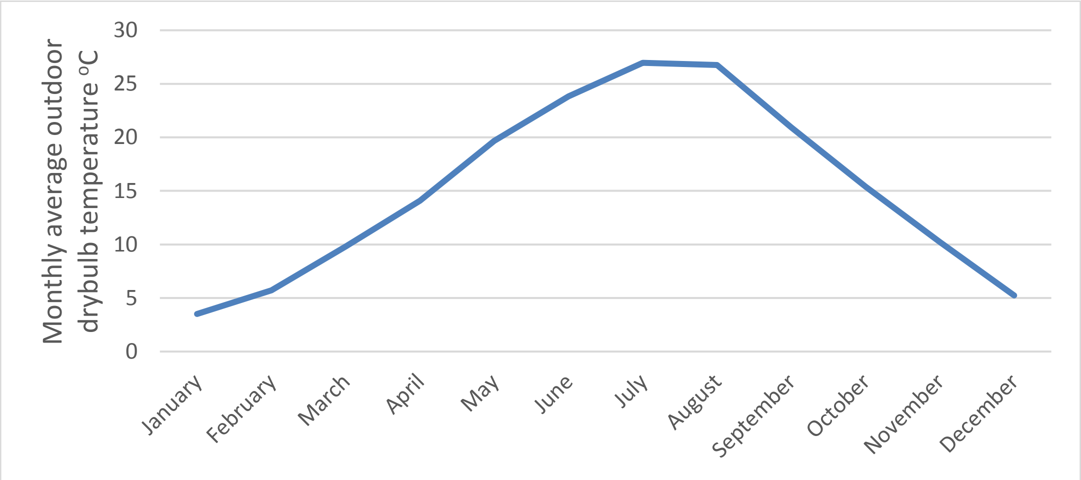

Diagram 1: Monthly site average outdoor drybulb temperature °C of C. Xenakis Museum

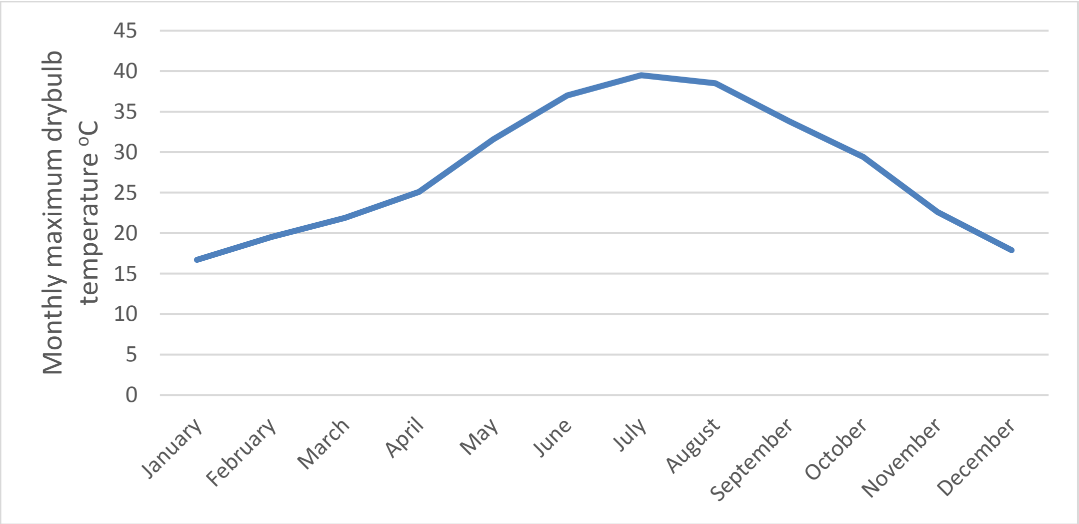

Diagram 2: Monthly site maximum outdoor drybulb temperature °C of C. Xenakis Museum

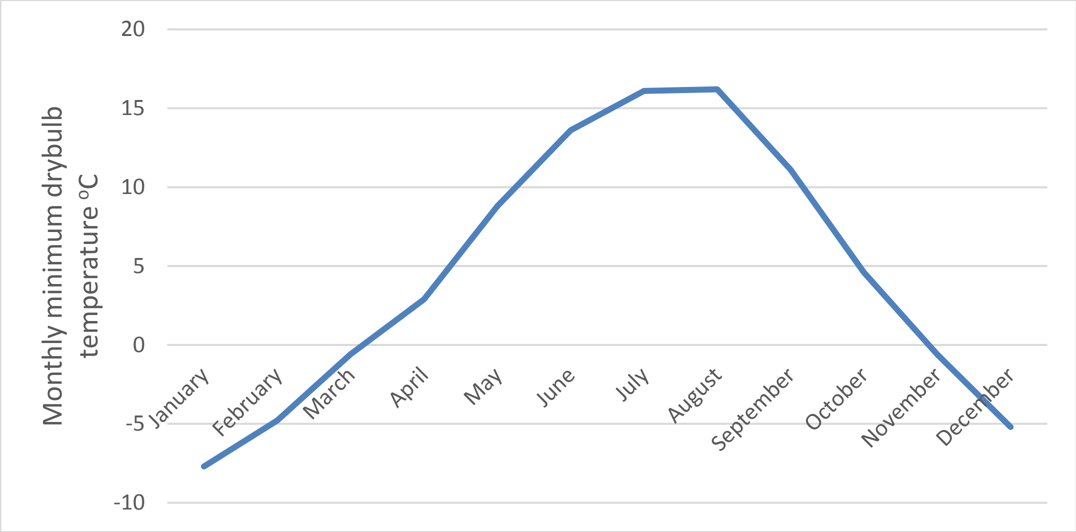

Diagram 3: Monthly site minimum outdoor drybulb temperature ºC of C. Xenakis Museum

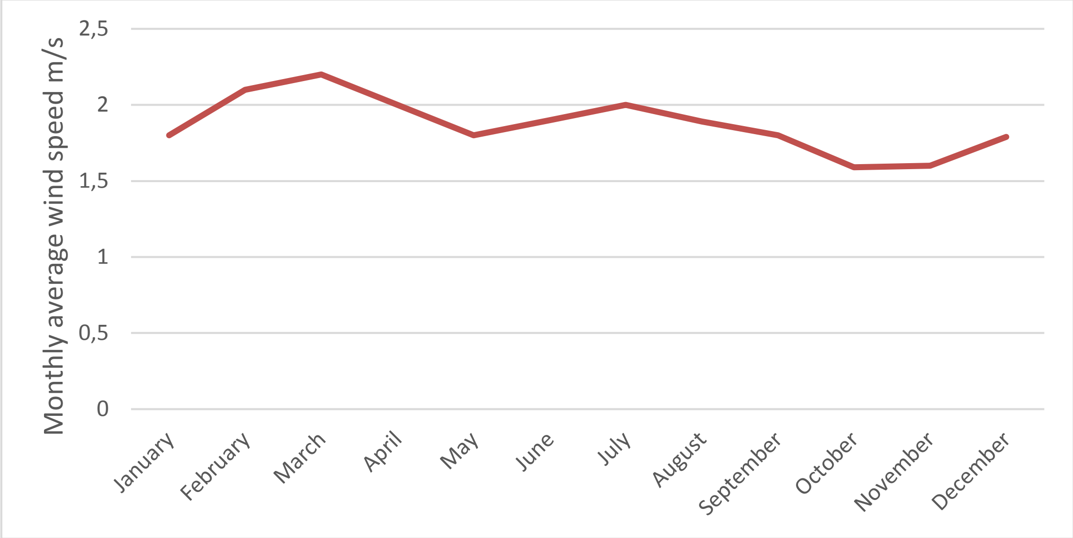

Diagram 4: Monthly site average wind speed of C. Xenakis Museum

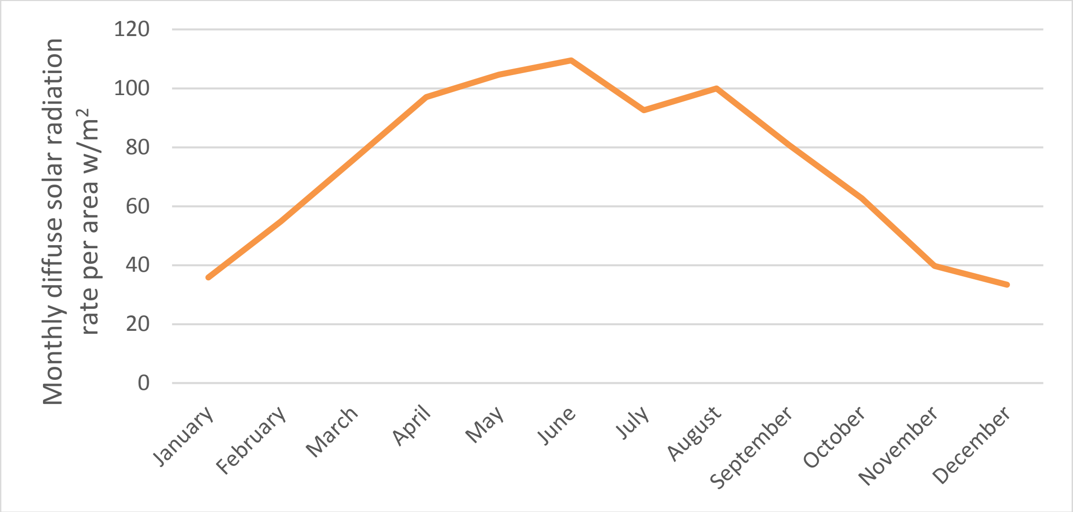

Diagram 5: Monthly site diffuse solar radiation rate per area W/m^2 of C. Xenakis Museum

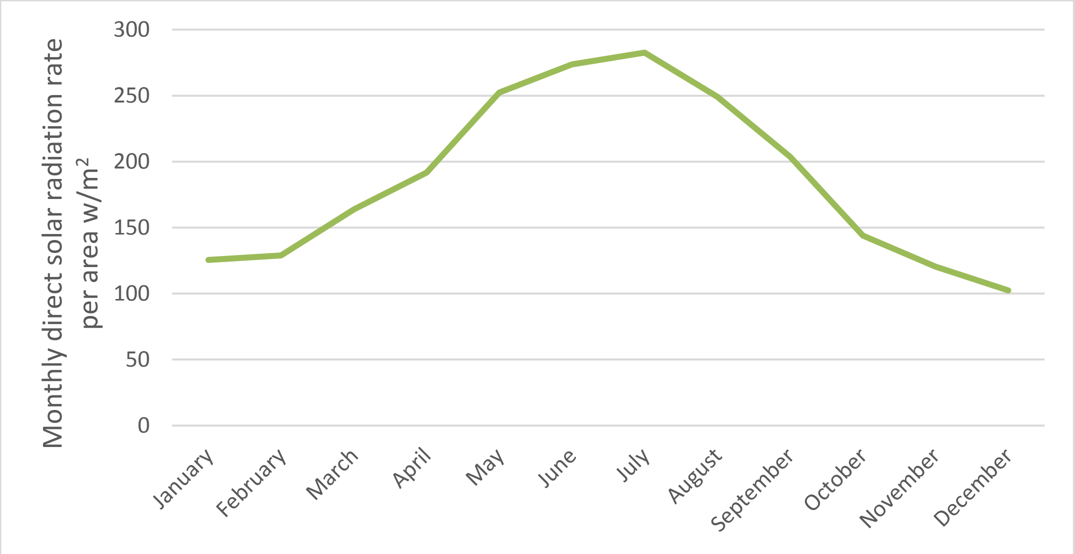

Diagram 6: Monthly site direct solar radiation rate per area W/m^2 of C. Xenakis Museum

2.3 General information of Museum C. Xenakis

2.3.1 Building description – Site area – Plans

The C .Xenakis Museum is part of a total group of eleven buildings in the military compound of "Papaloukas", at Serres. The total site area is around 124.000 m^2 which is intended for reconstruction and redevelopment and is easily accessible from its two entrances at the North west side and south west. At the west side, it borders the old ring road of Serres, at north side a residential area the while at the east and south side there are unconstructed areas.

Figure 3: Site plan of C. Xenakis Museum

The total area of the building is 651,91 m^2 and the total height of the examined conditioned area (from the outside layer of ground floor till the outside layer of the roof) is 4,85 m. The total volume amounts to 3.176,77 m3.

It is a single floor building with a slab roof, upon a ground surface with a minor slope of around 2%, and its two elongated sides are orientated in 25^0 from true North.

Figure 4: Orientation of C. Xenakis Museum from true North

It is composed of one rectangular shaped main body of 568,30 m^2 and its two smaller side projections in the north east and north west side of the building accounting for 68,30 m^2 and 15,40 m^2 respectively.

In the following Figures 5 – 9, the floor plan of the Museum and its facades of all its sides can be found.

The Museum will operate 6 days per week for 5 hours and will able to host more than thirty visitors for two to five hours per day. Also, the Museum C. Xenakis will remain open for the public and will be able to host educational programs for schools or visitors for six days per week throughout the year.

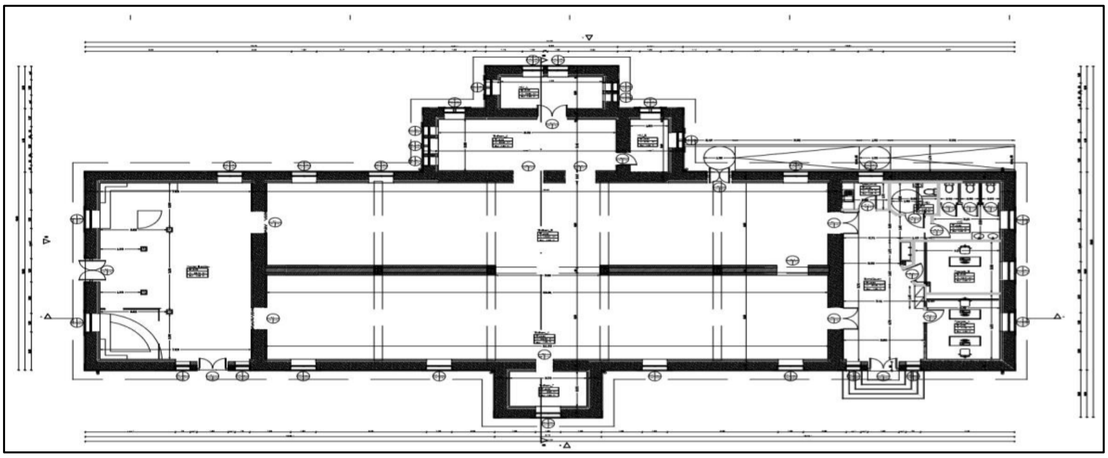

Figure 5: Floor plan of Museum C. Xenakis

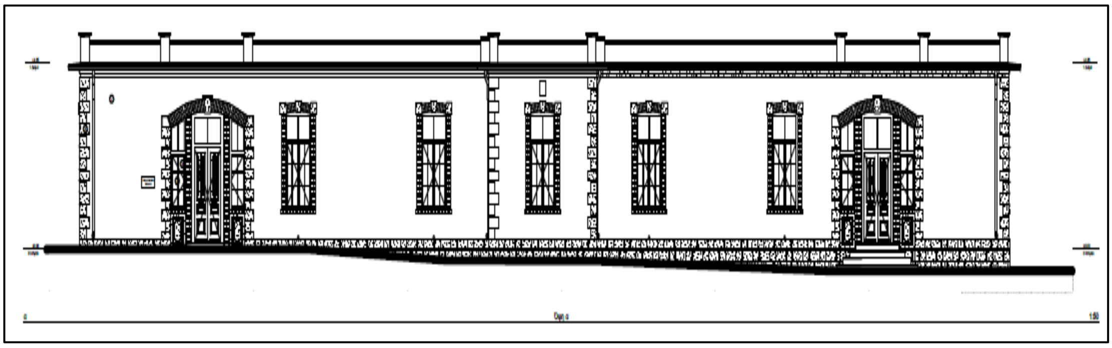

Figure 6: North West façade (Façade A) of Museum C. Xenakis

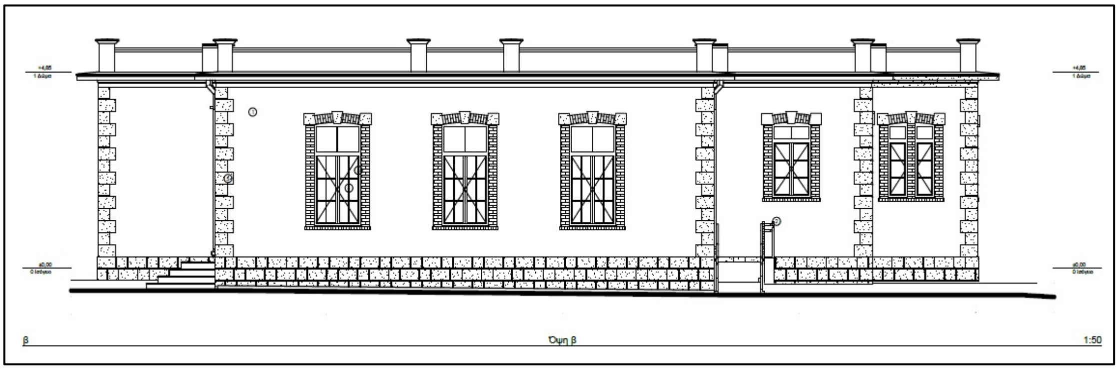

Figure 7: South West façade (Façade B) of Museum C. Xenakis

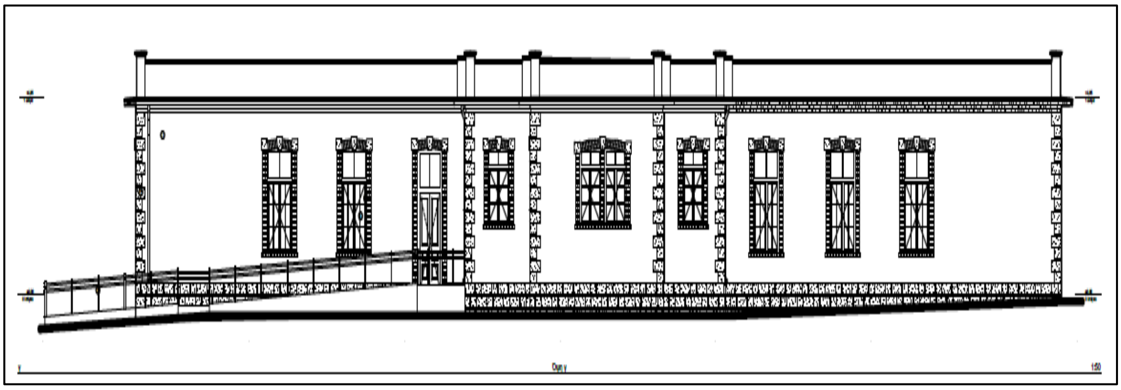

Figure 8: South East façade (Façade C) of Museum C. Xenakis

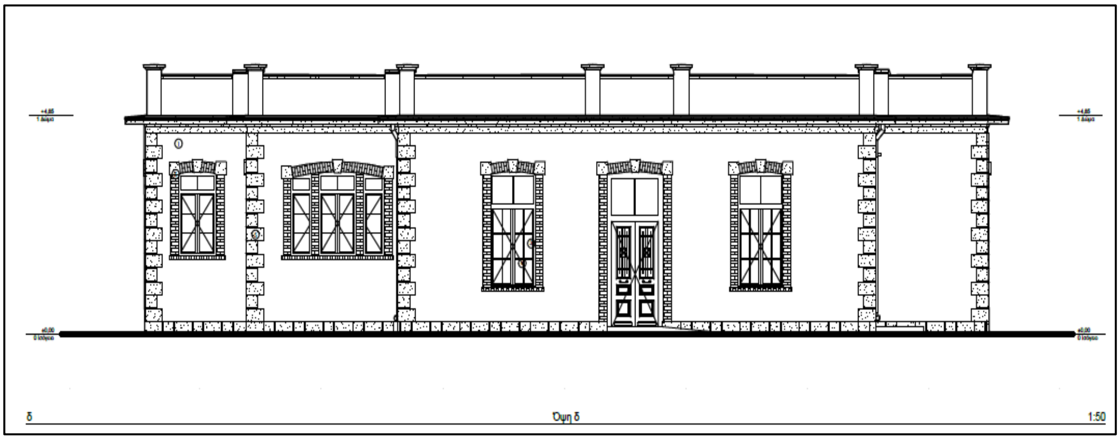

Figure 9: North East façade (Façade D) of Museum C. Xenakis

The Table 2 summarizes the Museum's total floor area and volume.

Table 2: Floor area and volume of Museum C. Xenakis

Floor	Area, m2	Floor Height, m	Volume, m3
Floor area of Museum C. Xenakis	651,91	4,85	3.176,76
Conditioned Spaces	651,91		3.176,76
Unconditioned Spaces	0		0

2.3.2 Construction details

The exterior wall of the Museum was constructed with limestone covered by an outer and an inner mortar coating. During the renovation, due to the prohibitions of the Greek legislation about traditional buildings, the outer coating of the building was carefully repaired and restored, while a layer of an 8 cm insulation of mineral wool (MW) was added to the interior of the building's walls. The insulation was covered by a gypsum plasterboard which was rendered with a pasty mixture, colored according to museum's standards. The total thermal transmittance (U-Value) of the exterior wall after the renovation is 0,336 W/m^{2}K, satisfying the threshold limits (U-value 0,45 W/m^{2}K) for external walls of new Greek regulation (KENAK) for renovated buildings.

The roof of the Museum was a Zoellner type flat roof covered by cement-sand mortar and old asphaltic membrane at the outer side, which were removed during the renovation of the building. A perlite concrete layer was added above the Zoellner slab, and was covered by a waterproof asphaltic membrane. At the inner side of the roof, a metallic grid with a layer of cement-sand mortar was applied to strengthen the slab, while a layer of a 10 cm of extruded polystyrene (XPS) was added for insulating purposes. The thermal transmittance (U-Value) of the roof after the renovation is 0,240 W/m^{2}K, satisfying the threshold limits (U-Value 0,40 W/m^{2}K) for roofs of new Greek regulation (KENAK) for renovated buildings.

The floor of the Museum was a reinforced concrete slab covered by an inner mortar coating. After the renovation, a layer of cement sand mortar, a 5 cm insulation of extruded polystyrene (XPS) were added to the interior of the building, covered by marble tiles. The thermal transmittance (U-Value) of the ground floor after the renovation is 0,543 W/m^{2}K, satisfying the threshold limits (U-Value 0,75 W/m^{2}K) for ground floors of new Greek regulation (KENAK) for renovated buildings.

Initially, the building had single glazed windows, with old wooden frame. After the renovation, the windows were replaced with double glazed 4mm-16mm with argon 90%-4mm with Low-E coating, maintaining the wooden material for the frames due to the prohibitions of the Greek legislation about traditional buildings. The thermal transmittance (U-Value) of the openings after the renovation is 1,30 W/m^{2}K, satisfying the threshold limits (U-Value 2,80 W/m^{2}K) for openings of new Greek regulation (KENAK) for renovated buildings.

Table 3: Construction details of Museum C. Xenakis

	Construction details (layers)	**(U-Value)**
Exterior wall	• Cement-sand mortar coating • Limestone • MineralWool (MW) • Gypsum board • Pasty finish render	0,336
Flat roof	• Waterproof asphaltic membrane • Perlite concrete • Zoellner type slab (Reinforced concrete with brickwork) • Cement-sand mortar coating • Extruded polystyrene (XPS)	0,240
Ground floor	• Unreinforced concrete or lightly reinforced • Extruded polystyrene (XPS)	0,543

	• Cement sand mortar • Marble tiles	
Openings(windows/doors)	• Wooden flamed, double glazed 4mm-16mm argon 90%-4mm with Low-E coating • Light transmission: 61% • Total solar transmission: 37%	1,300

**In the Appendix 1 of the deliverable, the calculations of U-Value of the construction elements are presented.*

2.3.3 Lighting

The Museum C. Xenakis has 146 anti-glare LED Gu10 lights 7,5 W, distributed throughout the spaces of the building (exhibition room, offices, entrance, educational room and auxiliary spaces) separated in three types: surface mount, recessed and suspended. The total power density of the install capacity is measured at 1,1 kW and operate according to the time schedule of the museum. In the Table 4, the lightning elements of the museum are presented.

Table 4: Lighting elements of Museum C. Xenakis

Lamp Type	No of Lamps	Hours of Operation	Installed Capacity (kW)
Surface mount anti-glare Led Gu10 7,5W	120	5 hours	0,90
Recessed anti-glare Led Gu10 7,5W	18	5 hours	0,14
Suspended anti-glare Led Gu10 7,5W	8	5 hours	0,06
Total Led Lights	146	5 hours	1,1

2.3.4 HVAC systems

The building initially didn’t have any heating, cooling or ventilation equipment so after the renovation, new highly efficient HVAC systems were installed to the Museum. A Ground Source Heat Pump (GSHP), also known as geothermal heat pump, was chosen to cover the heating and cooling needs of the Museum C. Xenakis, and two similar heat recovery units with cross-flow heat exchanger were installed for mechanical ventilation.

Due to the fact that the surrounding area of the museum was sufficient enough to accommodate a ground source heat pump, a slinky type, horizontal closed loop system was installed. The horizontal closed loop system consists of a pipe network with dedicated fluid circulation loop, buried in the soil, in order to exchange energy through the undisturbed temperatures of the ground according to the depth. At the north east side of the Museum C. Xenakis, occupying as less space as able, 35 trenches, at 1,2 m depth, were created to install the loop. The total length of the loop with the trenches is around 8.750 m.

Heating System

The Ground Source Heat Pump has heating capacity 58 kWth (58.220 W) with high COP at 3.8 and is able to meet the needs of the spaces of the Museum C. Xenakis for heating, providing hot water at 50 ^{o}C. The hot water loop consists of a two pipe system (supply and return), distributed from the heating collector to Fan Coils Units (FCU) located in each space of the Museum, three of which are installed in the floor of the educational room and auxiliary spaces, two are installed in the floor in the offices and four are installed in the interior roof in the exhibition room, presented at Table 5.

Cooling System

The Ground Source Heat Pump is also operating to cover the required cooling loads of the building. The cooling capacity of the heat pump is 52 kWco (52.608 W) with high EER at 4.8 and is able to provide cold water at 7 ^{o}C. The chilled water loop includes a two pipe system of supply and return which provides chilled water to cooling coils inside the Fan Coil Units (FCU). The cooling collector distributes the cold water to all the terminal units in each space of the Museum, presented at Table 5.

Table 5: Terminal Units (FCU) of Museum C. Xenakis

Location	Numbe r	Type	Air Flow	Cooling Capacity	Heating Capacity
			(m^3/h)	Kw	kw
Office	2	Floor FCU	550	3,2	4.2
Public rooms (educational room, entrance and auxiliary spaces)	3	Floor FCU	550	3,2	4.2
Exhibition room	4	Roof FCU	2.400	10,0	14,0

Mechanical Ventilation

For mechanical ventilation, two heat recovery units with cross-flow heat exchanger were installed with motor power 0,676 kW, each proving 2.000 m^3/h of fresh air, covering the ventilation requirements of the exhibition area of the museum. A supply ductwork begins from each air – air heat exchanger which is connected to the terminal units inside the exhibition room (FCUs located at the interior of the roof) for the distribution of the air while the air is extracted out of the space though a return ductwork. During this circulation, the two air flows of different temperatures pass through the heat exchanger, transferring heat between the fresh incoming air and the exhausted air, resulting to high energy saving.

3. Energy performance simulation methodology and inputs

3.1 Energy performance simulation tools

Energy Plus

The software that was used for the energy simulations for the Museum C. Xenakis is Energy Plus. Energy Plus is an integrated building energy simulation software which was developed by the U.S. Department of Energy (DOE) in collaboration with National Renewable Energy Laboratory (NREL) and other national and private research institutions, and is widely used by design engineers, researchers, architects and energy modelers (EnergyPlus™). It is a free energy simulation tool which underwent a series of updates since its initial creation and incorporates the capabilities of its predecessors BLAST and DOE-2. During the development of the software, Energy Plus has been tested through various standard methods in order to strengthen its validity. The tests focused on three major categories, analytical tests including HVAC and building fabric tests (ASHRAE), comparative tests (ANSI/ASHRAE, IEA SCH, BESTest) and release and executable tests (BESTest) (Castell A.,Solé C., 2015).

Figure 10: Energy Plus software [Source: Energy Plus internet site, www.energyplus.net]

Energy Plus is a complete energy simulation and thermal analysis tool for building envelope characteristics, real climate data, HVAC systems, shading, physical and artificial lighting, equipment, moisture and water use, and is able to conduct simulations at user defined time-steps of even less than an hour (Castell A.,Solé C., 2015).

The software allows a detailed definition of building geometry model, considering calculations for construction details (external and internal building elements, windows, ground domain, structure arrangement) while three-dimensional shading components (external and local) are taking into account, including calculations for daylight control, interior illuminance, glazing and solar penetration (Md. Faruque Hossain, 2019). Furthermore, the user is able to create and insert their own weather data in the software for a much more precise energy simulation of the building's location. The weather file proving the geographic location of the examined area, is able to determine the sun's position throughout the year and can contain annual data for dry and wet bulb temperatures, wind speed, air humidity, etc. along with sky modeling for solar radiation calculations (Corrado V., Enrico Fabrizio E., 2019).

Amongst its other capabilities, Energy Plus incorporates a heat air balance solution method taking into account the radiant and convective effects that generate temperatures in the interior and exterior surfaces of the building's envelope. Also, the software, includes a heat and mass transfer model, that is able to simulate the movement of the air between the thermal zones (Chowdhury A. A. et al., 2016).
One of the main strengths of the Energy Plus software is the highly sophisticated simulation of the HVAC systems. Heating, cooling and ventilation systems can be designed in simple or detailed way. The main components of the HVAC systems are: hot and chilled water loops, air loops, condenser loops, solar loops, domestic hot water loops, zone controls, and terminal units. Each loop is created with supply (boiler, chillers, cooling towers, water heaters) and demand nodes (hot and chilled water coils) which are connected to the installed terminal units (convectors, FCUs, AHUs, etc.). The user is able to insert a large number of input data including performance curves, capacities, flow rates etc. (EnergyPlus™).

DesignBuilder

Even though Energy Plus is one of the most complete, available for use, software for energy simulation, it still remains without a graphical interface. For that reason, many third parties created user friendly interfaces in order to allow a much easier building structure design and simplified data input, such as the DesignBuilder.

Figure 11: DesignBuilder software [Source: DesignBuiler internet site, https://designbuilder.co.uk/]

DesignBuilder is an easy to use software which combines a friendly graphical interface for complex three dimension building models along with a comprehensive data input layout. Users are able to design highly detailed building compounds with their boundary conditions rapidly, while navigating through its tabs to insert data easily and accurately. Its main strength it's the visualization of all the applied data in the model: the building structure and the site as a whole, the shading compounds, the construction elements, the climate data, the HVAC systems and its connections, the operating schedules, setpoints etc.
DesignBuilder is built upon the Energy Plus simulation engine and it updates according to latest versions. So, it's an integrated building simulation software for energy performance, taking into account all parameters which are incorporated in Energy Plus such as building envelope, climate data, HVAC systems, mechanical and natural ventilation, activity schedules, setpoint temperatures, heat gains and losses, internal loads, miscellaneous equipment, etc. while providing visualization and simplicity to the model (DesignBuilder).

The software that was used for the model design and data input for the Museum C. Xenakis is the DesingBuilder.

3.2 Building geometry construction – Thermal zone separation

In order to design the building's geometry in the DesignBuilder software, it was important to determine the thermal zones. According to the Greek regulation and its Technical Guidelines (TOTEE 20701-1/2017), it is important to separate the building into different thermal zones when the following conditions are met

- There are zones with different use, operation characteristics or operation conditions (temperature, humidity, fresh air, etc.)
- There are zones in the building which are conditioned by different HVAC system due their different interior conditions.
- There are zones which demonstrate large amounts of energy transfer (solar gains, thermal losses) in comparison with the other sides of the building such as south oriented zones.
- The temperatures setpoint in the zones differ by more than 4 ^{o}C in comparison with the other sides of the building.
- There are zones where the mechanical ventilation system provides less fresh air than the 80% of the total area of the zone.

According to the aforementioned suggestions, and due to its unique structural design, the Museum C. Xenakis, was separated into three different conditioned thermal zones which demonstrate distinct use and activity schedules, HVAC systems and temperature setpoints. The conditioned zones are: 1) Public Spaces (Educational room, entrance and auxiliary spaces), 2) Exhibition room, and 3) Office. Inside the building, there is an unconditioned area of around 60 m^3 were the mechanical equipment is located, which was included the Exhibition room thermal zone, according to the Greek regulation and its Technical Guidelines (TOTEE 20701-1/2017), spaces with volume less than 10% of the total volume of the building can be integrated into other zones.

The Figures 12 and 13 present the design of geometry of the building compound of the Museum C. Xenakis and its site in DesignBuilder software.

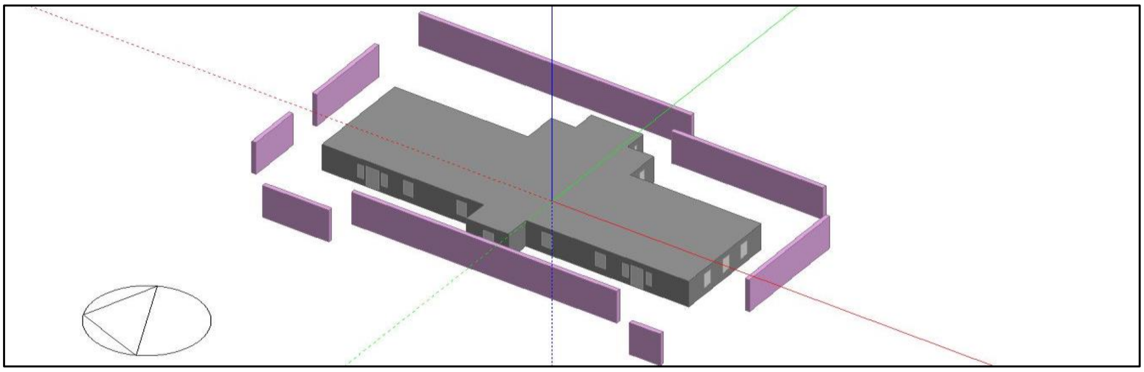

Figure 12: South West side of the Museum C. Xenakis

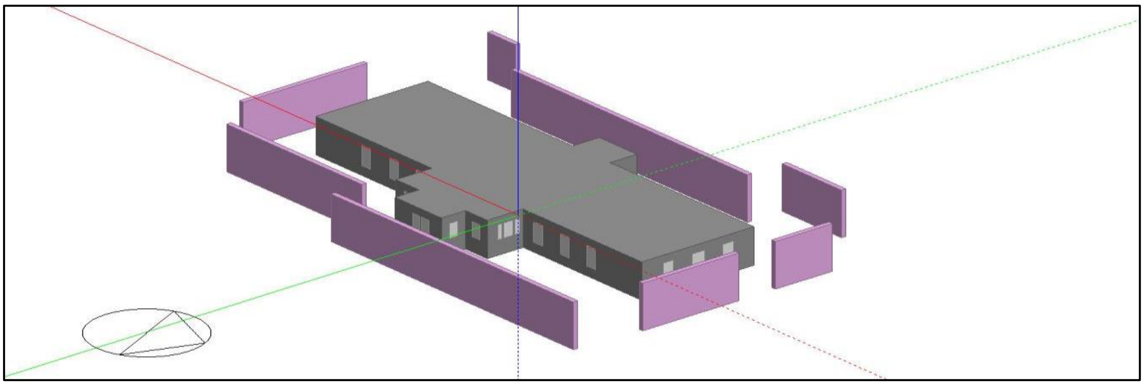

Figure 13: North East side of the Museum C. Xenakis

The Table 6 demonstrates all the conditioned thermal zones of the building along with all the areas and volumes, facades and window openings and the Figure 14 illustrate the separation of the thermal zones (each color represents a different thermal zone).

Table 6: Conditioned and unconditioned thermal zones of Museum C. Xenakis with areas and volumes, facades and window openings

	Area [m2]	**Volume [m3]**	**Opening Area [m2]**
Public Spaces	178,16	864,05	38,75
Exhibition room	436,23	2115,73	46,63
Office	37,52	181,99	6,24
Total	651,91	3161,77	91,62
Conditioned Total	651,91	3161,77	91,62
Unconditioned Total	0	0	0

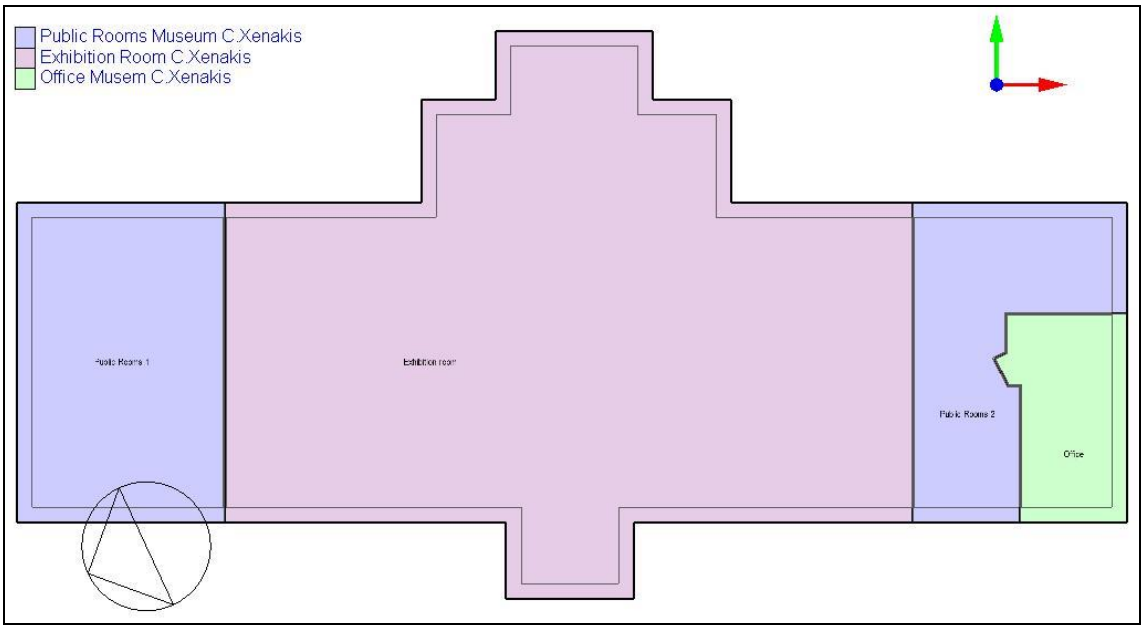

Figure 14: Plan of Museum C. Xenakis – Thermal Zone Separation

3.3 Construction elements of the building envelope

The data of each component of every layer of all the construction elements (exterior wall, flat roof, ground floor and openings) was imported to the DesignBuilder software. The imported data includes the thickness of every layer, its position (outermost or innermost) to the element and its thermal properties (thermal conductivity, density and specific heat), important for heat transfer and thermal transmittance (U-Value) calculations.

The construction element of the exterior wall of the Museum C. Xenakis consists of five layers from outermost to innermost: 5 cm cement-sand mortar coating, 60 cm limestone, 8 cm Mineral Wool (MW), 2 cm Gypsum board and 1 cm pasty finish render. The calculated total thermal transmittance (U-Value) of the exterior wall after the renovation is 0,336 W/m^{2}K.

The construction element of the flat roof of the Museum C. Xenakis consists of five layers from outermost to innermost: 4 mm waterproof asphaltic membrane, 8 cm perlite concrete, 30 cm Zoellner type slab (Reinforced concrete with brickwork), 3 cm cement-sand mortar coating, 10 cm extruded polystyrene (XPS). The calculated total thermal transmittance (U-Value) of the flat roof after the renovation is 0,240 W/m^{2}K.

The construction element of the ground floor of the Museum C. Xenakis consists of four layers from outermost to innermost: 15 cm unreinforced concrete or lightly reinforced, 5 cm extruded polystyrene (XPS), 8 cm cement-sand mortar, 3 cm marble tiles. The calculated total thermal transmittance (U-Value) of the flat roof after the renovation is 0,543 W/m^{2}K.

The windows are wooden framed double glazed 4mm-16mm with argon 90%-4mm with Low-E coating, adequate airtightness, light transmission 61%, and total solar transmission (SHGC) 37%. The total thermal transmittance (U-Value) of the openings is 1,30 W/m^{2}K.

Table 7: Construction details of Museum C. Xenakis

	Construction details (layers)	(U-Value)
Exterior wall	• Cement-sand mortar coating • Limestone • MineralWool (MW) • Gypsum board • Pasty finish render	0,336
Flat roof	• Waterproof asphaltic membrane • Perlite concrete • Zoellner type slab (Reinforced concrete with brickwork) • Cement-sand mortar coating • Extruded polystyrene (XPS)	0,240
Ground floor	• Unreinforced concrete or lightly reinforced • Extruded polystyrene (XPS) • Cement sand mortar • Marble tiles	0,543
Openings(windows/doors)	• Wooden flamed, double glazed 4mm-16mm argon 90%-4mm with Low-E coating • Light transmission: 61% • Total solar transmission: 37%	1,300

**In the Appendix 1 of the deliverable, the calculations of U-Value of the construction elements are presented.*

3.4 Building's hours of operation

The operation hours of the building will be the same for all the thermal zones. Even though, there are different thermal zones such as office and exhibition room which operate following different time schedules according to the Greek regulation and its Technical Guidelines (TOTEE 20701-1/2017), the workday schedule for the Museum C. Xenakis will be the same. The building will operate at the same hours: 5 hours per day and 6 days per week. The Table 8 demonstrates the workday schedule for all the thermal zones within the Museum C. Xenakis.

Table 8: Operation hours for all conditioned thermal zones of Museum C. Xenakis

	Hours per day	Days per weak	Months per year
Museum C. Xenakis	5	6	12

3.5 Occupancy – Internal gain from occupants – Clothing and activity rate

According to estimations, the Museum will be able to host more than thirty visitors for two to five hours per day per week. Also, the Museum C. Xenakis will remain open for the public and will be able to host educational programs for schools or visitors for six days per week throughout the year. The occupancy schedule was created taking into account the presence factor and the frequency of the external visits according to those estimations for the thermal zones of Exhibition room and public spaces.

The office's thermal zone will be occupied by one employer who, amongst other responsibilities, will welcome the visitors to the facilities and guide them through the exhibits. The working profile of the occupant and the occupancy schedule of the office's thermal zone was created taking into consideration all the parameters of the workday schedule of the museum.

Also, the metabolic rate of the occupants, along with their clothing for both the heating and cooling period was taken into account during the input of the data to the simulation software. The Table 9 presents the number of the occupants per area according to the estimations for all the conditioned thermal zones of the model, the percentage of their presence in the zone, and their metabolic rate.

Table 9: Number of occupants per area, factor of presence and metabolic rate

Thermal Zone	Number of occupants per area (occupants/m2)	Presence Factor	Metabolic rate, (W/person)
Public spaces	0,43	0,25	90
Exhibition room	0,43	0,25	90
Office	0,03	0,25	80

3.6 Shading and lighting

The C. Xenakis Museum is part of a total group of eleven buildings in the military compound of "Papaloukas" in Serres, at a total site area around 124.000 m^2. The surroundings of the museum are covered with tall trees which provide shading throughout the year and their dense foliage allows only a small portion of the solar radiation to reach the exterior walls of the building (Fig. 15, 16).

The windows of the museum are equipped with external wooden shades (panes) as a means of protection from the sun which remain closed at the exhibition room to prevent any unwanted solar radiation from entering the interior of the space. Also, in order the exhibits to be further protected, shades (drapes) are placed in the interior side of the windows which are covered with an extra anti-glare coating with 99% protection from UV radiation, 0,5 shading coefficient, light reflection 32% and light transmission 22%.

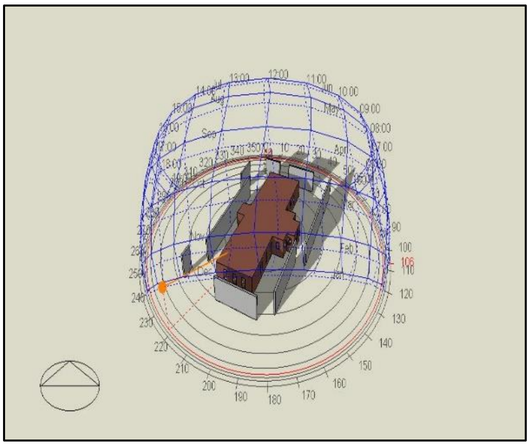

Figure 15: 1 January (Coldest day of the year according to the weather data)

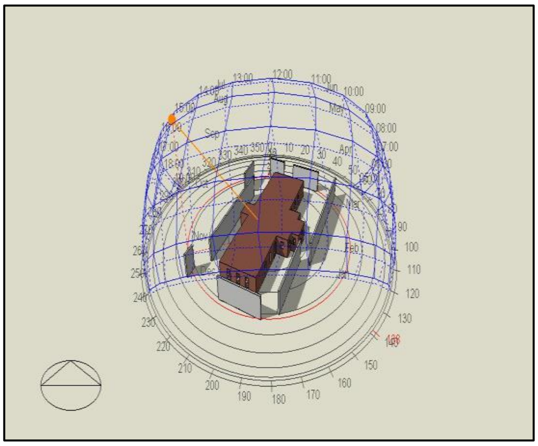

Figure 16 – 24 July (Hottest day of the year according to the weather data)

The Museum C. Xenakis has 146 anti-glare LED Gu10 lights 7,5 W, distributed throughout the spaces of the building (Exhibition room, offices, entrance, educational room and auxiliary spaces) separated in three types: surface mount, recessed and suspended. The total power density of the install capacity is measured at 1,1 kW and following the time schedule of the museum. In the Table 10, the lightning elements of the museum are presented.

Table 10: Lighting elements of Museum C. Xenakis

Lamp Type	No of Lamps	Hours of Operation	Installed Capacity (kW)
Surface mount anti-glare Led Gu10 7,5W	120	5 hours	0,90
Recessed anti-glare Led Gu10 7,5W	18	5 hours	0,14
Suspended anti-glare Led Gu10 7,5W	8	5 hours	0,06
Total Led Lights	146	5 hours	1,1

Table 11: Hours of operation of lighting and target illuminance of all the conditioned thermal zones

Thermal Zone	Hours per day	Days per weak	Months per year	Target illuminance, (lux)
Public spaces	5	6	12	100
Exhibition room	5	6	12	200
Office	5	6	12	500

3.7 Temperature setpoints and operation schedules

In order to provide thermal comfort for the occupants in each thermal zone, is important for setpoint temperatures to be defined. The setpoint temperatures for heating and cooling periods were determined according to the Greek Technical Guidelines (TOTEE 20701-1/2017). The Table 12 demonstrates the input data for setpoint temperatures.

Table 12: Temperature setpoints and Operation schedules of all conditioned thermal zones

Thermal Zone	Heating period, (°C)	Cooling period, (°C)
Public spaces	18	26
Exhibition room	20	23
Office	20	26

The heating and cooling setpoint temperatures are achieved with the installed Ground Source Heat Pump. The heating system of the Museum C. Xenakis is operating from the 15st of October until 30th of April, while the cooling system is operating from the 1th of June till 31th of August.

3.8 HVAC Systems

At the renovated Museum C. Xenakis, a Ground Source Heat Pump (GSHP) was installed to cover the heating and cooling needs. The system consists of one main Hot Water Loop and one main Chiller Water Loop which are connected to the heating and cooling collector in the storage room respectively, and through a two pipe network of supply and return, it is distributed in the terminal units (FCUs) at each space of the museum.

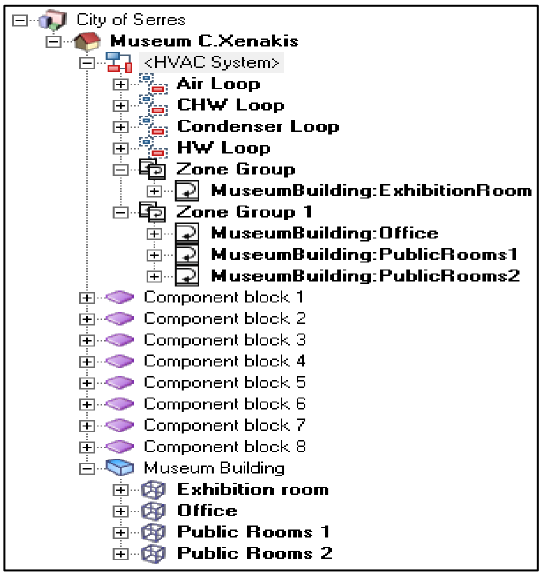

Figure 17: HVAC systems and zones of Museum C. Xenakis

The Ground Source Heat Pump (GSHP) was installed at the north east side of the building in order to take advantage of the unused area of the site. The system is a slinky type, horizontal closed loop, which was buried at 1,2 m in the ground, inside of 35 trenches of around 8.750 m length total. According to data from the Hellenic National Meteorological Service the yearly mean temperature for the ground at depth 1,0 m was 16,4 ^{o}C. Propylene glycol at 20% is used for antifreeze protection. The whole pipe network is adequately insulated and the temperature operating range of the system is -6 ^{o}C for heating and +49 ^{o}C for cooling. The system is stored in the equipment room inside the museum along with circulator pumps, the buffer tank, the expansion tank and the heating and cooling collector.
Two heat recovery units with cross-flow heat exchanger were installed in the building to cover the needs for ventilation while saving energy through heat recovery. The air loop of the system consists of a fresh air supply ductwork which is connected to the Fan Coil Units (FCUs) and a return ductwork of exhausted air.
The Figure 17 illustrates the connections and loops of all the HVAC systems of Museum C. Xenakis and the figure 18 illustrates the complete HVAC systems’ schematic.

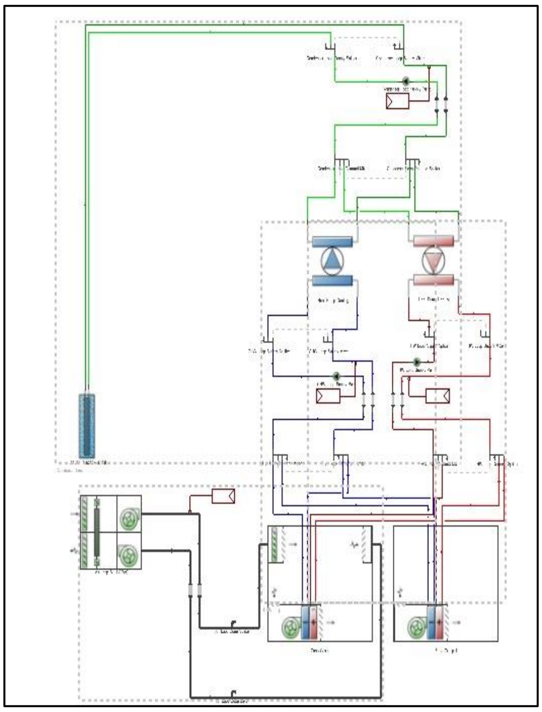

Figure 18: Schematic of the complete HVAC system of Museum C. Xenakis

Heating Systems

The Ground Source Heat Pump has heating capacity 58 kWth (58.220 W) with high COP at 3.8 and is able to meet the needs of the spaces of the Museum C. Xenakis for heating, providing

hot water at 50 ^{o}C through a two pipe hot water loop (supply and return), which is connected to the terminal units of each thermal zone (FCUs).
The heating systems are operating from the 15st of October until the 30th of April, and the setpoint temperature of each thermal zone were defined (Offices: 26 ^{o}C, Exhibition room: 23 ^{o}C, Public Spaces (Entrance, auxiliary rooms and education room): 26 ^{o}C). The Figure 18 presents the source of the heating system (GSHP), the two pipe hot water loop with supply and demand, and the thermal zones along with their terminal units (FCUs).

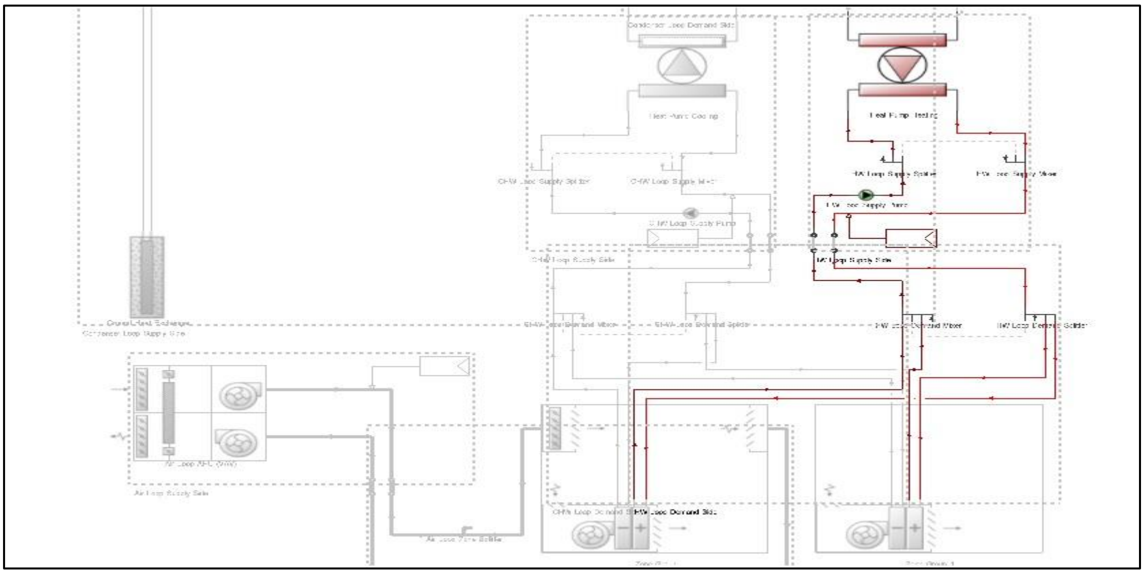

Figure 18: Schematic of the Heating systems – Hot water loops of Museum C. Xenakis

Cooling Systems
The Ground Source Heat Pump has cooling capacity 52 kWco (52.608 W) with high EER at 4.8 and is able to meet the needs of the spaces of the Museum C. Xenakis for cooling, providing cold water at 7 ^{o}C through a two pipe chilled water loop (supply and return), which is connected to the terminal units of each thermal zone.
The cooling system is operating at the period of 1st of June till 31th of August, and the setpoint temperatures of each thermal zone were defined (Offices: 20 ^{o}C, Exhibition room: 20 ^{o}C, Public Spaces (entrance, auxiliary rooms and education room): 18 ^{o}C). The Figure 19 illustrates the source of the cooling system (GSHP), the two pipe chilled water loop with supply and demand, and the pipe connection with the cooling coils inside the Fan Coils Units (FCUs) and the thermal zones along with the terminal units.

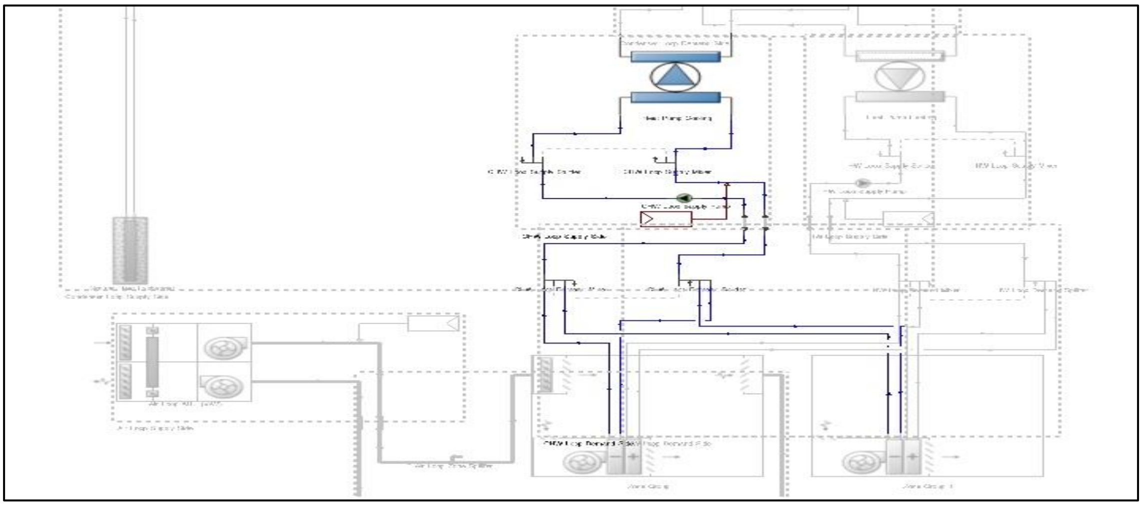

Figure 19: Schematic of the Cooling system – Chilled water loop of Museum C. Xenakis

Air handling units (AHUs) – Ventilation

The mechanical ventilation equipment of the C. Xenakis Museum consists of two heat recovery units with cross-flow heat exchanger with motor power 0,676 kW, each proving 2.000 m^3/h of fresh air to the space. They are operating without recirculation, covering the ventilation requirements of the exhibition area of the museum, following the working profile of the occupants of the thermal zone.

The Air Loop of the heat recovery unit consists of the supply and return ductwork. The intake fresh air is supplied through an insulated ductwork to the roof FCUs at the exhibition room, while the exhausted air is extracted out of the room through the return ductwork. The two air flows with different temperature meet at the heat exchanger transferring heat to each other, resulting to saving energy.

The figures illustrate the mechanical ventilation equipment which includes the air distribution unit, the supply fan, the ductwork, the zone extract fan and the air loop extract fan.

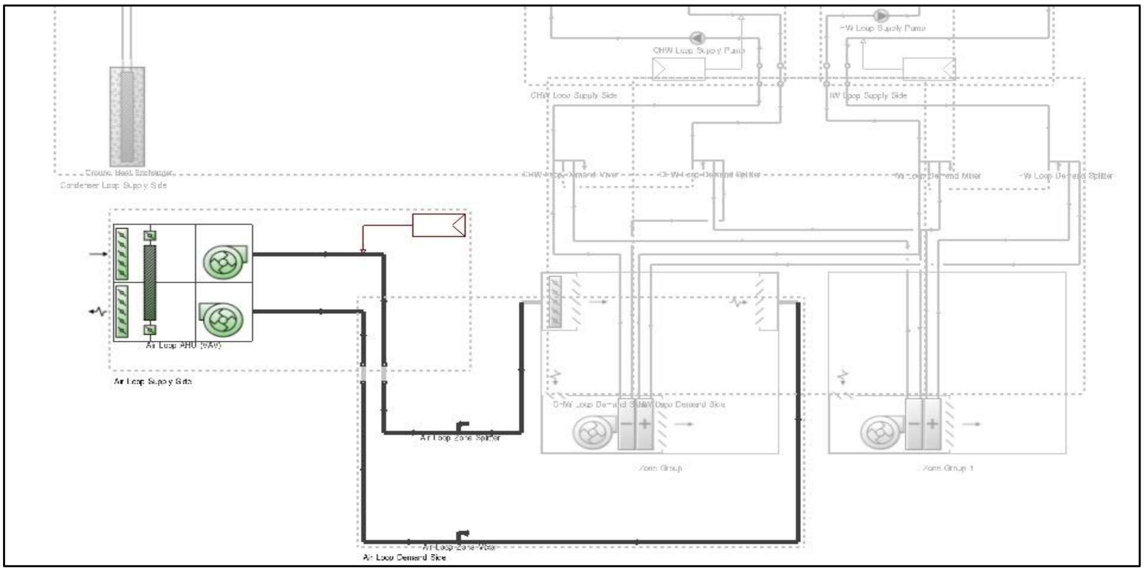

Figure 20: Schematic of mechanical ventilation of Museum C. Xenakis

5. Energy performance simulation

After the gathering of all the available information and data, an accurate building model was designed into the energy simulation software DesingBuilder. The site of the building contains the location's climate characteristics, illustrating the objects in the surroundings. The model was formed using the imported floor plan of the building, following the exact real building's geometry and features, taking into consideration the complexity of its zones and systems. The museum consists of three different thermal zones, including the public rooms, the exhibition room and the office. Material properties about all the layers of the construction elements of the building were input into the model, based on the available data.

After the construction of the building model, occupancy schedules, activity profiles, lighting and equipment specifications were imported into the software. For the museums' occupancy and working patterns, a rather consistent estimation was conducted throughout the week.

The building is heated and cooled with a high efficiency closed loop, horizontal, slinky type, ground source heat pump, according to the defined heating and cooling thermostat controls of each thermal zone. Furthermore, the building is mechanically ventilated with a heat recovery unit with cross flow heat exchanger, assisting in energy saving.

After the simulation, the energy performance of the building was conducted, and results about its energy consumption were extracted.

5.1 Results of simulation of Museum C. Xenakis

In the following Tables 14, 15 the monthly and yearly results about the net and primary energy consumption for the building are presented. Furthermore, there are detailed diagrams and Tables which illustrate the energy consumption per conditioned area and the energy

consumption separated per category (heating, cooling, etc.), showing their percentages out of the total energy consumption.
According to the Greek regulation (KENAK) and its Technical Guidelines, the conversion from net to primary energy is 2,9 for electricity.

The total net energy consumption of electricity of the museum which corresponds to heating, cooling, ventilation, lighting, and equipment, is presented in the Table 13 and is 11.448,25 kWh while the total primary energy is 33.199,93 kWh. The total net energy consumption per area is 17,56 kWh/m^2 and the primary energy consumption is 50,93 kWh/m^2.
The Diagram 7 presents the percentages of each consumption per category. The heating consumption is 35% of the total source consumption, the cooling electricity is 22%, the fans is 22%, the interior lighting is 9%, and the interior equipment is 12%.
The Diagram 8 presents the total primary energy consumption of each category per area. The heating consumption is 18,13 kWh/m^2, the cooling is kWh/m^2, the consumption of fans is 11,06 kWh/m^2, the consumption of lighting is 4,48 kWh/m^2 and the consumption of equipment is 6,00 kWh/m^2.

Table 13: Total net and primary energy consumption per category of Museum C. Xenakis

TOTAL ENERGY CONSUMPTION				
	NET Energy Consumption		**PRIMARY** Energy Consumption	
	kWh	kWh/m^2	kWh	kWh/m^2
Total electricity	11.448,25	17,56	33.199,93	50,93
TOTAL ENERGY CONSUMPTION PER CATEGORY				
	NET Energy Consumption		**PRIMARY** Energy Consumption	
	kWh	kWh/m^2	kWh	kWh/m^2
Heating	4.074,60	6,25	11.816,34	18,13
Cooling	2.531,03	3,88	7.339,99	11,26
Fans	2.486,16	3,81	7.209,86	11,06
Interior Lighting	1.008,11	1,55	2.923,52	4,48
Interior Equipment	1.348,35	2,07	3.910,22	6,00
TOTAL	11.448,25	17,56	33.199,93	50,93

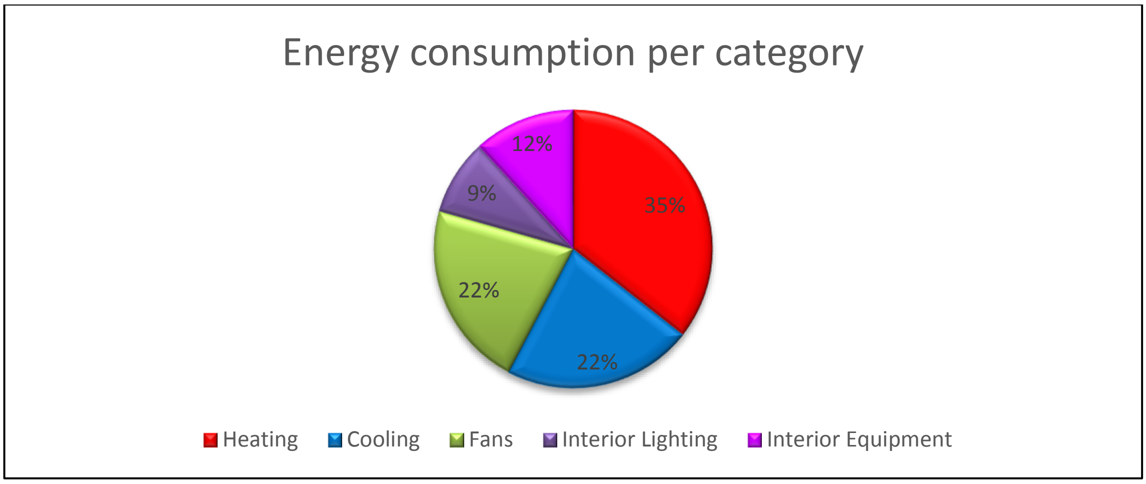

Diagram 7: Percentages of primary energy per category of Museum C. Xenakis

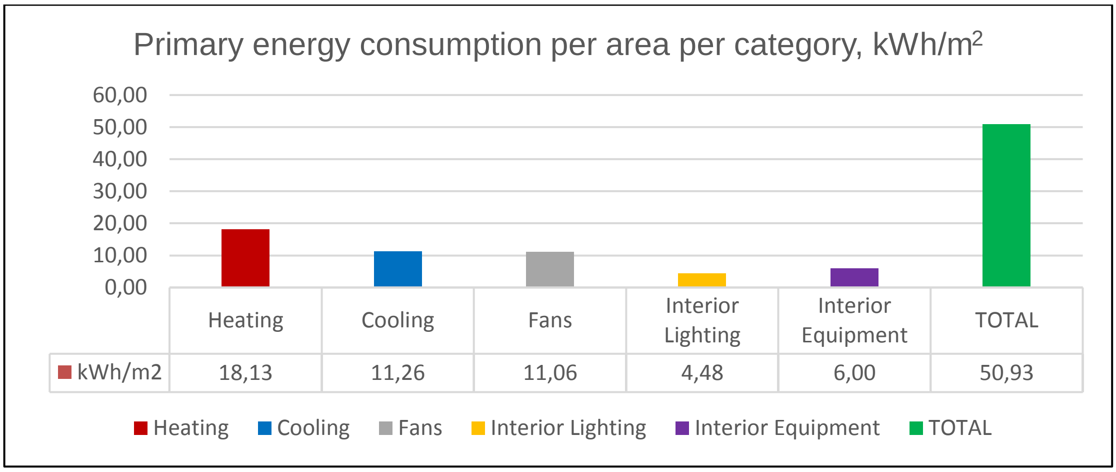

Diagram 8: Primary energy consumption per area per category of Museum C. Xenakis

The monthly net and primary energy consumption in kWh and kWh/m^2 is presented in the Table 14.

The highest energy consumption of the building is observed at August with 1.421,61 kWh net energy or 4.122,67 kWh primary energy, while the lowest energy consumption is observed at October with 582,30 kWh net energy or 1.688,67 kWh primary energy.

Table 14: Monthly net and primary energy consumption of Museum C. Xenakis

TOTAL MONTHLY ENERGY CONSUMPTION				
	NET Energy Consumption		Primary Energy Consumption	
	kWh	kWh/m^2	kWh	kWh/m^2
January	1.293,03	1,98	3.749,79	5,75

February	1.068,91	1,64	3.099,84	4,76
March	895,47	1,37	2.596,86	3,98
April	616,56	0,95	1.788,02	2,74
May	630,03	0,97	1.827,09	2,80
June	1.085,07	1,66	3.146,70	4,83
July	1.313,83	2,02	3.810,11	5,84
August	1.421,61	2,18	4.122,67	6,32
September	629,82	0,97	1.826,48	2,80
October	582,30	0,89	1.688,67	2,59
November	807,11	1,24	2.340,62	3,59
December	1.104,51	1,69	3.203,08	4,91
Annual Sum	11.448,25	17,56	33.199,93	50,93
Minimum of Months	582,30	0,89	1.688,67	2,59
Maximum of Months	1.421,61	2,18	4.122,67	6,32

The distribution of primary energy consumption in kWh/m^2 in all the different categories of the building is presented in Table 15.
The highest monthly primary energy consumption of the building for heating is observed at January with 4,29 kWh/m^2 and for cooling at August with 4,35 kWh/m^2. The highest total monthly primary energy consumption of the building is observed at August with 6,32 kWh/m^2, while the lowest primary energy consumption is observed at October with 2,59 kWh/m^2.

Table 15: Monthly primary energy consumption per category of Museum C. Xenakis in kWh/m^2

TOTAL MONTHLY ENERGY CONSUMPTION PER AREA PER CATEGORY						
kWh/m^2						
	Heating	Cooling	Fans	Interior Lighting	Interior Equipment	Total monthly Electricity
January	4,29	0,00	0,59	0,37	0,50	5,75
February	3,40	0,00	0,55	0,34	0,46	4,76
March	2,46	0,00	0,61	0,39	0,52	3,98

April	1,34	0,00	0,57	0,36	0,48	2,74
May	0,00	0,00	1,90	0,39	0,52	2,80
June	0,00	2,95	1,01	0,37	0,50	4,83
July	0,00	3,97	1,01	0,37	0,50	5,84
August	0,00	4,35	1,07	0,39	0,52	6,32
September	0,00	0,00	1,93	0,37	0,50	2,80
October	1,06	0,00	0,66	0,37	0,50	2,59
November	2,13	0,00	0,59	0,37	0,50	3,59
December	3,45	0,00	0,59	0,37	0,50	4,91
Annual Sum	18,13	11,26	11,06	4,48	6,00	50,93

The total monthly primary energy consumption in kWh/m^2 is presented in the Diagram 9 while the distribution of primary energy consumption in kWh/m^2 in all the different categories of the building is presented in Diagram 10.

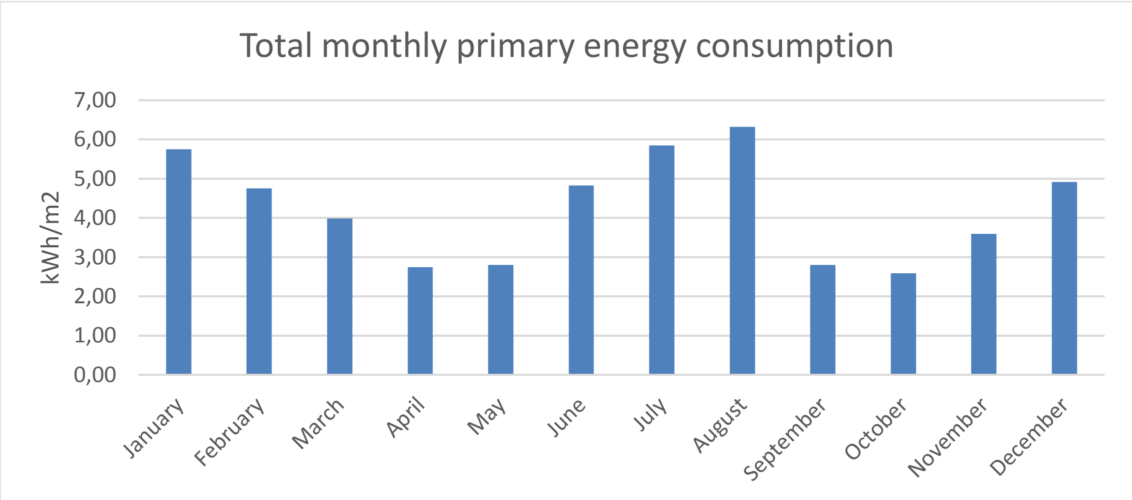

Diagram 9: Total monthly primary energy consumption of Museum C. Xenakis

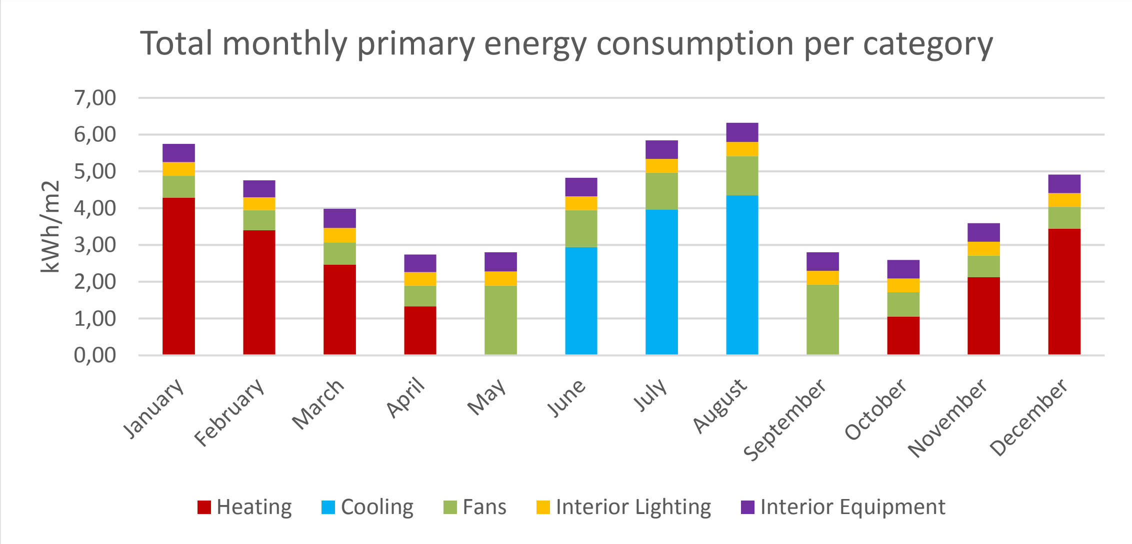

Diagram 10: Total monthly primary energy consumption per category of Museum C. Xenakis

6. Conclusion

The aim of this chapter, is to calculate the energy consumption of a renovated building museum and through an energy simulation software, to evaluate its energy performance towards a "nearly" zero energy consumption building (NZEB - consumption of primary energy <60 kWh / m^2).

The case study building of this deliverable was an old building which is considered "traditional" due to its unique specifications, with restrictions by the Greek legislation for any intervention to its facades. It was chosen for renovation, in order to host the contemporary art collection of "Constantin Xenakis", and is located at an area the city of Serres, which is called "Area of cultural activities and recreation parks", at the former military compound of "Papaloukas" renamed now into "Thematic Park Konstantinos Karamanlis".

The Museum C. Xenakis constructed during the Ottoman era, with eclecticism as architectural approach, is a single floor building with a slab roof, upon a ground surface surrounded by trees, and its two elongated sides are orientated in 25^0 from true North. Its total surface is 651,91 m^2 and its total height along with ground and roof slab is 4,85m.

The building initially had no insulation in any of it surfaces, with decorative elements at its corners and the perimeter of the windows and doors. The exterior wall was limestone with thickness 60 cm, the roof was a Zoellner type slab, and the ground floor was unreinforced concrete with cement sand mortar. The openings of the building were wooden framed, single glass with wooden panes.

In order to reduce the thermal losses and to improve the energy performance of the building, insulation is added in all of its surfaces (8 cm insulation layer of Mineral Wool placed at the internal side of the exterior walls, 10 cm insulation layer of Extruded Polystyrene with

waterproof membrane at the exterior side of the roof, 5 cm insulation layer of Extruded Polystyrene) and the old openings are replaced with new with low thermal transmittance U-Value (double glazed, with low-e coating at the glass and argon). The openings and panes are constructed from wood exactly as the former ones. Furthermore, shades (drapes) are placed in the interior side of the windows which are covered with an extra anti-glare coating to provide additional protection from the sun.
Also, it was important to install a Source of renewable Energy (RES). Due to the restrictions for traditional buildings, along with the availability of sufficient land at the surrounding area, the option of Geothermal Energy was preferred**.** A high efficient slinky type, horizontal closed loop, geothermal heat pump system was chosen, available for heating and cooling. The system is buried at 1,2 m in the ground, inside of 35 trenches, amounting of 8.750 m length total.
The heating capacity of the geothermal heat pump is 58 kWth with COP at 3.8, providing hot water at 50 ^{o}C through a two pipe hot water loop (supply and return) while the cooling capacity is 52 kWco with EER at 4.8, providing cold water at 7 ^{o}C through a two pipe chilled water loop (supply and return). The terminal units of the system are Fan Coil Units (FCUs) located at the roof at the exhibition room and at the floor at all the other places of the museum. The mechanical ventilation system consists of a heat recovery unti with cross flow heat exchanger for energy saving and the air is distributed through a supply and extract ductwork.

The building was simulated in the energy performance simulation tool DesignBuilder which incorporates the EnergyPlus engine and was separated into thermal zones, spaces with the same use, electromechanical equipment and operation schedules. The Museum C. Xenakis was separated into three thermal zones according to their occupancy profiles, operation characteristics, heating and cooling demands. The thermal zones are: Thermal Zone 1: Entrance and educational room, Thermal Zone 2: Exhibition room, Thermal Zone 3: Office and all the available data was input into the energy performance simulation software DesignBuilder to calculate the energy consumption of the building.
After the energy improvement interventions and the installation of the geothermal heat pump, including the energy consumption of the interior lighting and equipment the total net energy consumption of electricity of the museum which corresponds to all the categories (heating, cooling, ventilation, lighting, and equipment), is 11.448,25 kWh while the total primary energy is 33.199,93 kWh. The total net energy consumption per area is 17,56 kWh/m^2 and the primary energy consumption is 50,93 kWh/m^2.
Through the suggested interventions and the energy improvement installations, a low energy consumption building was designed, able to achieve the goal of a “nearly” zero energy consumption building (consumption of primary energy <60 kWh / m^2).

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APPENDIX 1

U Factor Calculation for Exterior Wall					
Number of layers	**Construction layers (outermost to innermost)**	**Density, P**	**Thickness, d**	**Conductivity, λ**	**Thermal Resistance, (R-Value)**
		kg/m^3	**m**	**W/(mK)**	**$(m^2K)/W$**
1	Cement-sand mortar coating	1800	0,050	0,870	0,057
2	Limestone	2200	0,600	1,700	0,353
3	MineralWool (MW)	80	0,080	0,035	2,286
4	Gypsum board	700	0,020	0,210	0,095
5	Pasty finish render	1820	0,010	0,700	0,014
Total thickness of the construction element (Σd), m			0,760	RΛ	2,806
Internal Surface Resistance, $(m^2K)/W$				Ri	0,130
External Surface Resistance, $(m^2K)/W$				Ra	0,040
Total Thermal Resistance, $(m^2K)/W$				Rtotal	2,976
Thermal Transmittance (U-Value), $W/(m^2K)$				**U**	0,336

U Factor Calculation for Flat Roof					
Number of layers	**Construction layers (outermost to innermost)**	**Density, P**	**Thickness, d**	**Conductivity, λ**	**Thermal Resistance, (R-Value)**
		kg/m^3	**m**	**W/(mK)**	**$(m^2K)/W$**
1	Waterproof asphaltic membrane	1100	0,004	0,230	0,017
2	Perlite concrete	450	0,080	0,140	0,571
3	Zoellner type slab (Reinforced concrete with brickwork)	2240	0,300	0,658	0,456
4	Cement-sand mortar coating	1800	0,030	0,870	0,034
5	Extruded polystyrene (XPS)	40	0,100	0,034	2,941
Total thickness of the construction element (Σd), m			0,514	RΛ	4,020
Internal Surface Resistance, $(m^2K)/W$				Ri	0,10
External Surface Resistance, $(m^2K)/W$				Ra	0,04
Total Thermal Resistance, $(m^2K)/W$				Rtotal	4,160
Thermal Transmittance (U-Value), $W/(m^2K)$				**U**	0,240

U Factor Calculation for Ground Floor					
Number of layers	**Construction layers (outermost to innermost)**	**Density, P**	**Thickness, d**	**Conductivity, λ**	**Thermal Resistance, (R-Value)**
		kg/m^3	**m**	**W/(mK)**	**(m^{2}K)/W**
1	Unreinforced concrete or lightly reinforced	2200	0,150	1,650	0,091
2	Extruded polystyrene (XPS)	40	0,050	0,033	1,515
3	Cement sand mortar	2000	0,080	1,400	0,057
4	Marble tiles	2800	0,030	3,500	0,009
Total thickness of the construction element (Σd), m			0,310	RΛ	1,672
Internal Surface Resistance, (m^{2}K)/W				Ri	0,17
External Surface Resistance, (m^{2}K)/W				Ra	0,00
Total Thermal Resistance, (m^{2}K)/W				Rtotal	1,842
Thermal Transmittance (U-Value), W/(m^{2}K)				**U**	0,543