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Ciclo XXXII

# ENERGY EFFICIENCY IN HISTORICAL BUILDINGS THROUGH ENERGY AUDIT SUPPORTED BY DYNAMIC ANALYSIS. THE CASE STUDY OF THE DUCAL PALACE OF MODENA.


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**Esame Finale Anno 2020**

*"La mia vita rimarrà a te legata"*

# ABSTRACT

This PhD thesis focuses on energy efficiency in historical-constrained buildings. The analysis covers energy performance of building envelope and HVAC system.

The main aim is to develop a methodology for defining energy retrofitting solutions in this particular type of buildings.

In Europe this issue is particularly relevant, because of the presence of numerous historical buildings: it is estimated that about a quarter of existing buildings were built before the middle of the last century.

The interest in these buildings derives from the inapplicability of many of the traditional energy retrofitting strategies and from the need for a different theoretical and practical approach.

The uses of these buildings are manifold but they have in common some constructive characteristics that distinguish them from all other buildings. For instance, these buildings are characterized by very massive envelope, high thermal inertia, large heated volumes, discontinuous use and inefficient heating system. These buildings are generally characterized by very high energy consumption and wastage.

This thesis project focuses on the development of innovative and cost-effective energy retrofitting solutions for historical buildings, which are able to offer significant improvements in energy performance while ensuring internal comfort requirements and non-invasive and reversible solutions.

The methodology, applied to a relevant case study, demonstrates the effectiveness of technologies, systems and tools developed and selected and the potential for replicability of the proposed solutions.

The selected case study is the Ducal Palace of Modena, a magnificent historic-constrained building which identifies the Modena city all over the world. In past centuries, the Palace was the home of the "Estensi Duke"; today it hosts the prestigious Military Academy, a training school for officers of the Italian National Army.

The objective of the thesis is achieved through the following main activities:

- Analysis of the state of the art of energy efficiency procedures for historic buildings and the relevant EU legislative framework;

- Development of a comprehensive methodology for the definition of energy retrofitting solutions for historic-constrained buildings, applied to the case study of the Ducal Palace of Modena. The methodology is based on an in-depth analysis of the building, in particular the envelope and its HVAC system. A particular attention is also paid to properties of materials, current use of thermal systems and energy consumption over the years. The study of the current building energy performance and the simulation of the various proposed energy retrofitting measures are performed with a dynamic simulation model in order to take the high thermal inertia of the building into account.

- Parametric analysis and normalization techniques to develop decision-making guidelines for the energy retrofitting of historic buildings. The guidelines should serve as a common set of practices applicable to this particular type of buildings all around Europe.

*Keywords*: Energy, Retrofitting solutions, Heritage, Dynamic analysis, Audit

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# NOMENCLATURE

| | |
|---|---|
| A | Area |
| cp | Specific heat capacity |
| E | Energy |
| l | Distance |
| H | Heat transfer coefficient |
| Q | Power |
| t | Time |
| T | Temperature |
| U | Thermal transmittance |
| $\alpha$ | Solar absorbance |
| $\theta$ | Angle of incident of solar radiation |
| $\lambda$ | Thermal conductivity |
| op | operative temperature |
| sol | related to solar radiation |
| V | volume |

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# 1.INTRODUCTION

Our world is changing faster than anyone predicted. Already, freshwater supplies are shrinking, agricultural yields are dropping, our forests are burning, and rising oceans are more acidic-all, in part, due to a warming climate. As our natural world changes around us, so does our way of life. Coastal home values drop as insurance premiums rise; more pollen and dust in the air aggravates asthma and allergies in kids and adults alike.

All us we must believe we can fight this consequential threat and build a safer, healthier and more resilient future for people and nature. We must rethink the way we produce and consume energy, food, and water; protect the world's forests; and help people prepare for a changing world.

Achieving this future will require action by everyone, and we are already well on our way. People are using their collective voices to demand change. Businesses are making investments in clean energy, already creating local jobs and stronger economies. Communities are redesigning their roads, buildings, airports, and railroads to make them climate resilient.

Nowadays buildings account for about 40% of the total energy consumption of the European Union (EU) and the sector is continuously expanding [1.1]. Therefore, reduction of energy consumption and the use of energy from renewable sources in the building sector have been identified as one of the priorities of the Union's strategy to reduce its energy dependency and greenhouse gas emissions and advance towards its goal of cutting overall energy consumption by 20% by 2020.

The EU is determined in its commitment to developing an energy system sustainable, competitive, and safe and decarbonized. The energy union and the framework energy and climate policy for 2030 set ambitious EU commitments for reduce even more greenhouse gas emissions by at least an additional 40% by 2030 compared to 1990, to increase the share of energy consumption from sources renewable and achieve energy savings in accordance with the ambitions a level of the EU, improving energy security, competitiveness and sustainability of the Union. Directive 2012/27 / EU of t1he European Parliament and of Council amended by Directive (EU) 2018/2002 of the European Parliament and of Council set a main energy efficiency target of at least 32.5% a Union level for 2030. Directive (EU) 2018/2001 of the European Parliament e of the Council establishes a binding energy target from sources at EU level by at least 32% by 2030. [1.2]

The 2015 agreement on climate change in Paris, resulting from the 21st Conference of the parties to the United Nations Framework Convention on Climate Change (COP 21), encourages the Union's efforts to de-carbonise its real estate components. Given the fact, that almost 50% of the final energy of the UE is used for heating and cooling, of which 80% in buildings, the achievement of the energy and climate objectives of the Union is linked to the efforts of the latter to renew its building stock, giving priority to efficiency energy, using the principle of "energy efficiency in the first place", as well evaluating the use of renewable energy.

The European Commission (EC) has highlighted the importance of energy efficiency and the role of building sector for the achievement of the energy and climate objectives of the Union and the transition to clean energy in the communication on energy efficiency and its contribution to energy security and the 2030 framework on climate and energy in the communication on the framework strategy for a Union resilient energy, accompanied by a forward-looking policy on the subject of climate changes and in the communication on European strategic vision for a long time term for a prosperous, modern, competitive and climate-neutral economy.

The UE communication emphasizes that energy efficiency measures should play a key role in achieving an economy climate-neutral by 2050 and reduce energy consumption by at least half compared to 2005.

Directive 2010/31 / EU of the European Parliament and of the Council on performance energy in buildings (Energy Performance of Buildings Directive) is the main legislation, together with directive 2009/125 / EC and the regulation (EU) 2017/13699, concerning the energy efficiency of buildings in the context of the objectives of energy efficiency for 2030. The Energy Performance of Buildings Directive has two complementary objectives: accelerate the renovation of existing buildings by 2050 and promote the modernization of all buildings by technology intelligent and a clearer connection with clean mobility.

The performance of technical building systems has a significant impact on overall energy performance of buildings and should therefore be optimized. It is important to ensure that the improvement of the energy performance of buildings is based on an integrated approach, which takes into account both related measures the building envelope and the technical building systems.

## 1.1. Framework of the research

Around a quarter of the existing building stock in Europe was built prior to the middle of the last century [1.3]. Italy in particular is characterized by a widespread and diffused presence of historic buildings, as it includes about 40% of world artistic heritage, according to UNESCO estimates [1.4]. Many such buildings, often valued for their cultural, architectural and historical significance not only reflect the unique character and identity of European cities but include essential infrastructure for housing, public buildings etc.

A significant number of these buildings continue to use conventional inefficient fossil-fuel based energy systems typically associated with high energy costs and CO2 emissions. Despite the relatively high energy consumption, indoor comfort is often scarce. The need to save costs increasingly leads to tighter rationing or shutdown of heating or cooling systems, further worsening conditions for conservation of the buildings, for artworks or collections and for comfort of occupants.

The wide variety of existing building, age by age, does not allow having a unique approach to the problem as it is often possible for new constructions. This is mainly the case of historic buildings, which, while belonging to the existing building category, have to be treated in a very specific way, usually on a case by case basis. Many recently developed energy retrofitting solutions are not compatible with historic buildings, especially for listed or protected buildings. In such cases, "non-invasive" but often less performing solutions have to be chosen, sometimes associated with a higher investment cost than the Best Available Technologies [1.5].

The European Union has enacted several directives dealing with energy efficiency in buildings. Relevant examples are Directive 2002/91/EC (EPBD) [1.6] and Directive 2010/31/EU (EPBD recasting), which set-up the basis for several actions to reduce buildings energy consumption. Those directives, while dealing with existing buildings, do not take into account the Architectural Heritage in a specific uniform way adopting the derogation regime [1.7]: exceptions are available at the national level to exclude from their application buildings listed in the Architectural Heritage as historic buildings.

Technical standards or specifications to clarify the heritage buildings position on their potential sustainable development have not yet been published by the European Commission. Therefore, the technical problems related to the energy retrofitting feasibility within an historic context were almost neglected or generally derogated.

In Italy EPBD and EPBD recast led to the Legislative decree 192/05 and subsequent amendments and Legislative Decree 63/13, which is the first legal instrument prescribing energy performance requirements for historic buildings. For historic buildings that fall within the scope of Legislative Decree 63/13, the EP (i.e. primary energy consumption referred to the useful area of gross volume) should be calculated and the building energy class must be evaluated as well, in order to fill out the energy performance certificate.

It is also difficult to fully assess and model reliably the energy performance of many different types of historic buildings across Europe or to assess the effect of energy measures or more sustainable solutions. Different studies can be found in literature on procedures to improve energy efficiency in buildings [1.8, 9]. In most of these studies the calculation of the building energy performance is performed according to the international standard ISO 13790 [1.10]. However, a lack of dynamic analysis of the energy performance of historic buildings is found in literature.

While this issue seems to only marginally interest discontinuously occupied historical buildings, such as museums, it is particularly significant for historical buildings that are used for residential, working and commercial purposes, which actually represent the greatest part of the historic buildings stock [1.5].

A significant number of historical and monumental buildings are poorly insulated and use conventional inefficient fossil-fuel-based energy systems, typically associated with high energy costs and CO2 emissions. Despite the relatively high energy needs, indoor thermal comfort is often scarce. The most common reasons for discomfort are related with insufficient local thermal control, poor insulation, large vertical temperature gradients and inadequate mean radiant and operative temperatures perceived by the occupants.

Energy efficiency in these buildings is a complex issue. To properly design and operate such buildings, a number of parameters which characterize most of historic institutional buildings, such as large thermal inertia and intermittent and variable usage, should be taken into account [1.12].

Many energy retrofitting solutions are not compatible with historic buildings, especially for listed or protected ones. In such cases, “non-invasive” but often less performing solutions have to be chosen, sometimes associated with a higher investment cost than Best Available Technologies.

Another common problem related with historic buildings is the difficulty to fully assess and reliably model the energy performance of many different building types across Europe and to assess the effect of energy measures or more sustainable solutions. Different studies can be found in the literature on procedures to assess and model the energy performance of historic buildings [1.8,9-14]. In most cases a need for dynamic simulation of the building energy performance is identified, which allows to properly take into account both the large thermal inertia of such buildings and the effects of intermittent usage and activation of HVAC systems.

In order to enhance thermal comfort and energy savings without undermining cultural architectural and historical significance, only few technical solutions can be applied.

## 1.2. Motivation, objectives and methodology

In a widely changing context with which heritage and heritage practice is faced, this research project will help cultural heritage to meet societal challenges and contribute to the development of society.

Cultural heritage should not be seen as a fixed concept or a given amount of canonized material or immaterial culture inherited from the past, but as a dynamic process of continuous production, selection, transmission, reception and appropriation of culture [1.11].

Cultural heritage should be very well connected with society. This is especially the case of many European historic buildings, often valued for their cultural, architectural and historical significance, as they do not only reflect the unique character which identify the European cities, but also include essential infrastructures for housing or public services.

While this issue seems to only marginally interest discontinuously occupied historical buildings, it is particularly significant for historical buildings that are used for residential, working and educational purposes, which actually represent the greatest part of the historic buildings stock. Most of historic buildings are currently institutional buildings [1.12], like schools, universities, town halls and administrative services.

It is often forgotten that these buildings can also be seen as storyteller: they can tell something about the past and at the same time inspire the future.

Cultural heritage should also face fundamental societal challenges, like the necessity for the economy to adapt and become more climate change resilient, resource efficient and at the same time remain competitive. To this respect, it has to be noted that a significant number of historical and monumental buildings are currently poorly insulated and use conventional inefficient fossil-fuel-based energy systems, typically associated with high energy consumption costs and CO2 emissions. In addition, despite the relatively high energy needs, the levels of indoor thermal comfort are often poor.

Energy efficiency in these buildings is a complex issue. Many energy retrofitting solutions are not compatible with historic buildings, especially for listed or protected ones. The main current barriers to the implementation of such measures are identified in technical uncertainty, users lack of involvement and financial risk.

At the same time it should be considered that technology is continuously redefined and reshaped by its users [1.3]. There is a need to carry out more research into ethical and societal aspects related to major changes in existing technological systems [1.13].

The aim of this project is therefore to overcome current barriers by providing a comprehensive tool to implement non-invasive innovative solutions for energy retrofitting of historic buildings.

There is a common need to address energy efficiency of historic buildings by holistic and deep renovation schemes that integrate innovative technologies, adapted standards and methodologies which consider district dimension and stakeholder involvement.

The project proposal is focusing on the development of innovative and cost-effective building renovation solutions for historic buildings that can deliver significant improvements in energy performance while ensuring indoor comfort requirements, non-invasive, reversible solutions.

Tools for planning and implementing the renovation of historic buildings are proposed, including non-invasive and non-destructive methods of surveying and diagnosis together with appropriate standards and information management for building maintenance, monitoring and control technologies.

The project demonstrates the effectiveness of technologies, methodologies, systems or tools developed and it proves the replication potential of the proposed solutions with the use of a case study.

The aforementioned reasons stablish the framework which motivates the present research to develop the retrofitting solutions of the historic buildings. Even if in the last decade an increased interest in developing of the themes of energy and heritage is observed, this type of methodologies should be further studied. This thesis is intended to fill this gap and further develop the methodology of the retrofitting of this type of buildings.

The case study is an emblematic historic building, Ducal Palace, in the Italian city of Modena, which belongs to the category of heritage houses.

The objective of the thesis is achieved through the following main activities:

- Analysis of the state of the art of energy efficiency procedures for historic buildings and the relevant EU legislative framework;

- Development of a comprehensive methodology for the definition of energy retrofitting solutions for historic-constrained buildings, applied to the case study of the Ducal Palace of Modena. The methodology is based on an in-depth analysis of the building, in particular the envelope and its HVAC system. A particular attention is also paid to properties of materials, current use of thermal systems and energy consumption over the years. The study of the current building energy performance and the simulation of the various proposed energy retrofitting measures are performed with a dynamic simulation model in order to take the high thermal inertia of the building into account.

- Parametric analysis and normalization techniques to develop decision-making guidelines for the energy retrofitting of historic buildings. The guidelines should serve as a common set of practices applicable to this particular type of buildings all around Europe.

# 2. LITERATURE SURVEY

*"Historical evidence indicates that when man first considered settlements and the order pertaining the rein, he showed concern for the conservation of this order and of monuments"* [2.1].

Historical and monumental buildings currently represent a large part of the historic buildings stock in Europe and Italy. These buildings mark the cultural and social foundations of the countries and therefore they need to be protected. The majority of these buildings have poor energy efficiency performance and some of them run in a bad state. Actions in terms of energy improvement do not mean just a lower consumption of fossil fuels and hence an environmental benefit, but they would mean a complete recovery from degradation and decay undergone over the centuries. Furthermore, the effect of lower cost of energy management, further stimulates retrofitting actions, resulting in a general benefit for society.

One of the most important challenges of adapting historical buildings to future usages is the enhancement of the energy performances of these building, that is crucial both for environmental and economic reasons.

The recently published ASHRAE Guideline 34 [2.2] provides comprehensive and detailed descriptions of the processes and procedures for the retrofitting of historic buildings in order to achieve greater measured energy efficiency. The purpose of this guideline is to provide sound advice on practices, processes, and workflows that should be followed when performing energy efficiency and energy conservation improvement projects and programs involving historic buildings, while minimizing disturbance to the historic character, characteristics, and materials (significance, value, and qualities) of the building.

The ASHRAE Guideline 34 is applicable to buildings that are listed as historic buildings or which are eligible to be listed by applicable law in the jurisdiction where the building is located.

This guideline applies to projects that are intended to improve the following:

a. Energy efficiency of operation and maintenance

b. Efficiency of energy-using building systems and equipment

c. Energy performance of the building’s envelope

This guideline applies to projects that include the following:

a. Envelope modifications and upgrades to control heat and moisture transfer and limit air infiltration

b. Adding new HVAC, service water heating, or lighting systems, or modifying existing systems, to improve energy efficiency while maintaining or improving human comfort and indoor environmental quality

In addition, in Italy, for the important presence of historic buildings in the area, different entities have developed guidelines for the retrofitting of this type of building. Relevant examples are MiBACT guidelines on "Energy efficiency improvements in cultural heritage"[2.3] and AiCARR guidelines on "Energy efficiency of historical buildings". [2.4]

Furthermore, E. Negro, Cardinale et al. [2.5] presented an interesting analysis on the compatibility of energy efficiency measures applied in Sassi buildings with the recent MiBACT guidelines on "Energy efficiency improvements in cultural heritage" and AiCARR guidelines on "Energy efficiency of historical buildings".

A transient analysis is used for almost all studies found in the literature on the energy efficiency of historic buildings.

## 2.1 Transient thermal performance analysis

For historical buildings, a traditional steady-state approach for the analysis of the thermal performance of the building may not be adequate. The study of the building envelope and the HVAC system based on a dynamic analysis allows to take into account factors such as thermal inertia, which is particularly relevant for historic buildings.

Dynamic simulations are able to provide to the designer an accurate reconstruction of the time variation of thermal loads obtained by using adequate time steps, thanks to the introduction of a large amount of input data [2.6]:

- geometrical information, from orientations and area of each envelope component for the simplest model to the coordinates that define each building component in a three-dimensional cartesian space, required in detailed models in which the internal radiative heat transfer is evaluated by means of view factors;

- thermo physical properties (i.e. thermal conductivity, density, specific heat capacity, water vapor permeability...) of each layer of massive envelope element like walls, roofs and floors;

- windows properties: optical and radiative glass properties, thermo physical data for the gas contained in windows cavity and for the frame;

- thermal zone user profiles: occupancy, internal gains, ventilation profiles, indoor temperature set-up schedule;

- performance maps of each HVAC component.

- weather data, like external temperature, vapor pressure, external humidity ratio, wind velocity and direction, solar radiation collected with hourly or sub-hourly frequency.

Contrary to transient analysis, models based on a steady-state approach require less input data: as an example, external conditions are described by monthly mean values, whilst for envelope elements only the thermal conductivity is considered among the thermo physical properties. The typology and the number of input data required by quasi-stationary models are described in several National Standards, like the UNI TS 11300 [2.7] in Italy, where standard profiles for ventilation and internal heat gains can be found.

On the contrary, when the transient approach is considered, up to date there is the lack of a Standard which defines the minimum input data required and where some standard schedule for the main user profile can be found. Moreover, it has to be remarked that all the input data required by models based on quasi-stationary approach can be obtained from technical data sheets, whilst for dynamic models more detailed information is required. This lack of standardization of the input data needed by dynamic models leads to two important drawbacks:

• Uncertainty of the building description, due to the lack of information;

• Variability of the input data required by different dynamic models.

In quasi-stationary simulations, internal conditions (i.e. air temperature) are constant input data and from these input data monthly energy consumption and energy losses through the building are estimated. On the other hand, in dynamic simulations internal conditions are not input data, but they are calculated as response to the external and internal (due to HVAC, presence of people, internal gains…) loads; the evaluation of internal conditions is possible thanks to the adoption of short time steps and a correct evaluation of the thermal inertia of the massive building elements in the energy balance equations. In addition, it has to be remarked that in dynamic simulations several physical phenomena are taken into account together.

As for input data, dynamic simulations are characterized by a huge number of outputs by means of which the dynamic behavior of the simulated building-HVAC system is described. The main outputs of a dynamic simulation are:

• Air temperature of the thermal zone;

• Surface temperature of each envelope component;

• Thermal fluxes of each envelope component;

• Occupant thermal comfort indexes (i.e. Predicted Mean Vote and Predicted Percentage of Dissatisfied);

• Instantaneous values of solar shadings;

• Thermal power released by the HVAC system to the thermal zone.

The simulation in dynamic regime is therefore a promising tool, but, it must be managed carefully, in order to avoid significant deviations from reality. To this respect, a very careful calibration phase of the model and a study of its limitations are necessary. [2.8-9]

A general calibration methodology was proposed by Agami et al. [2.10], which deem to be methodical, rational, robust and computationally efficient, while being flexible enough to satisfy different users with different person preferences and biases. The methodology was later validated with three case studies. [2.11]

M. Giuliani et al. presented an interesting analysis on the calibration of dynamic models of historic buildings that takes into account parameters such as surface temperatures and the solar and thermal absorbance of interior and exterior surfaces. [2.12]

There are several software in the market to carry out the analysis in dynamic regime, in this thesis TRNSYS has been deepened. TRNSYS is one of the most famous dynamic thermal modeling software, it is a commercial software package developed by the University of Wisconsin. [2.13] TRNSYS is an extremely flexible graphically based software environment used to simulate the behavior of transient systems, with a modular structure: its modular nature gives the program enormous flexibility. While the vast majority of simulations are focused on assessing the performance of thermal and electrical energy systems, TRNSYS can equally well be used to model other dynamic systems such as traffic flow, or biological processes.

TRNSYS is made up of two parts. The first is an engine (called the kernel) that reads and processes the input file, iteratively solves the system, determines convergence, and plots system variables. The kernel also provides utilities that (among other things) determine thermo-physical properties, invert matrices, perform linear regressions, and interpolate external data files. The second part of TRNSYS is an extensive library of components, each of which models the performance of one part of the system. The standard library includes approximately 150 models ranging from pumps to multi-zone buildings, wind turbines to electrolyzes, weather data processors to economics routines, and basic HVAC equipment to cutting edge emerging technologies. Models are constructed in such a way that users can modify existing components or write their own, extending the capabilities of the environment.

TRNSYS is actively being used in many of the following applications: Central Plant Modeling, Building Simulation (including LEED Energy Modeling), Solar Thermal Processes, Ground Coupled Heat Transfer, High Temperature Solar Applications, Geothermal Heat Pump Systems, Coupled Multi-zone Thermal/Airflow Modeling Optimization, Energy System Research, Emerging Technology Assessment, Power Plants (Biomass, Cogeneration), Wind and Photovoltaic Systems, Data and Simulation Calibration etc.

The dynamic analysis of buildings with the model of the building envelope – HVAC system are carried out with the following tools:

- Simulation Studio: The TRNSYS Simulation Studio serves as a robust, intuitive, graphical front end of the simulation, making the user's job of assembling a detailed system a simple endeavor - similar in nature to hooking up the pipes and wires in a real system. The outputs of one component are graphically connected to the inputs of another. Since its inception of in the mid 1990's, the Simulation Studio has replaced the need to manually edit the text input file. Users can watch the value of any system variable on an online plot as the simulation progresses (any temperature, flow rate, heat transfer etc.). Output devices also allow the user great flexibility in integrating, printing, and reporting any component output value.

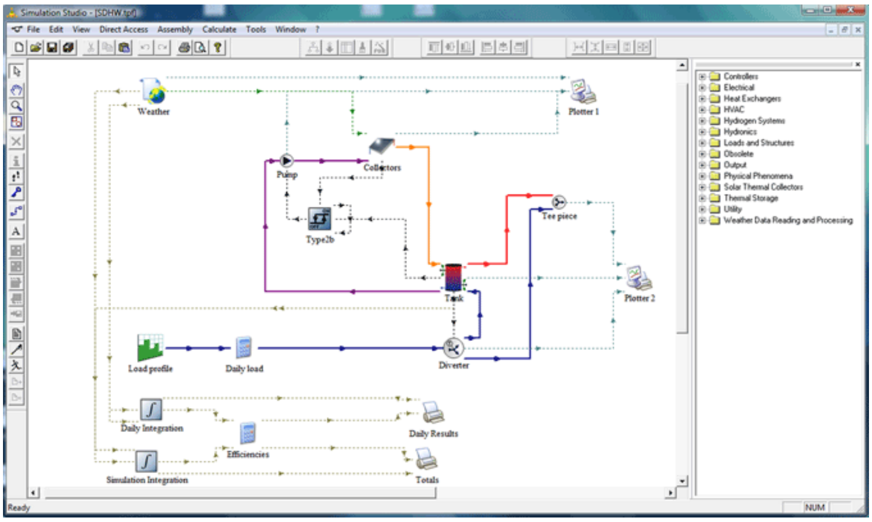



*Fig.2.1 – Simulation Studio*

- TRNSYS3D : it is a plugin for SketchUp™ that allows the user to draw multizone buildings and import the geometry (including building self-shading and internal view factors for radiation exchange) directly from the powerful SketchUp interface into the TRNSYS Building environment (TRNBuild).

- TRNBuild: it is an interface for creating and editing all of the non-geometry information required by the TRNSYS Building Model. TRNBuild allows the user extensive flexibility in editing wall and layer material properties, creating ventilation and infiltration profiles, adding gains, defining radiant ceilings and floors, and positioning occupants for comfort calculations.

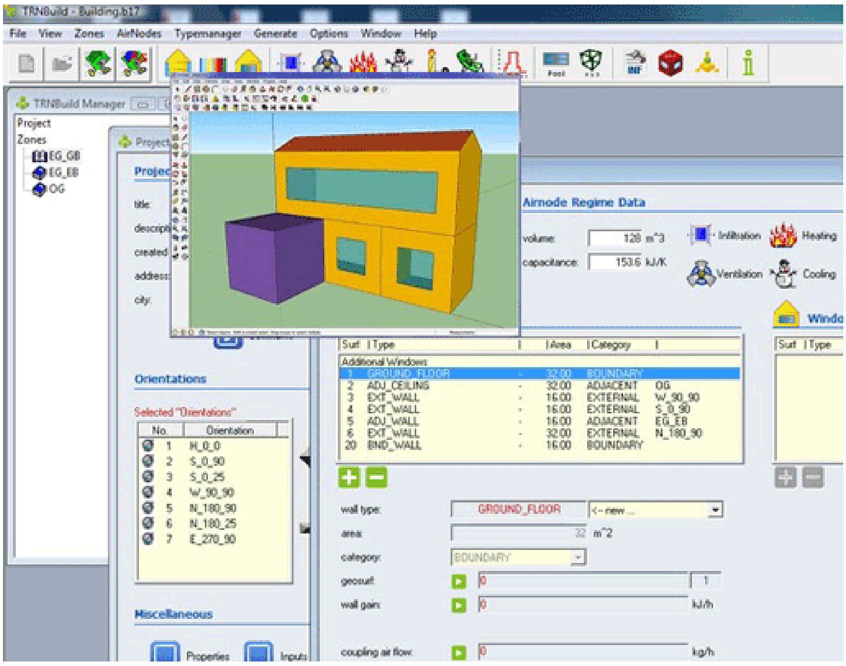



*Fig.2.2 – TRNBuild*

- TRNEdit: Historically, the text-based TRNSYS input file was generated manually. The addition of the Simulation Studio in the mid-1990s greatly reduced the need for manual editing. However, the TRNSYS environment still includes TRNEdit, a full-featured text editor for writing and viewing TRNSYS input and output files and for running parametric TRNSYS simulations. TRNEdit also serves as the editor for manually generating stand-alone distributable TRNSYS simulations called TRNSED applications.

## 2.2 Energy efficiency in historic buildings

Many studies analysed the improvement of energy performance of historic buildings in towns and rural environments with the use of the case studies.

U.Alev et al. [2.14] presented an interesting analysis on the improvement of energy performance of the historical rural houses with energy retrofitting solutions calculated for different scenarios (minimal influence on the appearance of the house, improvement of thermal comfort, improvement of building service systems) and different energy saving levels.

Bjarløv and Vladykova [2.15] demonstrated practical ways for significantly reducing thermal bridges, increasing air tightness, upgrading insulation and adding mechanical ventilation to approximately half of the housing stock without significantly changing the architectural expression or having to relocate the occupants during the renovation for standard family detached and semi-detached wooden houses in arctic Greenland. Todorovic´ [2.16] stated that it is impossible to reach sustainability without harmonious interdisciplinary interaction, without a balance between the physical and the spiritual, science and art, technology development and cultural and other human value improvements without an ethic of sustainability.

The issue of energy efficiency in historic buildings in city centers was analyzed by many authors, for example F. Ascione et al. [2.17] with the use of a case study "Palazzo dell'Aquila Bosco-Lucarelli" presented a methodology to evidence a best-practice specified for the Italian territorial context, which has several historical buildings needing restoration.

Also A.L. Pisello et al. [2.18] presented a methodology to reduce the building energy demand with a pilot case study "Palazzo Gallenga Stuart" with the introduction of the effective heat pump plant.

The criteria for choosing energy retrofitting in historic buildings at European level may be considered similar, as shown for example by the study done by F. Perez Galvez et al. [2.19] with the case study of a building located in Historic Center of Sivilla.

One of the essential measures, highlighted by MiBACT guidelines, is to ensure, in according to UNI EN 15251, the Indoor Environmental Quality improvement for historical architecture in order to preserve their identity and cultural heritage. [2.20] [2.21]

In the literature there are many papers that evaluate the thermal comfort of buildings (measured in according of PMV index and EN 15251 model), this is a fundamental parameter to always keep in mind during the energy retrofitting of historical buildings.[2.22-25]

The assessment of moderate thermal environments is traditionally carried out by means of the PMV (Predicted Mean Vote) and the corresponding PPD (Predicted Percentage of Dissatisfied) index [2.26-27].

One of the aspects that is always necessary to evaluate is the behavior of the occupants of the buildings. G.Spigliantini et.al. [2.28] presented a methodology focusing only on building use and operation possibilities, with a special focus on occupant awareness and education. The analysis of the comfort of the building occupants was based on a collection of information by questionnaires.

L. De Santoli et al. in the AICARR guidelines it describes a general methodology for energy retrofitting in historic buildings which is summarized in the following table. [2.29]

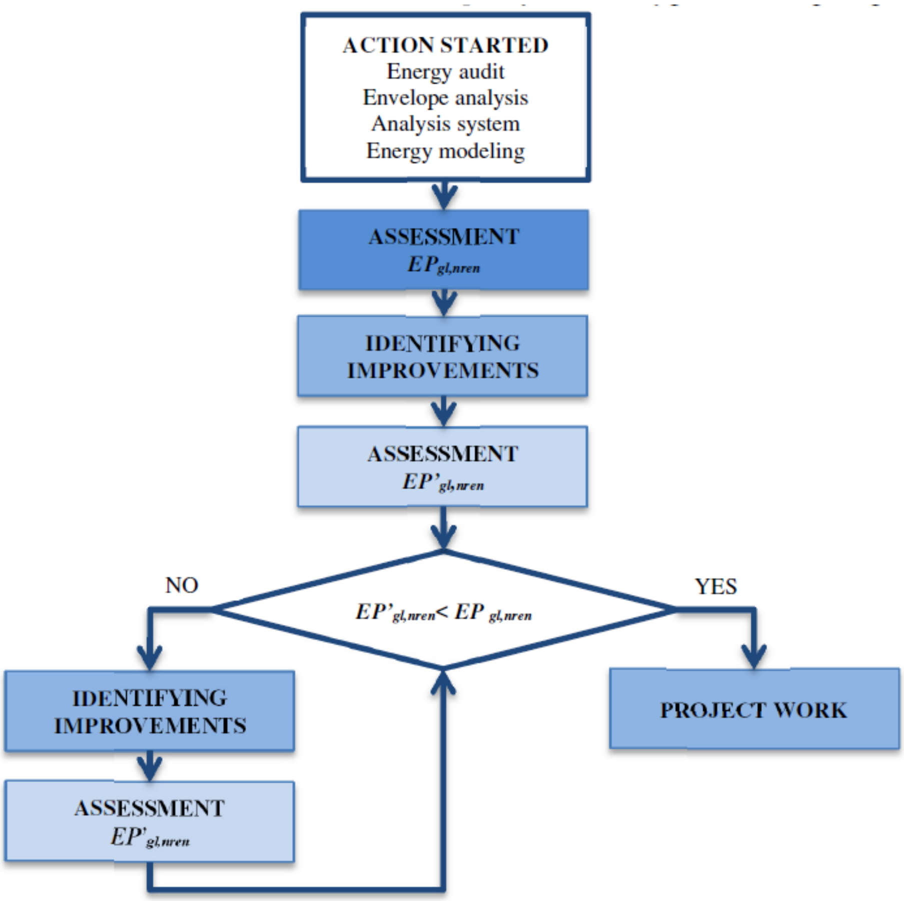



*Fig.2.3 – Flow chart of energy efficiency improvement [2.29]*

The analysis must always start from an analysis of the factual status of the buildings in question through a thorough energy audit and correct modeling.

The Italian guidelines (MiBACT) suggest that, first of all, the analysis of the technical-construction features of historical buildings with the historical interpretation and geometric survey is necessary.

From an operational point of view, the best configuration is the critical integration of various detection methodologies, both direct and indirect (photogrammetry, stereo-photogrammetry, laser scanning). These methodologies might be accompanied by a detailed topographical classification of building and supported by a detailed photographic documentation, which also extends to the environment, indicating the shooting points.

The identification of an optimal energy audit requires the knowledge of a range of relevant information on the building envelope, HVAC system and its features. To do this, at first it is necessary to identify the functions that the architectural and technological systems must satisfy.

The energy retrofitting solutions for the historical buildings can be multiple, from the simplest and most economical, to the most complex.

The energy retrofitting of historic buildings differs from that of standard buildings for some intrinsic characteristics.

Architectural constraints, for example, do not allow traditional insulation of the building envelope, therefore it is necessary to evaluate innovative technologies.

L. Bianco et al. [2.30] present a thermal, vegetal based, insulating plaster, which has recently been developed within a research project. The authors investigate its potential to reduce the heat flux exchanged through the vertical envelope of historic buildings, by means of measurements carried out in both the laboratory and in the field, for a real case application. The application of this innovative material has led to a significant reduction in the energy that crosses the wall (about 20–40%).

The issue related to the insulation of the components of the envelope is also addressed by J. Zagorskas et. al. [2.31] where they analyses five modern insulation materials. Measurements are made and best alternative is found using TOPSIS method with grey numbers.

In many cases, "non-invasive" but often less efficient solutions must be chosen for the energy requalification of historic buildings, sometimes associated with a higher investment cost than the best available technologies.

The selection of the most suitable solution should be based on a number of parameters which characterize most of historic buildings, such as large thermal inertia and intermittent and variable usage [2.32]-[2.35].

Among possible retrofitting solutions, personalized heating systems can be an efficient and cost-effective option, especially for buildings characterized by intermittent usage. [2.36-

40] Such systems aim to create a microclimate around a person, optimizing energy consumption while providing thermal comfort [2.41]. The benefit of such systems when compared with neutral ambient control systems is the need to condition only the heated island around each workstation and the potential enhanced comfort due to the higher control on the operational temperature perceived by the occupant. Recently Zhang et. al.[2.42] provided examples of comfort levels associated with energy-saving ambient control, in which personalized cooling systems allow the comfort to remain equivalent to, and in some cases better than, that of neutral ambient control. The results showed that a considerably wide range of indoor temperatures can be experienced when using these systems. In contrast to studies on personalized cooling, only a few studies deal with personalized heating as an energy saving solution [2.43]. Most of the investigated systems are feet or hand warmers, which normally might extend the range of conventional heating systems but cannot be substituted to them.

The use of renewable energies in historic buildings is an interesting challenge that was investigated by many authors. L. F. Cabeza et al. [2.44] classify different examples of the use of energy efficiency approaches and the integration of renewable energies in historical buildings, including solar and geothermal energy, and the use of heat pumps and other high-efficiency heating ventilation and air conditioning systems.

C. Lopez et al. [2.45] analyzed the installation of renewable energy solar systems in historic buildings and the critical issues of their installation due to respect for architectural constraints.

When energy efficiency measures cannot be carried out due to architectural constraints or the lack of convenience in economic or practical terms, C. Aghemo et al. demonstrate how savings can be achieved by designing intelligent ICT-based service to monitor and control environmental conditions, energy loads and plants operation. [2.46-47]

The scientific literature has also analyzed the iterations from the energy point of view between the historic buildings and the urban context in which they are located.

For example F. Rosso et al. develop the theme of the Urban Heat Island Effect , in particular the passive solutions to reduce the energy demands for the historical and monumental buildings (difficult due to strict regulations for the preservation of such historical and cultural heritage). [2.48]

## 2.3 Existing research projects on energy efficiency in historic buildings

Many research projects addressed the issue of energy retrofitting of historic buildings, also supported by recent European policies towards the establishment of procedures and tools for the sustainable management of heritage buildings. Some of the most significant projects are described in detail below.

The project "**EFFESUS - Energy Efficiency For EU Historic Districts Sustainability**" EFFESUS focuses on the energy efficiency of European historic urban districts and aim at developing technologies and systems for its improvement. The main object of EFFESUS research project are groups of historical buildings built before 1945 and representative of the period of their construction or history, not necessarily protected by heritage legislation. The main outcomes are the definition of a methodology for assessing and selecting energy efficiency interventions, based on existing and new technologies compatible with heritage values the main. The methodology has been implemented through case studies. A Decision Support System has been developed as a software tool able to select suitable energy efficiency interventions at different scales, by providing some information about the main characteristics of the historic district or of the building. The system help to select solutions and create intervention packages. Finally the EFFESUS project addressed the nontechnical barriers constituted by the discrepancies between existing building policies and cultural heritage preservation needs. [2.49]

*Table 2.1 – EFFESUS*

| | |
|---|---|
| Acronym | *EFFESUS* |
| Title | *Energy Efficiency For EU Historic Districts Sustainability* |
| Duration | 2012-2016 |
| Funded by | Framework Programme 7 |
| Aim of the project | - definition of a methodology for assessing and selecting energy efficiency interventions<br>- development of a Decision Support System, able to select suitable energy efficiency interventions at different scales<br>- fill up by the discrepancies between existing building policies and cultural heritage preservation needs |

The project "**3ENCULT Efficient Energy for EU Cultural Heritage**" aims at demonstrate that energy efficiency, structural protection, comfort of the occupants and conservation of cultural heritage elements are interdependent in the energy retrofit process and especially they are compatible with each other [2.50]. The research project identifies a number of passive and active solutions suitable for the energy retrofit of historic building. This has been proved by the assessment of the selected solutions to several case studies, dating different epochs, ranging from middle age to the 20th century, and including different buildings structures [2.51]. At the urban scale, the potential impact of energy refurbishments on historical city centers in terms of environmental energy and economic influence has been investigated. The work demonstrates that the application of solutions compatible with preservation needs enhances long-term-conservation and sustainable management of old towns [2.52]. The research ranges over various issues, including the analysis and diagnosis activities, the identification of active and passive retrofit solutions (HVAC, insulation, windows, monitoring and control) the proposal of integration to the current regulatory framework and dissemination as well.

*Table 2.2 – 3ENCULT*

| | |
|---|---|
| Acronym | *3ENCULT* |
| Title | *Efficient Energy for EU Cultural Heritage* |
| Duration | 2010-2014 |
| Funded by | Framework Programme 7 |
| Aim of the project | - support the sustainable refurbishment of Europe's built heritage through<br>- develop and demonstrate the effectiveness of new systems and technologies both for "hard facts" energy efficient building concept and "soft systems", such as the intelligent monitoring & control system. |

Another collaborative project between European institution is "**SEEM Pubs - Smart Energy Efficient Middleware for Public Spaces**". The project deals with the achievement of energy savings and CO2 footprint reduction in in existing Public buildings by an intelligent ICT-based service monitoring and managing the energy consumption, focusing also on historical buildings to avoid damage by extensive retrofitting [2.53]. Specifically, a combination of occupancy detection and daylight harvesting could achieve a significant energy saving during winter and summer seasons. The research activity consists in the development of an integrated electronic system suitable to control building's services and devices and to monitor environmental conditions and energy consumption; in the provision of a visualization of parameters of building operations and data sharing from technical systems; to raise people's awareness for energy efficiency in public spaces.

*Table 2.3 – SEEM Pubs*

| | |
|---|---|
| Acronym | SEEM Pubs |
| Title | Smart Energy Efficient Middleware for Public Spaces |
| Duration | 2010-2013 |
| Funded by | Framework Programme 7 |
| Aim of the project | - reduce energy usage and $CO_2$ footprint in existing Public buildings and spaces without significant construction works<br>- development of an intelligent ICT-based service monitoring and managing the energy consumption.<br>- Identification of solutions suitable to historical buildings, to avoid damage by extensive retrofitting. |

Another significant example is represented by "**Co2olBricks - Climate Change, Cultural Heritage & Energy Efficient Monuments**", [2.54] that aims to find solutions to combine the needs of climate protection with the energy optimization of historic buildings, suitable to the Baltic Sea Region brick architecture. The principal outcomes concern, among others, an handbook reporting energy-saving weak points and potentials of buildings with historical value and instruments to tackle the issue from the legislative and regulatory point of view, introducing proposals for the urban development, public funding, and integrating of existing standards as well. [2.55]

*Table 2.4 – Co2olBricks*

| | |
|---|---|
| Acronym | Co2olBricks |
| Title | Climate Change, Cultural Heritage & Energy Efficient Monuments |
| Duration | 2010-2013 |
| Funded by | Baltic Sea Region Programme 2007 – 2013 |
| Aim of the project | - reduce the energy consumption of historical buildings without destroying their cultural value and identity<br>- implement, monitor and evaluate pilot projects for adequately energy optimised historic buildings.<br>- focus on the Baltic Sea Region's brick architecture. |

The innovation brought by the project **CLIMATE FOR CULTURE** [2.56] concerns the impact of global climate change on Europe's cultural heritage assets. Simulation and modelling tools have been used to predict the influence of the changing outdoor climate on the microclimate in historic buildings, assessing the correlated damage potential on art collections in various climate zones [2.57]. As an example, a new simplified hygrothermal building model has been validated with an inverse modeling technique to identify its parameters. [2.58]

*Table 2.5 – Climate for Culture*

| | |
|---|---|
| Title | *Climate for Culture* |
| Duration | 2009-2014 |
| Funded by | Framework Programme 7 |
| Aim of the project | - investigate the potential impact of climate change on Europe's historic buildings and their interiors<br>- use of simulation and modelling tools to better predict the influence of the changing outdoor climate on the microclimate in historic buildings until 2100<br>- assess the damage potential of future microclimates on art collections in various climate zones.<br>- assess of the climatic functioning of historic buildings and their future energy demand using whole building simulation<br>- focus to the dangers for the interior equipment or works of art |

The "**GOVERNEE – Good Governance in Energy Efficiency**" project aim is the promotion of the energy efficiency and the use of Renewable Energy Sources in public and historic buildings, focusing and supporting governance and the decision-making processes [2.59]. The main result achieved within this project is the drafting of the "transnational Toolkit", an instrument to facilitate the path and the verifies that each public administration faces in managing its building heritage [2.60]. The document is organized in ten steps, that represent the fundamental topics to tackle: from organizational aspects of the offices, to operating tools for diagnosis, monitoring and contracts necessary for good management. The project incorporated EE measures into decision-making processes of municipalities by promoting a cross-sectoral approach through training and coaching activities. Every GovernEE partner presented a pilot project and a summary of the reported best practices has been produced. Best practices are examined from technical, legislative and economic point of view as well as from the perspective of knowledge sharing.

*Table 2.6 – GovernEE*

| | |
|---|---|
| Acronym | GovernEE |
| Title | *Good Governance in Energy Efficiency* |
| Duration | 2010-2013 |
| Funded by | Central Europe Program |
| Aim of the project | - promote the energy efficiency and the use of Renewable Energy Sources in public and historic buildings.<br>- focus not so directly on technological innovations, but rather on the good governance<br>- support the decision-making processes and promote energy-conscious interventions in public buildings. |

A similar target has been set by the project "**New4Old –New energy for old buildings**" dealing with the integration of renewable energy and energy efficiency technologies into historic buildings and the protection of their artistic value as well [2.61]. Furthermore the creation of a European-wide network of Renewable Energy Houses to overcoming the lack of information about these technologies has been pursued.

*Table 2.7 – New4Old*

| | |
|---|---|
| Acronym | New4Old |
| Title | *New energy for old buildings. Promoting the integration of RES & RUE measures in historic buildings.* |
| Duration | 2007-2010 |
| Funded by | Intelligent Energy for Europe Programme |
| Aim of the project | - promote the integration of renewable energy and energy efficiency technologies into historic buildings.<br>- Creation of a network of light-house Renewable Energy Houses, contributing to overcoming the lack of information about these technologies.<br>- Market Study of Renewable Energy House projects<br>- Marketing and communication campaign on building integration of RES & RUE measures |

Not specifically focused on historic building, but involving institutional and public ones, the project "**BRITA-in-PuBs - Bringing retrofit innovations to application in public buildings**" aims at increasing the market penetration of innovative and effective retrofit solutions to improve energy efficiency and implement renewables, focusing on the related socio-economic issues. [2.62]

*Table 2.8 – BRITA-in-PuBs*

| | |
|---|---|
| Acronym | BRITA-in-PuBs |
| Name | *Bringing retrofit innovations to application in public buildings.* |
| Duration | 2004-2008 |
| Funded by | Framework Programme 6 |
| Aim of the project | - increase the market penetration of innovative and effective retrofit solutions to improve energy efficiency and implement renewables, with moderate additional costs.<br>- retrofit of 9 demonstration public buildings in the four participating European regions<br>- develop socio-economic research such as the identification of real project-planning needs and financing strategies, the assessment of design guidelines. |

“**RESTART – Renewable Energy Strategies and Technology Applications for Regenerating Towns**” involves some large scale urban projects, concerning innovative energy-environmental integration on the city scale [2.63]. The “city projects” have been chosen basing on the complexity of urban situations involved, on the possibility to obtain a strong impact on the decisional mechanisms of the city and a high visibility for the inhabitants. High emphasis has been given at a multi-actor and multi-sector approach.

*Table 2.9 – RESTART*

| | |
|---|---|
| Acronym | *RESTART* |
| Name | *Renewable Energy Strategies and Technology Applications for Regenerating Towns* |
| Duration | 1996-2001 |
| Funded by | EU Programme Therme |
| Aim of the project | - Selection of eight "Exemplary Urban Projects” in industrial European Cities, concerning their rehabilitation by optimizing the use of renewable energy sources and by innovative energy-environmental integration on the city scale.<br>- Involvement of different players of such complex urban projects: city officers, promoters, professionals, local associations, technology manufactures, experts. |

The project “**Hist.Urban – Integrated and Implementation-oriented Revitalisation Approaches for Historic Town**” develops integrated strategies for the renewal of historical city centers, with a particular focus on socioeconomic and environmental revitalization, fostering the role of historical downtowns as engines for the social and economic development. [2.64]

*Table 2.10 – Hist.Urban*

| | |
|---|---|
| Acronym | *Hist.Urban* |
| Name | *Integrated and Implementation-oriented Revitalisation Approaches for Historic Towns* |
| Duration | 2006-2008 |
| Funded by | Interreg IIIB/Cadses |
| Aim of the project | - develop innovative and integrated strategies and approaches for the renewal of historical city centres, focusing on socioeconomic and environmental revitalization.<br>- Foster the role of historical urban city centers as engines for the social and economic development by new and interdisciplinary urban planning strategies |

At a national Italian level, it is worth noting the **A.T.T.E.S.S. project (Technology Transfer Actions for improving Energy and environmental performances of historical buildings according to Sustainable building criteria)** [2.65]. The main outcome of the project, promoted and coordinated by the Italian Veneto Meta-districts of Sustainable Building and of Cultural Heritage, is the drafting of the Guidelines [2.66], which take into account both restoration principles and sustainable building criteria. The program focuses on traditional construction techniques and materials, with the long term aim of promoting a dedicated specific legislation. The Guidelines issues range, among others, the thermal characteristics of traditional materials, the modeling of energy performance, and the bioclimatic analysis.

# 3. REGULATORY FRAMEWORK OF THE HISTORICAL BUILDINGS IN EU

Interventions on historic buildings and structure are generally subject to requirements at the international, national, state, or local government level, depending on the importance and significance of the building, its ownership, and the sources of funds or financial incentives for the planned activities. As part of the planning process, the applicable requirements must be researched and identified.

The EU Member States, in the last century, developed regulations regarding the conservation of historical and monumental buildings.

It is very important to tackle issues of energy retrofitting of historic buildings always with an approach aimed at preserving the historical components of the building.

However, given the peculiarity of each historic building, it is not possible to set a standard intervention methodology (like a precise list of practices) for all buildings. On the contrary, the national regulations, only defined operational guidelines for this type of buildings that are mainly apllicable on a case-by-case basis.

The regulations on the conservation of historical buildings have been analyzed below for different European Member States (i.e. Spain, Germany, France, United Kingdom and Italy), in addition to the analysis of the legislation developed at the European level.

## 3.1 European legislation

Several directives dealing with energy efficiency in building have been enacted by the European Union in order to counteract the great energy consumption required by building sector, one of the key consumers of energy in Europe [3.1]. Two Directives directly deal with Energy Performance of Buildings: Directive 2002/91/EC [3.2] and Directive2010/31/EU [3.3], respectively shortly named EPBD and EPBD recast. The Directive defines a common methodology for calculating the integrated energy performance of buildings. Moreover it fixes minimum standards on the energy performance of new and existing buildings subject to renovation. The EPBD establishes that each member state has to create systems for the energy certification of new and existing buildings. Moreover instructions about the frequency of maintenance and inspections of HVAC systems are set.

Though the first directive mainly focused on new constructions, the major innovation brought by the EPBD recast is the more emphasis given to the renovation of existing buildings, even if the retrofit concerns only building technical elements or systems. The new strategy adopted is due by the decreasing trend of new constructions. The main way to achieve objectives of consumption and CO2 emissions reduction is promoting the energy retrofit interventions on existing buildings.

The EPBD recast Directive defines the energy performance as "the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting". The minimum energy performance requirements will be applied to the existing building or to the renovated part, when they undergo major renovation, in so far as this is technically, functionally and economically feasible. In case of retrofit of building elements, requirements may be applied only to such renovated parts.

The EPBD addresses the energy retrofit of Cultural Heritage using a derogation regime. In facts, member States may decide if a historic building undertaking to renovation has to fulfill the energy efficiency requirements. Among the exempted building categories are included "buildings officially protected as part of a designated environment or because of their special architectural or historical merit, in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance". The use of the word "officially protected" cover a very large range of heritage buildings, without indicate a specific protection level. This expression implies that buildings under every level of protection, e.g. typically listed buildings but also buildings protected at a lower level, such as by planning legislations are exempted by the EPBD requirements. Antithetically, another result of the wording "officially protected" is the assimilation of historical buildings, that haven't yet be listed as cultural heritage, to existing buildings, therefore they are subject to the minimum energy performance requirements.

It can be assumed that the will of the legislator, reading the EPBD recast, was to leaving to member States the possibility to predispose a national legislation, tailored on the specific conditions. The threats brought by this approach is to have different interpretations by the member States of the same retrofit strategy. So an intervention could be acceptable in one country and at the same time judged as incompatible for another country.

Despite European building stock is characterized for a large part by "official protected buildings" [BPIE] there is a lack at the EU level of a clear set of rules dedicated to the interventions admitted in this kind of buildings. As underlined by Mazzarella [3.4], the main issue now is the definition of the "unacceptable alterations" that according to the EPBD would determine the unfeasibility of the energy retrofit. It would be interesting the draft of a list of materials or interventions that could be harmful for historic buildings and sharing this guide lines at an international level. As underlined by a recent work developed within the EU project EFFESUS [3.5], some typical energy retrofit interventions have been generally identified by project participants as detrimental for historic buildings, such as external insulation, internal insulation in case of painted walls, solar panels on the roof, interventions on windows or doors. Nevertheless, a lack of a unify policy even at a national level has been declared by several participant countries.

Another possible reason to support the derogation could be that regulation of Cultural Heritage is not competence of EU, while the EU Directives of other areas can impact negatively on maintenance and conservation of built heritage [3.6]. If the application of energy requirements leads to an unacceptable alteration to the built heritage character or appearance, the imposition of such requirements would create a conflict with Cultural Heritage national authorities. It is therefore essential a major influence of Cultural Heritage national administrations during the drafting of EU legal acts.

Also in the recent Energy Efficiency Directive (2012/27/EU) , establishing a set of binding measures to help the EU reach its 20% energy efficiency target by 2020, includes an explicit article on building renovation. Following the Directive, all EU countries are required to use energy more efficiently at all stages of the energy chain from its production to its final consumption, also considering energy savings achieved by existing building renovation. In particular, it is asked to Public Bodies' Buildings to play an exemplary role, through the progressive renovation (3% of the total floor area each year) of owned or occupied buildings, to meet the minimum energy performance requirements that each Member State has set in application of Article 4 of the Energy Performance of Buildings Directive.

## 3.2 Spain

Compared to other European Member States, Spain has adopted legislation on historical heritage more recently, the rules for the protection of historic urban textiles are based on the reasoning that there is a close correlation between heritage protection and urban planning.

As for the historical legislation in this area, the main laws are the following.

- "1926, Real Decreto-Ley sobre Proteccion y Conservacion de la riqueza artistica": Following the ideas of Giovannoni on the philological restoration and the importance of individual monuments in the urban context, it introduce the concept of the "Conjunto Historico" and extend the notion of monument from the single building to the "urban, picturesque or natural complexes".

- "1933, Ley sobre la defensa, conservación y acrecentamiento del patrimonio histórico-artístico nacional": It reviewes the previous law, going to restrict the protection of historical heritage to individual isolated buildings, no longer recognizing the "Conjunto Historico", and therefore the urban fabric in which they are located.

- "1964, Legislacíon de Ensanche": The Law on urban rents is part of an urban planning policy based on the expansion of the city projected to the outside: this law in fact blocks the rents of the properties in the historic centers at very low prices, thus encouraging the private individuals to demolish the own lodgings to rebuild and obtain much higher incomes.

- "1976, Ley sobre regimen del suelo y ordenaciòn urbana": Law on the soil regime and urban regulation.

- "1978, Real Decreto 2159/78 de 23 de junio" : Planning regulation. It contains the *Plan Especial de Protección*, which provides for the preservation of historic fabrics, and the *Plan Especial de Reforma Interior*, which provides for strong transformations of existing urban fabrics.

- "1985, Ley del Patrimonio Historico Español": Spanish Historical Heritage Act. Article n. 46 of the Spanish Constitution states that "the public authorities will guarantee the conservation and promote the recognition of the historical, cultural and artistic heritage of the peoples of Spain and of the assets that integrate it, whatever the legal regime and its ownership. The Criminal Law will sanction attacks against this heritage ", however it does not contain legal information on this notion.[3.7]

The Spanish Historical Heritage Law n. 16 of June 23, 1985 broadens the definition of cultural heritage: "integran el Patrimonio Historico Espagnol los inmuebles y objetos muebles de interes artistic, historico, paleontological, arqueological, ethnographic, scientific or technical" (the objects belong to the concept of Spanish historical heritage furniture and buildings of artistic, historical, palaeontological, archaeological, ethnographic, scientific or technical interest), it also sets among its main objectives "the protection, growth and transmission to future generations of the Spanish Historical Heritage".

The law provides for two levels of protection: the first, the maximum, provided for the so-called "*Bienes de Interès Cultural*" (BIC), movable and immovable property for which a formal declaration is envisaged with the inclusion of the same in the Register of Goods of Cultural Interest; the second, with less rigid rules, applies instead to movable assets registered in the General Inventory.

The laws proceed with the cataloging of the unitary elements (constructed buildings, external or internal spaces, significant structures and natural components) and possible interventions are defined for the various categories. For single elements total protection is provided, for all other components an adequate level of protection is provided. [3.8]

The law also provides for a process of decentralization with a distribution of responsibilities between the State and the Autonomous Communities (Catalonia, the Basque Country, etc.) The State is responsible for promoting the laws that define the competences of the Autonomous Communities, while the Autonomous Communities are responsible for the enforcement of the protection, the management of the assets bound by the law on historical heritage. They also deal with the declarations of Assets of Cultural Interest.

## 3.3 Germany

The Federal Republic of Germany presents a decentralized system that attributes the protection of cultural heritage and cultural heritage to the sixteen Lands, each of which has its own and different legislation.

In Germany there is no national responsible body for Cultural Heritage. In fact, no national Ministry of Culture exists and cultural responsibilities at the national level are shared between various ministries, although the main activities are concentrated at the Federal Chancellery, with the Federal Government Commissioner for Culture and Media [3.9]. The main duty of the Federal Commissioner for Culture is to offer advice and support the Chancellor on cultural matters, ranging from the performing arts to museums' affairs. Both the Federal and the sixteen Länder are responsible for formulating, developing and applying a policy whose principal aim is to co-ordinate and to make use of all the scientific, the technical, the cultural and other resources available to secure the effective protection, conservation and presentation of the cultural heritage. However, in accordance with the division of competences between the Federation and the Federal States, the Länd, as the highest heritage preservation authorities, is responsible for the preservation of monuments. For this reason, the structure and forms of the cultural heritage's organization and the authorities in charge of the preservation of monuments differ from one state to another. The Länder are responsible for both adopting laws on the protection and preservation of monuments and for implementing them [3.10]. The Land's laws on heritage preservation proceed from a central specialized authority: the Regional Office for the Preservation of Monuments (Landesdenkmalamt) [3.11], responsible for all specific questions related to the protection of historic monuments. As a bearer of public interest, the Regional Office for the Preservation of Monuments represents conservation interests in public planning and building projects. In some Länder, it is also responsible for keeping registers of historic monuments.

The Standing Conference of the Ministers of Education and Cultural Affairs of the Länder (KMK) is the coordinating body and represents the common interest of the Länder to the Federal Government, the European Union and UNESCO. It is therefore involved in building up the awareness of the Länder's federal approach to cultural affairs. The KMK (Kultusminister Konferenz) is composed by the ministers responsible for education and schooling, institutes of higher education and research and cultural affairs, and in this capacity formulates the joint interests and objectives of all 16 federal states. The agenda of the Standing Conference of the Ministers of Education and Cultural Affairs is to address "educational, higher education, research and cultural policy issues of supraregional significance with the aim of forming a joint view and intention and of providing representation for common objectives" [3.12]. Within the scope of their Standing Conference of the Ministers of Education and Cultural Affairs, the federal states assume self-coordinating responsibility for the country as a whole.

Therefore, in Germany cultural heritage management is administered only in a regional focus, and it is not considered as a main topic on the national level [3.13]. At a national level, besides Standing Conference of the Ministers of Education and Cultural Affairs, other institutions, such as the Association of State Conservators and the Association of State Archaeologists, are organized to ensure the continuous exchange of knowledge and experiences as well as the enhancement of cooperation between specialists at national level in fields of heritage conservation and science. Moreover, the German Cultural Heritage Committee (DNK) is an interdisciplinary forum on the protection and conservation of Germany's architectural and archaeological heritages. The DNK targets private and public stakeholders linked to the heritage protection and conservation.

The concept of cultural heritage, which includes both architectural heritage and archaeological heritage, is common to all Lands, but it is a concept of good that refers to the individual good, without considering either a set of goods or the surrounding environment. They are in fact defined in Article 10 of the Code of Cultural Heritage as "those material, movable or immovable assets, which have an artistic or historical, archaeological value, or which are characteristic elements of a territory or a city, whose conservation is appropriate for artistic, historical or scientific reasons or for the promotion of conscience historical and national, which establish a public interest in this sense ".

From the definition we can see how the characteristics necessary for the identification of cultural good (Denkmal) for German law are basically two: the ontological characteristic of the object, which makes it suitable to be a cultural asset, and the public interest, which makes it worthy of state protection.[3.14]

From the national point of view the main laws are the following.

- "1919, Constitution of Weimar": First true law for the protection of cultural heritage, it has as its object all categories of goods, including those belonging to private individuals, and sees the role played by the central government as central.

- "1949, German Law": In contrast to what was done before, the competence of the Federation is limited to the protection of the German cultural heritage against export, while the direct protection of the heritage is entrusted to the individual Land.

Beginning in the 1960s, with the influence of the new awareness raising across Europe and taking shape in the 1964 Venice Charter, the individual Landers, through the individual Constitutions, introduce laws and administrative apparatus for the protection of cultural heritage , defining the protection criteria.
The federal regulatory reference on the issue is the law on the building: it establishes that in drafting the reference building projects the needs of protection and conservation related to areas and monuments of historical interest and to natural areas that must be taken into account must be taken into consideration. kept intact, and roads and places of importance from an urban, historical and cultural point of view.
At the territorial level a Conservation Statute must then be introduced, identifying the specific areas that are subject to limitation and to a particular authorization regime with regards to modifications and use of the building.
Although varying from Land to Land, the procedure for placing urban areas under constraint still requires the compilation of lists, even if in some legislatures these lists have binding value in others only for information purposes.
The direct protection of monumental areas can also take place in the planning phase. In this case they are regulated in accordance with the building code (Baugesetz-buch), the same code to which the Municipalities refer for the granting of concessions. It follows that even a general building plan (Bauleitungplan) can become a tool for the protection of the historical, artistic and cultural heritage.
In addition, officials of the Superintendent must be present at the time of drafting the regulatory plans, as representatives of the public interest, to check that the public image of

the city is preserved and that changes of intended use do not damage the pre-existing archaeological sites and the man-made landscape

Within the German legislation, a distinction is made between protection (Denkmalschutz) and care (Denkmalpflege): the first indicates the measures taken for the classification, conservation and improvement of the state of assets; while the second identifies the activities of consulting, research, promotion and support, including financial complementary to the measures themselves.

The difference is therefore not so much in the object, which is the same in both cases, as in the means at their disposal, which are normative acts and authoritative provisions for the protection and technical-practical activities and economic contributions for the treatment.

## 3.4 France

In France the interest for the protection of the national cultural heritage has started to move since the French Revolution, when the first measures for the protection of the monuments are issued, but it will become part of the national legislature in 1913, when the public interest is sanctioned for the cultural heritage. However, in 1970, the definition of cultural heritage that is still considered today: the cultural heritage includes “all natural or man-made goods without time or place limit or the set of traces of human activity that a company considers essential for its identity and collective memory and that it is necessary to preserve for the purpose of transmission to future generations "[3.8].

From the national point of view the main laws are the following.

- “Loi du 31 décembre 1913”: On the protection of “monuments historiques”.

- “Loi du 2 mai 1930”: On the protection of “monuments naturels et sites”. In this law, as in the previous one, it is stated that the monuments can be subjected to two procedures:
  1. Classification: the consent of the Minister of Culture is needed for each intervention;
  2. Registration in the supplementary Inventory: the consent of the Prefect of the Region and of the Mayor is required.

  These procedures allow the State to have effective control over the national heritage.

- “Loi du 25 février 1943” : The definition of monument is also extended to what is connected to the monument itself and to the surrounding space up to 500 m.

- “Loi du 4 aout 1962, n. 62-903 - Loi Malraux”: Aimed at areas of historical, aesthetic or otherwise with characteristics that make it worthy of conservation measures. A “secteur sauvegardé” is created for them, and a “plan de sauvegarde et de mise en valeur” (PSMV) is drawn up for each area. [3.15]

- "Loi du 24 février 2004, n. 178 - Code du Patrimoine": The decree aims to collect, simplify and coordinate the various rules promulgated over time in the field of cultural heritage protection.The decree, which came into force in conjunction with the Italian Cultural Heritage Code, it is spread over seven books, each of which deals with a different area of cultural heritage (archives; libraries; museums; archeology; historical monuments; sites, landscapes, and protected areas, provisions relating to overseas territories).Regarding the monuments, the decree describes the classification procedure to be applied: in a first phase an organism must express itself regarding the interest for the conservation of the asset; in a second moment a relationship is established between the public administration and the owner of the property; in the last phase we proceed with a "classement", that is with a transcription in the register of mortgages. "The State, therefore, exercises permanent control over classified goods regarding conditions of use and conservation. While the public owner is under a positive obligation to ensure the safekeeping and conservation of the object, the private owner is only required to behave negatively, that is to say he must refrain from any modification, repair or restoration in the absence of the necessary authorization." The asset cannot therefore be modified or sold without the consent of the Minister of Cultural Heritage or without the supervision of the Administration, a rule that must be respected penalty of criminal penalties and whose verification is made by means of a periodic census. The owner therefore has the duty to request authorization from the administration before carrying out repairs, maintenance or restoration, he can only perform those considered necessary by the State and must perform them under his control. As early as the 1980s, we saw an ever greater decentralization of managerial skills and a greater connection with local authorities. The main protagonist with regard to cultural heritage is the Ministry of Culture and Communication, which carries out the tasks of making the works accessible, ensuring the use of the heritage, encouraging the creation of works of art, intervening in the classification process, in interventions of restoration. In particular, with regard to this last point, the Ministry, with the help of an advisory body (the Commision National des Monuments Historiques), also provides opinions on class proposals and on the interventions to be carried out. Within the Ministry of Culture and Communication there is the "Directorate Gènèrele des Patrimoines", responsible for the policy of protection, conservation, restoration and enhancement of monuments, archaeological, ethnological and protected sites. In addition, the Ministry is present throughout the national territory through the "Directions Régionales des Affaires Culturelles" (DRAC), subject to the authority of the Prefect, who work through a general manager and several councilors and conservators. In particular, the main tasks concern: the conduct of the state's cultural policy in the region, participation in planning, sustainable development policies and social cohesion, as well as the evaluation of public policies, contribution to scientific research in the areas of its competence, dissemination of public data on the culture of the region and its constituent services, supervision of the application of regulations and scientific and technical supervision in public interventions.

## 3.5 United Kingdom

English history has meant that the United Kingdom differs from continental European states in the preservation of historic buildings.

The industrial revolution of the nineteenth century and the rapid modernization that ensued led the private individual to become aware of the problems of safeguarding the historical-artistic heritage in advance with respect to the State, which began to promulgate laws on it only in the following century. This is how important foundations and private companies are born, some still active, for the preservation of historical heritage. Among all the National Trust [3.16] stands out, which, created to compensate for the lack of national laws, was the author of the development of the cultural heritage philosophy. Cultural heritage indicates "the idea of the past as national pride".

The first private interventions for the preservation of historical heritage on the English territory date back as far as 1500, when the population opposed the demolition of 850 monasteries wanted by Henry VIII. Some of those monasteries managed to save themselves and were almost always converted back into a private residence, one of the oldest examples of "conservation and conversion" of a building.

The ‘800 was the century in which the modern safeguard movement began, which began with the foundation of the “Society of Protection Ancient Buildings” (SPAB), followed by numerous other companies for the purpose of protecting and promoting the art and architecture. The importance of these companies was to begin to put pressure on the governing bodies for the enactment of a legislature on the protection and conservation of the historical heritage. [3.17]

From the national point of view the main laws are the following.

- “Ancient Monuments Protection Act del 1910”: Safeguard activities were also extended to medieval castles, allowing the state to acquire numerous important complexes.

- “Ancient Monument Consolidation and Amendment Act del 1913”: The powers of the authorities are expanded.

- “Ancient Monument Act del 1931”

- “Town and Country Planning Act del 1932”: The systematic cataloging of the buildings to be protected is introduced, also accompanied by photographs.

- “Town and Country Act del 1947”: It is recognized that groups of buildings can contribute to increasing the architectural value, compared to that resulting from the sum of the individual parts.

- “Historic Building and Ancient Monument Act del 1953”: It establishes new safeguard and protection measures for buildings of historical interest, with particular reference to the country houses. An innovative concept is also introduced: "the funds will be allocated provided that the public visit is allowed".

- “Town and Country Planning Act del 1968”: The Department of Environment (DoE), the Ministry of the Environment, is established.

- “Local Government Planning and Land Act del 1980”: The "immunity certificate" is introduced for buildings registered on the protection lists.

- “Legislative provision of 1983”: English Heritage is born, which represents the connection structure between the central power and the regional and local level, promoting the best practice.

- “Legislative provision of 1988” Buildings constructed for only 30 years can also be placed under protection. Beginning in the early 2000s, the English legislation began to follow the norms issued by Europe more closely, in virtue of the fact that even at the European level the necessity of a legislation to protect cultural heritage was realized.

## 3.6 Italy

The attention to the preservation of the historical cultural heritage is also expressed in the Italian Constitution, in article 9, "The Republic promotes the development of culture and research. It protects the landscape and the historical and artistic heritage of the nation "[3.18].

From the national point of view the main laws are the following.

- "Legge 1089 del 1939, Tutela delle cose di interesse artistico o storico": The law was one of the first complete texts that dealt with the protection of cultural heritage and natural beauty. In particular, this law contains the following definitions:
  • provides the definition of cultural asset;

  • affirms the principle of public enjoyment of the cultural property;

  • arranges authorizations in case of intervention of any nature on the cultural property;

  • regulates the alienations, loans, transfers, imports and exports of cultural goods;

  • establishes sanctions in the event of contravention of these principles.

  This law represented one of the main reference texts for the protection of cultural heritage until the birth of the "Code of Cultural Heritage" in 2004, which replaced the 1939 Law considered incomplete and inadequate.

- "D. L. 22 gennaio 2004, n. 42, Codice dei beni culturali e del paesaggio, art. 10 L. 06/07/2002, n. 137": The "Code of Cultural Heritage and Landscape" is an organic body of provisions concerning the cultural and landscape heritage of the Italian Republic, issued with the Legislative Decree of 22 January 2004. It represents the main Italian regulatory reference which attributes to the Ministry for Cultural Heritage and Activities the task of protecting, conserving and enhancing Italy's heritage.
  The code in articles 2 and 10 gives the definition of "cultural heritage". Article 21, on the other hand, defines how works carried out on a cultural asset in Italy are always subject to authorization by the Superintendency.

  Authorization is given on a project or on a technical description of the intervention and may contain prescriptions.

  The Superintendency carries out safeguarding and protection tasks, through the management of the measures for the protection of cultural interest (the so-called "constraints"), that is, through the exercise of the authorization power in relation to projects of interventions involving all or part of the cultural heritage architectural.

  The Superintendencies are peripheral bodies of the Ministry of Cultural Heritage and Activities (MiBAC) of the Italian Republic. The territorial character of this institution is on the one hand necessary for the importance of the role it plays and the necessary knowledge of the territory on the other hand each institution has its own peculiarities that prevent having an univocal response at a national level of what can be or it cannot be done on a particular building.

- “PSC-POC-RUE”: Historic buildings in Italy, in addition to being subjected to the national regulations in force, must be subject to the regulation of the Municipality to which they belong, present in the "Coordinated text of PSC-POC and RUE standards".

# 4. THE CASE STUDY: THE DUCAL PALACE OF MODENA

The methodology developed in the framework of this research project was applied to a case study, the Ducal Palace of Modena, a magnificent historic-constrained building which identifies the Modena city all over the world. In past centuries, the Palace was the home of the "Estensi Duke"; today it hosts the prestigious Military Academy, a training school for officers of the Italian National Army.

The first step of the methodology is the Energy Audit of the building. Energy Audit is defined as "systematic inspection and analysis of energy use and energy consumption of a site, building, system or organization with the objective of identifying energy flows and the potential for energy efficiency improvements and reporting them".

The Energy Audit aims to provide an adequate knowledge of the energy consumption of a building, identify and quantify energy-saving opportunities in terms of cost-benefits (UNI CEI / TR 11428: 2011).

Energy consumption depends on various factors such as local climatic conditions and characteristics of the building envelope, characteristics and adjustments of the technical systems of the building, activity and processes in the building and behavior of the occupants and operating regime.

The purpose of this Energy Audit is to:

• collect a basic inventory of energy consumption of the building;

• identify the actions necessary to reduce energy consumption and CO2 emissions.

The execution of the Diagnosis allowed to:

• examine the trend of thermal and electrical consumption (s) of the last year (s);

• check the weight of energy carriers (fuel and electricity) in terms of primary energy used and climate-changing emissions;

• set a baseline for consumption and CO2 emissions;

• identify a series of technological retrofitting measures for the envelope-HVAC system classifying them on the basis of a multi-criteria analysis and attributing to each: the estimate of savings obtainable energy, the payback period, the estimated emissions avoided, the estimate of achievable annual savings and the possible presence of usable national incentives;

• improve the comfort of the rooms and their usability;

• identify a series of behavioral measures that allow to further reduce energy consumption at no additional cost.

The buildings composing the overall building complex of the "Ducal Palace of Modena" are five (see Figure 4.1):

1. Ducal Palace (mail building);

2. Dardi Palace (service building);

3. Abba Palace (service building);

4. Aliprandi Palace (service building);

5. Fanti pool (swimming pool).

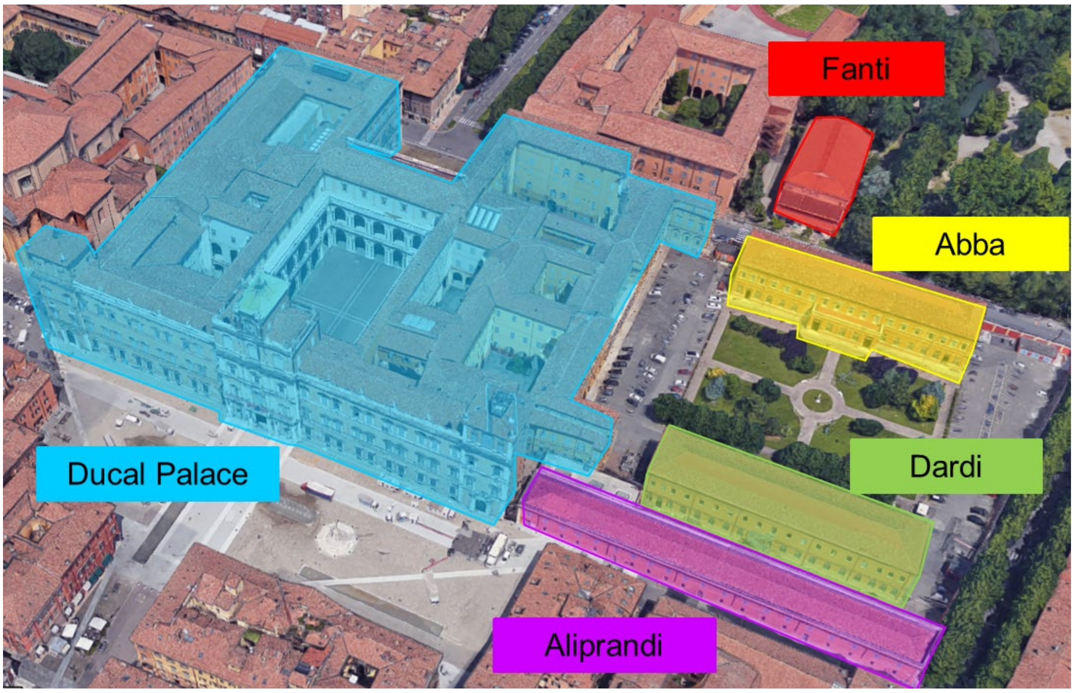



*Fig.4.1 – Ducal Palace of Modena*

The building complex is currently owned by the Public Property Office of the Historical and Archaeological Artistic State and today the building hosts the Italian Military Academy.

The entire complex has particular historical and artistic value and it is subject to the constraint of Scientific Restoration from the PSC of the Municipality of Modena.

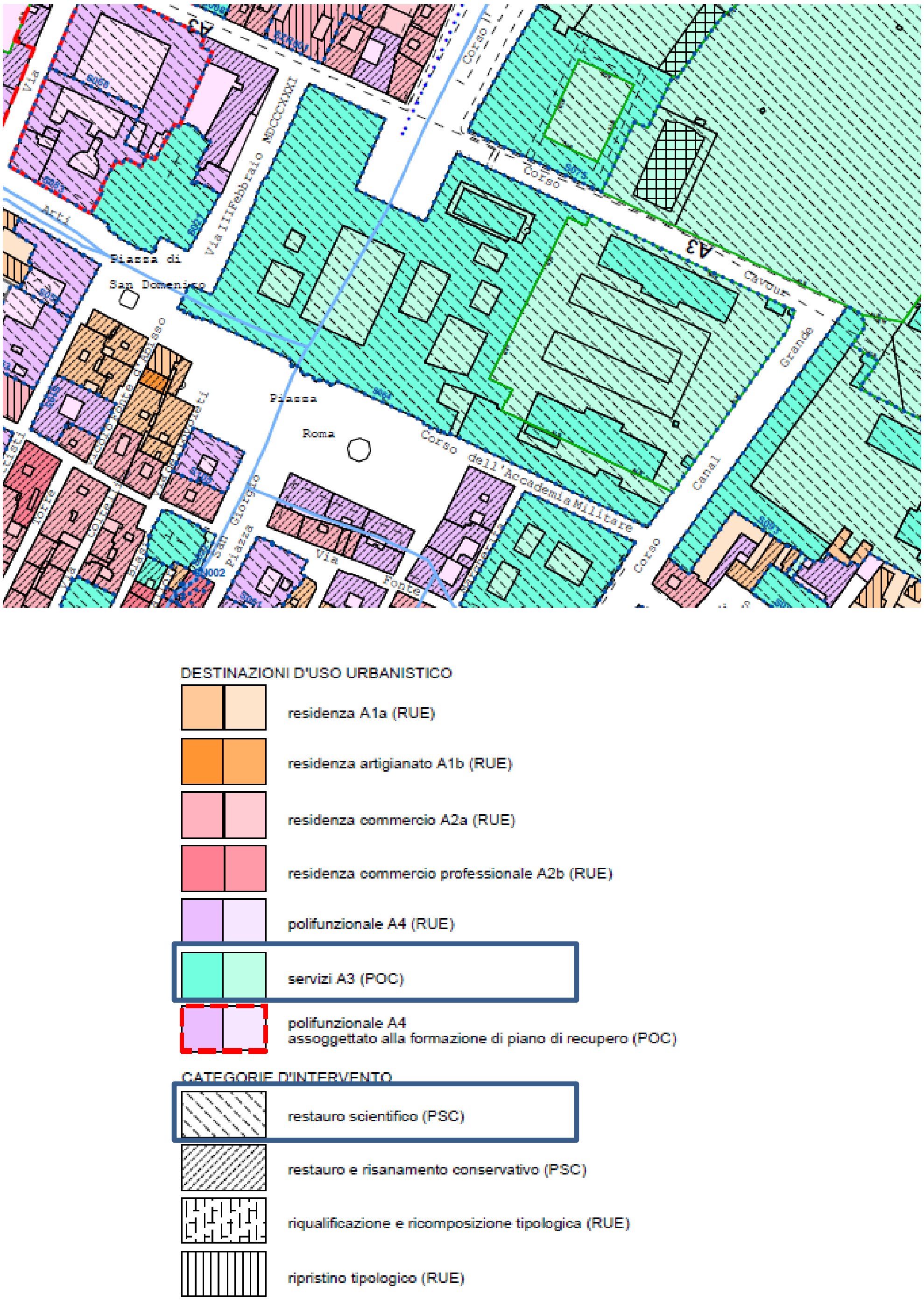



*Fig.4.2 – Constraints by PSC-POC-RUE of the Municipality of Modena*

The structure present in the urban building register of the Municipality of Modena on sheet 109, parcels 197-198-199-200-201, is located on the north side of Corso Cavour, to the east Corso Canal Grande, to the west with Via III February 1831 and Piazzale S. Domenico while to the south overlooking Piazza Roma.

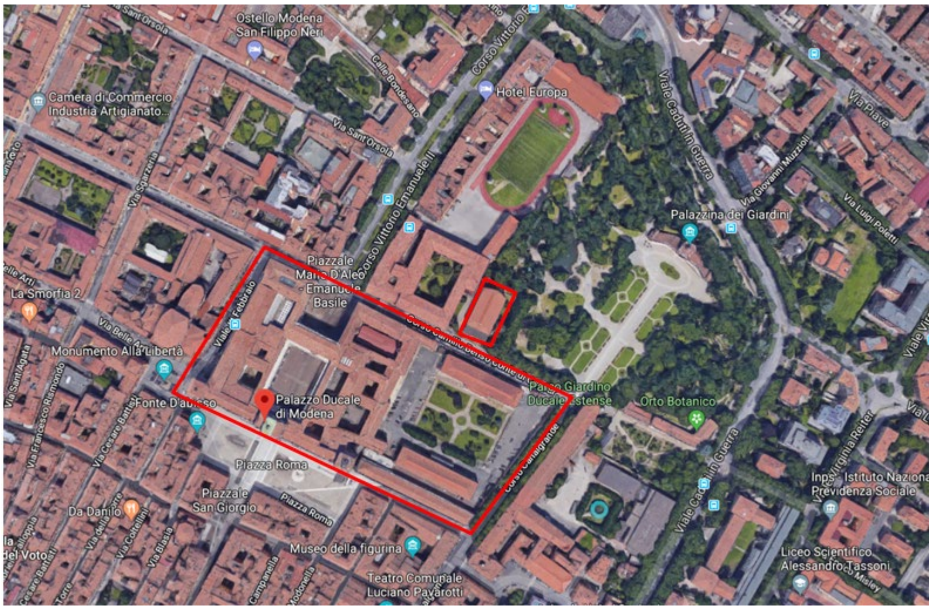



*Fig.4.3 – aerial photographic framing*

The Energy Audit was drafted in compliance with the criteria set out in Annex 2 of D.Lgs 2002/2014 “Implementation of Directive 2012/27 / EU on energy efficiency”:

a) it was based on operational data relating to updated, measured and traceable energy consumption and (for electricity) on load profiles;

b) it was included a detailed examination of the energy consumption profile of the buildings;

c) it was based, where it is possible, on the analysis of the life cycle cost, rather than on simple depreciation periods, in order to take into account the long-term savings, the residual values of long-term investments and interest rates Discount;

d) the results of the Diagnosis are proportionate and sufficiently representative to enable a true picture of the overall energy performance to be traced and to identify the most significant opportunities for improvement reliably.

The energy audit, thanks to detailed and validated calculations, can provide clear information on potential savings. The data used for the energy audit can be kept by the

Client for historical analyzes and for the monitoring of the performance after energy retrofit interventions.

The methodology used expressly refers to the scheme represented in the UNI CEI EN 16247-1: 2012 and UNI CEI EN 16247-2: 2014, All.A, correlated with the detailed procedure reported in the UNI CEI / TR 11428: 2011.

Within the general methodological framework envisaged by the aforementioned standards, for the definition and drawing up of the energy inventory, data mining of historical consumption was privileged, where provided, to guarantee the reliability of the results.

The analysis is carried out in the following phases:

• Acquisition of general data, explicitly requesting electricity and heat consumption data and the related billing data, with the aim of being able to analyze the actual consumption trend. In addition to this information, updated floor plans of the buildings and a scan of the Central Booklets containing the technical data of the heat generators present in the structure were requested.

• Survey of the state of affairs through:

- having read the premises subject to diagnosis, the heated and / or cooled rooms and those without heating;

- verification of the state of conservation of the envelope and the state of efficiency of the plants;

- verifies, without resorting to invasive tests and investigations, the stratigraphies of the building structure, also by finding design documentation where available;

- verification of the conditions, times and temperatures of use of the building.

• Analysis of the current state of the envelope-HVAC system of the building with subsequent calculation of the energy requirement, implemented taking into account the real conditions of use of the building with reference to:

- set point temperature for the different thermal zones,

- operating time of the air conditioning systems,

- simulated under static conditions or not taking into account the variability of the temperatures and the utilization regimes of the building during the simulation days.

Inside the building the thermal zones are defined as homogeneous zones for:

• internal room temperature,

• intended use and internal loads,

• prevailing issue system,

• ventilation loads.

In the event that it is impossible to find certain elements regarding the actual construction materials used in the building envelope, the thermostatic data are assumed based on non-invasive surveys, by construction analogy based on the time of construction (in compliance with UNI TS 11300 standards 1: 2014 and UNI TR 11552: 2014), to the thicknesses detected during the inspection and visual surveys on any uncovered areas of the structure itself. Of the transparent structures the coefficients of thermal transmittance for each window are estimated on the basis of the dimensions detected in the field, the material and thickness of the frame, the thickness of the glass measured by thick-glass, the presence or absence of a low-emissive coating on the inner side of the outer glass. The heat exchange towards the ground is calculated according to the UNI TS 11300-I, UNI EN ISO 6946, UNI EN ISO 13370. The thermal bridges of opaque building structures are calculated in according to the UNI EN ISO 14683 and UNI EN ISO 10211. Ventilation loads and consequent air changes refer to the UNI 10339 standard for the various destinations of use. For the calculation of the net area, from which to derive the standard crowding, one bases itself on the consistent surveys found during the inspection. The DHW requirement is calculated according to the schedules reported in UNI TS 11300-2. With regard to the calculation of the electricity demand for internal artificial lighting, reference is made to the UNI EN 15193 standard regarding the estimate of the daily start-up hours of each lamp of known power.

The regulatory references used in the energy audit are shown in Annex B.

Given the historical importance of the buildings of the case study, it was considered appropriate to provide a brief historical description of the same.

## 4.1 History and architectural features of the Ducal Palace Of Modena

The building selected as case study is the Ducal Palace of Modena. The building hosted for two centuries the Estense family and it is one of the most important Sixteenth Century princely palaces in Italy. The Palace currently houses the Italian Military Academy, the Military Museum and a precious library. The Italian Military academy is a military university and it was the first such military institution to be created in the world. University activities are carried out in collaboration with the Universities of Modena and Reggio Emilia, among others.

The building was built in 1634 and it was located in a strategic position, between the Medieval city center and the new neighborhoods of the ducal capital city. The construction was initially supervised by the architect Gaspare Vigarani and later by Bartolomeo

Avanzini. However it seems that the whole palace design was supervised by Gian Lorenzo Bernini, who contributed to the realization of a solemn and elegant Baroque architecture.

*Fig.4.4 – Ducal Palace of Modena*

### 4.1.1 History of The Ducal Palace Of Modena

Today's Military Academy has seen many transformations over the course of history also because of the different functions it had to perform.

The building, which belonged to the Este family since 1200, was fortified by the Marquis Obizzo II in 1291, a Parmesan chronicle of the time describing it as a circle of walls, surrounded by a moat, with drawbridges, four towers and a palace internal. [4.1]

The Castle dominated the Naviglio and the city for only 15 years, in fact in 1306 a coalition of notables and popular forces overthrew the Este Lordship and restored the town, the "respublica mutinensis", which had the Castle destroyed.

In 1336 the Marquis Nicolò brought back Modena under the Este dominion and in 1340 he began the works for the construction of the new castle in the footsteps of the previous one and expanding the walls.

The castle therefore remained the military base for the control of the Marquis of Este who became Dukes in 1452 and dominated the city of Modena until the year 1510 when the papal militias of Julius II seized the city. From that moment the castle hosted a papal governor in the name of Pope Julius II (later of Leo X and Clement VII), with some intervals of imperial delegates; the most famous of the papal delegates was the Florentine Francesco Guicciardini.

This situation of ecclesiastical dominion over the Castle lasted until 1527 when Alfonso II Este regained Modena but some years had to pass before the imperial award confirmed its possession (1531); during these years, which also saw two passages for the Emperor Charles V in Modena, the castle was also the seat of a delegate of the Empire.

With the return of the Estensi, the Castle was the seat of the governors who operated on behalf of the Dukes who resided in Ferrara; the last figure of the governor was that of Ferrante Estense Tassoni, who was "Lord of the Castle" for twenty-two years and it was he who on 29 January 1598 welcomed Cesare I Este to Modena who had expelled the Faentine Convention (along with the entire Estense family).

Under Caesar I and his successors the old and ruined castle turned into a palace that soon came to occupy a symbolic position for the city, seat of the Ducal Court and official residence of the dukes themselves became the center of the new straight quarters of the ducal capital.

The crucial moment of the transformation came under the duchy of Francesco I (1629-1658), it was he who overcoming the paternal objections started in 1634 the long-standing transformation of the castle into a palace, destined to remain unfinished for centuries.

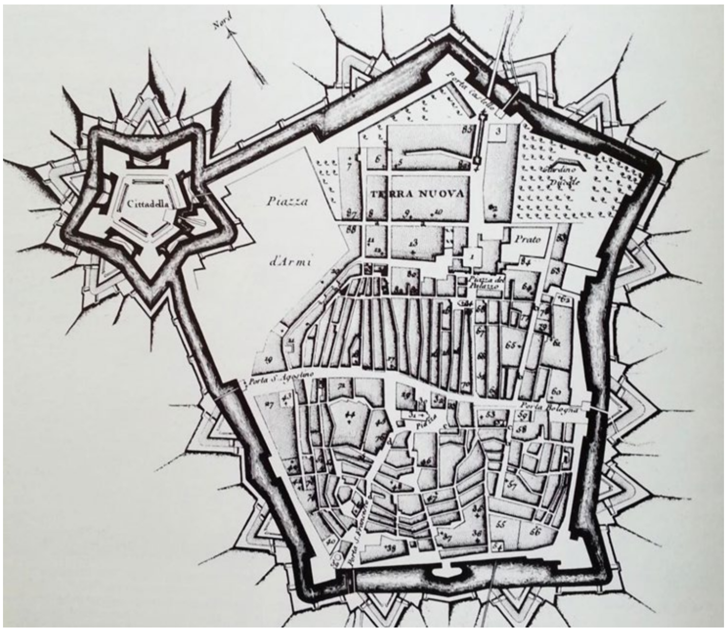



*Fig.4.5 – "Plan de Modéne - 1789"*

The foundation of an original military training institute dates back to the years of Este rule on the Dukes of Modena. The Ducal Military Architecture Academy and Conference, based in the Palace, came into operation in 1757 when Duke Francesco III d'Este commissioned Colonel Giuseppe Davia to complete the project to found a school for the training of officers Estense army. The Academy was active until 1772, when it was closed.

The “Avanzini” palace was the seat of the princes of Este until 1796 when the waves of the French revolution also touched these sleepy ducats, Ercole III d'Este abandoned the palace which took on different roles during the period of French domination (1796-1814 ).

In 1797 it received the Cispadano Government; between 1797 and 1798 it became the headquarters of the Central Administration of the Panaro, while from 1798 to 1814 it again became the seat of a prestigious military school (National School of Genius and Artillery), which provided dignified official approval to the Napoleonic armies until 1814, year of the fall of Napoleon.

Under the French rule the palace took the name of “Palazzo Nazionale” for the first time.

After the Restoration, the palace returned to host the Court, now Austro-Estense, in 1815 under the guidance of Francesco IV d'Este, who founded a Military Noble Academy, later called the Estense Military Academy, which lasted from 1821 to 1848.

From 1814 to 1859 the function of the Palace began to be public, and, in fact, it housed offices, libraries, art galleries and archives.

In 1859, following the abandonment of the Duke Francesco V and the definitive fall of the Estense Kingdom, the palace passed into the hands of the newly-born Italian State.

The Napoleonic experiences on the establishment of a military academy in Modena (the National School of Genius and Artillery, 1798-1814) suggested to the Minister of War of the newly born Kingdom of Italy, General Manfredo Fanti, the idea to establish a military training institute in Modena: the Military School of Central Italy (founded in 1859), then named in 1860 as the Military Infantry School. In 1865 it became a Military School of Infantry and Cavalry, to then simply assume the title of Military School until 1922. In 1923 it took the official name: Military Academy of Infantry and Cavalry (Modena). In 1928 he then acquired the title of Regia Accademia.

After the end of World War II, in 1947, at the behest of the Chief of Staff of the Army Raffaele Cadorna, the Military Academy of Artillery and Genius of Turin went to join the Military Academy of Infantry and Cavalry of Modena. From their union comes what is now known as the Military Academy of Modena.

Today the Palace also houses the Accademia Historical Museum and a precious Library. Therefore, the superior powers that dominated the palace during the centuries were different: Estensi, Chiesa, Impero, Estensi again, Republican France and then Napoleon, Austro-Estensi and finally the Italian unitary State.

### 4.1.2 Architectural Description Of The Ducal Palace Of Modena

The Ducal Palace of Modena is an impressive architectural work, presenting elements of historical and artistic value integrated over the centuries to the Palace and briefly described below.

The expansion works that gave the Palace its present appearance were first entrusted to the architect Gaspare Vigarani, and later, carried out in 1634 by Bartolomeo Avanzini by order of Francesco I d'Este; but it seems that the project has undergone the supervision of Gian Lorenzo Bernini: the great architect seems to have participated in the creation of a work that reveals a solemn, elegant and unitary style, typical of the baroque as can be well observed in the majestic facade, where it is placed the main entrance, lightened by the chromatic play of the marbles.

The main façade (overlooking "Piazza Roma"), which features an imposing and harmonious façade, has three rows of airy twin windows surmounted by triangular and curvilinear tympanums enclosed by two lateral towers (probably remembering the pre-existing fortress) surmounted by a balustrade with overhanging theory of statues.

*Fig.4.6 – The main façade (overlooking "Piazza Roma") of the Ducal Palace*

The façade, recently restored, is characterized by the color of the marble and decorated with statues and various artifices, which make it overall, symmetrical and harmonious; harmony that cannot be affected in any way and for this reason protected by the Ministry of Cultural Heritage and Activities and Tourism.

The central tower, slightly protruding from the remaining façade, is instead lightened by a loggia with three arches and by the clock loggia.

The columns, which support the large balcony and flank the main portal, frame the statues of Hercules and Emilio Lepido, by P. Sogari.

The statues on the balcony at the top of the facade of the Palace represent on the right side Hercules, Juno, Pallas and Mercury, built towards the end of the seventeenth century, while on the left side we can admire the statues of Vulcano, Ceres, Bacchus and Venus made by Giuseppe Graziosi. The central tower of Mars, Virtue, Fortress and Time crown, while Jupiter and Neptune are represented on the north side.

From the central door on “Piazza Roma”, one enters the atrium made with cross vaults on a series of columns transformed, in 1929, into a Lapidary where the names of the 7811 Officers, former students of the Academy, fallen in the wars for the Unity, Independence and Liberation.

The atrium leads to the most representative element of the building, the great Court of Honor “Cortile d’Onore”, the setting for the main military ceremonies of the academy (the Jury, the ceremony of the suggestive “Ballo delle Debuttanti”); conceived by Avanzini, it has a quadrangular shape and is delimited by two orders of overlapping round arches, interspersed with columns and pilasters separated by Doric and Ionic pilasters and surmounted, like the façade, by a balustrade.

*Fig.4.7 – Court of Honor “Cortile d’Onore”*

Regarding the morphology of the loggias, the effectiveness of Bernini's suggestion aimed at giving the whole more uniformity and speed through the replacement of the architrave angular gates with other serlians and the approach of the columns is well known.

Part of the elegant loggia consists of columns recovered in the Complex of the Royal Savoy Academy of Turin established on September 1, 1677 and destroyed by aerial bombing of the Second World War. Recovered part of the colonnade was in fact transported and reassembled in 1960 in the courtyard of the Ducal Palace of Modena.

From the “Cortile d’Onore” you reach the opulent “Scalone d’Onore”, an extremely refined and scenic realization; spread over six flights interrupted by four landings. Along the ramps are the statues of Prudence and Abundance, by A. Baratta; the other six are from the Roman era and come from the famous “Villa D’Este” in Tivoli. The most valuable sculpture is undoubtedly Minerva who, during the French occupation of 1796, was transported to “Piazza Grande” to represent Liberty and in that spot suffered serious damage.

The staircase leads to the upper “loggia” that surrounds the “Cortile d'Onore” on all four sides and allows access to the halls of the west wing of the building and to the ancient ducal apartments (of which the most famous rooms are the “Sala del Trono”, the “Salottino d'Oro”, the “Salone d'Onore” and the “Sala dello Stringa”). Inside the palace there are vast rooms richly decorated and frescoed, such as the suggestive “Salone d’Onore” where there is a majestic masterpiece by Marco Antonio Franceschini, made in the eighteenth century on the ceiling: fresco depicting the coronation of Bradamante, progenitor of the Este (celebrated by Ariosto in the “Orlando Furioso”).

*Fig.4.8 – Staircase of Honor “Scalone d’Onore” of the Ducal Palace of Modena*

*Fig.4.9 – Salon of Honor "Salone d'Onore" of the Ducal Palace of Modena*

Evocative testimony of the magnificence of the small court of Modena in the eighteenth century is the "Salottino d'Oro", the work cabinet of Duke Francesco III, who in 1756 had it covered and decorated with panels covered with pure gold. A curiosity: the panels were removable, which allowed the inhabitants of Modena to preserve the small living room, dismantled and hidden in the basements, despite the occupations and looting.

*Fig.4.10 – Gold room "Salottino d'Oro" of the Ducal Palace of Modena*

Inside the private ducal apartment, made up of rooms with valuable coffered ceilings, stuccos and embossed leathers, is the Historical Museum of the Military Academy which contains weapons and armor, memories, military memorabilia  (flags, uniforms, drums), etc. ). The apartment of the princes is currently the seat of the Library and the west wing of the building.


*Fig.4.11 – Gold Medal Gallery - Museum of the Military Academy of Modena*

The paintings that can be admired today in the palace belong to the Military Academy and to the Superintendency for the Historical, Artistic and Ethno-anthropological Heritage of Modena and Reggio Emilia. The most common authors are nineteenth-century portraitists, almost always teachers at the Academy of Fine Arts in Modena.

The Ducal Palace covers a total area of approximately 17.063,00 m², which also includes the six internal courtyards, shown in Figure: “Cortile d'Onore”, “Cortile Torino” , “Cortile Giulio Cesare”, “Cortile Infermeria”, “Cortile Colonne” and “Cortile Fontane”.

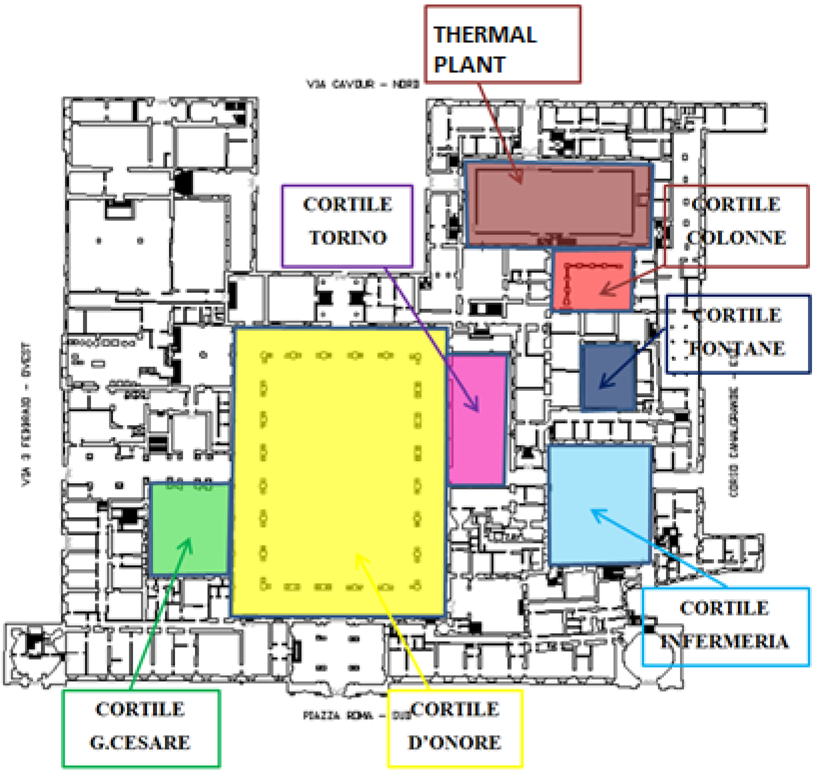



*Fig.4.12 – Ducal Palace Planimetry - Internal Courtyards*

The Palace develops on different levels:

**<u>a) Basement</u>**

The underground passages develop under almost the entire footprint of the Palace, including the courtyards (where there are underground passages and canals). The premises are mainly used for warehouses, warehouses, technical rooms. The main pipes develop in the basement ceiling, the rooms have a height of about 2 m, ventilated in some areas by windows. Always at the basement level there is the Thermal Plant.

*Fig.4.13 – Ducal Palace Basement Planimetry*

**b) Ground floor**

The entire floor is slightly elevated above the ground, there are over a hundred rooms with different uses:

- offices and archives (blue area);

- accommodation of the General Commander, representative and private apartments (yellow area);

- kitchen area, pantry and cold storage (gray area);

- great hall (red area);

- typography and paper deposit warehouses (pink area);

- military surveillance zone, picket officer, switchboard and artillery (green area);

- ambulatory area (blue area).

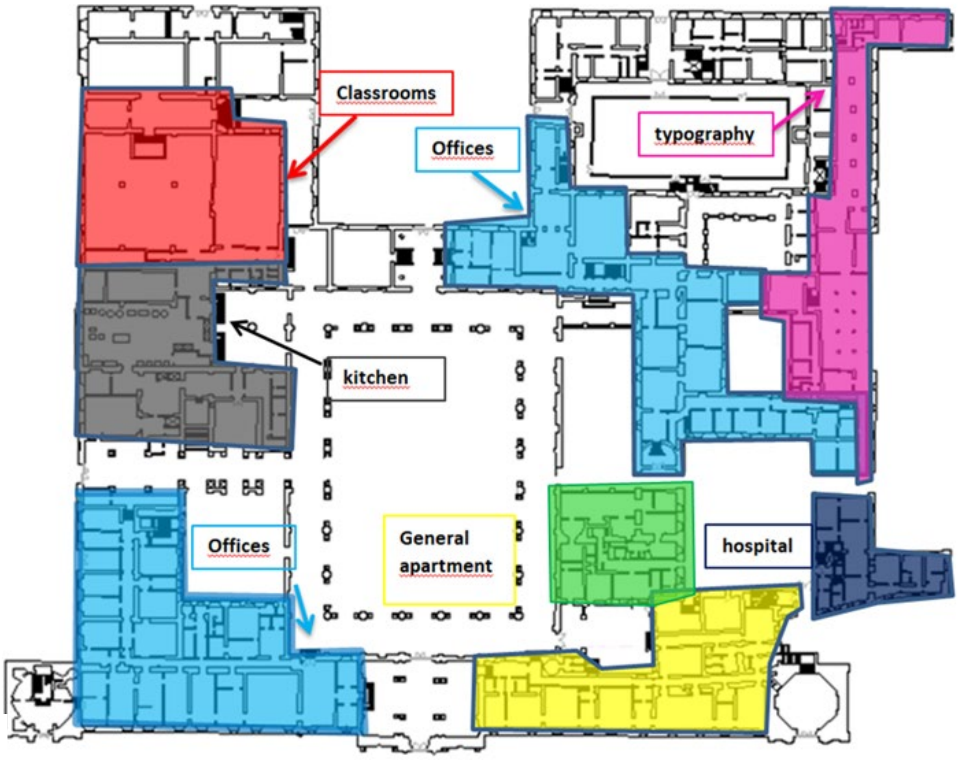



*Fig.4.14 – Ducal Palace Ground Floor Planimetry*

**c) First Floor (mezzanine floor)**

In the Palace, in various areas, mezzanine floors have been created; occupied by toilets, warehouses, depots (overlooking the “Cortile Infermeria”) and offices (overlooking the “Cortile Giulio Cesare”).

**d) Second Floor**

It is the noble floor that overlooks the balustrade overlooking the “Cortile d 'Onore”, the heart of the Palace. The main destinations of use are:

- cafè and canteen area Civil / Military Staff (yellow area);

- Duke Este apartments, Museum and Gold Medal Gallery, (red areas);

- Military student recreational club (pink area);

- military and managerial offices of the Chaplain (blue areas);

- hospital, clinic and sociopsychological agency (purple area);

- library and reading room (green area).

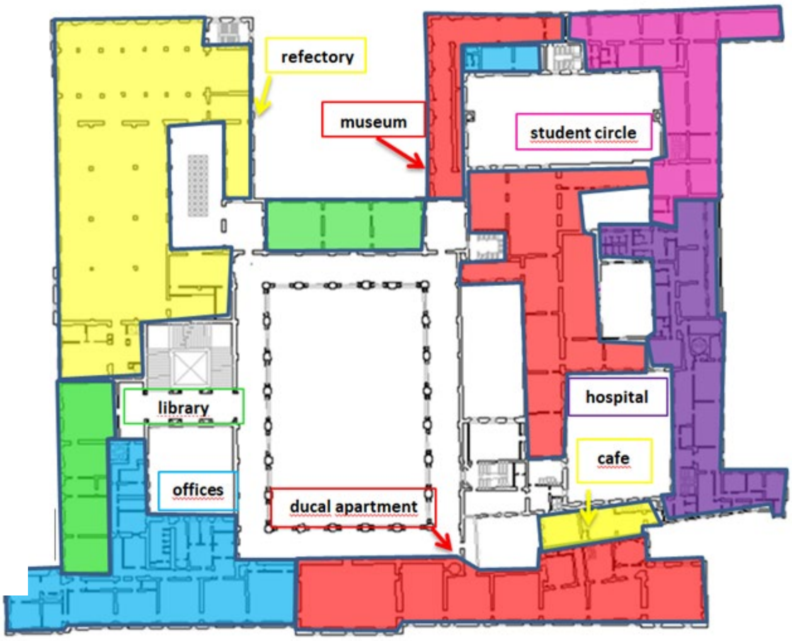



*Fig.4.15 – Ducal Palace Second Floor Planimetry*

**e) Third Floor (mezzanine floor)**

Occupied by the photo lab and archives.

**f) Fourth Floor**

The fourth floor is occupied by the following destinations of use:

- classrooms dedicated to lessons for students (red area);

- administrative offices with civil and military personnel (blue area);

- lodgings and non-commissioned officers club ("Nucleus 7" which is currently not accessible and not being used);

- Museum of Physics (yellow area).


*Fig.4.16 – Ducal Palace Fourth Floor Planimetry*

## g) Attic

The place is practicable, but scarcely used, there is a prestigious vinegar factory and you can see the functioning mechanism of the ancient clock allocated in the central tower of the Palace. The extrados of the floor sometimes, the environment has a variable height from about 3-5 m, the roof is made of wood and tiles, except in some areas where it was recently restored and built with beams in concrete.

*Fig. 4.17 – Attic of the Ducal palace*

## 4.2 The Dardi Palace

The building dating back to the early 1900s was built on two floors. The ground floor houses the offices of the Carabinieri nucleus and the gymnasium where the volleyball and basketball teams of the Military Academy train and play matches during the year.

On the first floor there are about thirty study rooms for the students of the Military Academy.

*Fig.4.18 – Dardi Palace*

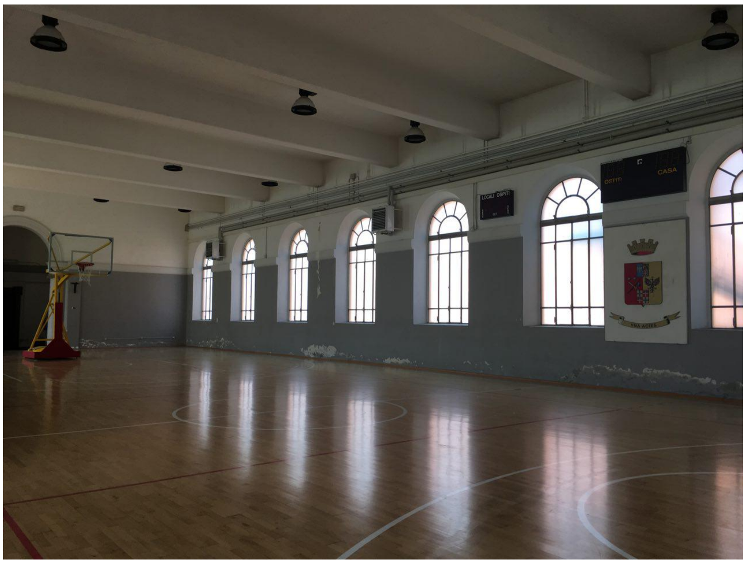


*Fig.4.19 – Dardi Palace - gymnasium*

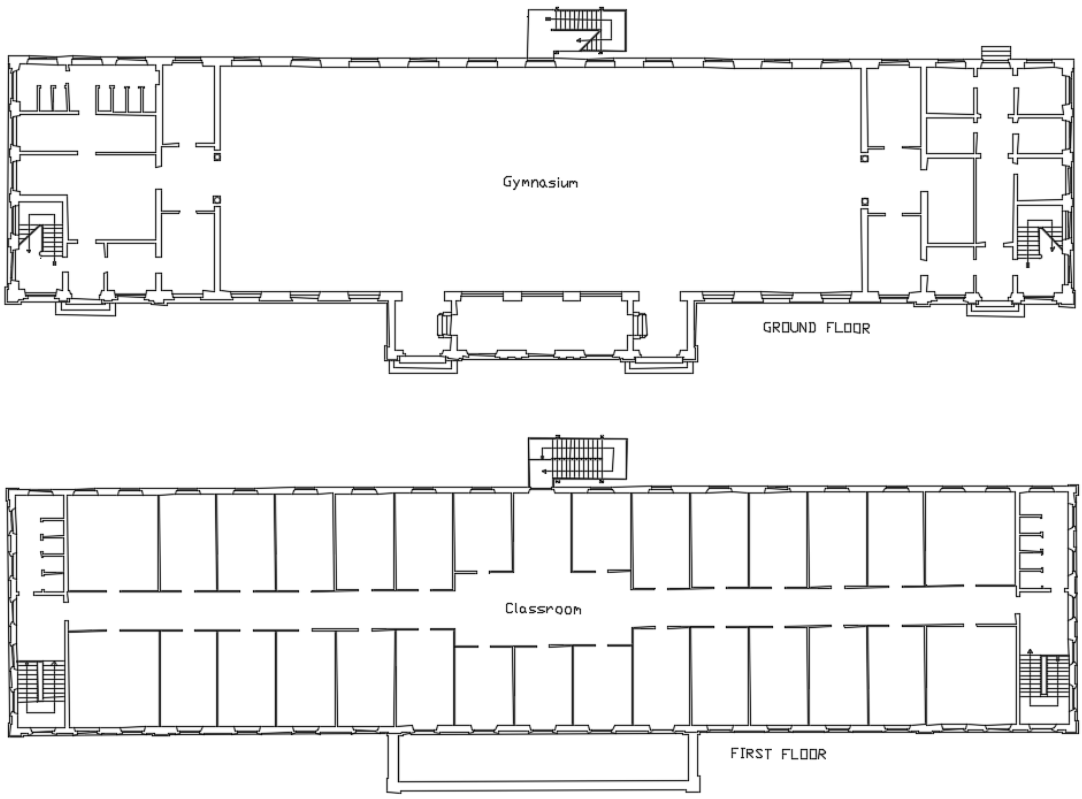



*Fig.4.20 – Dardi Palace - planimetry*

## 4.3 The Abba Palace

The building exactly mirroring the Dardi dates back to the construction period in the early 1900s and is spread over two floors.

The ground floor houses the personal defense gymnasium of the Military Academy. On the first floor there are about thirty study rooms for the students of the Military Academy.

*Fig.4.21 – Abba Palace - gymnasium*

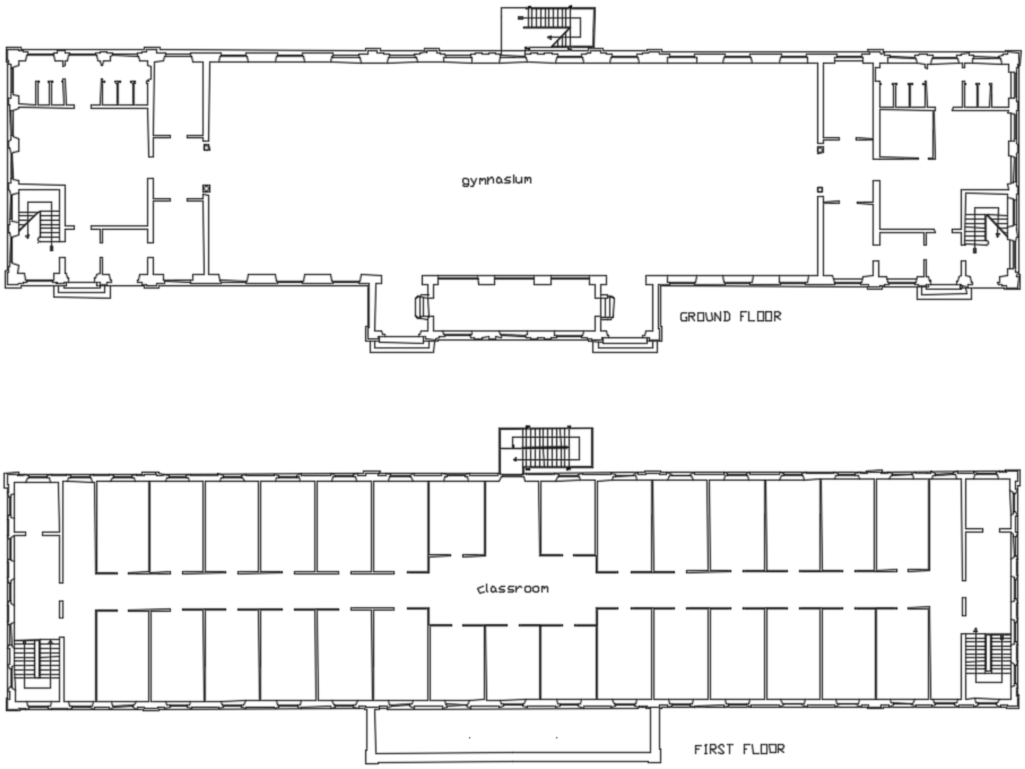



*Fig.4.22 – Abba Palace - planimetry*

## 4.4 The Aliprandi Palace

The building dating back to the early 1900s was built on two floors above ground.

On the ground floor there is an area destined to a warehouse, an area hosting a joinery and an area for office use (headquarters command).

While the first floor is entirely used as rooms and services as a dormitory.

*Fig.4.23 – Aliprandi Palace*

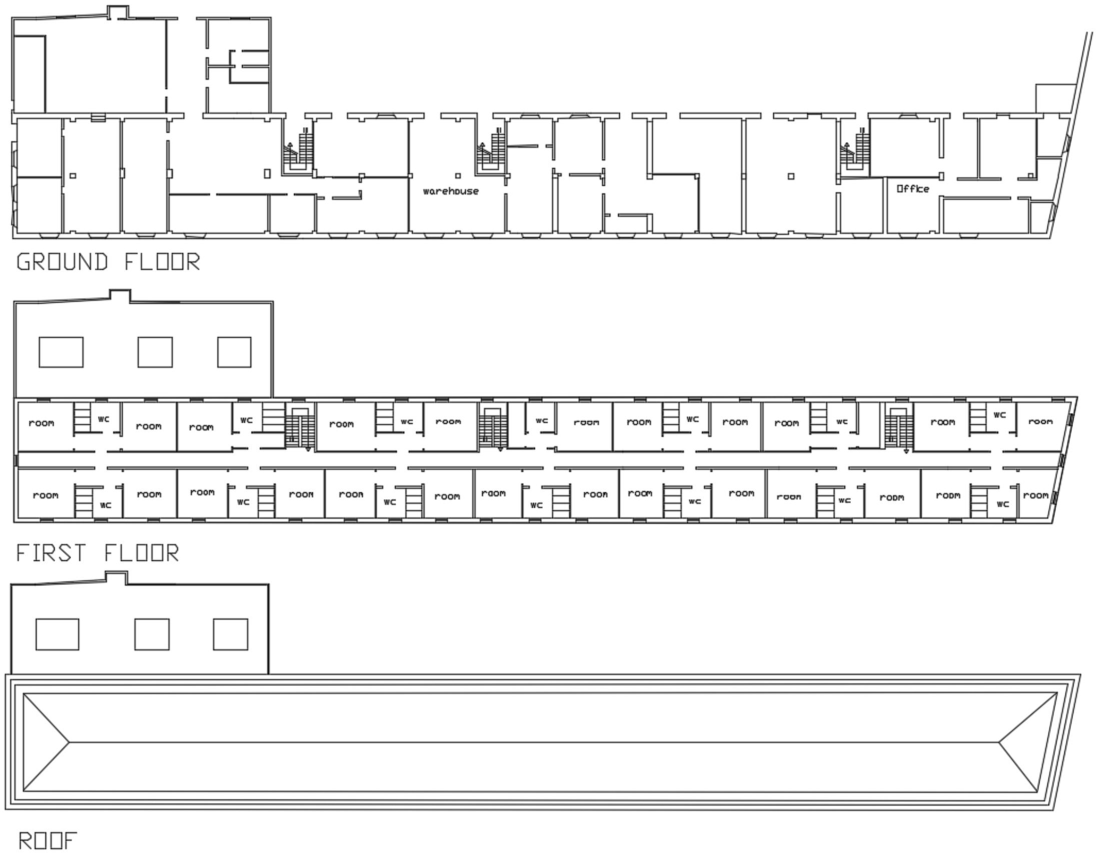



*Fig.4.24 – Aliprandi Palace - planimetry*

## 4.5 The Fanti Pool

The building dating back to the early 1900s is spread over three floors.

On the ground floor there is the entrance, the administrative offices of the pool and the technical room where the plant and the compensation tank are located. On the first floor there is the pool, the changing rooms and on the floor according to the stands for the spectators.

*Fig.4.25 – Fanti Pool*

*Fig.4.26 – Fanti Pool*

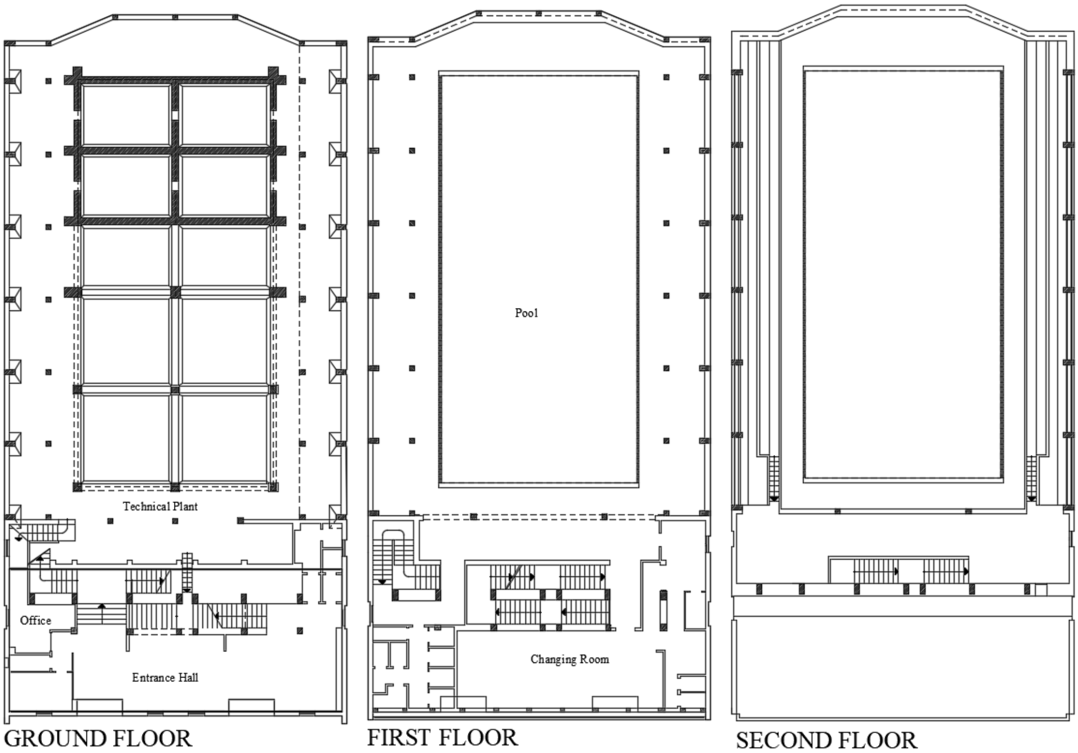



*Fig.4.27 – Fanti Pool - planimetry*

## 4.6 Characteristics Of The Building Envelope

The characteristics of thermal transmittance of the various components of the building envelope are shown below.

Transmittance U measures the amount of heat that passes through a flat element of 1 m² in the unit of time separating two aeriforms (1 K temperature difference) by radiation, convection and conductivity.

$$U = \frac{1}{\frac{1}{\alpha_i} + \sum_j \frac{L_j}{\lambda_j} + \sum_k \frac{1}{C_k} + \frac{1}{\alpha_e}} = \frac{1}{R_{si} + \sum_j \frac{L_j}{\lambda_j} + \sum_k R_k + R_{se}} \quad [4.1]$$

where:

- $C_k$ thermal conductance of the non-homogeneous component k-th, [W/m$^2$K];
- $\alpha_i$ internal adductive heat transfer coefficient, [W/m$^2$K];
- $\alpha_e$ external adductive heat transfer coefficient, [W/m$^2$K];
- $R_k = 1/C_k$ resistance of the non-homogeneous component k-th, [m$^2$K/W];
- $R_{si} = 1/\alpha_i$ internal surface resistance, [m$^2$K/W];
- $R_{se} = 1/\alpha_e$ external surface resistance, [m$^2$K/W].

### 4.6.1 Characteristics Of The Building Envelope of the Ducal Palace of Modena

The project for the execution of the structure isn’t available so the building envelope characteristic provided by the Italian Energy and Environment Thermo-technical Committee, a federated body of the UNI, were considered as a reference, presenting general indications on the geographical and periodic diffusion of the constructive stratigraphic typology. Considering the measurements carried out on site and the characteristic construction types of the 1600s, the following stratigraphies were considered.

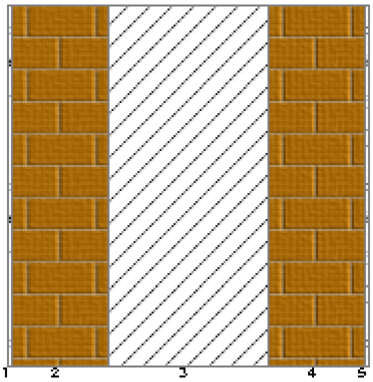
The external masonry is a “sack” with solid brick walls and inert materials inside (typical of the Italian construction period). The thermo-physical properties of the materials, not having the accompanying data of the CE marking, were obtained from prospectuses in accordance with (UNI 10351 and UNI 10355).

It is interesting to note the thickness of the wall which denotes one of the fundamental characteristics from the thermo-physical point of view of the building, the high thermal inertia.

## Opaque Vertical Walls

**Description of the components of the building envelope:  External Wall**

| | | |
|---|---|---|
| Thermal Trasmittance | **0,900** | $W/m^2K$ |
| Thickness | **1130** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **0,040** | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | **2528** | $kg/m^2$ |
| Surface Mass (without plaster) | **2480** | $kg/m^2$ |
| Periodic Transmittance | **0,001** | $W/m^2K$ |
| Attenuation Factor | **0,001** | - |
| Thermal Wave Phase Shift | **-7,7** | h |




**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,130 | - | - | - |
| 1 | Plaster | 15,00 | 0,800 | 0,019 | 1600 | 1,00 | 10 |
| 2 | Masonry | 300,00 | 0,810 | 0,370 | 1800 | 1,00 | 7 |
| 3 | stone | 500,00 | 3,500 | 0,143 | 2800 | 1,00 | 10000 |
| 4 | Masonry | 300,00 | 0,810 | 0,370 | 1800 | 1,00 | 7 |
| 5 | Plaster | 15,00 | 0,800 | 0,019 | 1600 | 1,00 | 10 |
| - | External Surface Resistance | - | - | 0,061 | - | - | - |

Symbol Legend

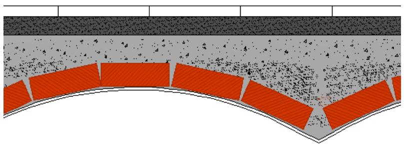
| | | |
|---|---|---|
| s | Thickness | mm |
| Cond. | Thermal Conductivity | W/mK |
| R | Thermal Resistance | $m^2K/W$ |
| M.V. | Volume Mass | $kg/m^3$ |
| C.T. | Specific heat capacity | kJ/kgK |
| R.V. | Resistance factor for vapor diffusion in dry head | - |

## Horizontal Floors

The same procedure was used to calculate the transmittance of horizontal walls; also the stratigraphy of the roof and inter-floor slab has been evaluated by means of reference schedules and on-site visual-instrumental analysis. Below are the stratigraphies of the floors with the relative transmittance.

**Description of the components of the building envelope: underground floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,012** | $W/m^2K$ |
| Thickness | **505** | mm |
| External Temperature (winter power calculation) | **10,0** | °C |
| Permeance | **0,001** | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | **874** | $kg/m^2$ |
| Surface Mass (without plaster) | **874** | $kg/m^2$ |
| Periodic Transmittance | **0,043** | $W/m^2K$ |
| Attenuation Factor | **0,042** | - |
| Thermal Wave Phase Shift | **-17,3** | h |

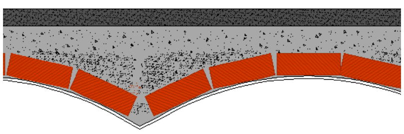


**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,170 | - | - | - |
| 1 | Floor | 15,00 | 1,300 | 0,012 | 2300 | 0,84 | 9999999 |
| 2 | Substrate of lean concrete | 40,00 | 0,700 | 0,057 | 1600 | 0,88 | 20 |
| 3 | Filling of bulk materials | 250,00 | 0,700 | 0,357 | 1500 | 1,00 | 5 |
| 4 | brick vault | 200,00 | 0,900 | 0,222 | 2000 | 0,84 | 10 |
| - | External Surface Resistance | - | - | 0,170 | - | - | - |

**Description of the components of the building envelope: Roofing towards the attic**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,157** | $W/m^2K$ |
| Thickness | **490** | mm |
| External Temperature (winter power calculation) | **5,0** | °C |
| Permeance | **28,209** | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | **823** | $kg/m^2$ |
| Surface Mass (without plaster) | **823** | $kg/m^2$ |
| Periodic Transmittance | **0,080** | $W/m^2K$ |



| | | |
|---|---|---|
| Attenuation Factor | **0,069** | - |
| Thermal Wave Phase Shift | **-16,0** | h |

**Stratigraphy:**

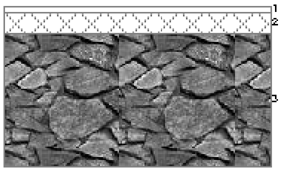
| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External Surface Resistance | - | - | 0,100 | - | - | - |
| 1 | Concrete | 40,00 | 0,470 | 0,085 | 1200 | 1,00 | 96 |
| 2 | Filling of bulk materials | 250,00 | 0,700 | 0,357 | 1500 | 1,00 | 5 |
| 3 | brick vault | 200,00 | 0,900 | 0,222 | 2000 | 0,84 | 10 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

## Ground Floor

**Description of the components of the building envelope: Ground Floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **2,115** | $W/m^2K$ |
| Ground thermal transmittance | **0,453** | $W/m^2K$ |

| | | |
|---|---|---|
| Thickness | **300** | mm |
| External Temperature (winter power calculation) | **13,3** | °C |
| Permeance | **44,944** | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | **520** | $kg/m^2$ |
| Surface Mass (without plaster) | **520** | $kg/m^2$ |




| | | |
|---|---|---|
| Periodic Transmittance | **0,794** | $W/m^2K$ |
| Attenuation Factor | **1,753** | - |
| Thermal Wave Phase Shift | **-7,7** | h |

**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,170 | - | - | - |
| 1 | Floor | 10,00 | 1,000 | 0,010 | 2300 | 0,84 | 200 |
| 2 | Substrate of lean concrete | 40,00 | 0,900 | 0,044 | 1800 | 0,88 | 30 |
| 3 | Coarse gravel without clay (um. 5%) | 250,00 | 1,200 | 0,208 | 1700 | 0,84 | 5 |
| - | External Surface Resistance | - | - | 0,040 | - | - | - |

**Windows**

The windows of the building are currently all single glass and painted wooden frame with fixed toplight, most of them in an ancient state of preservation.

Below is a "standard" window; there are about thirty different types of windows and doors in the building with the same thermal characteristic but different dimension.

The thermal transmittance of the glazed elements and their respective frames is calculated according to UNI EN ISO 10077-1.

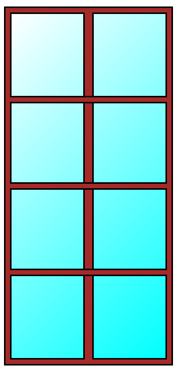
$$U_w = \frac{\sum U_g A_g + \sum U_p A_p + \sum U_f A_f + \sum I_g \Psi_g + \sum I_p \Psi_p}{\sum A_g + \sum A_p + \sum A_f} \quad [4.2]$$

where:

- $U_g$ Glass transmittance, [W/m$^2$K];
- $A_g$ Glass area, [m$^2$];
- $U_p$ Opaque panels trasmittance, [W/m$^2$K];
- $A_p$ Opaque panels area, [m$^2$];
- $U_f$ Frame trasmittance, [W/m$^2$K];
- $A_f$ Frame area, [m$^2$];
- $I_g$ Glass perimeteri, [m];
- $\Psi_g$ Spacers linear trasmittance, [W/mK];
- $I_p$ Opaque panels perimeters, [m];
- $\Psi_p$ Opaque panels linear trasmittance, [W/mK].

**Window description: windows 145 x 315 cm**

| | | | |
|---|---|---|---|
| Window characteristics | | | |
| Type of window frame | | **Single 4 mm** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **3,193** | W/m$^2$K |
| Glass transmittance | $U_g$ | **5,139** | W/m$^2$K |
| Data for the calculation of solar inputs | | | |
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **0,80** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **0,80** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,850** | - |



Characteristics of the blackout closures

| | | | |
|---|---|---|---|
| Thermal resistance closures | | **0,22** | $m^2K/W$ |
| f shut | | **0,6** | - |

Window size

| | | | |
|---|---|---|---|
| Width | | **145,0** | cm |
| Height | | **310,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **2,20** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **4,495** | $m^2$ |
| Glass area | $A_g$ | **3,619** | $m^2$ |
| Frame area | $A_f$ | **0,875** | $m^2$ |
| Form factor | $F_f$ | **0,81** | - |
| Glass perimeter | $L_g$ | **21,560** | m |
| Frame perimeter | $L_f$ | **9,100** | m |

**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **3,193** | $W/m^2K$ |

## 4.6.2 Characteristic Of The Building Envelope Of The Dardi / Abba Palace

The Dardi Palace dating back to the period of construction in the early 1900s and it spread over two floors.

The ground floor houses the offices of the Carabinieri nucleus and the gymnasium.On the first floor there are about thirty study rooms for the students of the Military Academy. The Abba Palace, exactly the same as the Dardi Palace, dates back to the early 1900s and it was built on two floors. The ground floor houses the personal defense gymnasium of the Military Academy. On the first floor there are about thirty study rooms for the students of the Military Academy.

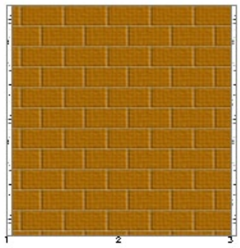
**Opaque Vertical Walls**

The Dardi and Abba buildings are exactly specular and present the same characteristics of building envelope, therefore they are presented together. The buildings have a masonry load-bearing structure and develop into two floors above ground.

The opaque vertical walls plastered on both sides are in bricks full of variable thickness between 50 cm on the ground floor and 38 cm on the first floor.

**Description of the components of the building envelope: External Wall – ground floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,091** | $W/m^2K$ |
| Thickness | **500** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **56,180** | $10^{-12} kg/sm^2Pa$ |
| Surface Mass (with plaster) | **804** | $kg/m^2$ |
| Surface Mass (without plaster) | **768** | $kg/m^2$ |
| Periodic Transmittance | **0,063** | $W/m^2K$ |
| Attenuation Factor | **0,058** | - |
| Thermal Wave Phase Shift | **-17,3** | h |

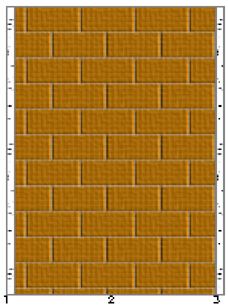


**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,130 | - | - | - |
| 1 | Plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| 2 | Masonry | 480,00 | 0,680 | 0,706 | 1600 | 1,00 | 7 |
| 3 | Plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| - | External surface resistance | - | - | 0,061 | - | - | - |

**Description of the components of the building envelope: External Wall – first floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,360** | $W/m^2K$ |
| Thickness | **380** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **72,727** | $10^{-12} kg/sm^2Pa$ |
| Surface Mass (with plaster) | **614** | $kg/m^2$ |
| Surface Mass (without plaster) | **560** | $kg/m^2$ |
| Periodic Transmittance | **0,196** | $W/m^2K$ |
| Attenuation Factor | **0,144** | - |
| Thermal Wave Phase Shift | **-13,0** | h |



**Stratigraphy:**

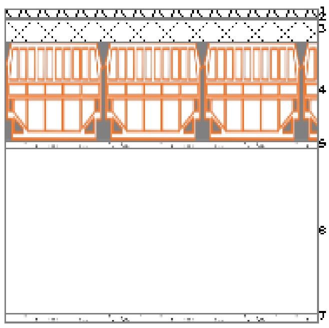
| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,130 | - | - | - |
| 1 | Plaster | 15,00 | 1,000 | 0,015 | 1800 | 1,00 | 10 |
| 2 | Masonry | 350,00 | 0,680 | 0,515 | 1600 | 1,00 | 7 |
| 3 | Plaster | 15,00 | 1,000 | 0,015 | 1800 | 1,00 | 10 |
| - | External surface resistance | - | - | 0,061 | - | - | - |

## Horizontal Floors

The roof of the first floor is composed by a false ceiling with the presence of a cavity and brick structure without insulation.

**Description of the components of the building envelope: Roof Dardi / Abba**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,257** | W/m$^2$K |
| Thickness | **569** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **0,971** | $10^{-12}$kg/sm$^2$Pa |
| Surface Mass (with plaster) | **318** | kg/m$^2$ |
| Surface Mass (without plaster) | **281** | kg/m$^2$ |
| Periodic Transmittance | **0,463** | W/m$^2$K |
| Attenuation Factor | **0,369** | - |
| Thermal Wave Phase Shift | **-8,0** | h |



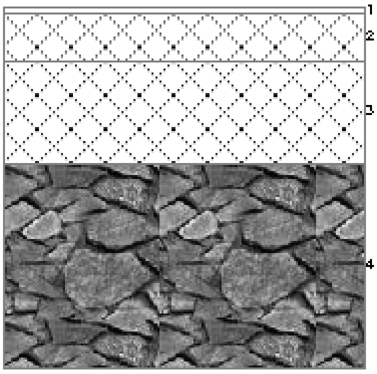
**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | 0,061 | - | - | - |
| 1 | roof covering | 15,00 | 1,000 | 0,015 | 2000 | 0,80 | 40 |
| 2 | waterproofing | 4,00 | 0,170 | 0,024 | 1200 | 0,92 | 50000 |
| 3 | concrete | 40,00 | 0,470 | 0,085 | 1200 | 1,00 | 96 |
| 4 | brick floor | 180,00 | 0,660 | 0,273 | 1100 | 0,84 | 7 |
| 5 | plaster | 15,00 | 0,800 | 0,019 | 1600 | 1,00 | 10 |
| 6 | unventilated interspace | 300,00 | 1,875 | 0,160 | - | - | - |
| 7 | false ceiling | 15,00 | 0,250 | 0,060 | 900 | 1,00 | 10 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

## Ground Floors

**Description of the components of the building envelope: Ground Floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,619** | $W/m^2K$ |
| Ground thermal transmittance | **0,288** | $W/m^2K$ |




| | | |
|---|---|---|
| Thickness | **530** | mm |
| External temperature (winter power calculation) | **13,3** | °C |
| Permeance | **9,709** | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | **1019** | $kg/m^2$ |
| Surface Mass (without plaster) | **1019** | $kg/m^2$ |
| Periodic Transmittance | **0,166** | $W/m^2K$ |
| Attenuation Factor | **0,575** | - |
| Thermal Wave Phase Shift | **-13,3** | h |

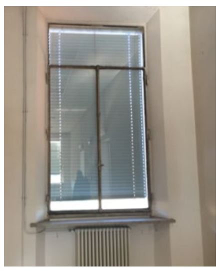
**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,170 | - | - | - |
| 1 | Floor | 10,00 | 1,000 | 0,010 | 2300 | 0,84 | 200 |
| 2 | Substrate of lean concrete | 70,00 | 0,900 | 0,078 | 1800 | 0,88 | 30 |
| 3 | Concrete | 150,00 | 2,150 | 0,070 | 2400 | 0,88 | 100 |
| 4 | Coarse gravel without clay (um. 5%) | 300,00 | 1,200 | 0,250 | 1700 | 0,84 | 5 |
| - | External surface resistance | - | - | 0,040 | - | - | - |

## Windows

The buildings have windows whose state of preservation is ancient, the fixtures are in metal sheet and the transparent single-glass component. These windows have an evident superficial degradation.

**Window description: windows 130 x 265 cm first floor**



Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | **Single 4 mm** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **5,563** | $W/m^2K$ |
| Glass-only transmittance | $U_g$ | **5,139** | $W/m^2K$ |

Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,850** | - |

Characteristics of the blackout closures

| | | | |
|---|---|---|---|
| Thermal resistance closures | | **0,00** | $m^2K/W$ |
| f shut | | **0,6** | - |

Window size

| | | | |
|---|---|---|---|
| Width | | **130,0** | cm |
| Height | | **265,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **7,00** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **3,445** | $m^2$ |
| Glass area | $A_g$ | **2,660** | $m^2$ |
| Frame area | $A_f$ | **0,785** | $m^2$ |
| Form factor | $F_f$ | **0,77** | - |
| Glass perimeter | $L_g$ | **14,120** | m |
| Frame perimeter | $L_f$ | **7,900** | m |

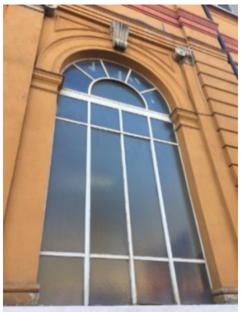
**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **5,563** | $W/m^2K$ |

**Window description:** **windows 190 x 380 cm ground floor**

Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | **Single 4 mm** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **5,617** | $W/m^2K$ |
| Glass-only transmittance | $U_g$ | **5,139** | $W/m^2K$ |



Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |

| | | | |
|---|---|---|---|
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,850** | - |

Characteristics of the blackout closures

| | | |
|---|---|---|
| Thermal resistance closures | **0,00** | $m^2K/W$ |
| f shut | **0,6** | - |

Window size

| | | |
|---|---|---|
| Width | **190,0** | cm |
| Height | **240,0** | cm |
| toplight height | **100,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **7,00** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **6,460** | $m^2$ |
| Glass area | $A_g$ | **4,800** | $m^2$ |
| Frame area | $A_f$ | **1,660** | $m^2$ |
| Form factor | $F_f$ | **0,74** | - |
| Glass perimeter | $L_g$ | **31,500** | m |
| Frame perimeter | $L_f$ | **10,600** | m |

**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **5,617** | $W/m^2K$ |

### 4.6.3 Characteristic Of The Building Envelope Of The Aliprandi Palace

The building, dating back to the early 1900s, was built on two floors above ground.

On the ground floor there is an area destined to a warehouse, an area hosting a joinery and an area for office use (headquarters command).

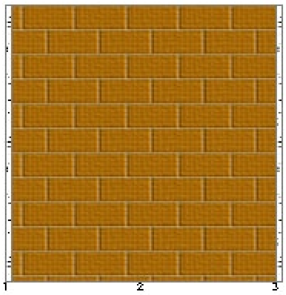
While the first floor is entirely used as rooms and services as a dormitory.

**Opaque Vertical Walls**

The opaque vertical walls plastered on both sides are in bricks full of variable thickness between 50 cm on the ground floor and 38 cm on the first floor.

**Description of the components of the building envelope: External Wall – ground floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,091** | W/m²K |
| Thickness | **500** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **56,180** | $10^{-12}$kg/sm²Pa |
| Surface Mass (with plaster) | **804** | kg/m² |
| Surface Mass (without plaster) | **768** | kg/m² |
| Periodic Transmittance | **0,063** | W/m²K |
| Attenuation Factor | **0,058** | - |
| Thermal Wave Phase Shift | **-17,3** | h |

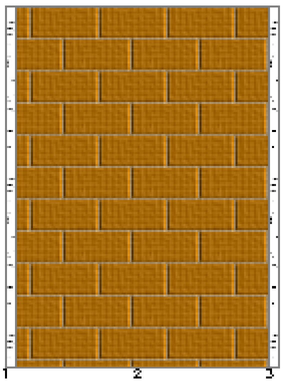



**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,130 | - | - | - |
| 1 | Plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| 2 | Masonry | 480,00 | 0,680 | 0,706 | 1600 | 1,00 | 7 |
| 3 | Plaster | 10,00 | 1,000 | 0,010 | 1800 | 1,00 | 10 |
| - | External surface resistance | - | - | 0,061 | - | - | - |

**Description of the components of the building envelope: External Wall – first floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,360** | W/m²K |
| Thickness | **380** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **72,727** | $10^{-12}$kg/sm²Pa |
| Surface Mass (with plaster) | **614** | kg/m² |
| Surface Mass (without plaster) | **560** | kg/m² |
| Periodic Transmittance | **0,196** | W/m²K |
| Attenuation Factor | **0,144** | - |
| Thermal Wave Phase Shift | **-13,0** | h |




**Stratigraphy:**

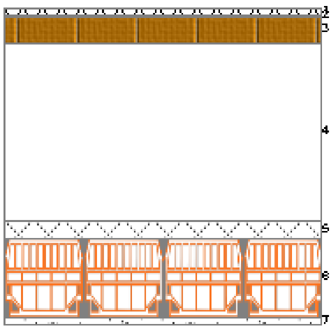
| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,130 | - | - | - |
| 1 | Plaster | 15,00 | 1,000 | 0,015 | 1800 | 1,00 | 10 |
| 2 | Masonry | 350,00 | 0,680 | 0,515 | 1600 | 1,00 | 7 |
| 3 | Plaster | 15,00 | 1,000 | 0,015 | 1800 | 1,00 | 10 |
| - | External surface resistance | - | - | 0,061 | - | - | - |

## Horizontal Floors

The attic of the first floor is in insulated brick with the presence of a cavity and the pitched roof.

**Description of the components of the building envelope: Aliprandi roof**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,142** | $W/m^2K$ |
| Thickness | **714** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **0,969** | $10^{-12} kg/sm^2Pa$ |
| Surface Mass (with plaster) | **342** | $kg/m^2$ |
| Surface Mass (without plaster) | **318** | $kg/m^2$ |
| Periodic Transmittance | **0,399** | $W/m^2K$ |
| Attenuation Factor | **0,349** | - |
| Thermal Wave Phase Shift | **-8,7** | h |



**Stratigraphy:**

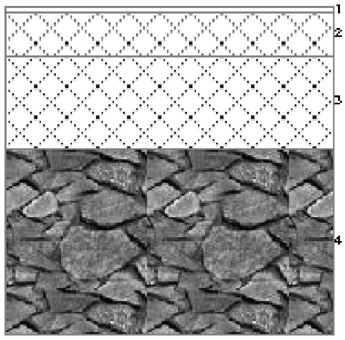
| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | 0,061 | - | - | - |
| 1 | roof covering | 15,00 | 1,000 | 0,015 | 2000 | 0,80 | 40 |
| 2 | waterproofing | 4,00 | 0,170 | 0,024 | 1200 | 0,92 | 5000<br>0 |
| 3 | brick floor | 60,00 | 0,429 | 0,140 | 617 | 0,84 | 9 |
| 4 | unventilated interspace | 400,00 | 2,500 | 0,160 | - | - | - |
| 5 | Concrete | 40,00 | 0,470 | 0,085 | 1200 | 1,00 | 96 |
| 6 | brick floor | 180,00 | 0,660 | 0,273 | 1100 | 0,84 | 7 |
| 7 | Plaster | 15,00 | 0,800 | 0,019 | 1600 | 1,00 | 10 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

## Ground Floors

**Description of the components of the building envelope:**
**Ground Floor**

**Code: P1**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,619** | W/m²K |
| Ground thermal transmittance | **0,288** | W/m²K |
| Thickness | **530** | mm |
| External temperature (winter power calculation) | **13,3** | °C |
| Permeance | **9,709** | $10^{-12}$kg/sm²Pa |
| Surface Mass (with plaster) | **1019** | kg/m² |
| Surface Mass (without plaster) | **1019** | kg/m² |
| Periodic Transmittance | **0,166** | W/m²K |
| Attenuation Factor | **0,575** | - |
| Thermal Wave Phase Shift | **-13,3** | h |




**Stratigraphy:**

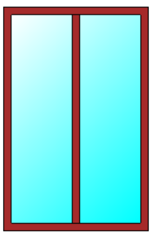
| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,170 | - | - | - |
| 1 | Floor | 10,00 | 1,000 | 0,010 | 2300 | 0,84 | 200 |
| 2 | Substrate of lean concrete | 70,00 | 0,900 | 0,078 | 1800 | 0,88 | 30 |
| 3 | Concrete | 150,00 | 2,150 | 0,070 | 2400 | 0,88 | 100 |
| 4 | Coarse gravel without clay (um. 5%) | 300,00 | 1,200 | 0,250 | 1700 | 0,84 | 5 |
| - | External surface resistance | - | - | 0,040 | - | - | - |

## Windows

**Window description:** **windows 130 x 200 cm**

Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | **Single 4 mm** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **3,125** | W/m²K |
| Glass-only transmittance | $U_g$ | **5,139** | W/m²K |



Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,850** | - |

Characteristics of the blackout closures

| | | |
|---|---|---|
| Thermal resistance closures | **0,22** | $m^2K/W$ |
| f shut | **0,6** | - |

Window size

| | | |
|---|---|---|
| Width | **130,0** | cm |
| Height | **200,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **2,20** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **2,600** | $m^2$ |
| Glass area | $A_g$ | **2,027** | $m^2$ |
| Frame area | $A_f$ | **0,573** | $m^2$ |
| Form factor | $F_f$ | **0,78** | - |
| Glass perimeter | $L_g$ | **9,620** | m |
| Frame perimeter | $L_f$ | **6,600** | m |

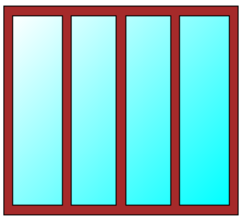
**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **3,152** | $W/m^2K$ |

**Window description: windows 180 x 160 cm**

Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | **Single 4 mm** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **3,079** | $W/m^2K$ |
| Glass-only transmittance | $U_g$ | **5,139** | $W/m^2K$ |



Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |

| | | | |
|---|---|---|---|
| Solar transmittance factor | $g_{gl,n}$ | **0,850** | - |

Characteristics of the blackout closures

| | | | |
|---|---|---|---|
| Thermal resistance closures | | **0,22** | $m^2K/W$ |
| f shut | | **0,6** | - |

Window size

| | | | |
|---|---|---|---|
| Width | | **180,0** | cm |
| Height | | **160,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **2,20** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **2,880** | $m^2$ |
| Glass area | $A_g$ | **2,117** | $m^2$ |
| Frame area | $A_f$ | **0,763** | $m^2$ |
| Form factor | $F_f$ | **0,74** | - |
| Glass perimeter | $L_g$ | **14,580** | m |
| Frame perimeter | $L_f$ | **6,800** | m |

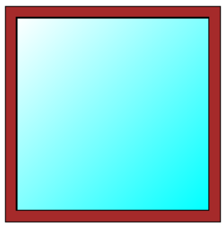
**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **3,079** | $W/m^2K$ |

**Window description: windows 130 x 130 cm**

Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | **Single 4 mm** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **3,179** | $W/m^2K$ |
| Glass-only transmittance | $U_g$ | **5,139** | $W/m^2K$ |



Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,850** | - |

Characteristics of the blackout closures

| | | | |
|---|---|---|---|
| Thermal resistance closures | | **0,22** | $m^2K/W$ |
| f shut | | **0,6** | - |

Window size

| | | | |
|---|---|---|---|
| Width | | **130,0** | cm |
| Height | | **130,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **2,20** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **1,690** | $m^2$ |
| Glass area | $A_g$ | **1,346** | $m^2$ |
| Frame area | $A_f$ | **0,344** | $m^2$ |
| Form factor | $F_f$ | **0,80** | - |
| Glass perimeter | $L_g$ | **4,640** | m |
| Frame perimeter | $L_f$ | **5,200** | m |

**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **3,179** | $W/m^2K$ |

## 4.6.4 Characteristic Of The Building Envelope Of The Fanti Pool

The building, dating back to the early 1900s, was built on three floors above ground. On the ground floor there is the entrance, the administrative offices of the pool and the technical room where the plant and the compensation tank are located.

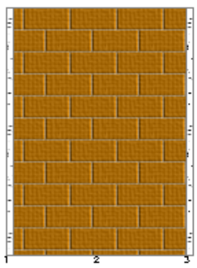
On the first floor there is the pool, the changing rooms and on the floor according to the stands for the spectators.

### Opaque Vertical Walls

The opaque vertical walls plastered on both sides are in bricks full of thickness about 33 cm.

**Description of the components of the building envelope: External Wall**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,511** | $W/m^2K$ |
| Thickness | **330** | mm |
| External temperature (winter power calculation) | **-5,0** | °C |
| Permeance | **83,333** | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | **534** | $kg/m^2$ |
| Surface Mass | **480** | $kg/m^2$ |



(without plaster)

| | | |
|---|---|---|
| Periodic Transmittance | **0,311** | W/m$^2$K |
| Attenuation Factor | **0,206** | - |
| Thermal Wave Phase Shift | **-11,3** | h |

**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,130 | - | - | - |
| 1 | Plaster | 15,00 | 1,000 | 0,015 | 1800 | 1,00 | 10 |
| 2 | Masonry | 300,00 | 0,680 | 0,441 | 1600 | 1,00 | 7 |
| 3 | Plaster | 15,00 | 1,000 | 0,015 | 1800 | 1,00 | 10 |
| - | External surface resistance | - | - | 0,061 | - | - | - |

## Horizontal Floors

The floors are in brick-cement towards the attic and towards the unheated underground area where there is the passage of the air ducts of the heating system.

**Description of the components of the building envelope: attic ceiling**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,846** | W/m$^2$K |
| Thickness | **230** | mm |
| External temperature (winter power calculation) | **5,0** | °C |
| Permeance | **38,388** | $10^{-12}$kg/sm$^2$Pa |
| Surface Mass (with plaster) | **276** | kg/m$^2$ |
| Surface Mass (without plaster) | **262** | kg/m$^2$ |

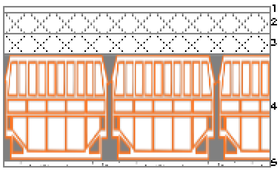
| | | |
|---|---|---|
| Periodic Transmittance | **1,036** | W/m$^2$K |
| Attenuation Factor | **0,562** | - |
| Thermal Wave Phase Shift | **-6,1** | h |

**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | 0,100 | - | - | - |
| 1 | Concrete | 40,00 | 0,730 | 0,055 | 1600 | 1,00 | 96 |
| 2 | Brick floor | 180,00 | 0,660 | 0,273 | 1100 | 0,84 | 7 |
| 3 | Plaster | 10,00 | 0,700 | 0,014 | 1400 | 0,84 | 11 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

**Description of the components of the building envelope: basement floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,232** | $W/m^2K$ |
| Thickness | **300** | mm |
| External temperature (winter power calculation) | **7,5** | °C |
| Permeance | **28,944** | $10^{-12} kg/sm^2Pa$ |
| Surface Mass (with plaster) | **375** | $kg/m^2$ |
| Surface Mass (without plaster) | **357** | $kg/m^2$ |
| Trasmittanza periodica | **0,302** | $W/m^2K$ |
| Fattore attenuazione | **0,245** | - |
| Sfasamento onda termica | **-9,5** | h |



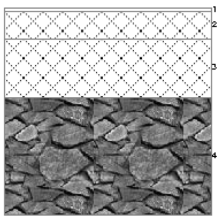
**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,170 | - | - | - |
| 1 | Floor | 10,00 | 0,220 | 0,045 | 850 | 2,40 | 60 |
| 2 | Substrate of lean concrete | 40,00 | 0,700 | 0,057 | 1600 | 0,88 | 20 |
| 3 | Concrete | 40,00 | 0,730 | 0,055 | 1600 | 1,00 | 96 |
| 4 | Brick floor | 200,00 | 0,660 | 0,303 | 1100 | 0,84 | 7 |
| 5 | Plaster | 10,00 | 0,900 | 0,011 | 1800 | 0,84 | 27 |
| - | External surface resistance | - | - | 0,170 | - | - | - |

## Ground Floors

**Description of the components of the building envelope: Ground Floor**

| | | |
|---|---|---|
| Thermal Trasmittance | **1,619** | $W/m^2K$ |
| Ground thermal transmittance | **0,644** | $W/m^2K$ |
| Thickness | **530** | mm |
| External temperature (winter power calculation) | **13,3** | °C |
| Permeance | **9,709** | $10^{-12} kg/sm^2Pa$ |
| Surface Mass | **1019** | $kg/m^2$ |



(with plaster)

Surface Mass (without plaster) **1019** kg/m$^2$

Periodic Transmittance **0,166** W/m$^2$K

Attenuation Factor **0,257** -

Thermal Wave Phase Shift **-13,3** h

**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | Internal Surface Resistance | - | - | 0,170 | - | - | - |
| 1 | Floor | 10,00 | 1,000 | 0,010 | 2300 | 0,84 | 200 |
| 2 | Substrate of lean concrete | 70,00 | 0,900 | 0,078 | 1800 | 0,88 | 30 |
| 3 | Concrete | 150,00 | 2,150 | 0,070 | 2400 | 0,88 | 100 |
| 4 | Coarse gravel without clay (um. 5%) | 300,00 | 1,200 | 0,250 | 1700 | 0,84 | 5 |
| - | External surface resistance | - | - | 0,040 | - | - | - |

## Windows

The windows are metal with no thermal break; on the ground floor there are some double-glazed windows, while the majority is in single-glazed windows.

**Window description: windows 400 x 400 cm**

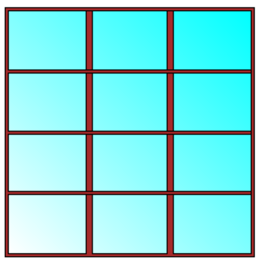
Window characteristics

Type of window frame **Single 4 mm**

Permeability class **without classification**

Thermal transmittance $U_w$ **5,914** W/m$^2$K

Glass-only transmittance $U_g$ **5,747** W/m$^2$K



Data for the calculation of solar inputs

emissivity $\varepsilon$ **0,837** -

Curtain factor (winter) $f_{c\ inv}$ **1,00** -

Curtain factor (summer) $f_{c\ est}$ **1,00** -

Solar transmittance factor $g_{gl,n}$ **0,850** -

Characteristics of the blackout closures

Thermal resistance closures **0,12** m$^2$K/W

f shut **0,6** -

Window size

Width **400,0** cm

| | | | |
|---|---|---|---|
| Height | | **400,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **7,00** | $W/m^2K$ |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **16,000** | $m^2$ |
| Glass area | $A_g$ | **13,875** | $m^2$ |
| Frame area | $A_f$ | **2,125** | $m^2$ |
| Form factor | $F_f$ | **0,87** | - |
| Glass perimeter | $L_g$ | **52,100** | m |
| Frame perimeter | $L_f$ | **16,000** | m |

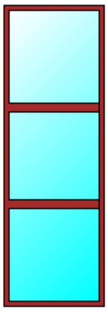
**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **5,914** | $W/m^2K$ |

**Window description: windows 100 x 300 cm**

Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | | **-** |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **2,675** | $W/m^2K$ |
| Glass-only transmittance | $U_g$ | **3,300** | $W/m^2K$ |



Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | $\varepsilon$ | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,750** | - |

Characteristics of the blackout closures

| | | |
|---|---|---|
| Thermal resistance closures | **0,12** | $m^2K/W$ |
| f shut | **0,6** | - |

Window size

| | | |
|---|---|---|
| Width | **100,0** | cm |
| Height | **300,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **2,80** | W/m²K |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **3,000** | m² |
| Glass area | $A_g$ | **2,466** | m² |
| Frame area | $A_f$ | **0,534** | m² |
| Form factor | $F_f$ | **0,82** | - |
| Glass perimeter | $L_g$ | **10,880** | m |
| Frame perimeter | $L_f$ | **8,000** | m |

**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **2,675** | W/m²K |

**Window description: windows 277 x 366 cm**

Window characteristics

| | | | |
|---|---|---|---|
| Type of window frame | | **-** | |
| Permeability class | | **without classification** | |
| Thermal transmittance | $U_w$ | **2,699** | W/m²K |
| Glass-only transmittance | $U_g$ | **3,300** | W/m²K |

Data for the calculation of solar inputs

| | | | |
|---|---|---|---|
| emissivity | ε | **0,837** | - |
| Curtain factor (winter) | $f_{c\ inv}$ | **1,00** | - |
| Curtain factor (summer) | $f_{c\ est}$ | **1,00** | - |
| Solar transmittance factor | $g_{gl,n}$ | **0,750** | - |

Characteristics of the blackout closures

| | | |
|---|---|---|
| Thermal resistance closures | **0,12** | m²K/W |
| f shut | **0,6** | - |

Window size

| | | |
|---|---|---|
| Width | **277,0** | cm |
| Height | **366,0** | cm |

**Window frame features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the frame | $U_f$ | **2,80** | W/m²K |
| K spacer | $K_d$ | **0,00** | W/mK |
| Total area | $A_w$ | **10,138** | m² |
| Glass area | $A_g$ | **9,013** | m² |

| | | | |
|---|---|---|---|
| Frame area | $A_f$ | **1,125** | $m^2$ |
| Form factor | $F_f$ | **0,89** | - |
| Glass perimeter | $L_g$ | **24,280** | m |
| Frame perimeter | $L_f$ | **12,860** | m |

**Module features**

| | | | |
|---|---|---|---|
| Thermal transmittance of the module | U | **2,699** | $W/m^2K$ |

## 4.7 Characteristic Of The Thermal Plant

The building complex is equipped with a fully functioning natural gas system, located in a suitable thermal power plant (as required by current legislation DM 12.04.96 for powers exceeding 35 kW) sufficiently ventilated and equipped with safety valve outlets and for emptying the system.

The thermal power plant is located in an internal courtyard in the northern area of the Ducal Palace and contains two types of plant (steam and hydronic) served by a single methane gas supply network with a single meter.

The Thermal Plant contains two independent systems:

- **steam system plant:** it powered by a single boiler that serves the internal ironing of the “Caserma Montecuccoli” and the Fanti Pool (production of hot water for heating water of the swim and heating building with air handling unit - AHU);

- **hydronic system plant**: it powered by three boilers where the heat transfer fluid (water) is distributed to the various terminals in the various rooms of the Ducal Palace and the Dardi, Abba and Aliprandi buildings for winter heating and for the production of hot water for hygienic-sanitary uses.

*Fig.4.28 – Roof of the thermal plant*

Inside the buildings of the Ducal Palace there isn’t a summer cooling system.

### 4.7.1 Steam system plant

The steam system plant is powered by a boiler ("ICI Caldaie" brand) installed in 2007 and running with methane gas. The boiler has a maximum thermal power of 1550 kW and a maximum useful power of 1395 kW.

The superheated steam at a temperature of about 120°C is sent through the distribution network to the Fanti Pool and to the ironing inside the "Caserma Montecuccoli".

*Fig.4.29 – Steam boiler inside the thermal plant*

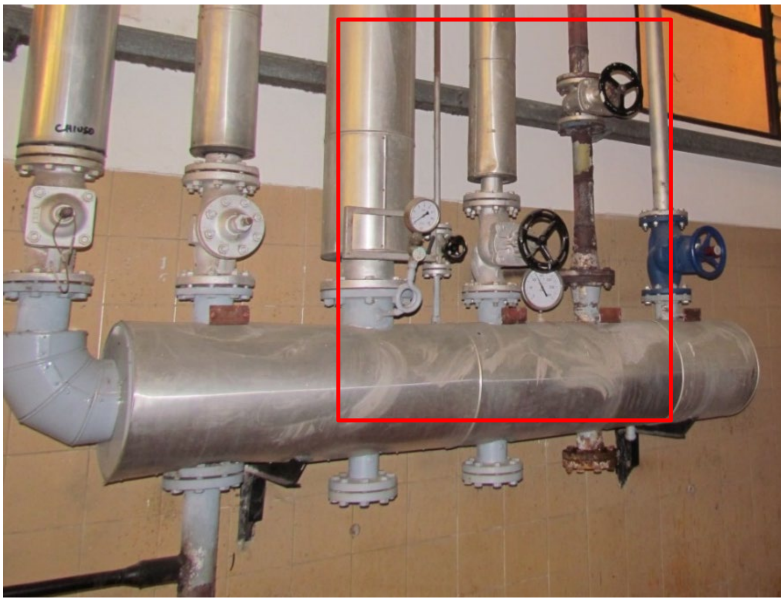


*Fig.4.30 – Plant distribution piping system of the Steam boiler*

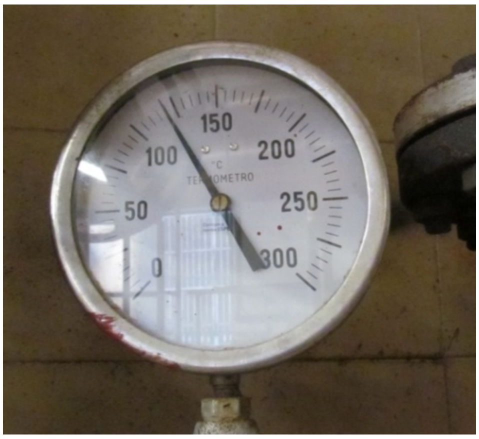



*Fig.4.31 – Flow temperature of the steam*

The steam return circuit enters an accumulation of condensation at a temperature of about 70 ° C; the thermal flywheel is open at the top where it is possible to see the steam coming out of the exhaust pipes.

*Fig.4.32 – Thermal flywheel of the steam plant*

In the thermal flywheel the necessary water from the aqueduct is reintegrated (after having been treated by a special osmotic system) and through a pump it is sent to an accumulator to then return to the boiler with a thrust given by gravitational fall.

*Fig.4.33 – Steam boiler accumulator*

The steam through an underground distribution network is distributed to the ironing room where it serves the machines present (steam irons, presses) for a total maximum required power of 50 kW.

*Fig.4.34 – Ironing room inside the "Caserma Montecuccoli"*

The steam through an under-road distribution network is also distributed to the Fanti Pool where, through a system of exchangers, it serves the hot unit of the masonry Air Handling Unit – AHU - with oil filters (heating system of the Pool Fanti) and it is used for heating water from the swimming pool.

*Fig.4.35 – AHU inside of Pool Fanti  and Fig.4.36 – Steam system exchangers*

As it is possible to deduce from the description above, the system is very inefficient, the generation and emission system are old, the regulation almost non-existent and the distribution network very dispersed and in a very bad state.

The efficiency of the emission system is that of the air vents according to UNI 11300/2, while as regards regulation, it has been estimated as centralized with climatic compensation from an external probe.
The generation efficiency was determined in accordance with UNI / TS 11300-2, the distribution efficiency (more delicate given the length of the pipes present) was determined by analytical calculation.

The losses given by the total distribution circuit are calculated as:

$$Q_{l,d} = \sum_{i} L_i \cdot U_i \cdot \left(T_{w,awg,i} - T_{a,i}\right) \cdot t_i \quad [4.3]$$

where:

- $L_i$ length of the pipe, [m];
- $U_i$ average linear transmittance of the pipes, [W/mK];
- $t_i$ circuit activation time in the calculation period;
- $T_{w,awg,i}$ average temperature of the water in the circuit;
- $T_{a,i}$ average temperature of the environment where the pipes are installed.

*Table 4.1 – Steam System Plant Efficiency*

| **Steam System Plant Efficiency** | | |
|---|---|---|
| Emission system | nH,e | 94,0 % |
| Regulation system | nH,rg | 81,0 % |
| Distribution system | nH,du | 70,0 % |
| Generation system | nH,gn | 87,1 % |
| **Average seasonal steam system plant efficiency** | **nH,g** | **46,4 %** |

### 4.7.2 Hydronic System For Heating And Domestic Hot Water

The centralized hydronic system that produces hot water for heating and hygienic sanitary uses for the Ducal Palace and Dardi, Abba and Aliprandi Palace is composed by:

- Number 3 boilers for the combined production of hot water for heating and hygienic-sanitary use, for a nominal useful thermal power $\Phi_{Pn}$ of 2770 kW complete with steel smoke channels, burners and safety accessories to INAIL standards;

*Table 4.2 – Boiler of the Hydronic System*

| **Boiler of the Hydronic System** | | | | | |
|---|---|---|---|---|---|
| N. | Brand | Model | Serial number | Fuel | Useful Power |
| G1 | UNICAL | TRISTAR 370 | A09U02110 | Methane Gas | 370 kW |
| G2 | UNICAL | TRISTAR 1400 | A09U02701 | Methane Gas | 1400 kW |
| G3 | UNICAL | TRISTAR 1000 | A09U02941 | Methane Gas | 1000 kW |

- Number 2 plate heat exchangers (heating use);

*Table 4.3 – Plate Heat Exchanger (heating)*

| **Plate Heat Exchanger (heating)** | |
|---|---|
| Brand | ALFA LAVAL |
| Model | M10-BFM 153 PL |
| Power | 1500 kW |

- Number 1 starting circuit for supplying the heating system to the various terminals and relative return circuit;
- Number 2 plate heat exchangers (sanitary water use);

*Table 4.4 – Plate Heat Exchanger (hygienic-sanitary use)*

| **Plate Heat Exchanger (hygienic-sanitary use)** | |
|---|---|
| Brand | ALFA LAVAL |
| Model | M6-MFG 23 P2 |
| Power | 300 kW |

- Number 1 starting circuit for supplying the domestic hot water system to the various terminals and relative return circuit (plus recirculation circuit);
- Number 4 expansion vessels;
- Number 1 water softener for water treatment;
- Number 3 accumulators for domestic hot water, for a total storage water volume of 13000 Liters;
- Number 20 electric pumps.

Each circuit is equipped with an independent thermoregulation (three-way mixing valve).

The system has only the central adjustment, with climatic compensation from an external probe, not sufficient therefore to guarantee a high regulation efficiency, as it does not allow a satisfactory recovery of the free contributions.

The hydronic system is entirely with forced circulation, there are n. 20 electric pumps having the following characteristics.

*Table 4.5 – Electric pumps*

| **Electric pumps** | | | |
|---|---|---|---|
| Brand | Number | Model | Power |
| KSB | 2 | TRIALINE N 65-160/074 | 7,5 kW |
| KSB | 2 | ETABLOC 32-160.1/034 | 0,37 kW |
| KSB | 2 | ETABLOC 32-160.1/222.2 | 2,2 kW |
| KSB | 3 | ETABLOC 80-160/224.2 | 2,2 kW |
| KSB | 2 | ETABLOC 65-160/224 | 2,0 kW |
| KSB | 2 | ETABLOC 40-160/074 | 1,8 kW |
| KSB | 4 | TRIALINE N 80-250/554 | 7,5 kW |
| KSB | 3 | ETABLOC 80-200/554 | 2,5 kW |

*Fig.4.37 – Boiler of the Hydronic System inside of the thermal plant*

*Fig.4.38 – Plate Heat Exchanger (heating) inside of the thermal plant*

*Fig.4.39 – expansion vessels inside of the thermal plant*

*Fig.4.40 – water softener inside of the thermal plant*

*Fig.4.41 – accumulators for domestic hot water inside of the thermal plant*

*Fig.4.42 – Electric pumps inside of the thermal plant*

*Fig.4.43 – Thermal plant*

The sealed chamber boilers operating on methane gas are complete with regulation and safety accessories in accordance with INAIL regulations (safety valves, thermostat, thermometers, pressure switches, pressure gauges and electrical safety equipment), the system is also equipped with self-pressurized closed expansion vessels.

The labels with the relative technical characteristics of the three boilers are shown below.


*Fig.4.44 - 4.45 – Technical plate – Boiler G1 and G2*

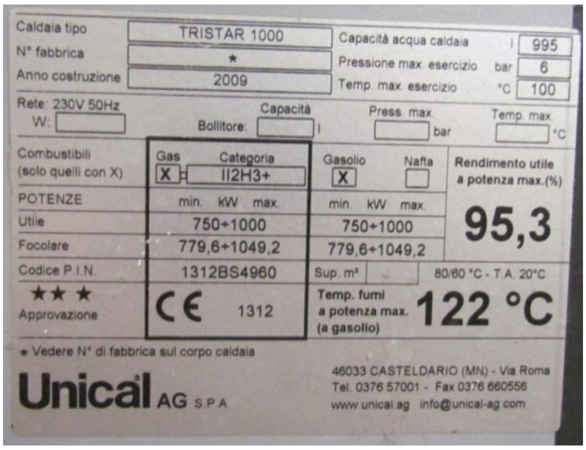



*Fig.4.46 – Technical plate – Boiler G3*

The forced circulation plant uses water as a working fluid, which reaches the various terminals through an important distribution network, which is the most delicate part of the plant.

The distribution network has a traditional layout, with outgoing piping (from the boiler to the emission systems) and return piping (from the heating elements to the boiler).

The main distribution system is a ring positioned in the basements of the building (Ducal Palace) from which the distribution posts are developed.

There are also main pipes that go to the Dardi, Abba and Aliprandi Palace (where there is a thermal sub-station with 2 accumulators for DHW of 1000 liters each).

The pipes are visible in the underground area, the network then develops through tunnels, trying to make the most of the obsolete spaces that the building offers.

The emission sub-system of the Ducal Palace is composed by:

- Radiators (most in cast iron) on external and internal walls;
- Fan coils in the canteen and ground floor classrooms;
- Radiant floor panels placed in the Hall of Honor on the second floor (an important restoration work was recently carried out in the Hall of Honor for which underfloor heating was inserted and the restored original parquet rested). To guarantee the optimum temperature for the radiant panel system, a fixed point temperature control has been inserted on the distribution manifold complete with a block thermostat connected to the relaunch pump.


*Fig.4.47 – Radiators – external wall and Fig.4.48 – Fan coil (canteen area)*

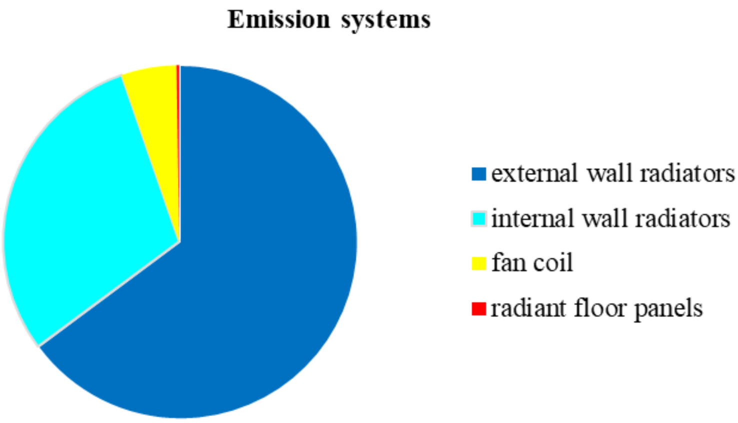



*Fig.4.49 – Types of the emission sub-system of the Ducal Palace*

Inside the Dardi and Abba Palace the emission sub-system is composed by:

- Ground floor air heaters in gymnasiums;
- Radiators in the first floor in the classroom area.

*Fig.4.50 – air heaters*

Inside the Aliprandi Palace the only emission sub-system are radiators.

Instead, inside the Pool Fanti  the emission system is with supply and return vents from the AHU ducts.

Even in the case of the hydronic system, the bad condition in which the thermal system is located is immediately visible.

The efficiency of the sub-system emission was calculated as a weighted average of the efficiency of the different type of emission plants.

The regulation efficiency is calculated according to UNI TS 11300/2 as climatic with regulation with external probe.

The generation efficiency was determined according to UNI TS 11300/2 while the efficiency of the distribution sub-system was calculated with an analytical method as it is more appropriate given the extension of the network and the complexity of the distribution system of the heat transfer fluid.

The losses given by the distribution circuit are calculated as:

$$Q_{l,d} = \sum_i L_i \cdot U_i \cdot (T_{w,awg,i} - T_{a,i}) \cdot t_i \quad [4.4]$$

where:

- $L_i$ length of the pipe, [estimated 4438 m];
- $U_i$ average linear transmittance of the pipes, [estimated 0,41 W/mK];
- $t_i$ circuit activation time in the calculation period [from user interviews the heating network is active 10 hours a day for the 183 heating days per year];
- $T_{w,awg,i}$ average temperature of the water in the circuit [70°C];
- $T_{a,i}$ average temperature of the environment where the pipes are installed [15°C].

The average linear transmittance of the pipes is obtained by:

$$U_i = \frac{\pi}{\frac{1}{2 \cdot \lambda_i} \cdot \ln \frac{D_i}{d_i} + \frac{1}{\alpha_{air} \cdot D_i}} \quad [4.5]$$

The efficiency of the distribution system can be defined as the ratio between the energy required for space heating with a perfect theoretical distribution (in which the resources for distribution are zero) and the energy required for space heating with the system real distribution.

$$\eta_d = \frac{Q_{l,d}}{Q_{reale}} = \frac{398292,00}{581449,00} = 0.685 \quad [4.6]$$

*Table 4.6 – Hydronic System Heating Plant Efficiency*

| Hydronic System Heating Plant Efficiency | | |
|---|---|---|
| Emission system | nH,e | 90,0 % |
| Regulation system | nH,rg | 87,3 % |
| Distribution system | nH,du | 68,5 % |
| Generation system | nH,gn | 90,9 % |
| **Average seasonal hydronic system heating plant efficiency** | **nH,g** | **49,1 %** |

*Table 4.7 – Hydronic System (Domestic Hot Water) Plant Efficiency*

| Hydronic System (Domestic Hot Water) Plant Efficiency | | |
|---|---|---|
| Supply system | nW,e | 95,0 % |
| Distribution system | nW,du | 62,7 % |
| Storage system | nW,s | 97,7 % |
| Recirculation pipes system | nW,ric | 77,7 % |
| Generation system | nH,gn | 83,4 % |
| **Average seasonal hydronic system heating plant efficiency** | **nH,g** | **37,7 %** |

### 4.7.3 Heating System Management

The temperatures and hours of heating actually required in the Supply and Heat Management Contract for the buildings of the Ducal Palace for the 2016/2017 heating season were provided by the Customer.

*Table 4.8 – Internal temperatures*

| | OCT. | NOV. | DEC. | JAN. | FEB. | MAR. | APR. |
|---|---|---|---|---|---|---|---|
| Ducal Palace | 19° C | 19° C | 19° C | 19° C | 19° C | 19° C | 18°C |
| Dardi Palace | 19° C | 19° C | 18-19° C* | 18-19° C* | 19° C | 19° C | 18°C |
| Abba Palace | 19° C | 19° C | 18-19° C* | 18-19° C* | 19° C | 19° C | 18°C |
| Aliprandi Palace | 19° C | 19° C | 18-19° C* | 18-19° C* | 19° C | 19° C | 18°C |

* The 18°C in the month of December refers to the Christmas holiday periods (from December 24th to January 7th).

The internal temperatures in the heating season of the Fanti pool aree not available, but thanks from an interview with the Customer, it is clear that the temperature is higher than 20°C.
The water inside the pool has a temperature, in normal use conditions, varying between 26°C and 28°C.

*Table 4.9 – Heating Times Required – Ducal Palace*

| HEATING TIMES REQUIRED – DUCAL PALACE | | | | |
|---|---|---|---|---|
| Period | M-T-W-T-F | Hours per day | S-S | Hours per day |
| From 19/10 to 8/12 | 6:00 – 10:00<br>18:00 – 22:00 | 8 | 6:00 – 10:00<br>18:00 – 22:00 | 8 |
| From 9/12 to 23/12 | 6:00 – 12:00<br>18:00 – 22:00 | 10 | 6:00 – 10:00<br>18:00 – 22:00 | 8 |
| From 24/12 to 08/01 | 7:00 – 15:00 | 8 | 7:00 – 11:00 | 4 |
| From 09/01 to 30/03 | 6:00 – 14:00<br>18:00 – 22:00 | 12 | 6:00 – 14:00<br>18:00 – 22:00 | 12 |
| From 31/03 to 15/04 | 6:00 – 8:00<br>17:00 – 22:00 | 7 | 6:00 – 8:00<br>17:00 – 22:00 | 7 |

*Table 4.10 – Heating Times Required – Abba Palace*

| HEATING TIMES REQUIRED – ABBA PALACE | | | | | | |
|---|---|---|---|---|---|---|
| Period | M-T-W-T-F | Hours per day | S | Hours per day | S | Hours per day |
| From 19/10 to 8/12 | 6:00 – 10:00<br>17:00 – 21:00 | 8 | 8:00 – 12:00<br>17:00 – 21:00 | 8 | - | 0 |
| From 9/12 to 23/12 | 6:00 – 10:00<br>17:00 – 21:00 | 8 | 8:00 – 12:00<br>17:00 – 21:00 | 8 | - | 0 |
| From 24/12 to 08/01 | 8:00 – 12:00 | 4 | 8:00 – 12:00 | 4 | - | 0 |
| From 09/01 to 15/04 | 6:00 – 10:00<br>17:00 – 22:00 | 9 | 6:00 – 10:00<br>17:00 – 22:00 | 9 | 6:00 – 10:00<br>17:00 – 22:00 | 9 |

*Table 4.11 – Heating Times Required – Dardi Palace*

| HEATING TIMES REQUIRED – DARDI PALACE | | | | | | |
|---|---|---|---|---|---|---|
| Period | M-T-W-T-F | Hours per day | S | Hours per day | S | Hours per day |
| From 19/10 to 8/12 | 6:00 – 10:00<br>17:00 – 21:00 | 8 | 8:00 – 12:00<br>17:00 – 21:00 | 8 | - | 0 |
| From 9/12 to 23/12 | 6:00 – 10:00<br>17:00 – 21:00 | 8 | 8:00 – 12:00<br>17:00 – 21:00 | 8 | - | 0 |
| From 24/12 to 08/01 | 8:00 – 12:00 | 4 | 8:00 – 12:00 | 4 | - | 0 |
| From 09/01 to 15/04 | 6:00 – 10:00<br>17:00 – 22:00 | 9 | 6:00 – 10:00<br>17:00 – 22:00 | 9 | 6:00 – 10:00<br>17:00 – 22:00 | 9 |

*Table 4.12 – Heating Times Required – Aliprandi Palace*

| HEATING TIMES REQUIRED – ALIPRANDI PALACE | | | | | | |
|---|---|---|---|---|---|---|
| Period | M-T-W-T-F | Hours per day | S | Hours per day | S | Hours per day |
| From 19/10 to 8/12 | 7:00 – 15:00<br>F: 7:00-12:00 | 8<br>5 | - | 0 | - | 0 |
| From 9/12 to 23/12 | 7:00 – 15:00<br>F: 7:00-12:00 | 8<br>5 | - | 0 | - | 0 |
| From 24/12 to 08/01 | 7:00 – 15:00<br>F: 7:00-12:00 | 8<br>5 | 8:00 – 12:00 | 4 | - | 0 |
| From 09/01 to 15/04 | 7:00 – 15:00<br>F: 7:00-12:00 | 8<br>5 | - | 0 | - | 0 |

*Table 4.13 – Heating Times Required – Fanti Pool*

| HEATING TIMES REQUIRED – FANTI POOL | | | | | | |
|---|---|---|---|---|---|---|
| Period | M-T-W-T-F | Hours per day | S | Hours per day | S | Hours per day |
| From 19/10 to 8/12 | 7:00 – 11:00 | 8 | 6:00 – 10:00 | 8 | 7:00 – 13:00 | 6 |
| | 15:00-19:00 | | 15:00-19:00 | | - | |
| From 9/12 to 23/12 | 7:00 – 11:00 | 10 | 7:00 – 13:00 | 10 | - | 0 |
| | 15:00-21:00 | | 15:00-19:00 | | | |
| From 24/12 to 08/01 | 8:00 – 12:00 | 4 | 8:00 – 12:00 | 4 | - | 0 |
| From 09/01 to 12/04 | 7:00 – 11:00 | 10 | 7:00 - 13:00 | 10 | 7:00 - 13:00 | 10 |
| | 15:00-21:00 | | 15:00 - 19:00 | | 15:00 - 19:00 | |
| From 12/04 to 15/04 | 6:00 – 10:00 | 4 | - | 0 | - | 0 |

### 4.7.4 Annual Energy Consumptions

The annual consumption recorded for each energy carrier, relating to the conditioned area of the various buildings, is reported below.

The client provided data of methane gas and electric consumption.

The consumptions reported concern the only methane gas meter serving the thermal plant which includes the centralized hydronic system for heating and domestic hot water production (serving the Ducal Palace building complex) and the steam thermal plant.

*Table 4.14 – Annual Methane Gas Consumption*

| Methane Gas Consumption [$m^3$] | | | |
|---|---|---|---|
| **Month** | **2015** | **2016** | **2017** |
| **January** | 206.555,00 | 138.517,60 | 112.142,80 |
| **February** | 183.081,00 | 163.193,40 | 131.951,60 |
| **March** | 138.764,00 | 111.461,40 | 73.031,20 |
| **April** | 55.198,00 | 48.304,10 | 38.654,00 |
| **May** | 22.933,00 | 28.441,40 | 25.183,40 |
| **June** | 28.868,00 | 38.439,70 | 17.756,20 |
| **July** | 10.585,00 | 28.202,20 | 17.559,30 |
| **August** | 12.510,00 | 20.722,00 | 6.554,90 |
| **September** | 22.772,00 | 46.250,10 | 26.147,00 |
| **October** | 70.955,00 | 68.088,60 | 34.312,30 |
| **November** | 106.477,00 | 115.237,50 | 113.118,50 |
| **December** | 121.635,00 | 173.746,50 | 107.395,20 |
| **TOTAL** | **980.333,00** | **980.604,50** | **703.806,40** |

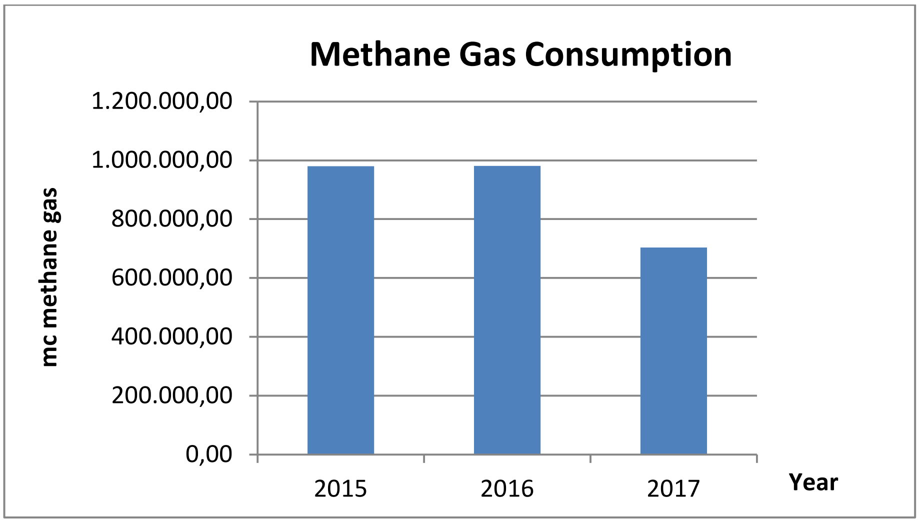



*Fig.4.51 – Methane Gas Consumption*

Analyzing the consumption of methane gas in the last three years there is a net drop in fuel in the last thermal season due to both the elimination of the steam circuit serving the kitchens of the ducal palace and the optimization of the Management Service.

In favor of safety with respect to energy saving analyzes and above all wishing to carry out analyzes as close as possible to the actual behavior of the coming years of the plexus in question, it was decided to use the consumptions of the last thermal season 2016/2017 taking care to proceed to normalization of day degrees compared to real ones.

*Table 4.15 – Annual Methane Gas Consumptions (2016/2017)*

| **Methane Gas Consumptions Of Thermal Season 2016/2017 [m$^3$]** | |
|---|---|
| **Month** | **Methane Gas Consumption [m$^3$]** |
| **October** | 68.088,60 |
| **November** | 115.237,50 |
| **December** | 173.746,50 |
| **January** | 112.142,80 |
| **February** | 131.951,60 |
| **March** | 73.031,20 |
| **April** | 38.654,00 |
| **May** | 25.183,40 |
| **June** | 17.756,30 |
| **July** | 17.559,30 |
| **August** | 6.554,90 |
| **September** | 26.147,00 |
| **TOTAL** | **806.053,10** |

Consumption has been normalized with respect to the degree days, the actual temperatures of the thermal season have been taken from the Meteorological Station of the Geophysical Observatory of the University of Modena, located right in the East tower of the Ducal Palace of Modena.

- Real Day Degrees: 2.205,50
- Day Degrees according to UNI 10349/2016: 2.258,00

The normalized methane gas consumption for the 2016/2017 thermal season used with reference to this energy diagnosis is **825.240,49** cubic meters.

The annual electrical consumption data (year 2017) collected from the various PODs present and surveyed within the complex "Palazzo Ducale di Modena" were provided.

*Table 4.16 – Annual Electrical Consumptions*

| **Annual Electrical Consumptions (2017)** | | | | | |
|---|---|---|---|---|---|
| **POD** | **Yearly consumption [kWh]** | **electric voltage** | **electric power** | **electric voltage** | **address** |
| IT011E10084260 | 555.292,33 | 400 | 185 | low | Piazza Roma 15 |
| IT011E10084264 | 67.024,53 | 400 | 75 | low | Piazza Roma 15 |
| IT011E10084267 | 76.836,95 | 400 | 62,5 | low | Piazza Roma 15 |
| IT011E10111576 | 39.055,03 | 400 | 90 | low | Piazza Roma 15 |
| IT011E10108363 | 592.202,68 | 15000 | 300 | medium | Corso Vitt. Eman. 22 |

The Medium Voltage POD actually only serves the Thermal Power Plant inside the Palace, the rest of the consumption is related to the “Montecuccoli Palace” not covered by this project.

## 4.8 The Energy Model

To construct the energy calculation model, each building was divided into distinct thermal zones and listed below according to the intended use and similar characteristics.
The surfaces and volumes of the various buildings under analysis are shown below.

**Ducal Palace**

*Table 4.17 – Areas and Volumes – Ducal Palace*

| Description | V [m$^3$] | S [m$^2$] | S/V [1/m] | Su [m$^2$] |
|---|---|---|---|---|
| office p0 | 25838,0 | 9150,16 | 0,35 | 3656,00 |
| apartment p0 | 5526,0 | 1819,22 | 0,33 | 765,00 |
| classroom p0 | 12720,0 | 3333,00 | 0,26 | 1980,00 |
| canteen 1 | 17400,0 | 1520,80 | 0,09 | 2700,00 |
| office p1 | 10800,0 | 1221,54 | 0,11 | 1500,00 |
| Duke Este halls p1 | 7800,0 | 1090,80 | 0,14 | 1050,00 |
| bar p1 | 1700,0 | 260,70 | 0,15 | 225,00 |
| infirmary p1 | 6240,0 | 1172,00 | 0,19 | 920,00 |
| Army officer club p1 | 5580,0 | 938,34 | 0,17 | 800,00 |
| museum p1 | 14400,0 | 2321,64 | 0,16 | 2140,00 |
| office p2 piazza roma | 13500,0 | 4168,37 | 0,31 | 1930,00 |
| office p2 corso cavour | 2100,0 | 874,24 | 0,42 | 230,00 |
| classroom p2 | 28560,0 | 8179,20 | 0,29 | 4148,00 |

| | net | gross | |
|---|---|---|---|
| Total Floor Area | 22.044,00 | 25.530,00 | m$^2$ |
| Total Volume | 131.467,00 | 152.164,00 | m$^3$ |

| | | |
|---|---|---|
| gross external area | 36.050,01 | m$^2$ |
| S/V ratio | 0,24 | m$^{-1}$ |

**Dardi Palace**

*Table 4.18 – Areas and Volumes – Dardi Palace*

| Description | V [m$^3$] | S [m$^2$] | S/V [1/m] | Su [m$^2$] |
|---|---|---|---|---|
| Ground floor Dardi | 9393,00 | 2713,81 | 0,29 | 1126,63 |
| First floor Dardi | 5130,00 | 1967,40 | 0,38 | 1060,00 |

| | net | gross | |
|---|---|---|---|
| Total Floor Area | 2.186,63 | 2.418,00 | $m^2$ |
| Total Volume | 11.110,34 | 14.523,00 | $m^3$ |

| | | |
|---|---|---|
| gross external area | 4.681,21 | $m^2$ |
| S/V ratio | 0,32 | $m^{-1}$ |

## Abba Palace

*Table 4.19 – Areas and Volumes – Abba Palace*

| Description | V $[m^3]$ | S $[m^2]$ | S/V [1/m] | Su $[m^2]$ |
|---|---|---|---|---|
| Ground floor Abba | 9393,00 | 2713,81 | 0,29 | 1126,63 |
| First floor Abba | 5130,00 | 1967,40 | 0,38 | 1060,00 |

| | net | gross | |
|---|---|---|---|
| Total Floor Area | 2.186,63 | 2.418,00 | $m^2$ |
| Total Volume | 11.110,34 | 14.523,00 | $m^3$ |

| | | |
|---|---|---|
| gross external area | 4.681,21 | $m^2$ |
| S/V ratio | 0,32 | $m^{-1}$ |

## Aliprandi Palace

*Table 4.20 – Areas and Volumes – Aliprandi Palace*

| Description | V $[m^3]$ | S $[m^2]$ | S/V [1/m] | Su $[m^2]$ |
|---|---|---|---|---|
| Aliprandi | 13449,00 | 5709,80 | 0,42 | 2898,00 |

| | net | gross | |
|---|---|---|---|
| Total Floor Area | 2.898,00 | 3.150,00 | $m^2$ |
| Total Volume | 10.672,90 | 13.449,00 | $m^3$ |

| | | |
|---|---|---|
| gross external area | 5.709,80 | $m^2$ |
| S/V ratio | 0,42 | $m^{-1}$ |

## Fanti Pool

*Table 4.21 – Areas and Volumes – Fanti Pool*

| Description | V $[m^3]$ | S $[m^2]$ | S/V [1/m] | Su $[m^2]$ |
|---|---|---|---|---|
| Fanti | 13449,00 | 5709,80 | 0,42 | 2898,00 |

| | net | gross | |
|---|---|---|---|
| Total Floor Area | 740,00 | 770,00 | $m^2$ |
| Total Volume | 4.748,00 | 5.271,00 | $m^3$ |

| | | |
|---|---|---|
| gross external area | 2.182,63 | $m^2$ |
| S/V ratio | 0,41 | $m^{-1}$ |

Various simulations have been made for the energy diagnosis under examination. The most important was made through the TRNSYS software using the dynamic regime. The description of the simulation of the Ducal Palace are shown below.

## 4.8.1 TRNSYS Energy model

The simulations have been carried out using TRNSYS 17 dynamic thermal modelling software.

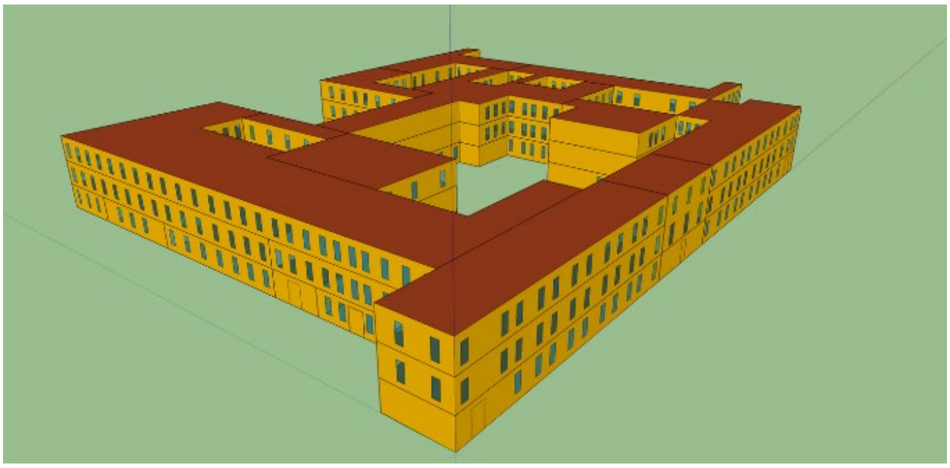


*Fig.4.52 – Building simulation model*

Given the complexity of the building under analysis, it was decided to divide the heated volume of the Palace into zones, combining in this way rooms with the same intended use and considering only the three floors main. Locations characterized by the same intended use have similar needs in terms of required temperatures and plant operating hours.

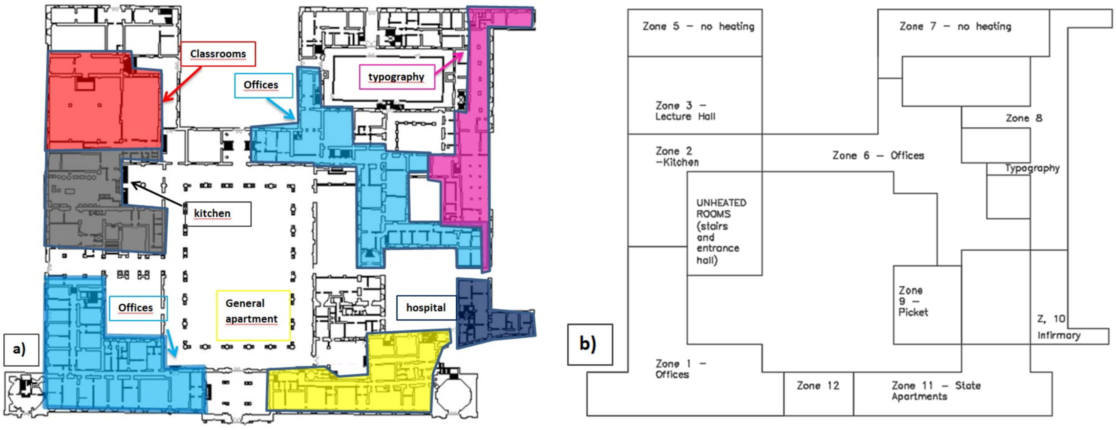



*Fig. 4.53 - a) Ground floor plan and intended uses. b) Thermal zones of the ground floor in the simulation model*

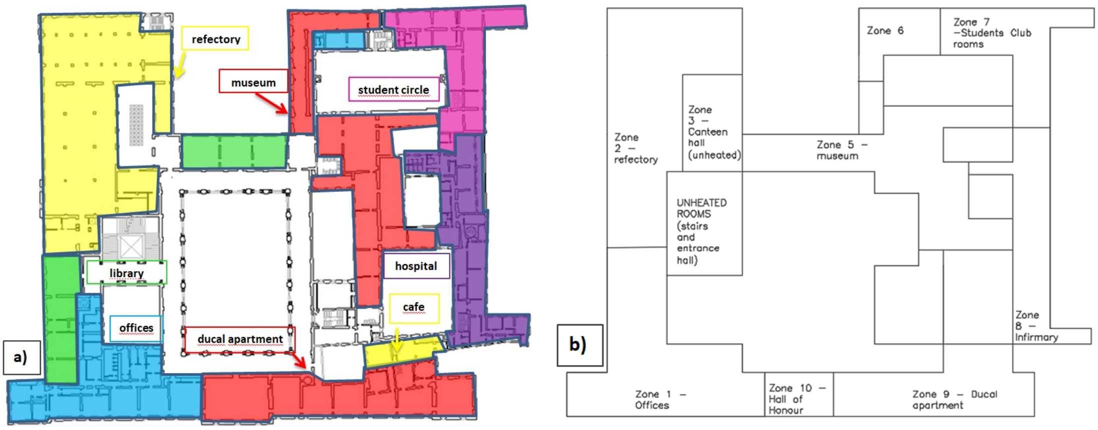



*Fig. 4.54 - a) First floor and intended uses. b) Thermal zones of the first floor in the simulation model*

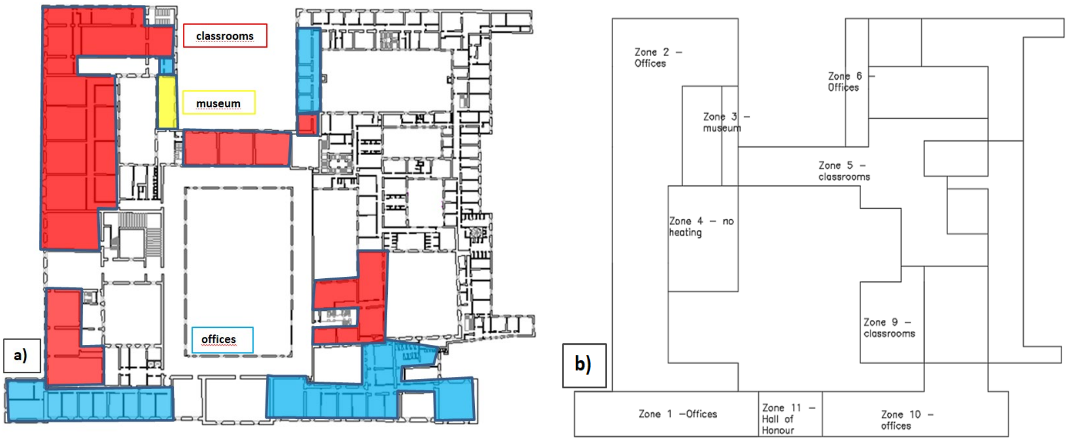



*Fig. 4.55 - a) Second floor and intended uses. b) Thermal zones of the second floor in the simulation model*

In the simulation model the air changes per hour are supposed to range from 0.5 to 1 vol/h, according to the rooms different uses, as defined in ISO 13789.

Internal gains, such as lighting, equipment and occupants are defined according to the conventional opening hours of the building. Air infiltration losses have been estimated with the calculation method of ISO 13789. Such average values are used due to the unavailability of more detailed information.

The meteorological data used in the simulations were collected by the University of Modena and Reggio Emilia weather station, which is located in the selected building. The hourly weather data include horizontal global radiation, dry bulb temperature, wind speed and relative humidity. [4.2]

The values relating to ventilation rates and internal contributions have been varied in order to obtain a calibration of the model that coincides with real energy consumption and the real behavior of the thermal zones.

The first step to evaluate the use of a model in a dynamic regime is the possibility to validate the model through a calibration procedure. The model of the Ducal Palace is calibrated with the use of the monthly building energy consumption data and thanks to the use of data loggers it was possible to calibrate the model through hourly temperature and relative humidity data recorded in some areas of the building.

### 4.8.2 TRNSYS Calibration Procedure

The collection of real data on site is essential for a correct setting of the model.

The external temperature and humidity data of the case study were collected from the weather station located on the east tower of the academy and the internal temperature and humidity data through the application of temperature probes positioned for a certain period within the environments.

*Fig.4.56 – UNIMORE weather station located on the east tower of the Ducal Palace*

*Fig.4.57 – data logger for internal temperature measures*

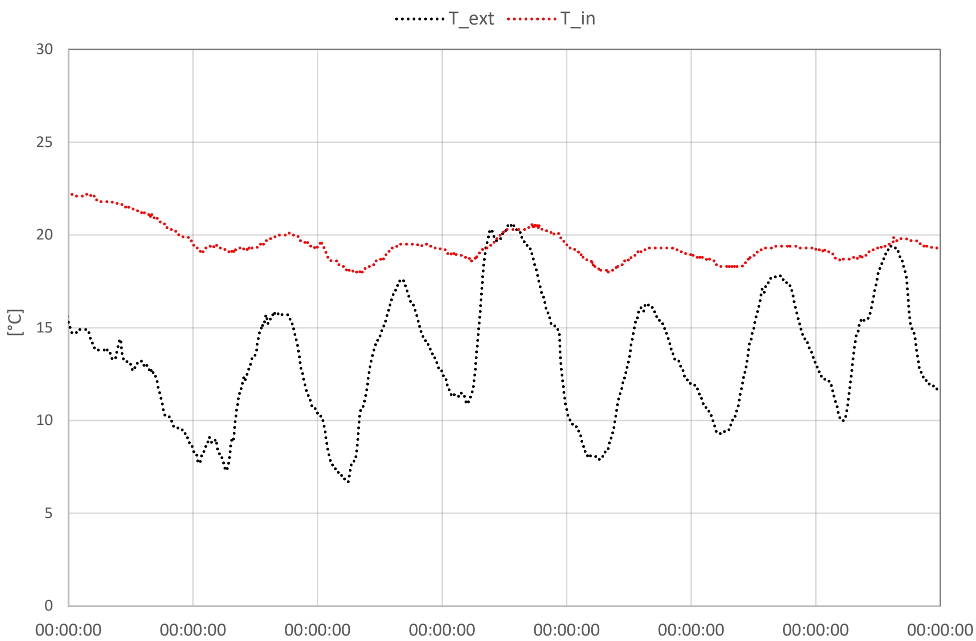



*Fig.4.58 – Internal and external temperature measurements for an unheated room in the building. Period considered: 24-30 April 2016*

Through the TRNSYS model it is possible to evaluate the internal temperature in some rooms of the Palace and compares with the real temperature measured with the data loggers.

The normalized mean bias error (NMBE) and the coefficient of variance of the root mean square error (CV(RMSE)) were used for the analysis in according with ASHRAE

Guidelines 14. Respectively, the NMBE and the CV(RMSE) of the hourly indoor air temperature were 4% and 5%. The results show that the selected indexes are in agreement with the tolerance range and the model has been considered representative of the actual energy performance of the selected rooms.

| | | | | | |
|---|---|---|---|---|---|
| 1 | | | *Temperature Calibration* | | |
| 2 | | | **RMSE** | **CV(RMSE)** | **NMBE** |
| 3 | INF | 0,5 | 0 | *<30%* | *<10%* |
| 4 | BUI | V1 | 1,31 | 4,79% | -3,81% |
| 5 | | | | | |
| 6 | INF | 0,5 | 0 | *<30%* | *<10%* |
| 7 | BUI | V2 | 1,33 | 4,88% | -3,95% |
| 8 | | | | | |
| 9 | INF | 0,5 | 0 | *<30%* | *<10%* |
| 10 | BUI | V3 | 1,50 | 5,49% | -4,64% |
| 11 | | | | | |
| 12 | INF | 1 | 0 | *<30%* | *<10%* |
| 13 | BUI | V1 | 1,51 | 5,51% | -4,93% |
| 14 | | | | | |
| 15 | INF | 1 | 0 | *<30%* | *<10%* |
| 16 | BUI | V2 | 1,53 | 5,60% | -5,01% |
| 17 | | | | | |
| 18 | INF | 1 | 0 | *<30%* | *<10%* |
| 19 | BUI | V3 | 1,68 | 6,13% | -5,40% |
| 20 | | | | | |

*Fig.4.59 – Calibration*

Being the extension of the building very large, it was not possible to carry out a complete measurement campaign, therefore the model was also calibrated through the energy consumption data.

## 4.9 Results Obtained With Energy Audit

Following the results obtained through the energy audit, the impact of the consumption of the various buildings and subsystems is shown below.

### 4.9.1 Analysis of the Electrical Consumptions

*Table 4.22 – Electric Energy*

| Electric Energy | |
|---|---|
| Lighting | 62% |
| Other utilities | 20% |
| Transportation services | 8% |
| Pumps | 10% |

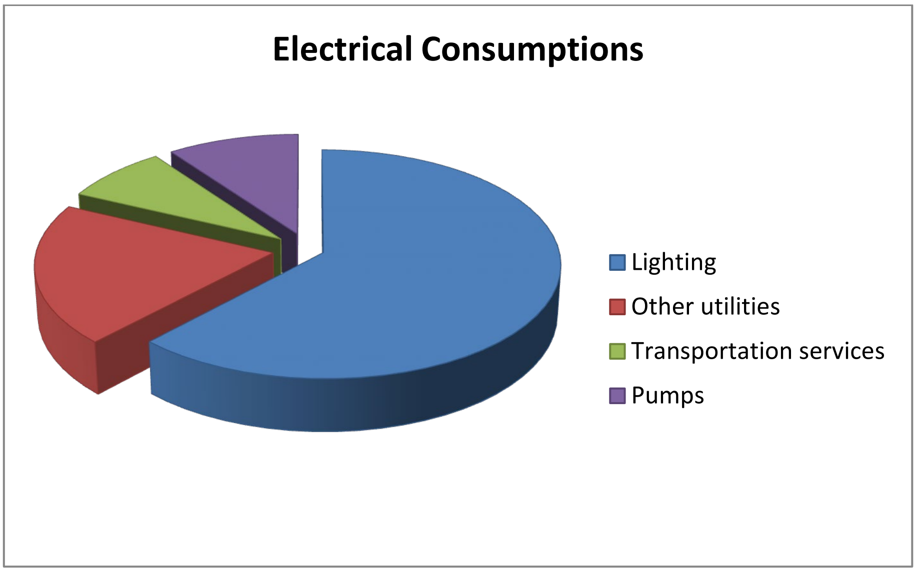



*Fig.4.60 – Electrical Consumptions*

### 4.9.2 Analysis of the Methane Gas Consumptions

*Table 4.23 – Methane Gas Consumptions*

| Methane Gas Consumptions | | |
|---|---|---|
| Heating Ducal-Abba-Dardi-Aliprandi Palace | 581.449,00 $m^3$ | 70% |
| Heating Fanti Pool | 28.891,00 $m^3$ | 4% |
| Steam Fanti Pool + Ironing | 104.384,49 $m^3$ | 13% |
| DHW Ducal - Abba - Dardi - Aliprandi Palace | 110.516,00 $m^3$ | 13% |

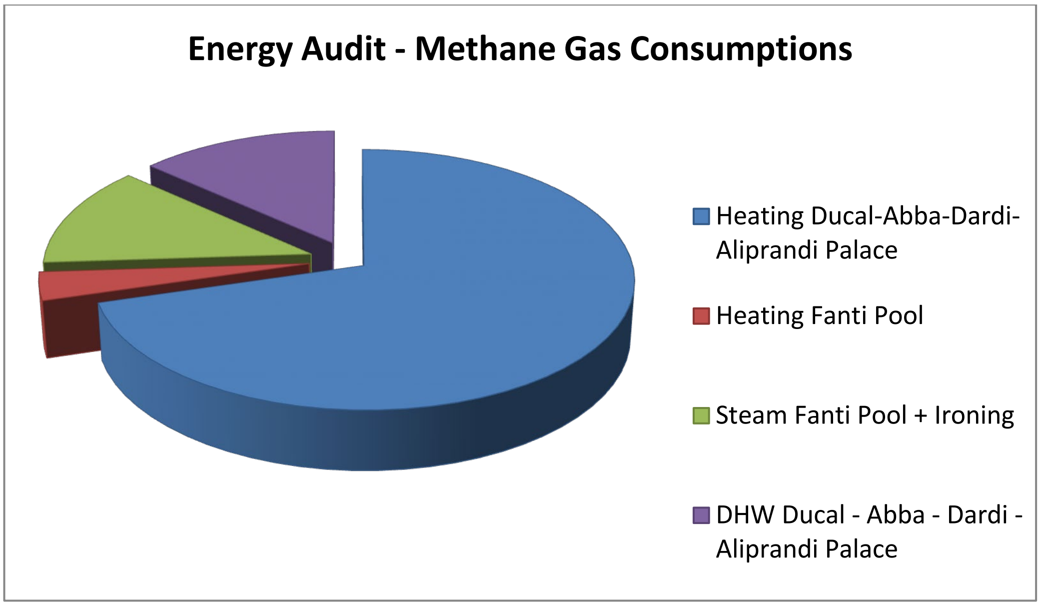



*Fig.4.61 – Methane Gas Consumptions*

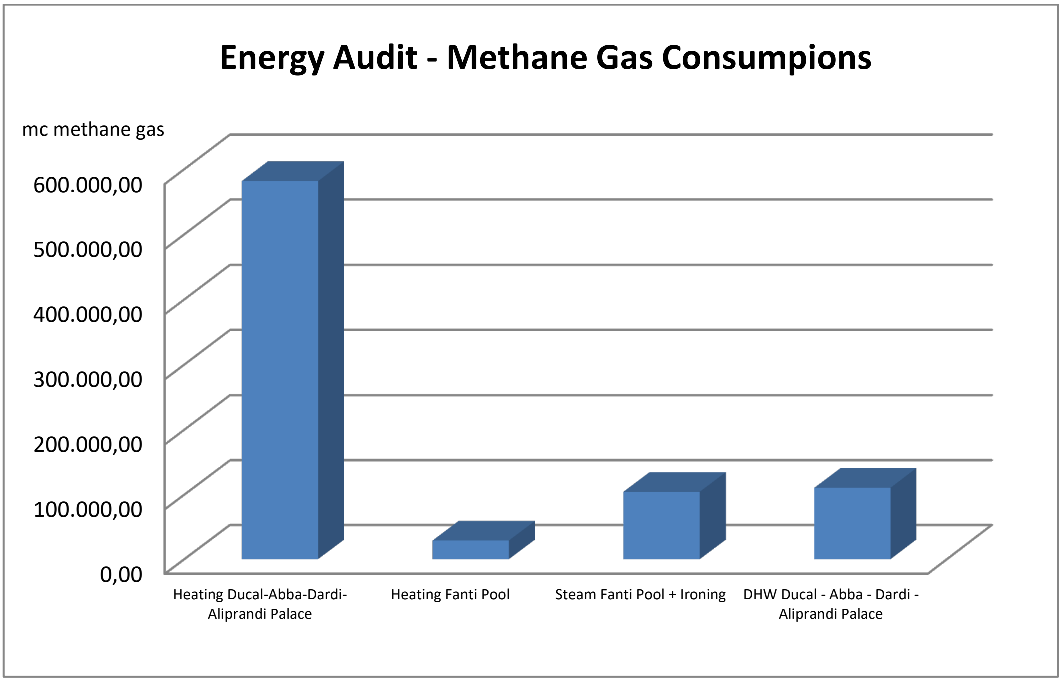



*Fig.4.62 – Methane Gas Consumptions*

### 4.9.3 Analysis of the consumption of centralized Domestic Hot Water (DHW) Production for the Ducal Palace - Dardi Palace - Abba Palace and Aliprandi Palace

The following figures show the consumption of methane gas for the production of domestic hot water for each building.

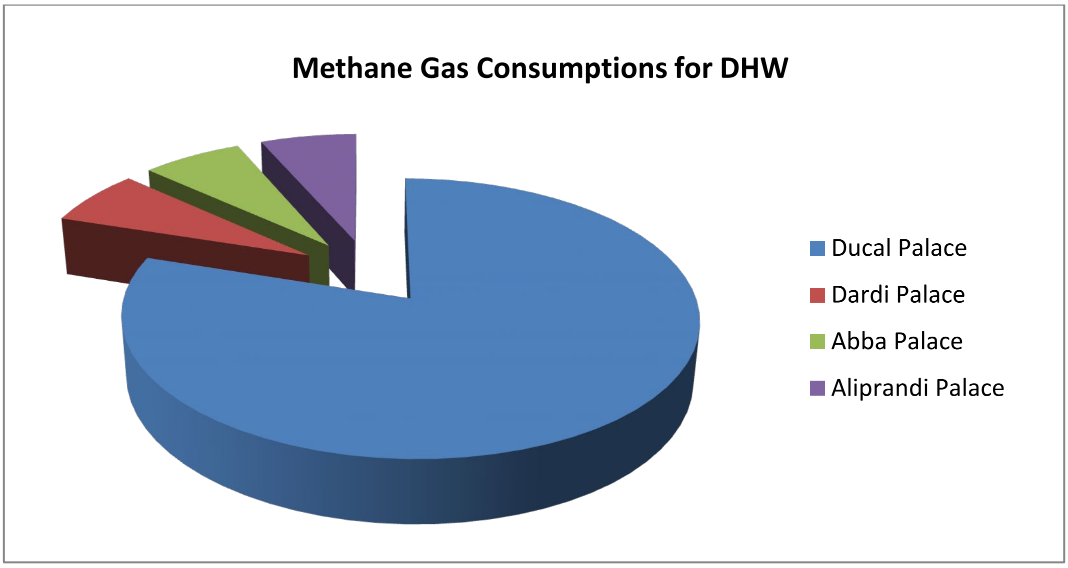



*Fig.4.63 – Methane Gas Consumptions for DHW*

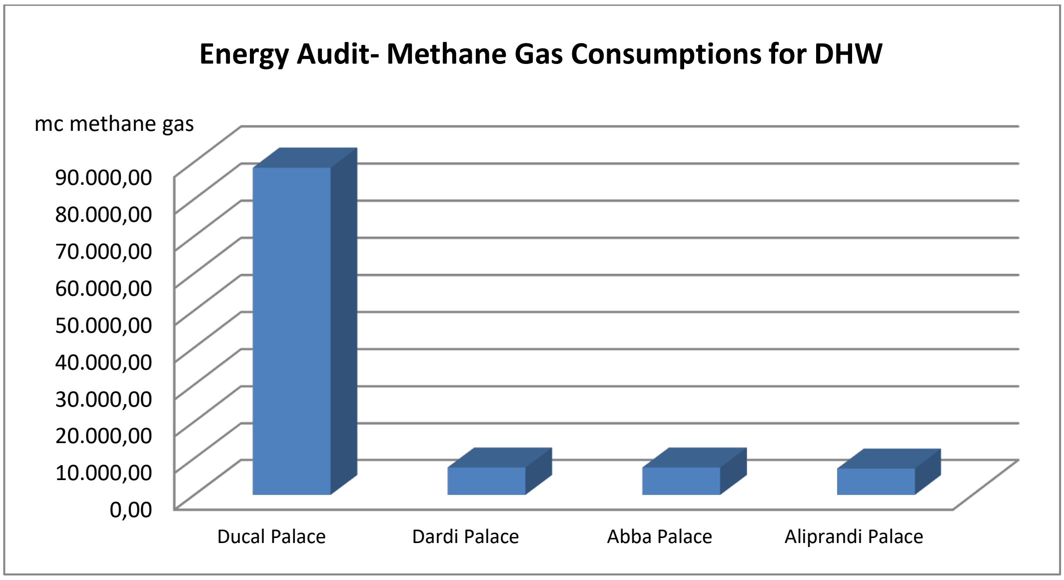



*Fig.4.64 – Methane Gas Consumptions for DHW*

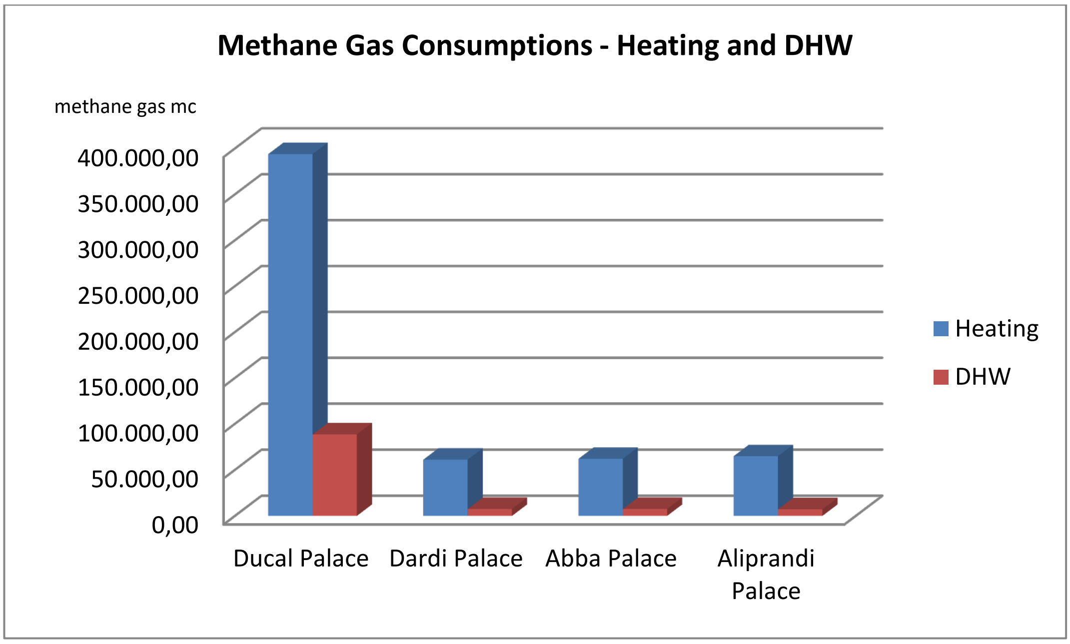



*Fig.4.65 – Methane Gas Consumptions – Heating and DHW*

### 4.9.4 Analysis of the Ducal Palace methane gas consumptions

The following figures show the consumption of methane gas for the heating and the production of domestic hot water for the Ducal Palace.

*Table 4.24 – Methane Gas Consumptions of the Ducal Palace*

| Ducal Palace | |
|---|---|
| **Methane Gas Consumptions for Heating [m$^3$]** | **Methane Gas Consumptions for DHW [m$^3$]** |
| 393.750,00 | 88.399,10 |

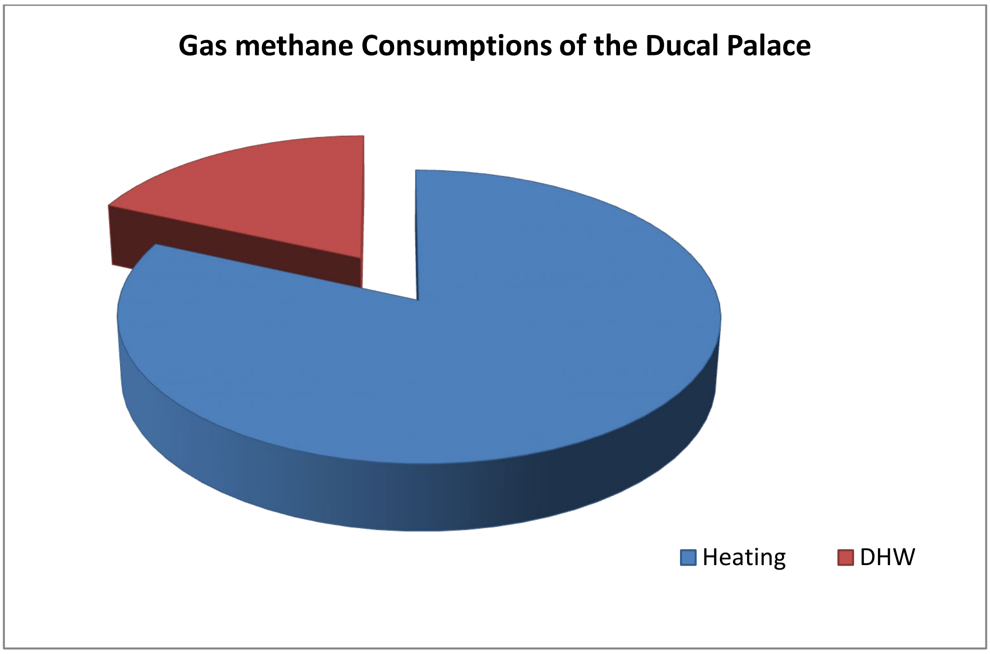



*Fig.4.66 – Methane Gas Consumptions of the Ducal Palace– Heating and DHW*

The analysis of the various components of the heating requirement for the Ducal Palace is shown below.

*Table 4.25 – Components of the heating requirement for the Ducal Palace*

| Ducal Palace | | |
|---|---|---|
| **Description** | **Annual Energy [kWh]** | **Percentage** |
| Heat loss for transmission | 1.616.795,00 | 52,13% |
| Heat loss for ventilation | 881.232,00 | 28,42% |
| Internal Gains | 232.710,00 | 7,50% |
| Solar Gains | 370.440,00 | 11,95% |

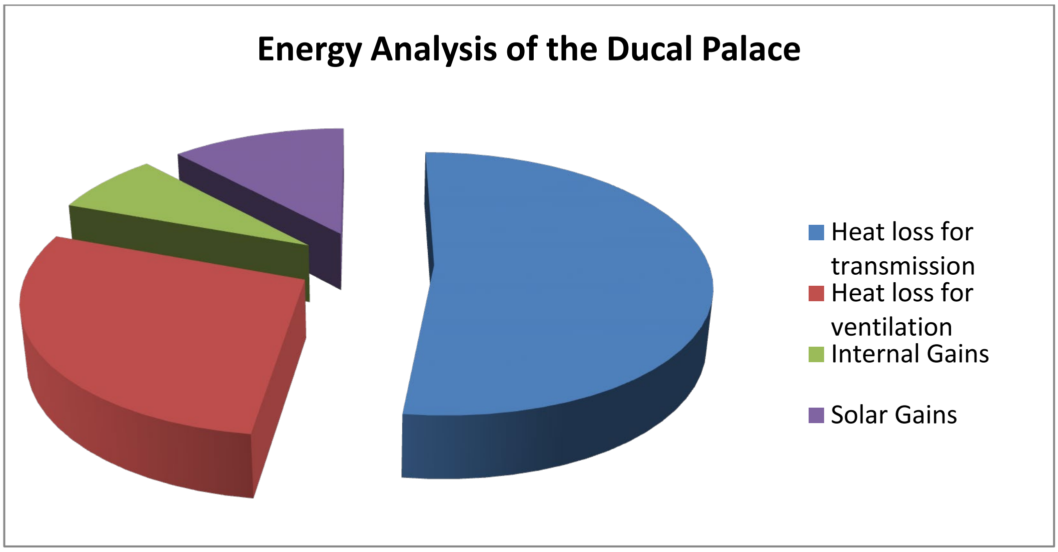



*Fig.4.67 – Energy Analysis of the Ducal Palace*

*Table 4.26 – Energy Analysis of the components of the building envelope of the Ducal Palace*

| **Ducal Palace** | |
|---|---|
| **Component of the building envelope** | **Percentage** |
| vertical walls | 51,60% |
| floors | 9,91% |
| roofs | 17,48% |
| windows | 21,02% |

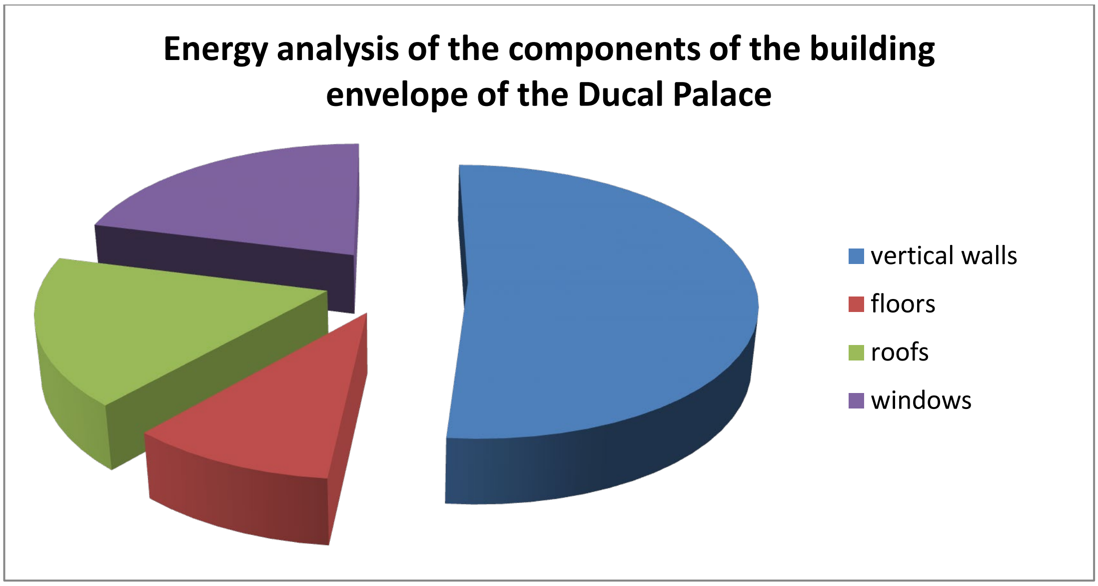



*Fig.4.68 – Energy Analysis of the components of the building envelope of the Ducal Palace*

### 4.9.5 Analysis of the Dardi Palace methane gas consumptions

The following figures show the consumption of methane gas for the heating and the production of domestic hot water for the Dardi Palace.

*Table 4.27 – Methane Gas Consumptions of the Dardi Palace*

| Dardi Palace | |
|---|---|
| **Methane Gas Consumptions for Heating [$m^3$]** | **Methane Gas Consumptions for DHW [$m^3$]** |
| 61.019,00 | 7.470,54 |

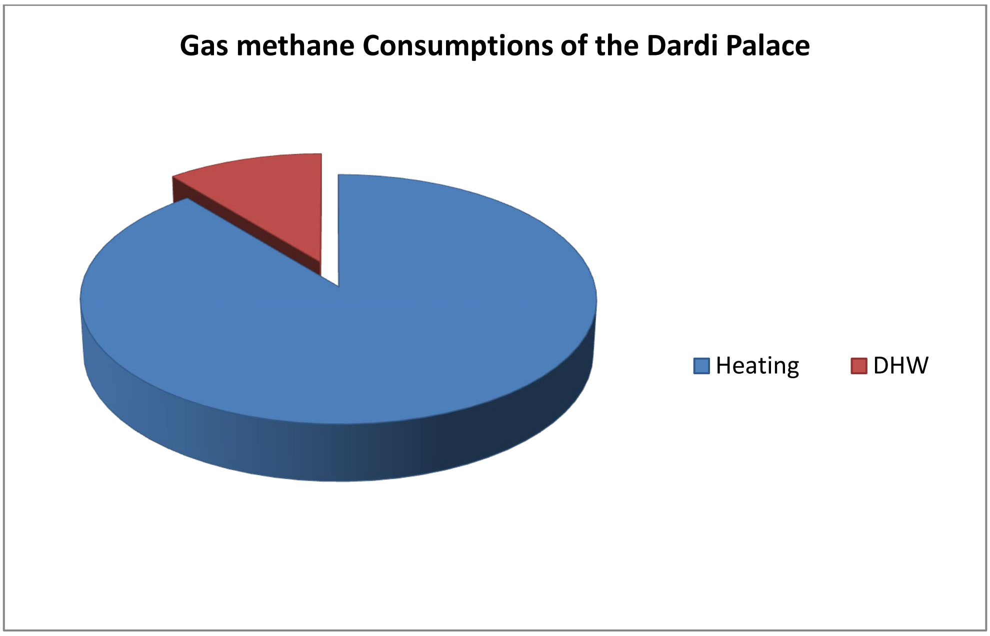



*Fig.4.69 – Methane Gas Consumptions of the Dardi Palace– Heating and DHW*

The analysis of the various components of the heating requirement for the Dardi Palace is shown below.

*Table 4.28 – Components of the heating requirement for the Dardi Palace*

| Dardi Palace | | |
|---|---|---|
| **Description** | **Annual Energy [kWh]** | **Percentage** |
| Heat loss for transmission | 304.556,00 | 61,72% |
| Heat loss for ventilation | 55.854,00 | 11,32% |
| Internal Gains | 43.636,00 | 8,84% |
| Solar Gains | 89.437,00 | 18,12% |

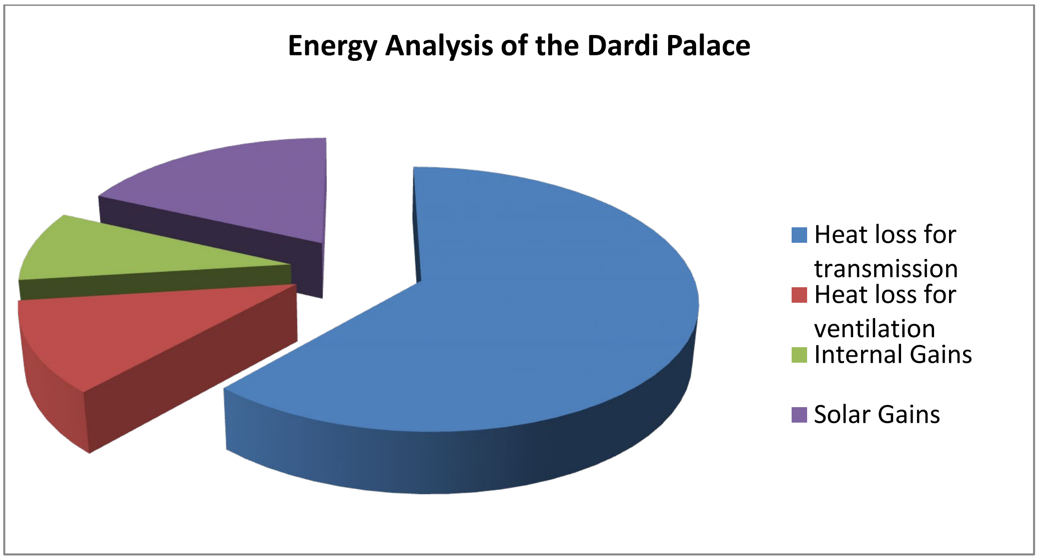



*Fig.4.70 – Energy Analysis of the Ducal Palace*

*Table 4.29 – Energy Analysis of the components of the building envelope of the Dardi Palace*

| **Dardi Palace** | |
|---|---|
| **Component of the building envelope** | **Percentage** |
| vertical walls | 31,68% |
| floors | 5,41% |
| roofs | 24,70% |
| windows | 38,21% |

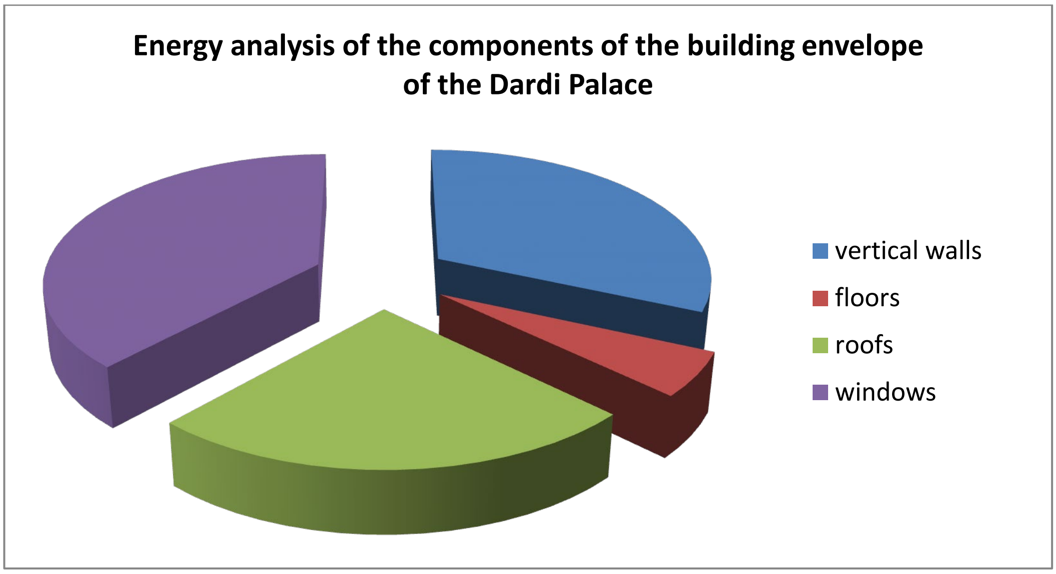



*Fig.4.71 – Energy Analysis of the components of the building envelope of the Dardi Palace*

### 4.9.6 Analysis of the Abba Palace methane gas consumptions

The following figures show the consumption of methane gas for the heating and the production of domestic hot water for the Abba Palace.

*Table 4.30 – Methane Gas Consumptions of the Abba Palace*

| Abba Palace | |
|---|---|
| **Methane Gas Consumptions for Heating [$m^3$]** | **Methane Gas Consumptions for DHW [$m^3$]** |
| 61.019,00 | 7.470,54 |

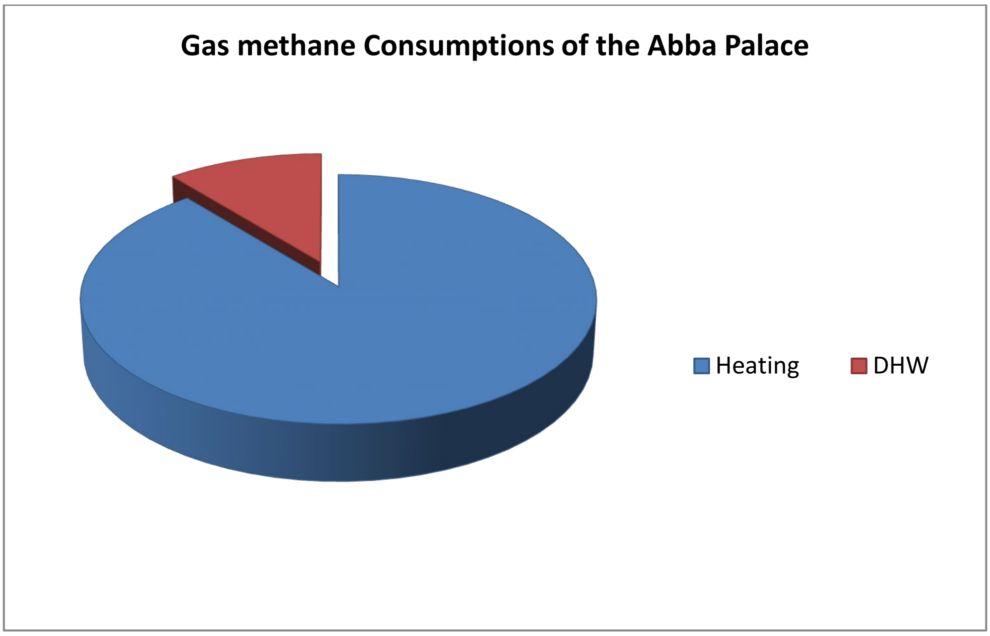



*Fig.4.72 – Methane Gas Consumptions of the Abba Palace– Heating and DHW*

The analysis of the various components of the heating requirement for the Abba Palace is shown below.

*Table 4.31 – Components of the heating requirement for the Abba Palace*

| Abba Palace | | |
|---|---|---|
| **Description** | **Annual Energy [kWh]** | **Percentage** |
| Heat loss for transmission | 304.091,00 | 62,49% |
| Heat loss for ventilation | 55.854,00 | 11,48% |
| Internal Gains | 43.363,00 | 8,91% |
| Solar Gains | 83.342,00 | 17,13% |

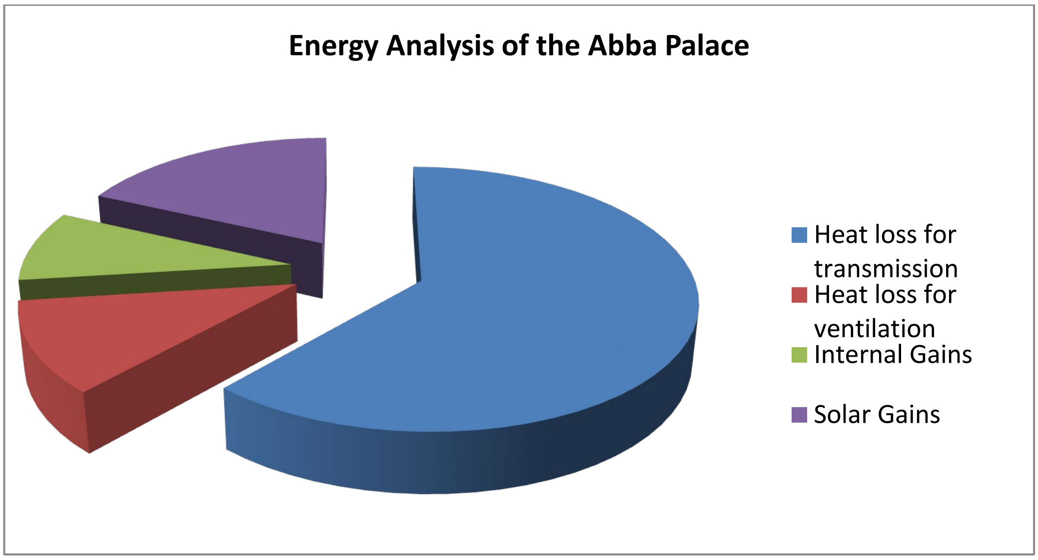



*Fig.4.73 – Energy Analysis of the Abba Palace*

*Table 4.32 – Energy Analysis of the components of the building envelope of the Abba Palace*

| Abba Palace | |
|---|---|
| **Component of the building envelope** | **Percentage** |
| vertical walls | 31,73% |
| floors | 5,40% |
| roofs | 24,76% |
| windows | 38,11% |

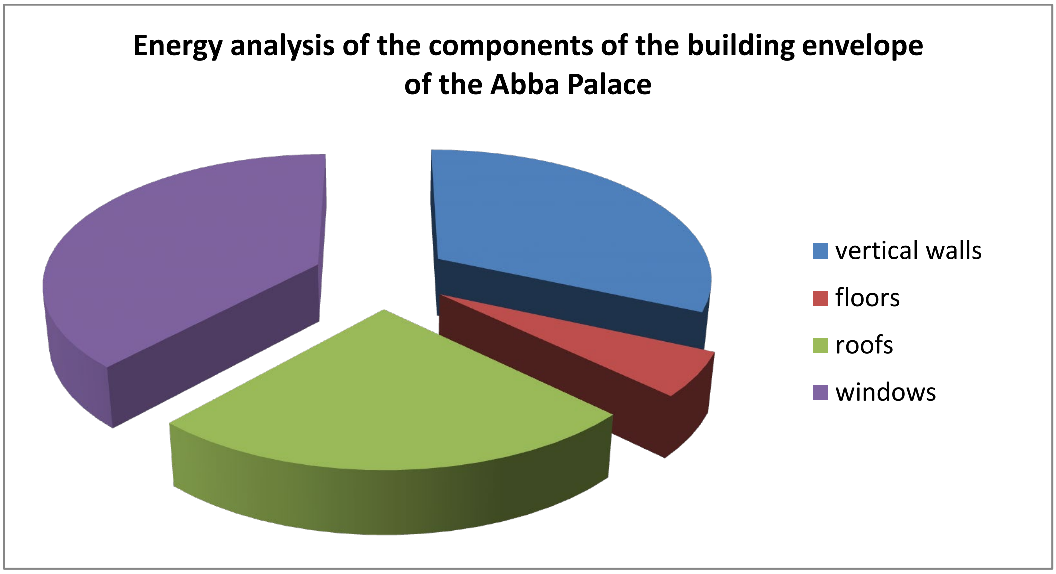



*Fig.4.74 – Energy Analysis of the components of the building envelope of the Abba Palace*

## 4.9.7 Analysis of the Aliprandi Palace methane gas consumptions

The following figures show the consumption of methane gas for the heating and the production of domestic hot water for the Aliprandi Palace.

*Table 4.33 – Methane Gas Consumptions of the Aliprandi Palace*

| Aliprandi Palace | |
|---|---|
| **Methane Gas Consumptions for Heating [$m^3$]** | **Methane Gas Consumptions for DHW [$m^3$]** |
| 64.728,00 | 7.175,83 |

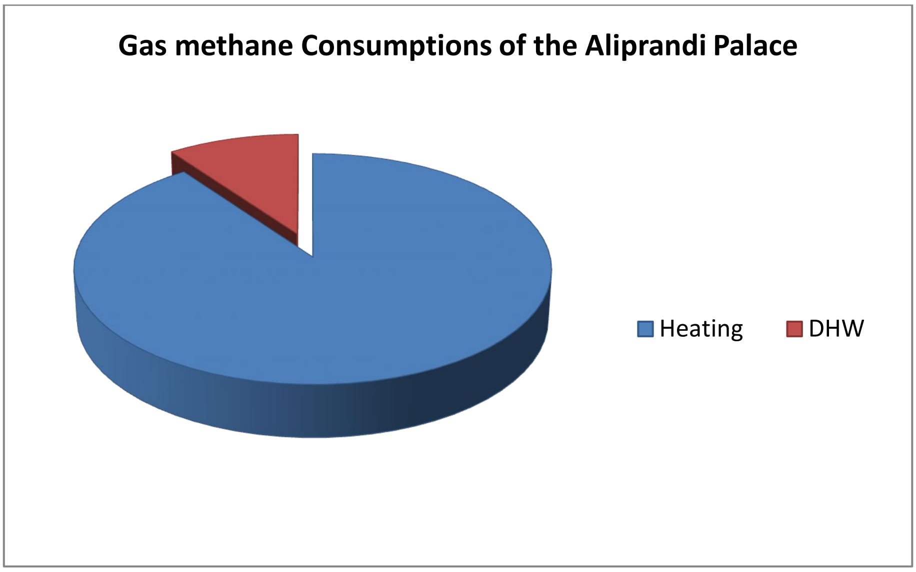



*Fig.4.75 – Methane Gas Consumptions of the Aliprandi Palace– Heating and DHW*

The analysis of the various components of the heating requirement for the Aliprandi Palace is shown below.

*Table 4.34 – Components of the heating requirement for the Aliprandi Palace*

| Aliprandi Palace | | |
|---|---|---|
| **Description** | **Annual Energy [kWh]** | **Percentage** |
| Heat loss for transmission | 256.039,00 | 58,20% |
| Heat loss for ventilation | 89.924,00 | 20,44% |
| Internal Gains | 50.912,00 | 11,57% |
| Solar Gains | 43.071,00 | 9,79% |

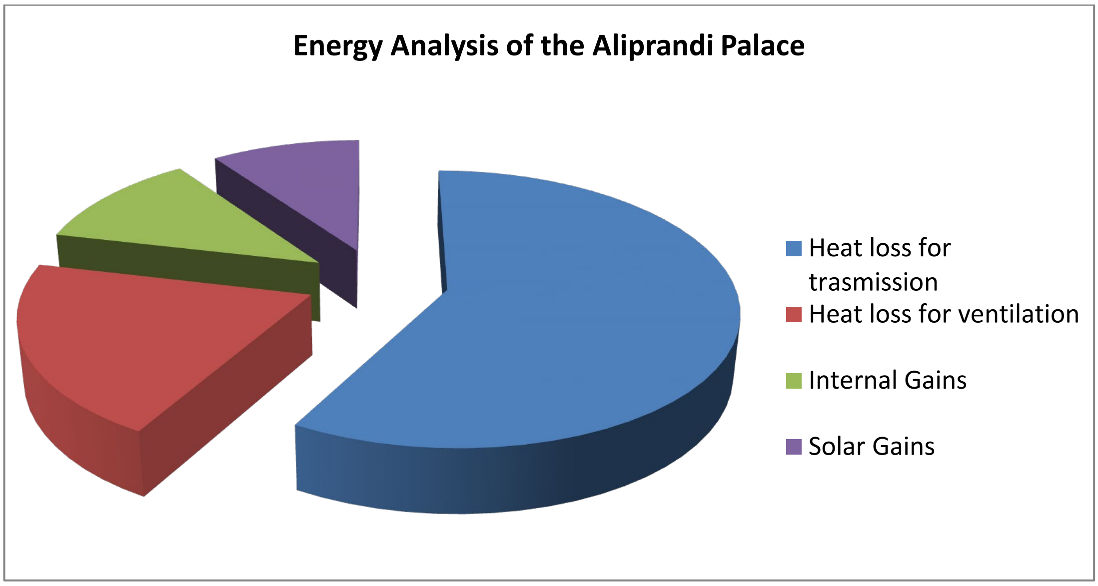



*Fig.4.76 – Energy Analysis of the Aliprandi Palace*

*Table 4.35 – Energy Analysis of the components of the building envelope of the Aliprandi Palace*

| Aliprandi Palace | |
|---|---|
| **Component of the building envelope** | **Percentage** |
| vertical walls | 31,73% |
| floors | 5,40% |
| roofs | 24,76% |
| windows | 38,11% |

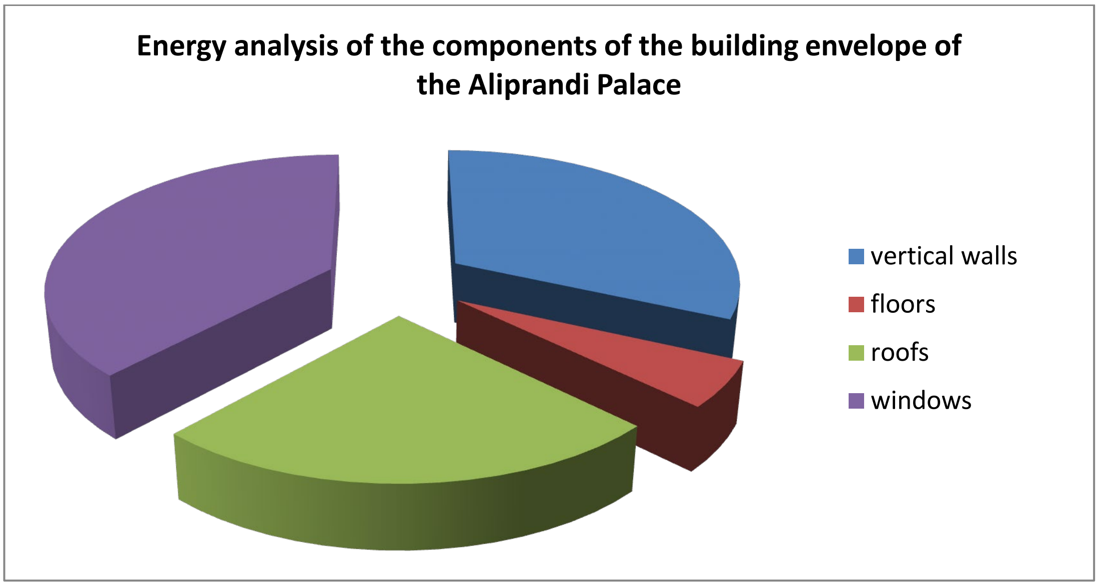



*Fig.4.77 – Energy Analysis of the components of the building envelope of the Aliprandi Palace*

## 4.9.8 Analysis of the Fanti Pool methane gas consumptions

The analysis of the various components of the heating requirement for the Pool Fanti is shown below.

*Table 4.36 – Components of the heating requirement for the Pool Fanti*

| Pool Fanti | | |
|---|---|---|
| **Description** | **Annual Energy [kWh]** | **Percentage** |
| Heat loss for transmission | 162.243,00 | 56,31% |
| Heat loss for ventilation | 41.723,00 | 14,48% |
| Internal Gains | 32.501,00 | 11,28% |
| Solar Gains | 51.643,00 | 17,92% |

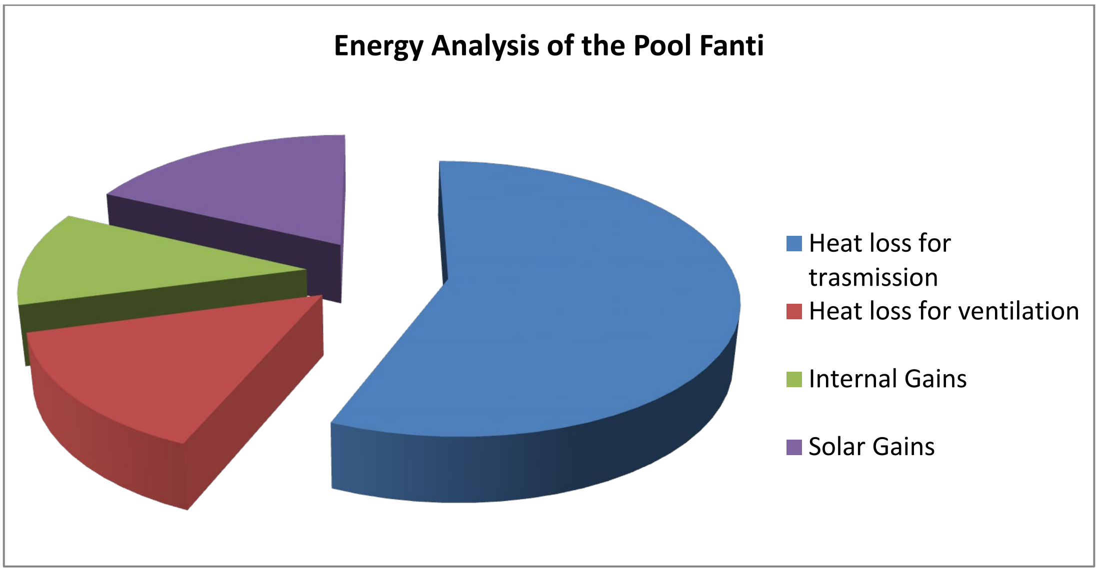



*Fig.4.78 – Energy Analysis of the Pool Fanti*

*Table 4.37 – Energy Analysis of the components of the building envelope of the Pool Fanti*

| Pool Fanti | |
|---|---|
| **Component of the building envelope** | **Percentage** |
| vertical walls | 23,35% |
| floors | 25,56% |
| roofs | 22,89% |
| windows | 28,20% |

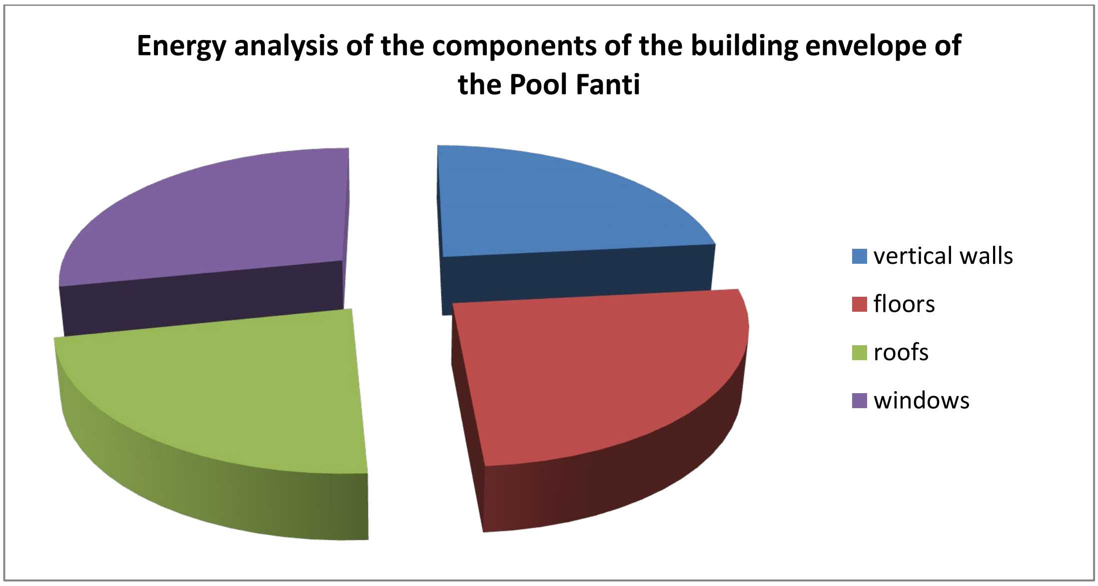



*Fig.4.79 – Energy Analysis of the components of the building envelope of the Pool Fanti*

## 4.9.9 The role of the Thermal Inertia

The role of thermal inertia in historic buildings is significant compared to buildings built in more recent times, this is due to the important thickness of the walls.

The following figures show the diversity of thermal behavior between the areas of the ground floor, first and second floors of the case study , the Ducal Palace, during a spring week. It is possible to notice how the zones analyzed, in the absence of heating, have a markedly different thermal behavior in some cases, even if they belong to the same plane. The results of the simulations also allow to observe the effect of the thermal inertia of the walls, which represents the combined effect of the thermal accumulation and the thermal resistance of the building envelope component.

A criticism of the dynamic simulation software used (TRNSYS) is precisely in the study of the role of thermal inertia of the walls of the building. TRNSYS is a software born in the United States where the prevalent typology of buildings is light-walled therefore it was not born for the study of massive walls as in the case of historic buildings.

To be able to take into account the thermal inertia in the building simulations, it was necessary to interface with the software developers who suggested increasing the time base up from the default value of 1 hour.

The time base is a kind of time step for witch a wall's transfer function coefficients are computed; the time base is a kind of time step for a wall's transfer function coefficients are computed. It is not the same as the simulation time step; it has more to do how often the wall's thermal profile is updated during the course of the simulation.

In the simulations the time-base increased to 3 hours gived reasonable results.

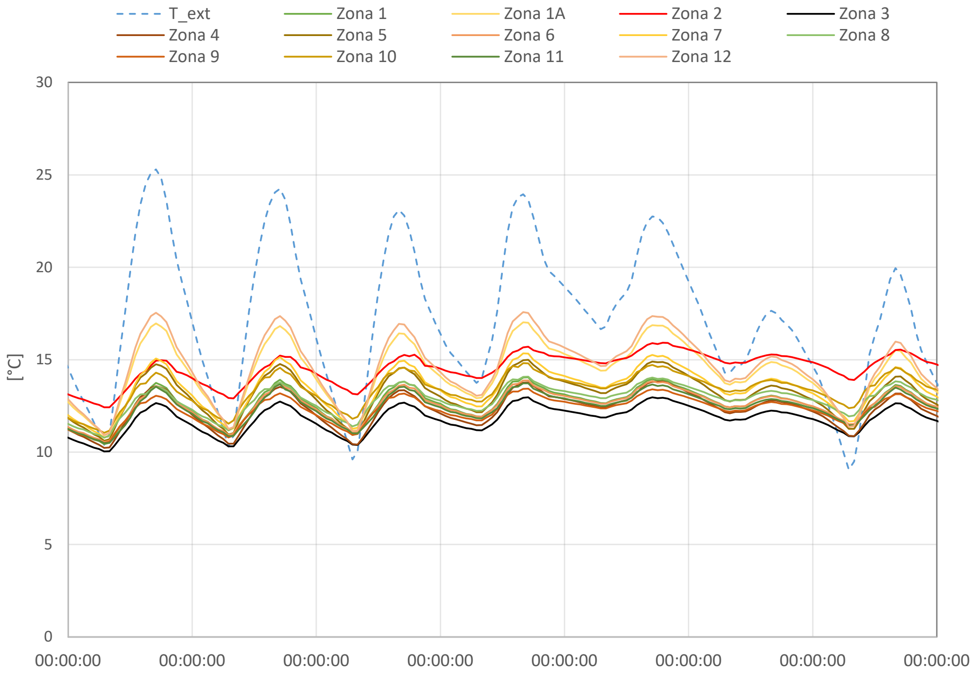



*Fig.4.80 – Temperature trend in the ground floor of the building. Period considered: spring week*

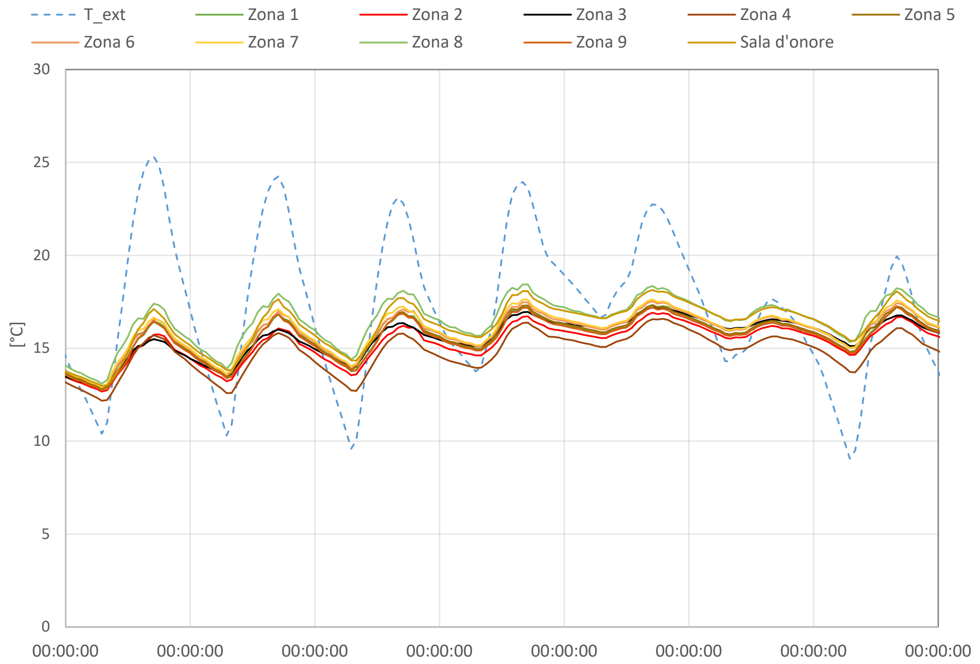



*Fig.4.81 – Temperature trend in the first floor of the building. Period considered: spring week*

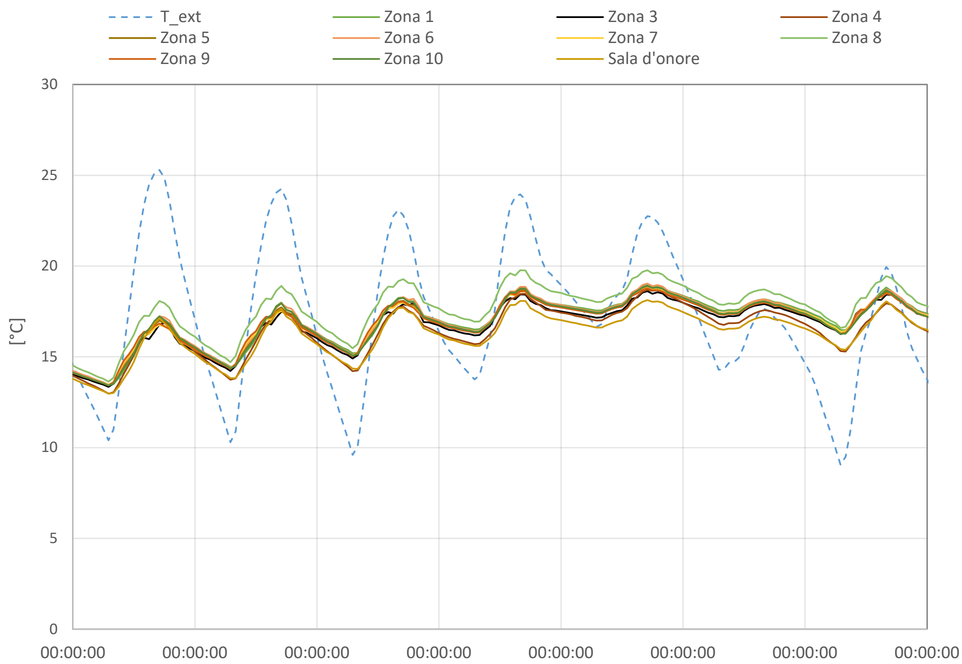



*Fig.4.82– Temperature trend in the second floor of the building. Period considered: spring week*

In Figure 4.83 it is possible to observe the drop in temperatures in the different areas of the foreground following a hypothetical shutdown of the heating system, once again showing the effect of the inertia of the walls.

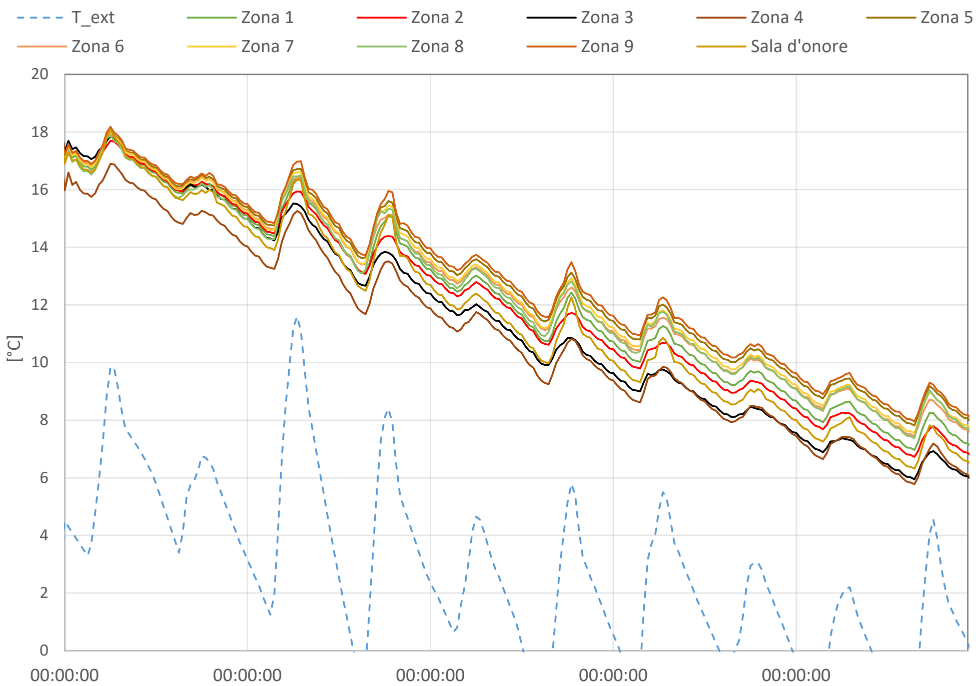



*Fig.4.83 – Temperature trend in the first floor of the building after hypothetical shutdown of the heating system. Period considered: winter week*

# 5. ENERGY RETROFITTING SOLUTION FOR THE DUCAL PALACE OF MODENA

The energy retrofitting solutions of the case study respect the following parameters:

- greater cost / investment benefits;

- compatibility with the architectural constraints of the building.

The complex of interventions was identified on the basis of economic and functional assessments with respect to the structural and plant characteristics of the building and the cost / benefit ratio.

The center of the city of Modena is a UNESCO so the use of renewable energy has not been envisaged such as the installation of a photovoltaic system on the roof of the building.

The value of the investment of each single proposed action has been estimated using, where possible, reference price lists (Public Works, Construction works, Chamber of Commerce, etc.). The cost of the intervention is intended as a work carried out in a workmanlike manner and is inclusive of any temporary works, business reload (profit and general expenses), net of VAT.

In order to make the results of the Energy Audit comparable with other buildings the following data have been used:

• Tariff of fuel (methane): 0.6557 € / mc, excluding VAT.

• Electricity rate: 0.2172 € / kWh, excluding VAT.

## 5.1 Windows Retrofitting Solution

For the energy retrofitting solution of the windows, a series of meetings were made with the local Superintendency.

In particular, the Superintendency requested that the new windows maintain the same geometric design of the frame, the same color and the same type of material (therefore the windows with wooden frame must keep the wood while the metal ones can be aluminum with thermal break).

The proposal that had been made was to use a metal frame with wooden cladding which, given the considerable weight of the windows, would have been more suitable, however the solution was not accepted by the Superintendency.

The double glazing of the new windows will be perfectly transparent, with thermal transmittance ≤ 1.3 W/m$^2$ K.

Below are the results of the window retrofitting intervention in terms of energy saving and payback time.

*Table 5.1 – Windows Retrofitting Solution*

| Windows Retrofitting Solution | | | |
|---|---|---|---|
| **Investment Cost (€)** | **Energy saving [mc methane gas]** | **Annual saving (€)** | **CO2 saving (ton/y)** |
| 2.686.480,00 € | 66.912,00 | € 43.874,20 | 139,4 ton. |

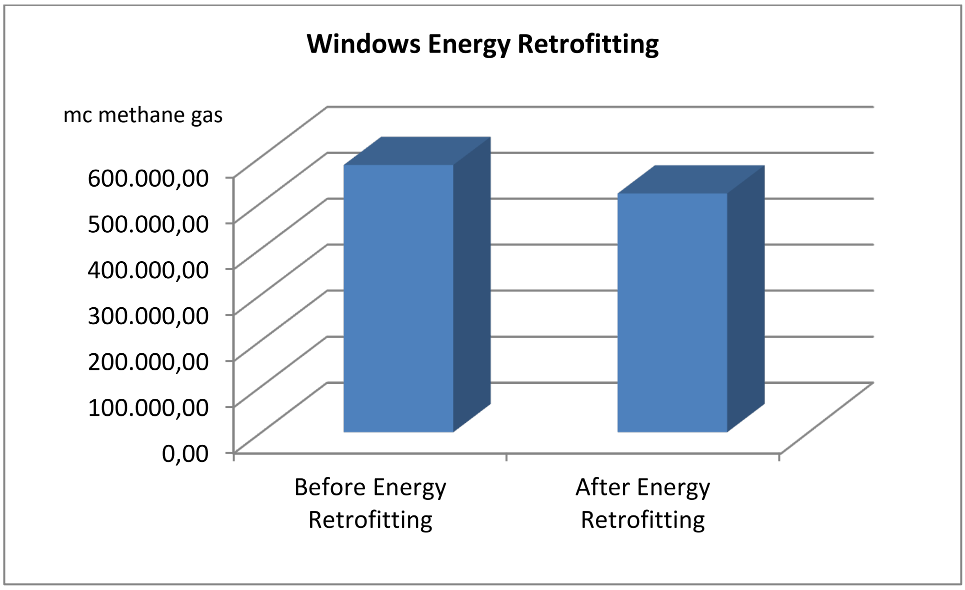



*Fig.5.1 – Windows retrofitting solution*

Simple pay back time of the windows retrofitting solution: **61,23 years**.

The energy saved with the intervention of the windows is only that given by the savings in terms of thermal transmittance, surely the savings can be greater for the reduced air infiltration of the new windows compared to the existing ones.

In addition to the proposed replacement of windows, innovative interventions such as the application of low-emissivity films to existing window glass were also studied from my research group. [5.1]

A typical single glass of the original windows of historic buildings has not only a high transmittance and a low reflectance in the visible and near infrared regions, but also a low transmittance and a low reflectance, and thus a high emittance in the far infrared region. As a result, the windows cause a large increase in the winter heating and summer cooling loads of the building [5.2]. Low emissivity (low-E) coatings, applied at the inner face of the window glasses, have a high transmittance in the visible region, a high reflectance in the near infrared region and a low emittance in the far infrared region. Therefore these coatings limit absorption of infrared radiation in the glass and thus radiation heat losses of the glazing [5.3]. The reduced emittance in the far infrared region causes a decrease in the thermal transmittance of the window (U-value). Low-emissivity coatings can be combined with window sealing, e.g. made by silicone, to reduce the significant air infiltration.

One type of low-emissivity coating available in the market has been selected for the analysis. The thermal properties of the coating declared by the manufacturer has been verified in the UNIMORE Energy Efficiency Laboratory (EELab). In particular, the thermal emissivity of the coating has been measured with a emissometer (INGLAS TIR 100-2). Table 5.2 summarizes the measurement results.

*Table 5.2 – The effect of low-E coating on the thermal emissivity and U-value of single glazing*

| **Thermal emissivity** | |
|---|---|
| Single glazing | Coated single glazing |
| 0.86 | 0.11 |

Results are obtained in terms of energy saving and payback period. Fig. 5.2 shows the energy demand of the existing building and the simulation cases with low-emissivity coatings and the combination of coatings and window existing sealing.

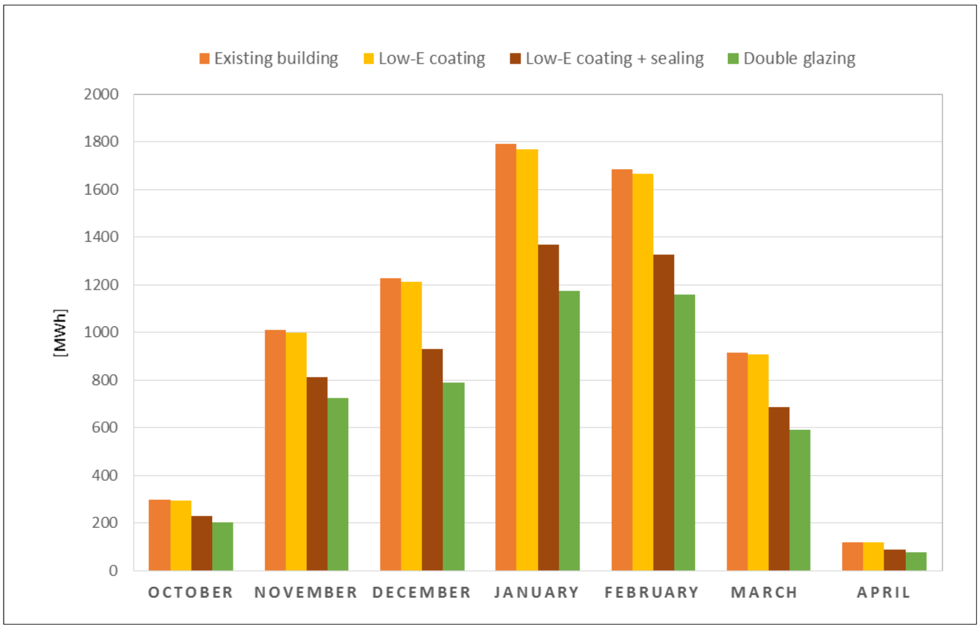



*Fig.5.2 – Energy saving for the retrofitting solutions*

The results show that the use of low-emissivity coatings allows to achieve average reductions in energy needs of about 1% while the use of these coating and window sealing allows an average reduction of about 23%. The replacement of existing windows with double-glazed windows allows to achieve the highest reduction in energy needs (i.e. about 33%).

Considering an investment cost of about 150 €/m2 for the coating and window sealing the pay back time of the investment is about 30 years,

however it was not possible to carry out experimental tests on the real capacities and duration of the window seals therefore the data remains to be verified.

For the case study, given the bad state in which the existing windows are, it was also chosen for security reasons to replace the windows.

## 5.2 Building Envelope Insulation Retrofitting Solution

All buildings are externally constrained therefore the insulation solutions will be done where possible, in the attics and with the use of low thickness internal thermal plaster in the Dardi, Abba, Aliprandi, Fanti Palace.

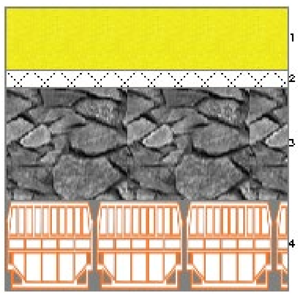
The intervention involves of the insertion of an insulating mat (140 mm thick with thermal conductivity equal to 0.035 W/mK in order to guarantee an overall transmittance of the floor of less than 0.22 W/m²K).

The new stratigraphies in the project will be the following.

**Description of the components of the building envelope:**

**Roofing towards the attic – Ducal Palace**

| | | |
|---|---|---|
| Thermal Trasmittance | 0,206 | W/m$^2$K |
| Thickness | 630 | mm |
| External Temperature (winter power calculation) | 5,0 | °C |
| Permeance | 27,663 | 10$^{-12}$kg/sm$^2$Pa |
| Surface Mass (with plaster) | 829 | kg/m$^2$ |
| Surface Mass (without plaster) | 829 | kg/m$^2$ |
| Periodic Transmittance | 0,004 | W/m$^2$K |
| Attenuation Factor | 0,020 | - |
| Thermal Wave Phase Shift | -18,6 | h |




**Stratigraphy:**

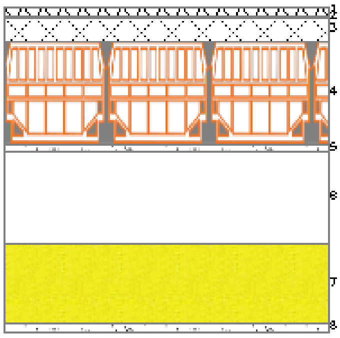
| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External Surface Resistance | - | - | 0,100 | - | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Rock wool panel | 140,00 | 0,035 | 4,000 | 40 | 1,03 | 1 |
| 2 | Concrete | 40,00 | 0,470 | 0,085 | 1200 | 1,00 | 96 |
| 3 | Filling of bulk materials | 250,00 | 0,700 | 0,357 | 1500 | 1,00 | 5 |
| 4 | brick vault | 200,00 | 0,900 | 0,222 | 2000 | 0,84 | 10 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

**Description of the components of the building envelope:**

## Roof Dardi / Abba Palace

| | | |
|---|---|---|
| Thermal Trasmittance | 0,209 | $W/m^2K$ |
| Thickness | 569 | mm |
| External Temperature (winter power calculation) | -5,0 | °C |
| Permeance | 0,970 | $10^{-12}kg/sm^2Pa$ |
| Surface Mass (with plaster) | 324 | $kg/m^2$ |
| Surface Mass (without plaster) | 286 | $kg/m^2$ |
| Periodic Transmittance | 0,043 | $W/m^2K$ |
| Attenuation Factor | 0,205 | - |
| Thermal Wave Phase Shift | -10,3 | h |



**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External Surface Resistance | - | - | 0,100 | - | - | - |
| 1 | roof covering | 15,00 | 1,000 | 0,015 | 2000 | 0,80 | 40 |
| 2 | waterproofing | 4,00 | 0,170 | 0,024 | 1200 | 0,92 | 5000<br>0 |
| 3 | concrete | 40,00 | 0,470 | 0,085 | 1200 | 1,00 | 96 |
| 4 | brick floor | 180,00 | 0,660 | 0,273 | 1100 | 0,84 | 7 |
| 5 | plaster | 15,00 | 0,800 | 0,019 | 1600 | 1,00 | 10 |
| 6 | unventilated interspace | 300,00 | 1,875 | 0,160 | - | - | - |
| 7 | rock wool panel | 140,00 | 0,035 | 4,000 | 40 | 1,03 | 1 |
| 8 | false ceiling | 15,00 | 0,250 | 0,060 | 900 | 1,00 | 10 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

**Description of the components of the building envelope:**

## Aliprandi roof

Thermal Trasmittance 0,205 $W/m^2K$

| | | |
|---|---|---|
| Thickness | 714 | mm |
| External Temperature (winter power calculation) | -5,0 | °C |
| Permeance | 0,968 | $10^{-12}$kg/sm$^2$Pa |
| Surface Mass (with plaster) | 347 | kg/m$^2$ |
| Surface Mass (without plaster) | 323 | kg/m$^2$ |
| Periodic Transmittance | 0,043 | W/m$^2$K |
| Attenuation Factor | 0,212 | - |
| Thermal Wave Phase Shift | -11,2 | h |

**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External Surface Resistance | - | - | 0,100 | - | - | - |
| 1 | roof covering | 15,00 | 1,000 | 0,015 | 2000 | 0,80 | 40 |
| 2 | waterproofing | 4,00 | 0,170 | 0,024 | 1200 | 0,92 | 50000 |
| 3 | brick floor | 40,00 | 0,470 | 0,085 | 1200 | 1,00 | 96 |
| 4 | unventilated interspace | 180,00 | 0,660 | 0,273 | 1100 | 0,84 | 7 |
| 5 | rock wool panel | 140,00 | 0,035 | 4,000 | 40 | 1,03 | 1 |
| 6 | Concrete | 15,00 | 0,800 | 0,019 | 1600 | 1,00 | 10 |
| 7 | brick floor | 300,00 | 1,875 | 0,160 | - | - | - |
| 8 | Plaster | 140,00 | 0,035 | 4,000 | 40 | 1,03 | 1 |
| - | Internal Surface Resistance | 15,00 | 0,250 | 0,060 | 900 | 1,00 | 10 |

**Description of the components of the building envelope:**

**Fanti attic ceiling**

| | | |
|---|---|---|
| Thermal Trasmittance | 0,219 | $W/m^2K$ |
| Thickness | 370 | mm |
| External Temperature (winter power calculation) | 5,0 | °C |
| Permeance | 37,383 | $10^{-12} kg/sm^2Pa$ |
| Surface Mass (with plaster) | 282 | $kg/m^2$ |
| Surface Mass (without plaster) | 268 | $kg/m^2$ |
| Periodic Transmittance | 0,048 | $W/m^2K$ |
| Attenuation Factor | 0,219 | - |
| Thermal Wave Phase Shift | -9,1 | h |

**Stratigraphy:**

| N. | Description layer | s | Cond. | R | M.V. | C.T. | R.V. |
|---|---|---|---|---|---|---|---|
| - | External surface resistance | - | - | 0,100 | - | - | - |
| 1 | rock wool panel | 140,00 | 0,035 | 4,000 | 40 | 1,03 | 1 |
| 2 | Concrete | 40,00 | 0,730 | 0,055 | 1600 | 1,00 | 96 |
| 3 | Brick floor | 180,00 | 0,660 | 0,273 | 1100 | 0,84 | 7 |
| 4 | Plaster | 10,00 | 0,700 | 0,014 | 1400 | 0,84 | 11 |
| - | Internal Surface Resistance | - | - | 0,100 | - | - | - |

Below are the results of the retrofitting intervention in terms of energy saving and payback time.

*Table 5.3 – Rock wool panels Retrofitting Solution*

| Rock wool panels Retrofitting Solution | | | |
|---|---|---|---|
| Investment Cost (€) | Energy saving [mc methane gas] | Annual saving (€) | CO2 saving (ton/y) |
| € 907.200,00 | 78.394,00 | € 50.956,10 | 189,4 ton. |

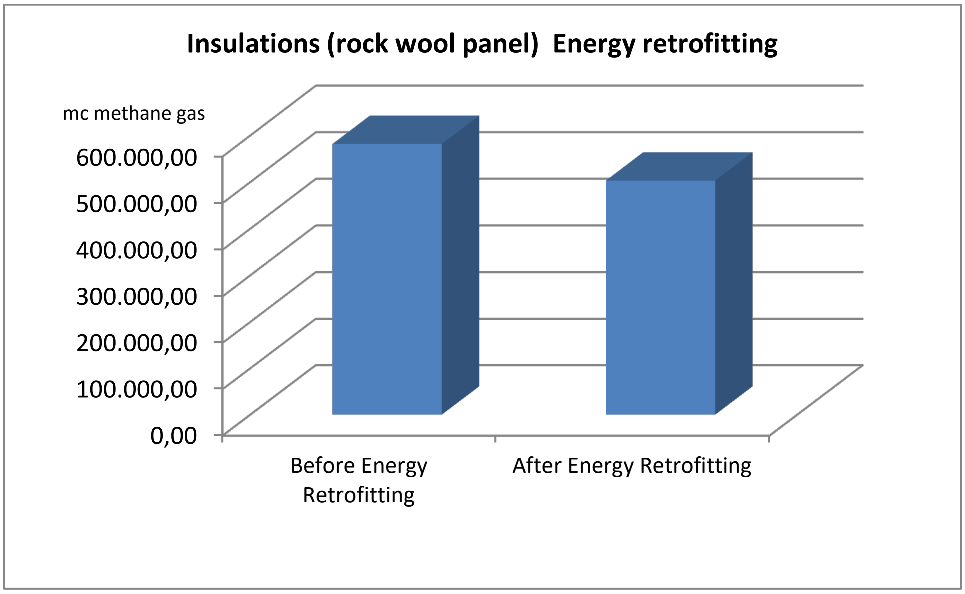



*Fig.5.3 – Rock wool panels retrofitting solution*

Simple pay back time of the rock wool panels retrofitting solution: **17,80 years**.

Since the buildings are architecturally constrained, it is not possible to use traditional wall insulation solutions, therefore it was decided to use experimentally the thermal insulating plasters. The application of thermo-plasters on the internal walls is envisaged of the Palazzine Dardi and Abba (without frescoes or internal historical value). The use of the thermal plaster is also foreseen in the walls of the Fanti Pool.

The application of 3 cm of thermo-plaster on internal walls is foreseen, the thermo plaster is developed by the University of Modena in collaboration with local construction companies.

The plaster has very high breathability (water vapor resistance coefficient μ 5), a high porosity (≥ 40%), a natural thermal conductivity (equal to 0.14 W / mK), a remarkable air blocked in the mixing phase (≥ 25%), a total resistance to salts (WTA 2-2-91 / D Exceeded) and a reduced depth of water infiltration (in 24 h ≤ 5 mm).

Below are the results of the retrofitting intervention in terms of energy saving and payback time.

*Table 5.4 – Thermo plaster Retrofitting Solution*

| **Thermo plaster Retrofitting Solution** | | | |
|---|---|---|---|
| **Investment Cost (€)** | **Energy saving [mc methane gas]** | **Annual saving (€)** | **CO2 saving (ton/y)** |
| € 114.080,16 | 5.033,00 | € 3.271,45 | 0,7 ton. |

Simple pay back time of the thermo-plaster retrofitting solution: **34,87 years**.

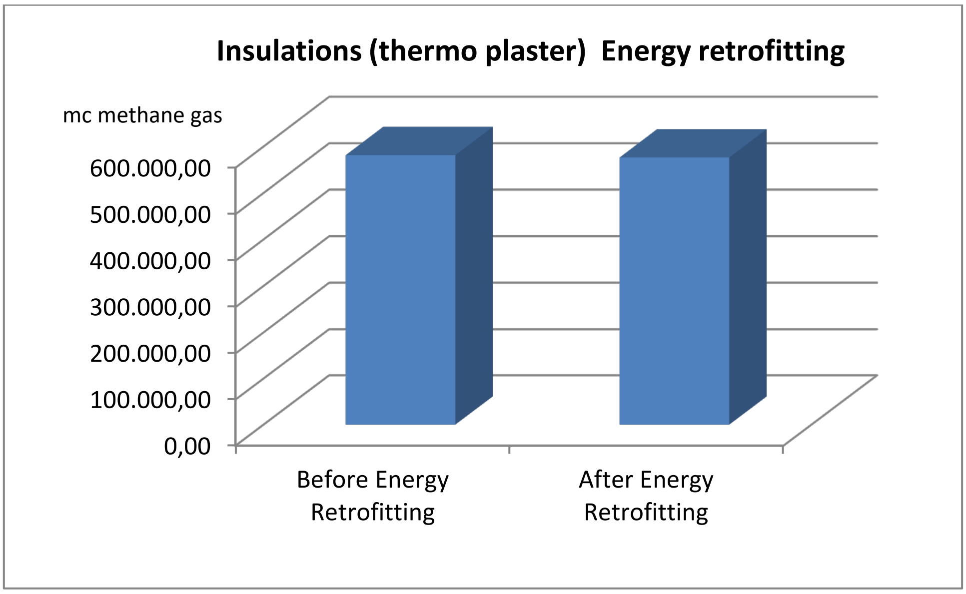



*Fig.5.4 – Thermo plaster retrofitting solution*

Below are the results of the insulation retrofitting intervention (rock wool panels and thermo plaster) in terms of energy saving and payback time.

*Table 5.5 – Insulation Retrofitting Solution*

| **Insulation Retrofitting Solution** | | | |
|---|---|---|---|
| **Investment Cost (€)** | **Energy saving [mc methane gas]** | **Annual saving (€)** | **CO2 saving (ton/y)** |
| 1.096.279,10 € | 91.238,00 | € 59.824,75 | 190,1 ton. |

Simple pay back time of the insulation retrofitting solution: **19,29 years**.

## 5.3 Retrofitting of the Hydronic Thermal Plant System

The retrofitting intervention includes:

- **Generation sub-system**: Replacement of current heat generators with new modular condensing boilers (efficiency of the boiler from Hs 98% to Hi 109%). Other generation systems, such as heat pumps, have not been taken into account as the whole plant works with high temperature systems.

- **Distribution sub-system**: The existing pipes are largely free of insulation and in a bad state of conservation, this in addition to causing frequent system losses causes the loss of 31.5% of heat. The intervention consists in the refurbishment of the distribution network of the heating system with the supply and installation of black steel pipes for the execution of the distribution networks in the thermal plant, main distribution line ( having a length of about 2000 meters) in a ring in the basement of the Ducal Palace, the main distribution network serving Dardi, Abba and Aliprandi Palaces. Vertical risers and distribution to the floors for connecting all the heating bodies. The new distribution network will have to make the most of the existing cavities for the passage of the pipes and develop in the criterion of minimal invasiveness from the aesthetic point of view of the premises (with maximum precautions for the museum areas and the ducal apartments where the situation will have to be restored existing and / or improve where possible) and in order to preserve the existing wall structures.

- **Regulation sub-system**: Having clearly identifiable thermal zones and with very different needs from a thermal point of view, the regulation system significantly increase energy efficiency and comfort within the various rooms. The intervention consist in the supply and installation of a thermoregulation complex with a PID type system placed in the thermal plant complete with Building Automation System, digital controller, delivery probe, room thermo-probe, climate probe, 3-valve mixing valve ways complete with servomotor. Installation of pre-regulation thermostatic valves on individual heating radiators complete with motorisation with knx zone controllers with wi-fi zones connected to the thermal plant. To guarantee an intelligent regulation system, the control unit can be implemented with software in a dynamic regime with predictive weather data.

- **Emission sub-system**: Installation of new column-type steel radiators of adequate thermal power to replace the existing cast iron radiators complete with a valve with thermostatic head, regulation lockshield, air vent valve and support shelves, caps and reductions included, to improve the thermal response of the heating bodies in terms of inertia and to eliminate all dated, poorly functioning and in a bad condition radiators.

- **DHW system**: Reconstruction of the distribution network for domestic hot water and installation of new storage systems.

*Table 5.6 – Hydronic System Heating Plant Efficiency*

| Retrofitting Hydronic System Heating Plant Efficiency | | |
|---|---|---|
| Emission system | nH,e | 92,0 % |
| Regulation system | nH,rg | 99,0 % |
| Distribution system | nH,du | 92,9 % |
| Generation system | nH,gn | 98,8 % |

*Table 5.7 – Hydronic System (Domestic Hot Water) Plant Efficiency*

| Retrofitting Hydronic System (Domestic Hot Water) Plant Efficiency | | |
|---|---|---|
| Supply system | nW,e | 95,0 % |
| Distribution system | nW,du | 92,6 % |
| Storage system | nW,s | 97,5 % |
| Recirculation pipes system | nW,ric | 87,1 % |
| Generation system | nH,gn | 94,8 % |

Below are the results of the hydronic thermal plant retrofitting intervention in terms of energy saving and payback time.

*Table 5.8 – Hydronic System Retrofitting Solutions*

| Hydronic Thermal Plant Retrofitting Solution | | | |
|---|---|---|---|
| **Investment Cost (€)** | **Energy saving [mc methane gas]** | **Annual saving (€)** | **CO2 saving (ton/y)** |
| 4.552.150,00 € | 228.540,00 | € 149.853,68 | 476,2 ton. |

Simple pay back time of the hydronic thermal plant retrofitting solution: **30,18 years**.

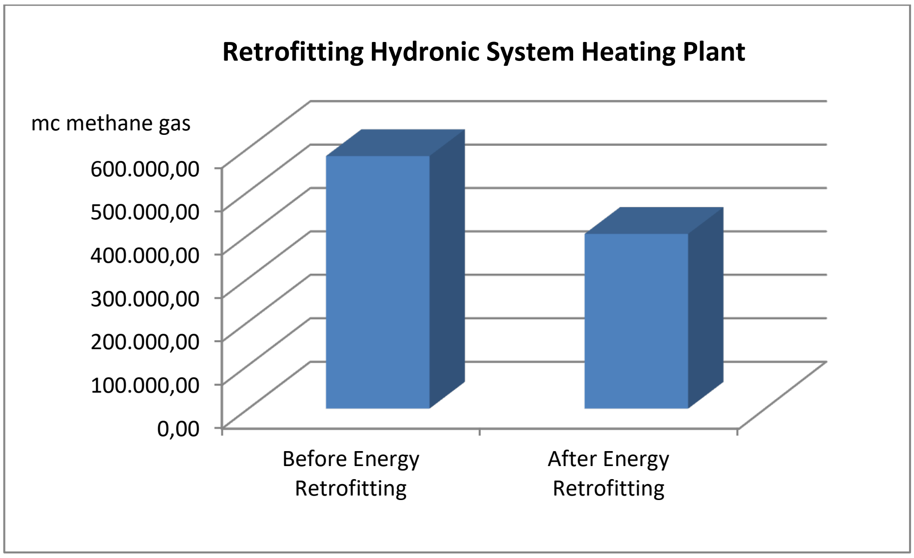



*Fig.5.5 – Retrofitting Hydronic System Heating Plant*

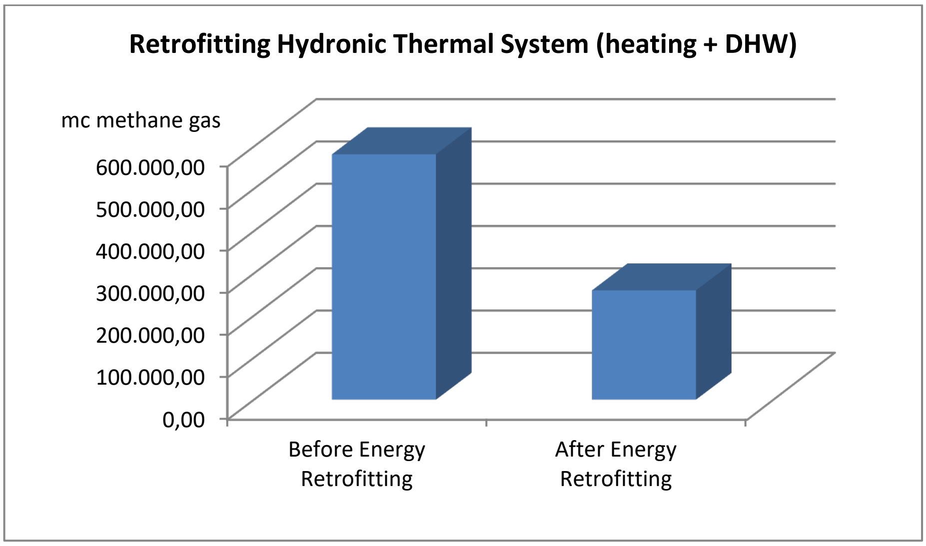



*Fig.5.6 – Retrofitting HydronicThermal  System (Heating + DHW)*

## 5.4 Retrofitting of the Steam Plant System

The retrofitting solutions includes:

- Replacement of the existing steam generator with n. 1 condensing basement boiler (Thermal Power 800 kW) serving the Fanti Pool and n. 1 steam boiler (Thermal Power 50 kW) located near the ironing room of the "Caserma Montecuccoli";

- Installation of a new AHU for the heating system in the swimming pool and new pipes;

- Installation of PID type thermoregulation system (see the describtion of the retrofitting hydronic regulation system), zone chronothermostats, thermostatic valves are knx wi-fi system.

As regards the production of hot water for the swimming pool and the steam of the ironing room, the post-intervention efficiency as follows.

*Table 5.9 –System Plant Efficiency*

| **Retrofitting System Plant Efficiency** | | |
|---|---|---|
| Distribution system | nH,du | 92,0 % |
| Generation system | nH,gn | 92,6 % |

As regards the winter heating of the pool, the post-intervention efficiency as follows.

*Table 5.10 – Retrofitting System Heating Plant Efficiency*

| **Retrofitting System Heating Plant Efficiency** | | |
|---|---|---|
| Emission system | nH,e | 96,0 % |
| Regulation system | nH,rg | 97,0 % |
| Distribution system | nH,du | 92,0 % |
| Generation system | nH,gn | 92,6 % |

Below are the results of the steam thermal plant retrofitting intervention in terms of energy saving and payback time.

*Table 5.11 – Steam System Retrofitting Solutions*

| **Steam Thermal Plant Retrofitting Solution** | | | |
|---|---|---|---|
| **Investment Cost (€)** | **Energy saving [mc methane gas]** | **Annual saving (€)** | **CO2 saving (ton/y)** |
| 434.097,50 € | 37.629,78 | € 24.673,85 | 78,4 ton. |

Simple pay back time of the steam thermal plant retrofitting solution: **17,59 years**.

## 5.5 Cogeneration Plant Installation

As part of the project, assessments were made on the installation of a cogeneration plant in order to increase the building's resilience characteristics and the economic benefit for users of the plant.

The feasibility study performed analyzed the trend of the thermal loads of the building complex and the electrical loads of the medium voltage POD IT011E10108363 located inside the "Caserma Montecuccoli" to which the cogeneration plant will be connected.

### Electric Load Analysis

An annual electrical load analysis was performed with data available every 15 minutes of electrical kW consumed with regard to the medium voltage POD n. IT011E10108363.

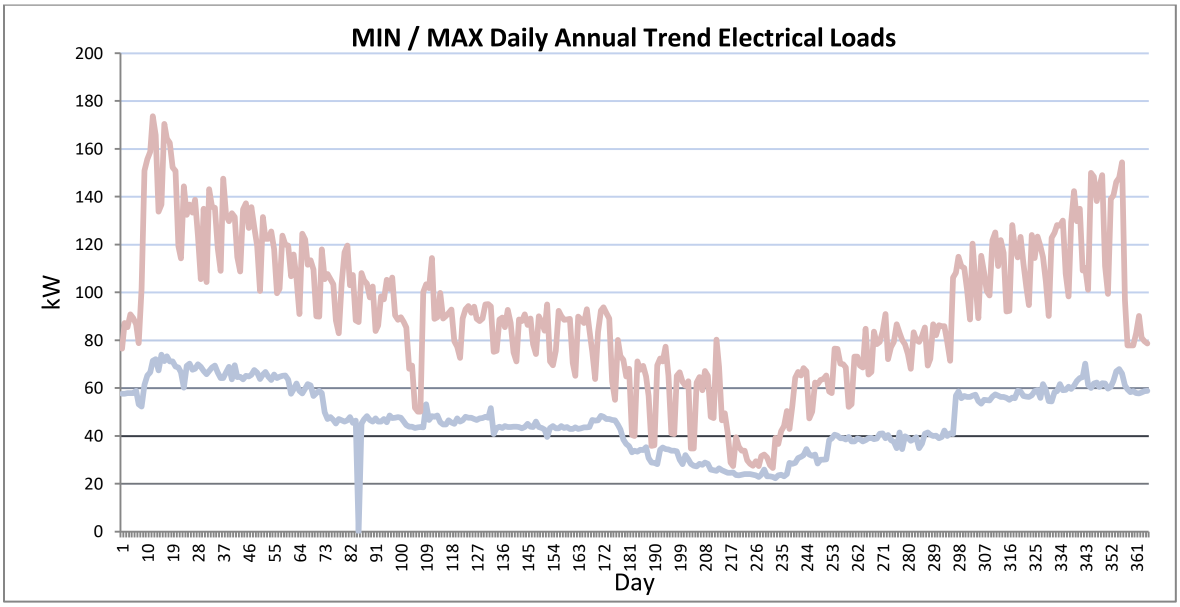



*Fig.5.7 – MIN / MAX Daily Annual Trend Electrical Loads*

### Cogenerator Installation

The project involves the installation of n. 2 cogenerators, one at the service of the Fanti swimming pool system and one at the service of the thermal power plant of the Ducal Palace.

The technical characteristics of the cogenerators to be installed and the energy produced by the cogeneration plant with monthly indication of the number of operating hours are shown below.

*Table 5.12 – Characteristic of the cogenerator*

| | 100% | 75% | 50% |
|---|---|---|---|
| Nominal electrical power | 50 kW | 37 kW | 25 kW |
| Nominal thermal power | 79 kW | 61 kW | 49 kW |
| Thermal power of the fuel (PCI) | 148 kW | 116 kW | 94 kW |
| Electric efficiency | 33,80% | 31,90% | 26,60% |
| Thermal efficiency | 53,40% | 52,60% | 52,10% |
| Total efficiency | 87,20% | 84,50% | 78,70% |

**Cogenerator installed in the thermal plant of the Ducal Palace of Modena**

*Table 5.13 – Characteristic of the cogenerator (Ducal Palace)*

| COGENERATOR INSTALLED IN THE THERMAL PLANT OF THE DUCAL PALACE OF MODENA: 79 KW THERMAL - 50 KW ELECTRIC | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| month | thermal requirement | electrical requirement | hours of cogenerator operation | cogenerator thermal energy produced | boiler thermal energy | cogenerator electricity produced | electricity purchased | methane taken from the cogenerator [Nmc] |
| Jan. | 790.804,00 | 71.173,02 | 465 | 36.735,00 | 754.069,00 | 23.250,00 | 47.923,02 | 7279,59 |
| Feb. | 488.680,00 | 61.264,26 | 420 | 33.180,00 | 455.500,00 | 21.000,00 | 40.264,26 | 6575,11 |
| Mar. | 335.086,00 | 57.400,13 | 465 | 36.735,00 | 298.351,00 | 23.250,00 | 34.150,13 | 7279,59 |
| Apr. | 110.368,00 | 46.830,53 | 300 | 23.700,00 | 86.668,00 | 15.000,00 | 31.830,53 | 4696,51 |
| May | 49.169,00 | 47.680,60 | 155 | 12.245,00 | 36.924,00 | 7.750,00 | 39.930,60 | 2426,53 |
| Jun. | 47.099,00 | 43.383,67 | 150 | 11.850,00 | 35.249,00 | 7.500,00 | 35.883,67 | 2348,26 |
| Jul. | 48.447,00 | 30.504,52 | 155 | 12.245,00 | 36.202,00 | 7.750,00 | 22.754,52 | 2426,53 |
| Aug. | 48.506,00 | 23.225,00 | 155 | 12.245,00 | 36.261,00 | 7.750,00 | 15.475,00 | 2426,53 |
| Sep. | 47.459,00 | 37.044,05 | 150 | 11.850,00 | 35.609,00 | 7.500,00 | 29.544,05 | 2348,26 |
| Oct. | 106.488,00 | 48.013,45 | 310 | 24.490,00 | 81.998,00 | 15.500,00 | 32.513,45 | 4853,06 |
| Nov. | 378.974,00 | 60.690,76 | 450 | 35.550,00 | 343.424,00 | 22.500,00 | 38.190,76 | 7044,77 |
| Dec. | 681.868,00 | 64.992,68 | 465 | 36.735,00 | 645.133,00 | 23.250,00 | 41.742,68 | 7279,59 |
| Tot. | 3.132.948,00 | 592.202,68 | 3640 | 287.560,00 | 2.845.388,00 | 182.000,00 | 410.202,68 | **56.984,33** |

It is expected that the thermal energy dissipated and the electricity fed into the network are zero, all the energy produced goes into self-consumption.

*Table 5.14 – Primary energy saving (Ducal Palace)*

| | |
|---|---|
| Primary energy requirement before cogenerator | 4.762.680,49 |
| Primary energy requirement after cogenerator | 4.582.062,20 |
| Primary Energy Saving | 180.618,30 |

## Cogenerator installed in the thermal plant of the Fanti Pool

*Table 5.15 – Characteristic of the cogenerator (Fanti Pool)*

| COGENERATOR INSTALLED IN THE THERMAL PLANT OF THE FANTI POOL: 79 KW THERMAL - 50 KW ELECTRIC | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| month | thermal requirement | electrical requirement | hours of cogenerator operation | cogenerator thermal energy produced | boiler thermal energy | cogenerator electricity produced | electricity purchased | methane taken from the cogenerator [Nmc] |
| Jan. | 75.890,00 | 71.173,02 | 310 | 24.490,00 | 51.400,00 | 15.500,00 | 55.673,02 | 4853,06 |
| Feb. | 63.083,00 | 61.264,26 | 280 | 22.120,00 | 40.963,00 | 14.000,00 | 47.264,26 | 4383,41 |
| Mar. | 56.048,00 | 57.400,13 | 310 | 24.490,00 | 31.558,00 | 15.500,00 | 41.900,13 | 4853,06 |
| Apr. | 50.024,00 | 46.830,53 | 240 | 18.960,00 | 31.064,00 | 12.000,00 | 34.830,53 | 3757,21 |
| May | 49.107,00 | 47.680,60 | 248 | 19.592,00 | 29.515,00 | 12.400,00 | 35.280,60 | 3882,45 |
| Jun. | 29.259,00 | 43.383,67 | 150 | 11.850,00 | 17.409,00 | 7.500,00 | 35.883,67 | 2348,26 |
| Jul. | 49.107,00 | 30.504,52 | 155 | 12.245,00 | 36.862,00 | 7.750,00 | 22.754,52 | 2426,53 |
| Aug. | 49.107,00 | 23.225,00 | 155 | 12.245,00 | 36.862,00 | 7.750,00 | 15.475,00 | 2426,53 |
| Sep. | 49.107,00 | 37.044,05 | 232 | 18.328,00 | 30.779,00 | 11.600,00 | 25.444,05 | 3631,97 |
| Oct. | 50.185,00 | 48.013,45 | 310 | 24.490,00 | 25.695,00 | 15.500,00 | 32.513,45 | 4853,06 |
| Nov. | 59.435,00 | 60.690,76 | 300 | 23.700,00 | 35.735,00 | 15.000,00 | 45.690,76 | 4696,51 |
| Dec. | 71.467,00 | 64.992,68 | 310 | 24.490,00 | 46.977,00 | 15.500,00 | 49.492,68 | 4853,06 |
| Tot. | 651.819,00 | 592.202,68 | 3000 | 237.000,00 | 414.819,00 | 150.000,00 | 442.202,68 | **46.965,10** |

It is expected that the thermal energy dissipated and the electricity fed into the network are zero, all the energy produced goes into self-consumption.

*Table 5.16 – Primary energy saving (Fanti Pool)*

| | |
|---|---|
| Primary energy requirement before cogenerator | 2.125.853,11 |
| Primary energy requirement after cogenerator | 1.976.991,88 |
| Primary Energy Saving | 148.861,23 |

## 5.6 Overall Energy Retrofitting Intervention

The expected savings in terms of energy and pay back time of the overall retrofitting intervention are shown below, therefore the sum of all the interventions previously described.

*Table 5.17 – Total Retrofitting Solutions*

| | **Before Energy Retrofitting** | **After Energy Retrofitting** |
|---|---|---|
| Mc methane gas | 825.240,49 | 400.920,71 |
| Primary energy [kW/y] | 8.188.448,76 | 3.978.135,74 |
| CO2 [kg/y] | 1.719.574,24 | 835.408,51 |

| **Total Retrofitting Solution** | | | |
|---|---|---|---|
| **Investment Cost (€)** | **Energy saving [mc methane gas]** | **Annual saving (€)** | **CO2 saving (ton/y)** |
| 8.739.007,20 € | 424.319,78 | 278.226,48 € | 884,17 ton. |

Simple pay back time of the total retrofitting solution: **31,41 years**.

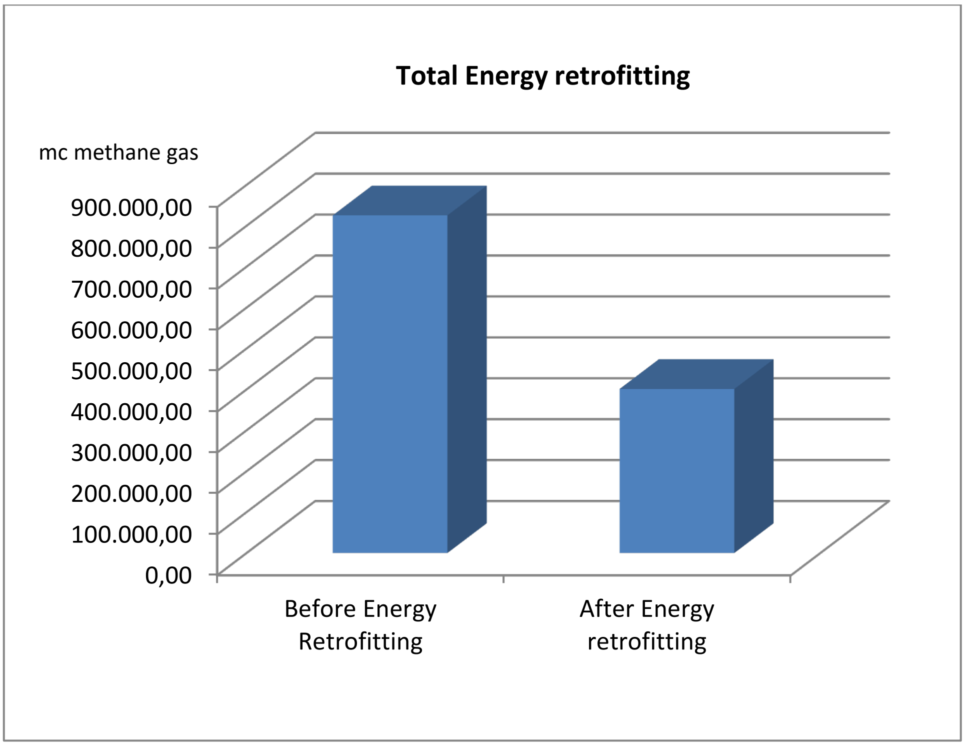



*Fig.5.8 – Total Energy Retrofitting*

# 6. RESULTS OBTAINED WITH THE ENERGY RETROFITTING PROJECT OF THE DUCAL PALACE OF MODENA

The University of Modena, in particular the Applied Physics group of the Department of Engineering "Enzo Ferrari", has been dealing with energy redevelopment in the building sector for several years.

Amongst its many activities, the group runs the EELab [6.1], a highly recognised laboratory on energy efficiency of buildings and processes, with a particular focus on the development of anti-solar materials for buildings.

The department also runs the Bio-Energy Efficiency Laboratory (Beelab) [6.2], focused on research and scientific support services on renewable energies related topic.

Of direct relevance to the current proposal, the research group is deeply involved in research projects and industrial R&D collaborations regarding the assessment and optimization of performance of buildings. Other relevant experiences are related to the measurement and optimization of the thermal properties of materials for building elements and energy systems, for which a large set of state-of-the-art instruments is available and innovative techniques were developed. The group provided scientific support to the development of the energy efficiency codes of the Republic of San Marino and the Emilia-Romagna Region of Italy.

The research group has also carried out a census work from the energy point of view of all the university buildings through energy audits (energy plan of the university) for the monitoring of consumption and the study of the most convenient interventions in terms of cost-benefits of the energy retrofit.

In this context, full of ideas, the first research studies on the energetic retrofitting solutions of historic buildings were born, in particular on the most important and significant building for the city of Modena, the Ducal Palace.

These studies have strongly attracted the attention of the occupants of the building who live every day the limits and critical points in terms of energy (very high costs of consumption, management and maintenance and low thermal comfort).

The interest in the project was such that on September 12, 2017, the University of Modena and the Ministry of Defense signed a framework agreement and an operational collaboration agreement on the energy requalification study of the buildings of the Ministry of Defense in particular of the Ducal Palace of Modena.

*Fig.6.1 – September 12, 2017, the University of Modena and the Ministry of Defense signed a framework agreement*

Following this agreement, research work was carried out on economic resources and on the most appropriate way to ensure that the energy requalification project of the Ducal Palace of Modena became a reality.

Through an important collaboration with AESS (Agency for Energy and Sustainable Development of Modena) who is the advisor of the European Energy Efficiency Fund (EEEF), the road to realize the project has been found.

## 6.1 - European Energy Efficiency Fund (EEEF)

The European Energy Efficiency Fund (eeef) [6.3] aims to support the goals of the European Union to promote a sustainable energy market and climate protection.

a) Contribute to the mitigation of climate change - EEEF contributes with a layered risk/return structure to enhance energy efficiency and foster renewable energy in the form of a targeted private public partnership, primarily through the provision of dedicated financing via direct finance and partnering with financial institutions. Investments should contribute significantly towards energy savings and the reduction of greenhouse gas emissions to promote the environmentally friendly use of energy. Maximizing its impact, eeef facilitates investments in the public sector, which offers an enormous potential, but in which projects are often hindered or decelerated due to budget restrictions and lack of experience with this kind of investments.

b) Achieve economic sustainability of the Fund - EEEF pursues its environmental goals by offering funding for energy efficiency and small scale renewable energy projects. The Fund observes the principles of sustainability and viability, combining environmental considerations and market orientation. It does so by financing economically sound projects, allowing for a sustainable and revolving use of its means.

c) Attract private and public capital into climate financing - By achieving the first two objectives, EEEF aims to attract additional capital into climate financing. The environmentally and socially responsible way of conducting its business, the innovative public-private partnership structure and the experience of its stakeholders will be used to bring more capital into an area whose financial means are currently insufficient to strongly contribute to the mitigation of climate change.

The institutions backing the fund are the follower:

1) Initiator - The European Commission that is one of the main institutions of the European Union.

2) Founding Investors - The European Investment Bank (EIB) that is the bank of the European Union and is owned by the 27 Member States and the Cassa Depositi e Prestiti SpA (CDP) that is a joint-stock company under public control, with the Italian government holding 82.8 percent, a broad group of bank foundations holding 15.9 percent, the remaining percentage being treasury shares (as of March 2017).

3) Investor and Investment Manager - Deutsche Bank that is a leading global investment bank with a strong private clients franchise.

The fund pays all the technical assistant , so the technical costs of the preliminary design of the project and the costs for the construction of the call for tenders, the ESCO that wins the tender can decide whether to take the money on loan from the fund or return the money spent by the fund for the project.

## 6.2 - Intended process and procurement procedure for ESCO selection

The investment scheme is based on EPC model, a contractual arrangement under which an energy service company (ESCO) designs and implements an energy retrofit with a guaranteed level of energy performance. The payment for the services delivered is based (either wholly or in part) on the achievement of energy efficiency improvements and on meeting the other agreed performance criteria. In an EPC, the achievement of actual improvement of the energy performance is one of the conditions for the ESCO to be paid.

The tenders will be an Energy Performance Contract developed according to the Italian Low and the National Guidelines for green procurement (PAN GPP).

According to the energy consumption baseline and to the retrofit interventions identified, it will be defined the energy saving objective achievable with the EPC tender and it will be developed the legal, administrative, technical and functional specification.

The call for tenders will be published by a centralized commissioning body, under an open procedure, giving a wide visibility to the tender at national and regional level, after the formal approval of the retrofit projects by the applicant.

The investment program will be one tender for the public building retrofit.

At the end of the procurement procedure the "most economically and technical advantages" one ESCO will be awarded and the applicant will sign its contract with the ESCO.

The investment required by the EPC to retrofit the public building and to make possible an improvement of its energy performance will be financed by the ESCO, combining different financing instruments available at National and Regional level (ERDF funds, National financing, National incentive "Conto termico" and private investments).

## 6.3 - Financial loans obtained

With the collaboration of AESS and the support of SPE (the Energy Project Structure of the Ministry of Defense) the energy retrofitting project of the Ducal Palace of Modena has obtained two important loans, fundamental for supporting the tender economic plan.

**POR-FESR 2014-2020**

The Emilia-Romagna Regional Operational Programme [6.4] is the planning document that defines the strategy and operations of use of Community funds allocated to the Region by the European Regional Development Fund, in the framework of the cohesion policy, in furtherance of the economic growth and attractiveness of the regional territory, being the main investment instrument of the european union.

With the Notice approved with DGR n.1978 / 2017 [6.5] graduation approval of eligible and financial projects the project of the energetic requalification of the Ducal Palace of Modena has obtained a financing of € 259.989, 45.

**PREPAC 2018**

The Program for the Energy Redevelopment of Central Public Administration buildings (PREPAC) aims to achieve the energy requalification of at least 3% per annum of the air-conditioned useful surface.

With the Approval of the program of measures to improve the energy performance of buildings in the central public administration, pursuant to Article 5, paragraph 2 of Legislative Decree 4 July 2014, n. 102 and article 9, paragraph 1 of the Ministerial Decree 16 September 2016. 2018 annuality [6.6] , the project of the energetic requalification of the Ducal Palace of Modena has obtained a financing of € 6.381.300,00.

## 6.4 - Tender procedure and economic plan

As can be seen in chapter 5, the energy retrofitting solutions of the Ducal Palace have very long pay back times. This is one of the main operating limits of historic buildings, interventions are often very expensive and with energy savings alone they are not repaid.

Retrofit solutions with better pay back time cannot often be done due to the architectural constraints of the building.

In the case of the Ducal Palace of Modena, the economic investment plan is based on the financings obtained for the works (POR-FESR 2014-2020 and PREPAC 2018) and by a very high annual fee paid for the current energy supply and maintenance service.

By continuing to pay the same annual fee, the Ministry of Defense will be able to return the investment within 10 years.

The tender for the Ducal Palace is currently being published.

# 7. ENERGETIC RETROFITTING METHODOLOGY FOR HISTORICAL BUILDINGS

The PhD thesis aims to define a comprehensive methodology, based on a series of best practices, processes and workflows for the energy retrofitting of historical buildings.

The purpose of this thesis is to create a guideline applicable to projects that are intended to improve the following:

- energy efficiency of historical buildings taking into consideration their architectural constraints, covering both envelope and systems;

- efficiency of operation and maintenance of this particular category of buildings, mainly owned by public authorities;

- control of heat, moisture transfer and air infiltration;

The methodology to approach this typology of buildings is divided into the following phases:

1 - analysis of existing regulation on the preservation of heritage and architectural constraints of the buildings in the relevant region (based on in-depth knowledge of the European legislation framework);

2 - in-depth energy audit of the building;

3 - identification of the most cost-effective energy retrofitting interventions and verification of their feasibility based on architectural constraints;

Defining a unique detailed methodological of approach for this type of building is feasible, due to the architectural constraints and the historical interest that distinguish each building. The interventions must always be studied on an ad-hoc basis.

However, it has to be noted that historic buildings have common and unavoidable characteristics that allow to make general considerations and provide shared solutions and approaches.

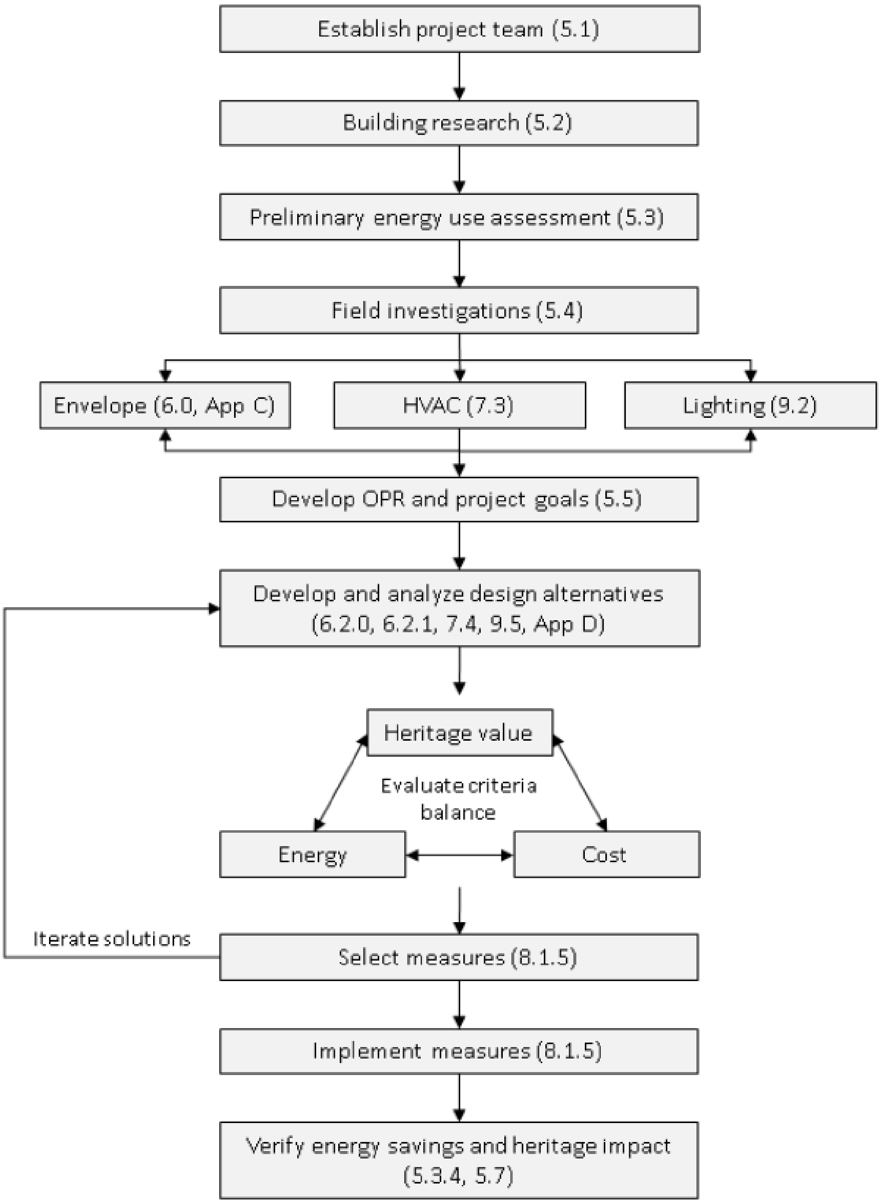



*Fig.7.1 – Main steps involved in planning and implementing a typical retrofit project (ASHRAE Guideline 34)*

## 7.1 Analysis of existing regulation on the preservation of heritage and architectural constraints of the buildings in the relevant Region

Regardless of the particular laws and regulations in force in eachparticular Region, the aim for preserving a historic building may be expressed by two important goals:

1. the conservation of historical materials;

2. the preservation of the distinctive character of a building.

Every historical building is unique, with its own identity and its own distinctive character.

A building may be individually significant, or it may be a contributing building in a group of buildings that are significant as a district. The significance of a historic building is generally based on one or more of the following:

a. Its architecture as a unique design, as a representative example of a specific style, or for its use of materials or construction technology

b. Its role in an important historical event, moment, or a longer period in time

c. Its association with an important person or persons

Historic buildings are generally expected to possess authenticity and integrity.

These complementary concepts relate to the ability of a historic building to convey its significance by way of its "form and design, materials and substance, use and function, traditions and techniques, location and setting, and spirit and feeling, and other internal and external factors ."[7.1,2]

The significance of a historic building also relates to the integrity of its character defining exterior and interior features.

The degree of significance of a historic building will generally determine the appropriate approach to be taken in its treatment.

The two general criteria of intervention on historical constrain buildings are not-invasiveness and reversibility.

As can be seen from chapter 3, the line of European states on historic buildings is very similar, there are general national laws in which there are general guidelines on historic buildings and then the tendency is to decentralize responsibilities locally.

This mechanism has the disadvantage that it is impossible to understand in advance if in a certain European country a retrofit solution that can modify some architectural features can be implemented. The energy retrofit interventions on the historical heritage are in fact always identified as the iteration between local experts in architecture, history and energy saving.

The analysis of the energy retrofit interventions at the local level of each country allows to evaluate case by case which are the constraints and peculiarities of each building to evaluate which interventions can be made based on the architectural constraints present.

What can certainly be done in a historic building is to intervene on the HVAC systems and in a non-invasive way on the building envelope.

## 7.2 In-depth Energy Audit Of The Buildings

As per the procedure reported in chapter 4, the preliminary phase of any energy retrofitting solutions is the development of an in-depth energy audit of the building.

The first phase for the preparation of the energy audit is the collection of the relevant material and information, such as the historic structures report, the preservation plan, the drawings, the conditions assessments, the surveys, the plats and the photographs.

The second step is the collection of the documents of the history and evolution of energy using systems in the building, including the existing nonmechanical (passive) systems and original architectural features, mechanical systems, service water heating systems and lighting and plug loads.

The third step is the construction of a complete energy use analysis based on a minimum of 12 months consumption data from utility bills to develop the Energy Use Intensity of the building. Benchmarking the most recent 12 months of energy data for a building against data from previous years can be performed on an annual or monthly basis. When comparing with previous years' data, energy data should always be normalized for weather to remove the effects of varying weather conditions in different years. Other normalizations may make use of additional factors (e.g. number of occupants).

After the collection of the material and the inspections, the creation of an energy model is necessary. As described in chapter 4, the use of a transient model allows for a more in-depth analysis that takes into account important aspects such as thermal inertia.

The calibration of the model is fundamental to obtain realistic results of the energy audit. The calibration can be carried out with a campaign of measurements and with the real consumption of the building. Each model must contain an analysis of uncertainties for the evaluation of the data. Historic buildings, particularly those built without mechanical cooling or ventilation systems, often relied on architectural features to reduce heating and cooling loads and create tolerable interior conditions. Because cool, dry air was not available from a mechanical system, many of these features (e.i., operable windows, massive walls) rely on comfort factors other than dry-bulb temperature to ameliorate hot and humid conditions. Operable windows, for instance, can increase air movement, and massive walls can lower mean radiant temperature.

While these strategies are often simple and require no energy, adequately accounting for them in an energy simulation can require deliberate effort that may involve requesting non default model outputs or more specialized modeling.

## 7.3 Identification Of The Most Cost-Effective Energy Retrofitting Solutions

An energy audit should support the identification of achievable savings and expected economic payback periods.

While alterations to a historic building should be as reversible and unobtrusive as possible, the impact of a design decision may still result in the destruction of some historic fabric. Given the important consequences of design decisions in historic buildings, energy simulations should be calibrated to ensure that decisions are made based on sufficiently accurate model results.

The convenience of energy retrofitting solutions of the buildings depend on several factors, one of which is, for example, the climatic zone where the building is located.

## 7.4 Incidence of the climatic zones

The following simulations were carried out with the aim of observing the economic convenience of energy efficiency interventions according to the climatic zones in which one operates and according to the characteristics of the building.

The heating consumption of a building is given by the winter energy requirement compared to the HVAC performance.

The percentage on the energy consumption of the building envelope compared to the heating system is an intrinsic characteristic of each building (see Figure 7.4).

By way of example, it is assumed that the Palazzo Ducale model will be transferred to completely different climatic zones, such as Spain and Denmark.

Hourly climatic data from two locations, Valencia in Spain and Herning in Denmark, were taken as an example to evaluate the behavior of the building.

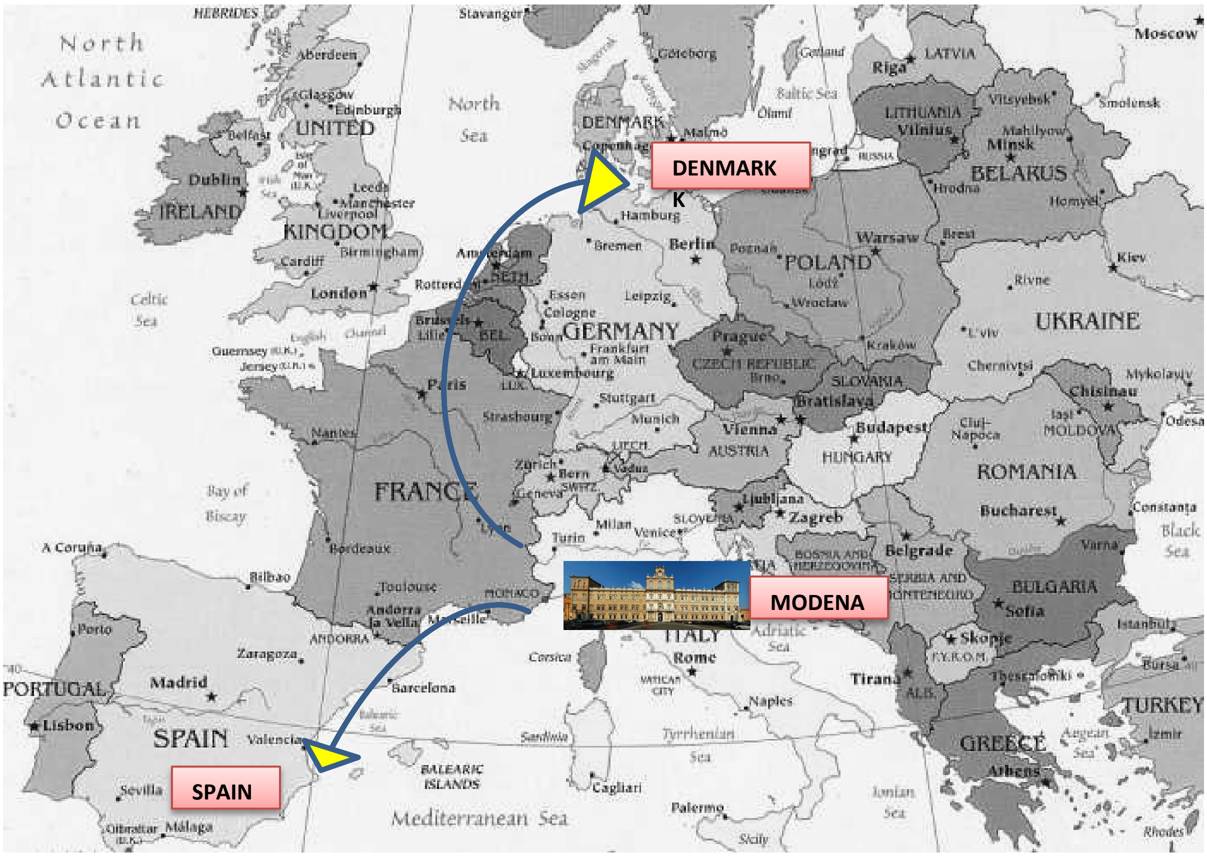



*Fig.7.2 – Incidence of the climatic zones*

The same complex of buildings with the same characteristics as the HVAC system and the building envelope have very different thermal consumptions, due to the different external temperature, the duration of the heating season and the different solar gains.

The day degrees for the three locations are shown in the following table, where the different thermal consumptions are also reported for the three localities.

*Table 7.1 – Data of the three climatic zones*

| | Denmark | Modena | Spain |
|---|---|---|---|
| **duration of the heating season** | 200 | 183 | 121 |
| **Degree Day** | 4.918 | 2.258 | 751 |
| **mc methane gas** | 988.564,00 | 581.515,00 | 155.589,00 |

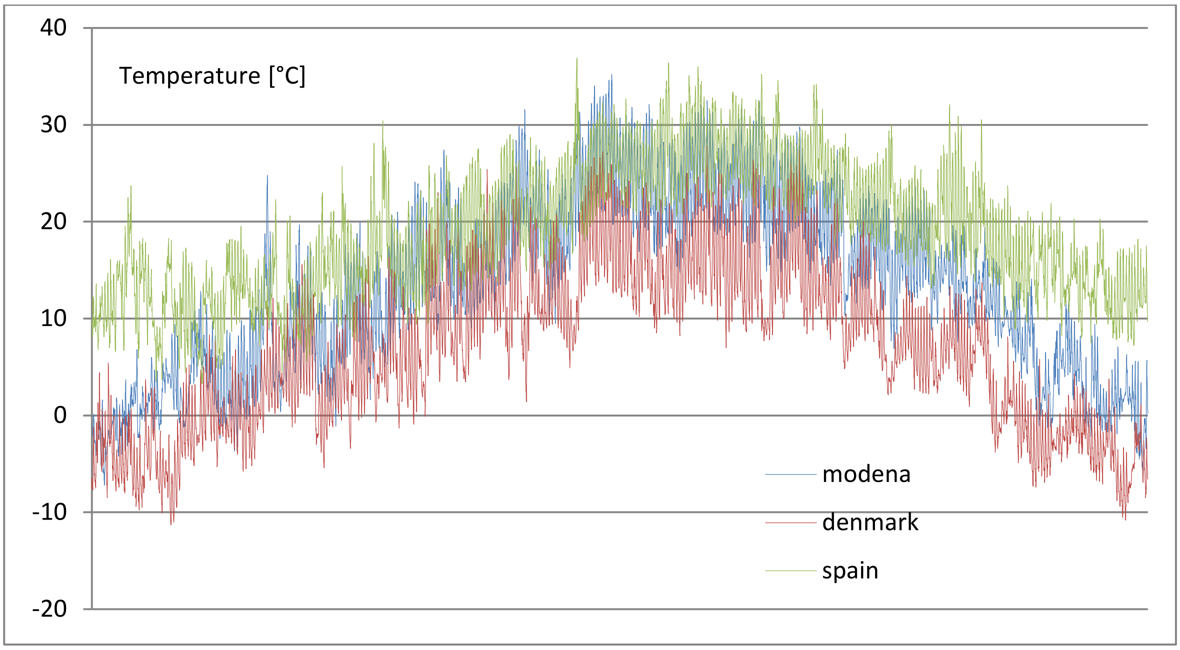



*Fig.7.3 – Annual Outdoor Hours Temperature Trend*

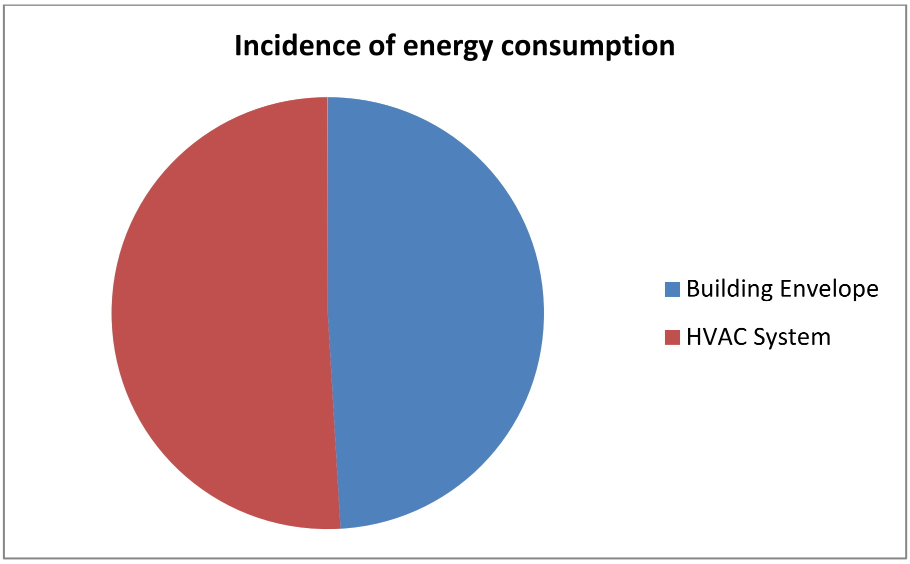



*Fig.7.4 – Incidence of the energy consumption*

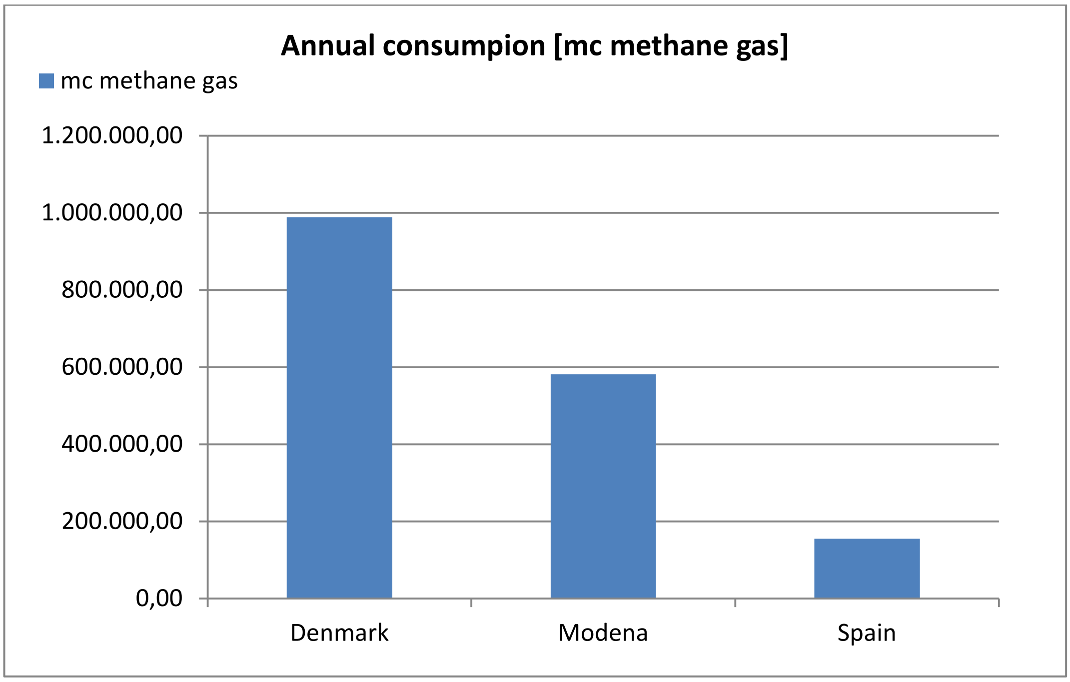



*Fig.7.5 – Annual consumptions of methane gas*

The simulation consists in performing the same energy retrofitting intervention for the three cases (the three climatic locations) and seeing the differences in terms of energy savings and payback time.

The percentage incidence on consumption of the building envelope respect to the HVAC system is the same in all climatic zones, the case study of the Ducal Palace sees a catastrophic situation from the HVAC system point of view (the energy audit has estimated that the the incidence on total energy consumption of the HVAC system is 50%).

## 7.4.1 HVAC System Retrofitting solutions

The first simulation consists in applying the same HVAC retrofitting solution described in the chapter 5.3 of the thesis.

Figure 7.6 shows how the energy savings achieved in Denmark are significantly higher than those obtained in milder climatic zones.

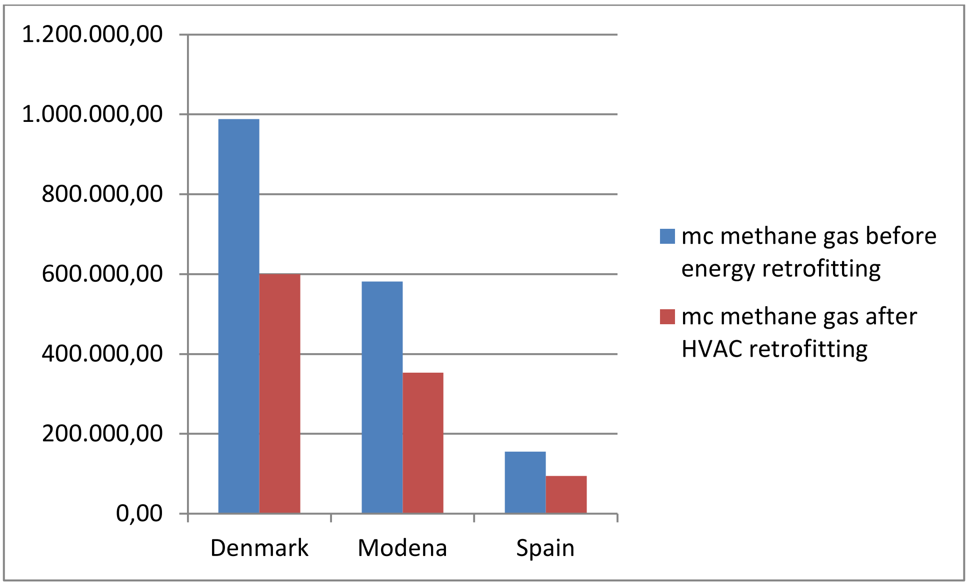



*Fig.7.6 – Annual consumptions of methane gas before / after HVAC retrofitting of the different thermal zones*

Figure 7.7 shows the trend of the payback time of the HVAC retrofitting solution, the economic evaluations were all carried out keeping the cost of natural gas constant to make the results comparable.

The payback time goes from 30 years of the case study of the Ducal Palace of Modena to 17 years for very cold climates to greater than 100 years for warm climates.

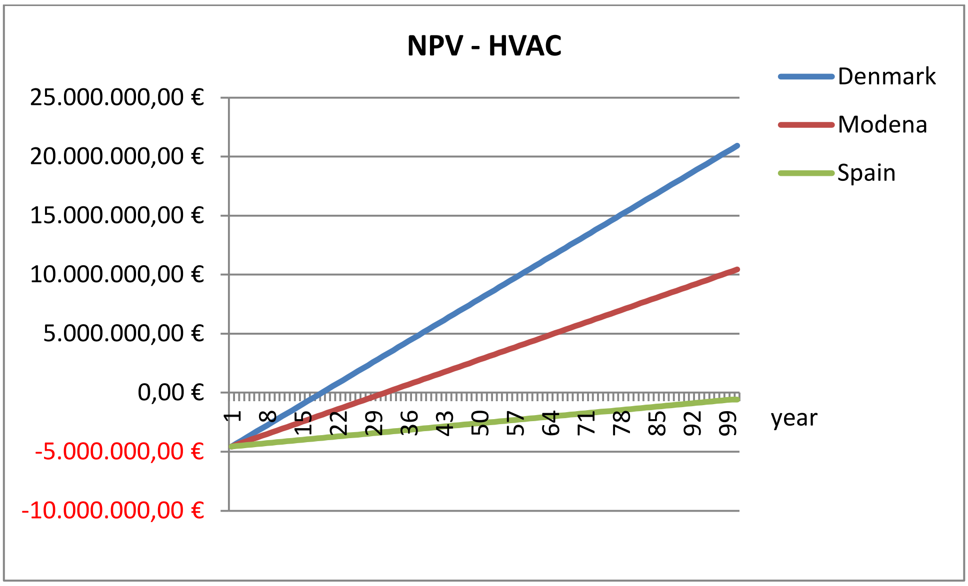



*Fig.7.7 – NPV of HVAC retrofitting of the different thermal zones*

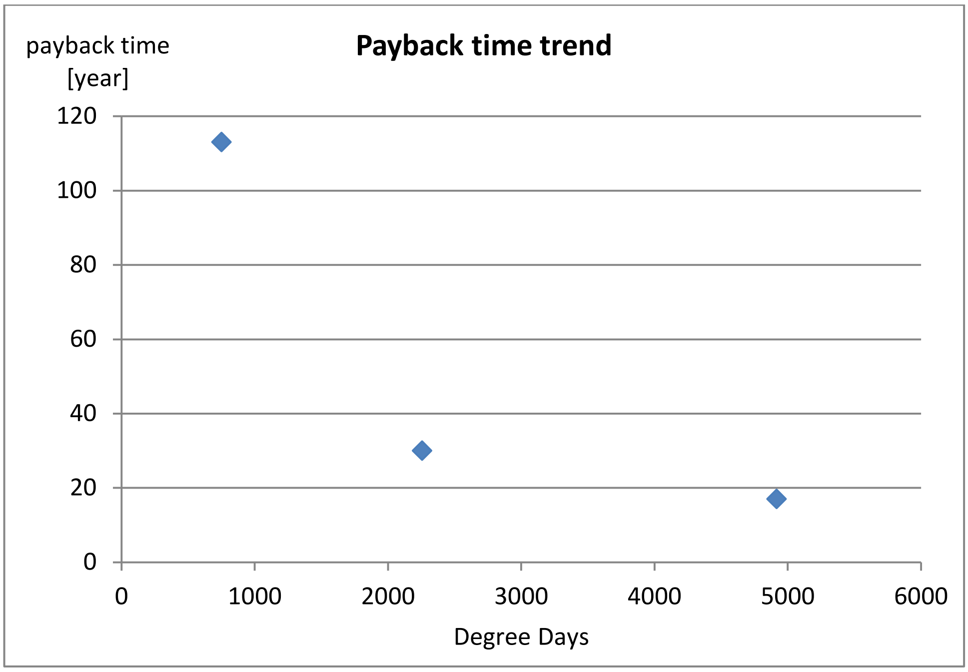



*Fig.7.8 – Payback time trend of HVAC retrofitting of the different thermal zones*

### 7.4.2 Windows Retrofitting Solutions

The second simulation consists in applying the windows retrofitting solution described in the chapter 5.1 of the thesis.

Figure 7.9 shows, also in this case, how the energy savings achieved in Denmark are significantly higher than those obtained in milder climatic zones.

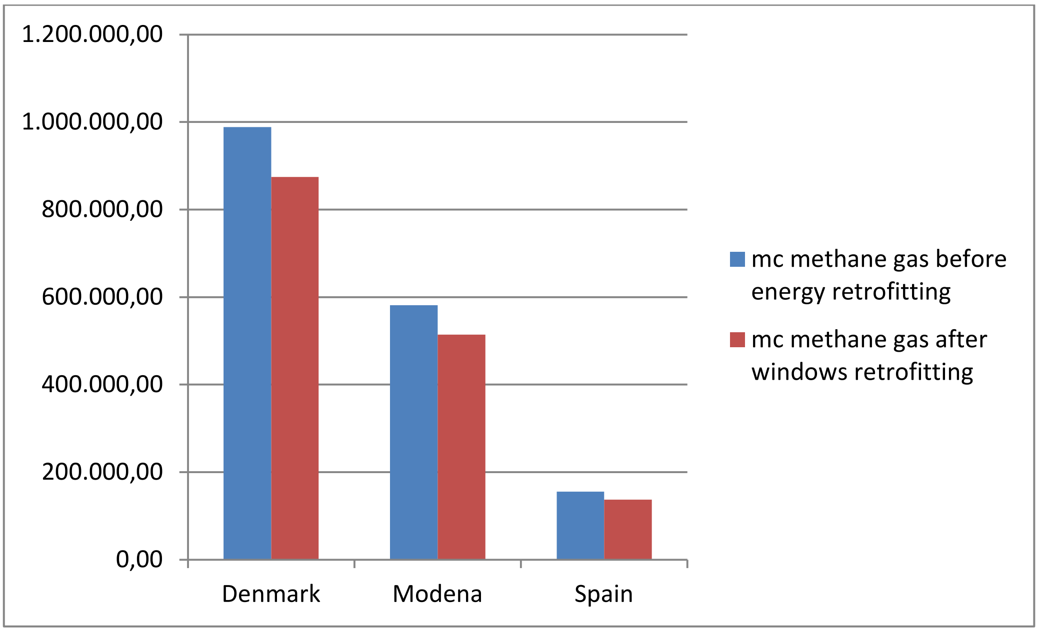



*Fig.7.9 – Annual consumptions of methane gas before / after windows retrofitting of the different thermal zones*

Figure 7.10 shows the trend of the payback time of the windows retrofitting solutions. Also in this case the economic evaluations were all carried out keeping the cost of natural gas constant to make the results comparable.

The payback time goes from 61 years of the case study of the Ducal Palace of Modena to 36 years for very cold climates to greater than 100 years for warm climates.

The retrofitting intervention of the windows from the point of view of payback time is not convenient, both because the windows do not have a big impact on the total consumption and because the investment cost of the wooden windows is very high.

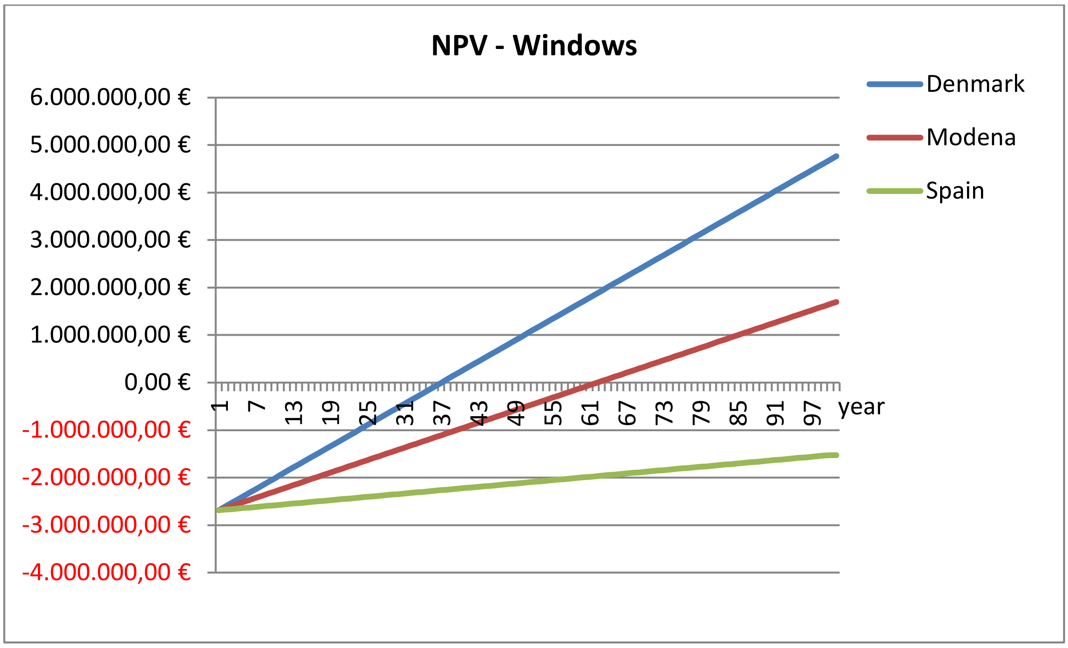



*Fig.7.10 – NPV of windows retrofitting of the different thermal zones*

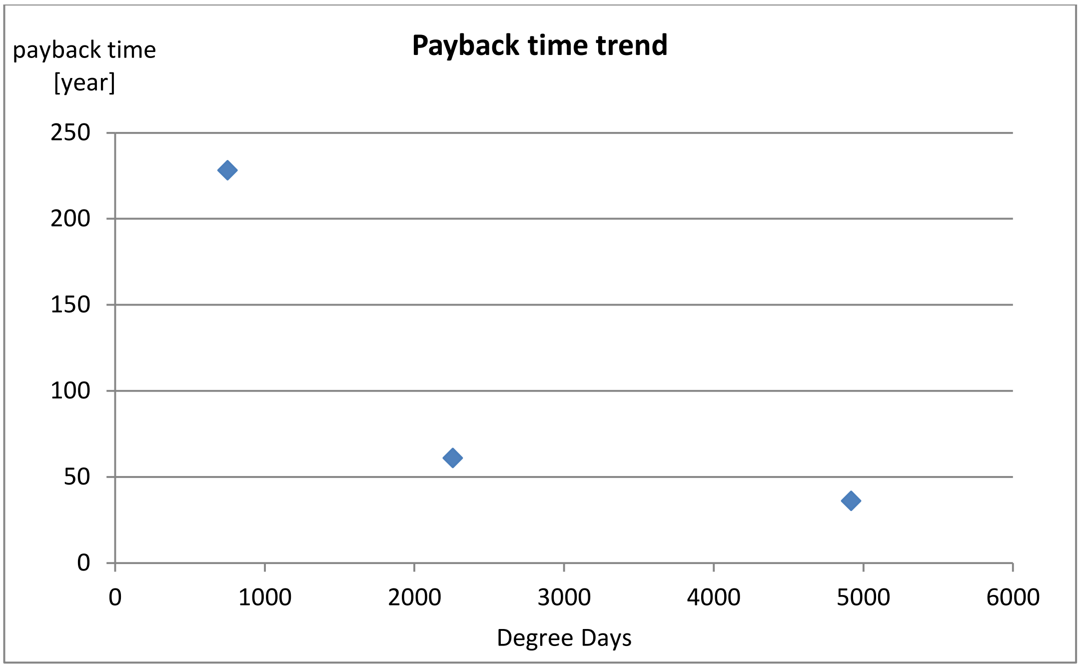



*Fig.7.11 – Payback time trend of windows retrofitting of the different thermal zones*

### 7.4.3 Insulation retrofitting solution

The third simulation consists in applying the windows retrofitting solution described in the chapter 5.2 of the thesis.

Figure 7.12 shows, also in this case, how the energy savings achieved in Denmark are significantly higher than those obtained in milder climatic

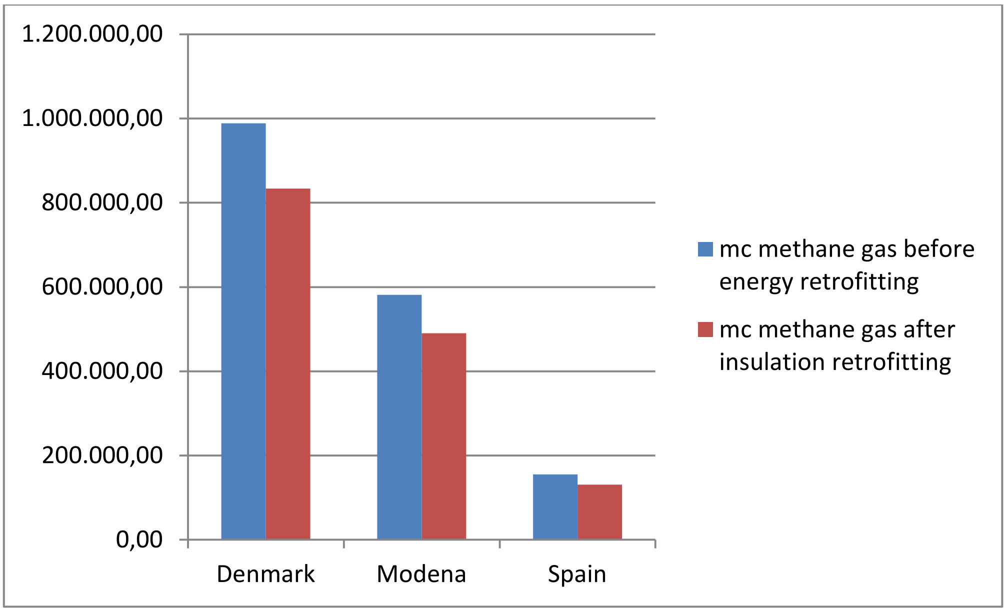



*Fig.7.12 – Annual consumptions of methane gas before / after insulation retrofitting of the different thermal zones*

Figure 7.13 shows the trend of the payback time of the insulation retrofitting solutions. Also in this case the economic evaluations were all carried out keeping the cost of natural gas constant to make the results comparable.

The payback time goes from 18 years of the case study of the Ducal Palace of Modena to 10 years for very cold climates to greater than 64 years for warm climates.

For the conditions of the case study this is the most convenient single intervention in terms of energy costs and benefits.

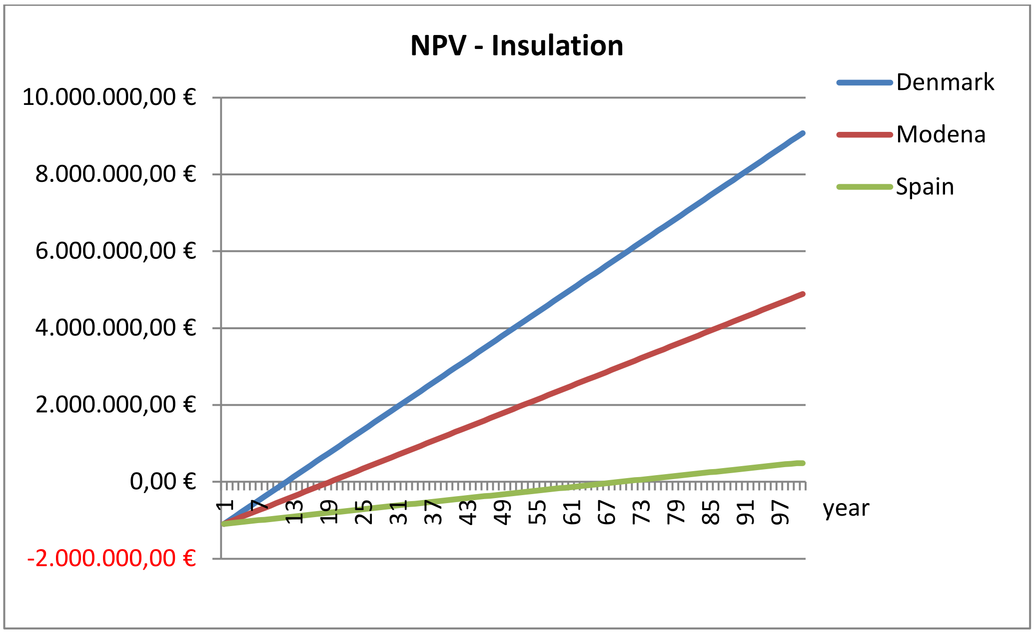



*Fig.7.13 – NPV of insulation retrofitting of the different thermal zones*

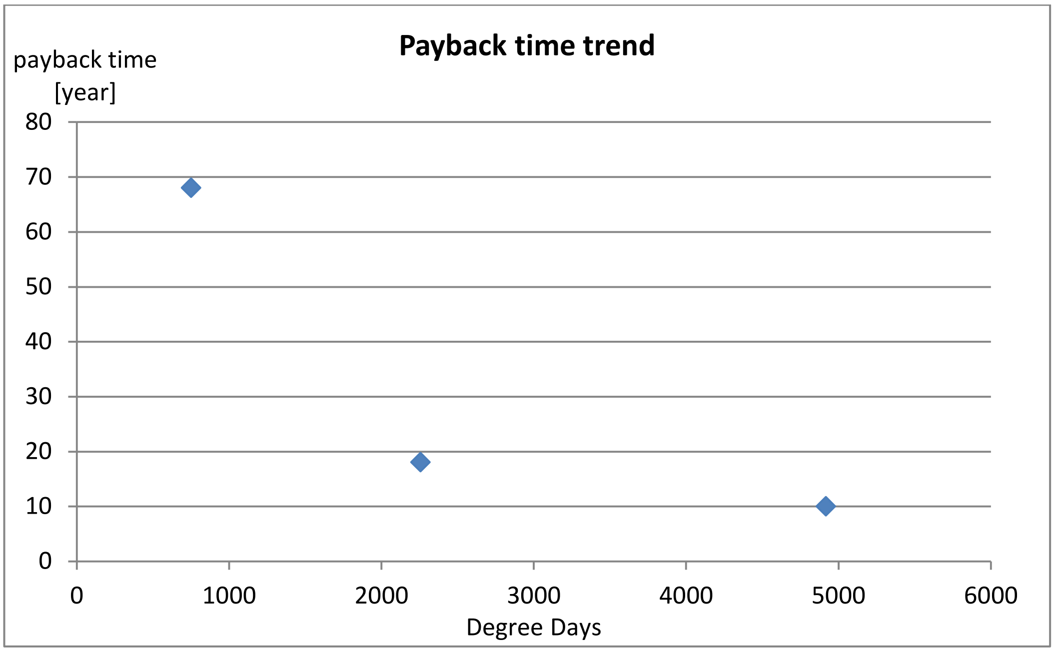



*Fig.7.14 – payback time trend of insulation retrofitting of the different thermal zones*

### 7.4.4 Combined Retrofitting solutions (Windows + HVAC system + Insulation)

The last simulation consists in applying the global retrofitting solution inclusive of the energy retrofitting showed in chapter 7.4.1-7.4.2 and 7.4.3 (HVAC system, windows and insulation).

The gap of the energy saving achieved in the three different climatic zones is always greater.

From these trends we observe that for the same building envelope-HVAC system, the same retrofitting solutions according to the climatic zone produces very different benefits in terms of energy saved and payback time of the investments.

The payback time of the global retrofitting solution goes from 32 years of the case study of the Ducal Palace of Modena to 19 years for very cold climates to greater than 100 years for warm climates.

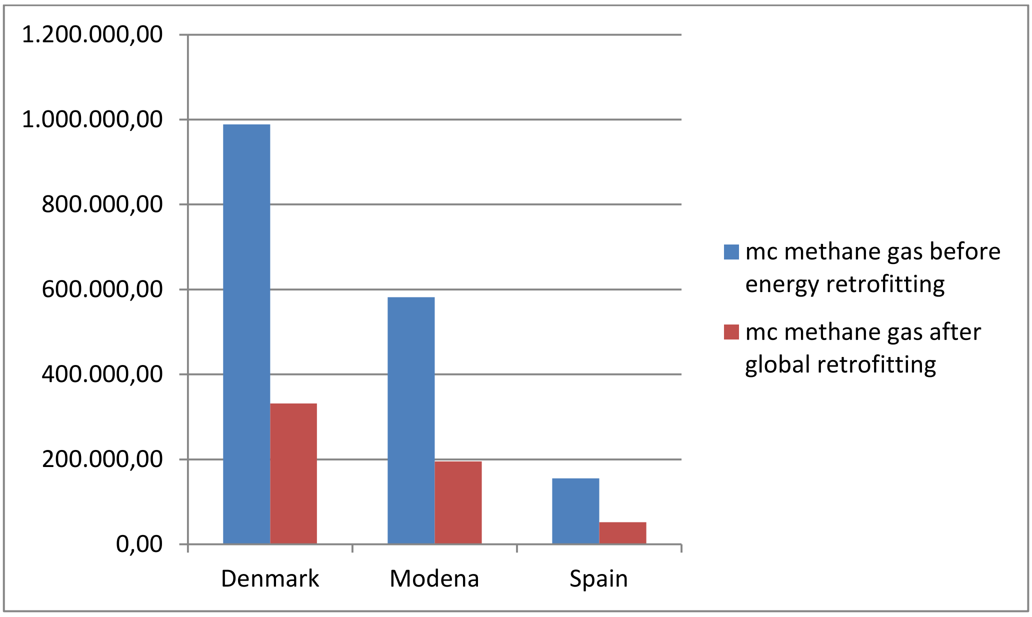



*Fig.7.15 – Annual consumptions of methane gas before / after global retrofitting for different thermal zones*

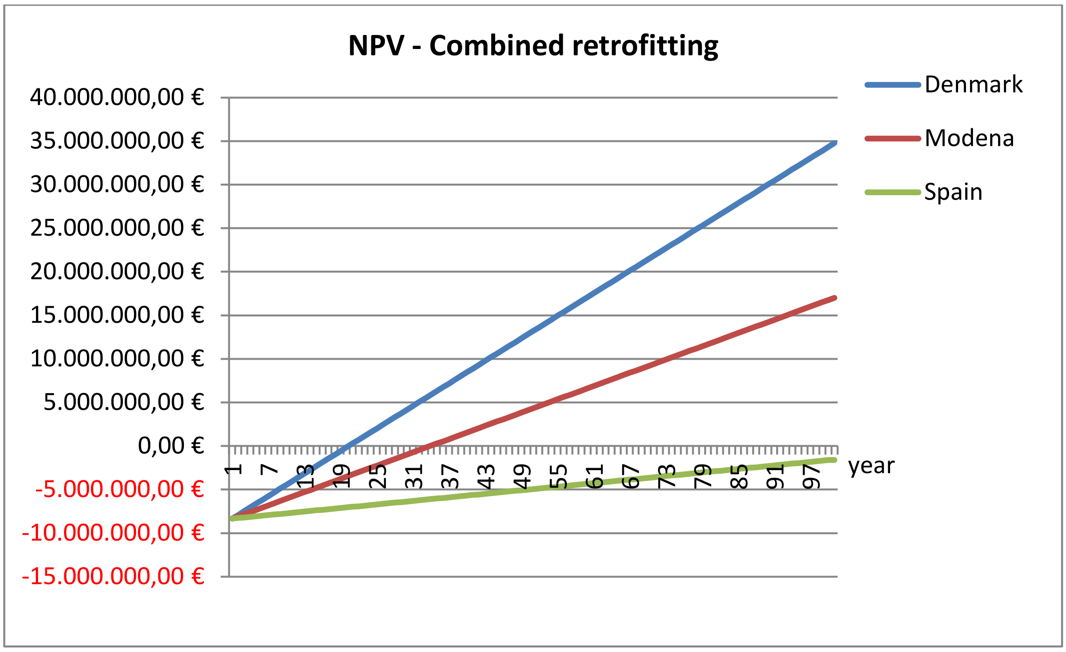



*Fig.7.16 – NPV of global retrofitting for different thermal zones*

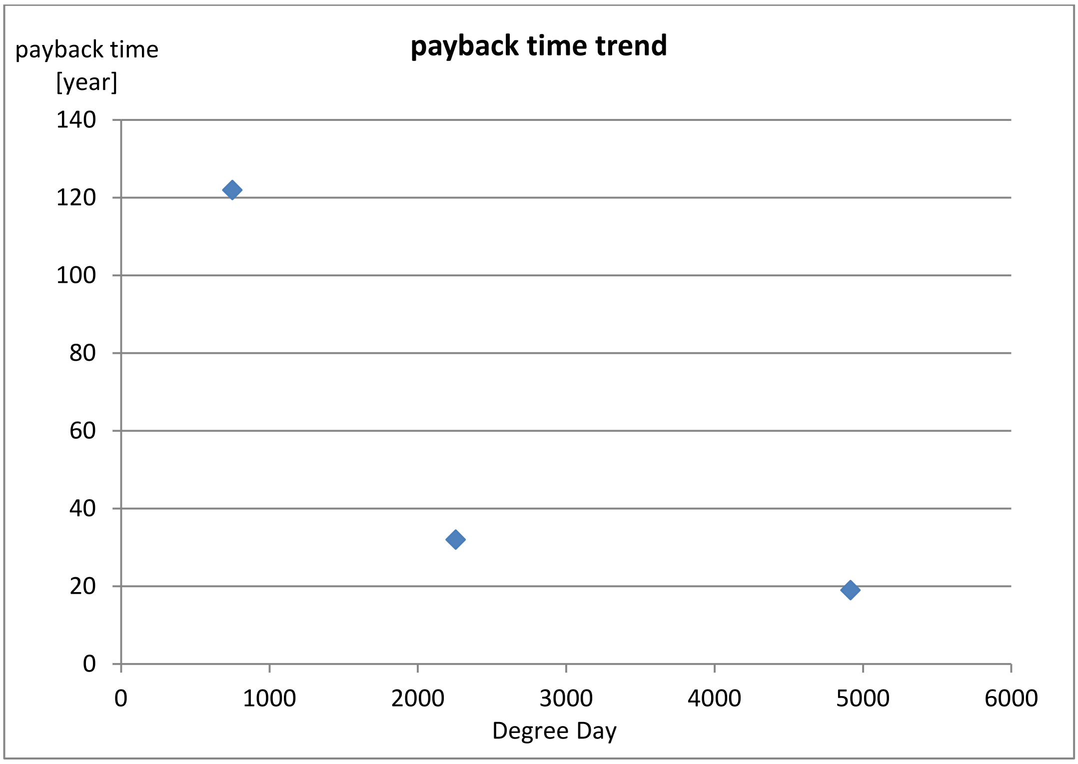



*Fig.7.17 – payback time trend of global retrofitting of the different thermal zones*

To have an idea of the extent of the impact of the climatic zone in evaluating the convenience of an intervention, the following figures shows the cost of the investment for the three areas to obtain the payback time of 19 years and about 66% of the energy saving.

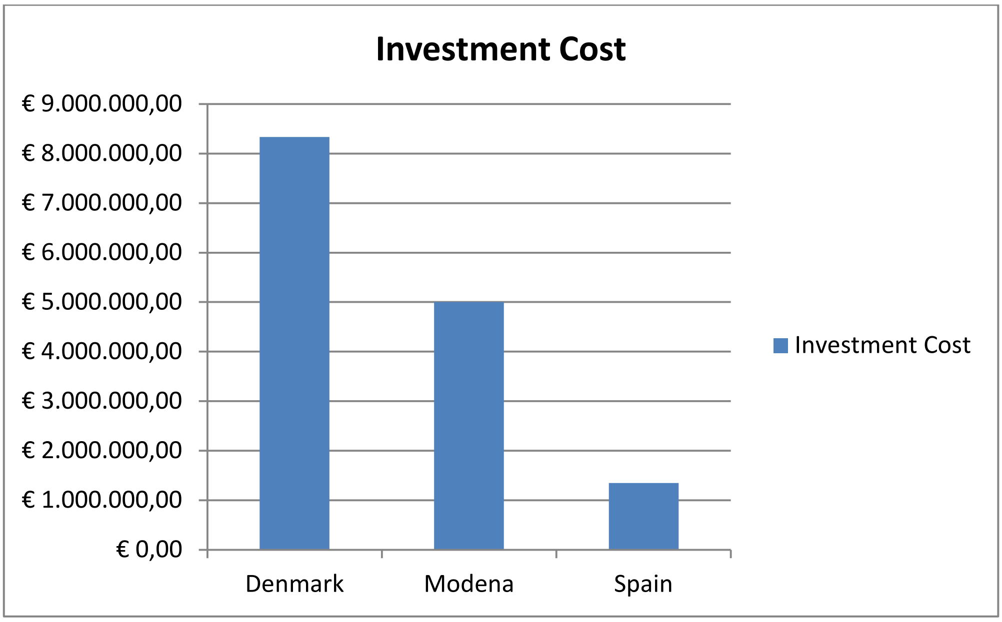



*Fig. 7.18 - cost of the investment for the three climatic zones to obtain the payback time of 19 years and about 66% of the energy saving*

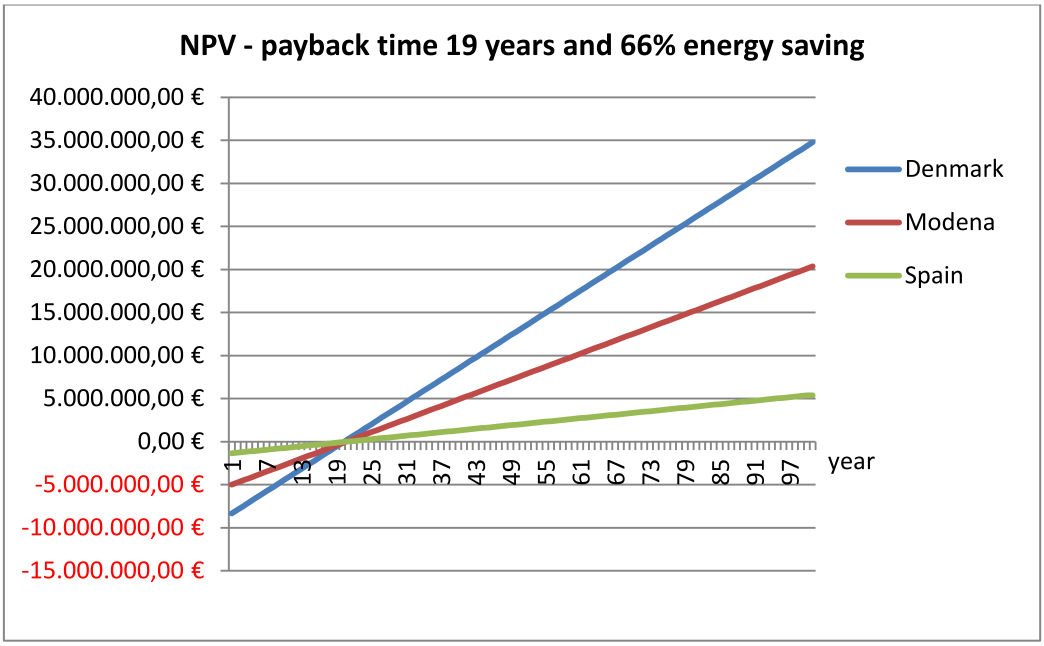



*Fig. 7.19 – NPV for the three climatic zones to obtain the payback time of 19 years and about 66% of the energy saving*

Energy retrofitting for the winter heating of a buildings in cold climates is much simpler and more convenient than going to work in temperate or warm climates; to have acceptable payback time for the retrofitting solutions in warm climates the only way would be through the use of alternative energy but whose installation is often not compatible with the architectural constraints of the historic building.While the use of heat pumps in buildings such as the Ducal Palace of Modena would have been inadequate given the size of the centralized system and the use at high temperatures, in warmer climates could certainly be a more appropriate solution to be taken into consideration.

## 7.5 Incidence of the components of the HVAC system and the Building Envelope

Another important factor for assessing the convenience of the various retrofitting measures is the impact on consumption of the various components.

The case analyzed in chapter 7.4 reported the situation of the case study with a heating system in disastrous conditions, in the following simulations it is observed what happens if the conditions of the HVAC system in the building are medium-good (incidence of the HVAC system is the 30% of the total energy consumptions).

The efficiency of the components of the HVAC system assigned for the simulation are described in Table 7.2.

*Table 7.2 – Hydronic System Heating Plant Efficiency*

| **Hydronic System Heating Plant Efficiency** | | |
|---|---|---|
| Emission system | nH,e | 90,0 % |
| Regulation system | nH,rg | 95,0 % |
| Distribution system | nH,du | 90,0 % |
| Generation system | nH,gn | 90,9 % |
| **Average seasonal hydronic system heating plant efficiency** | **nH,g** | **69,3 %** |

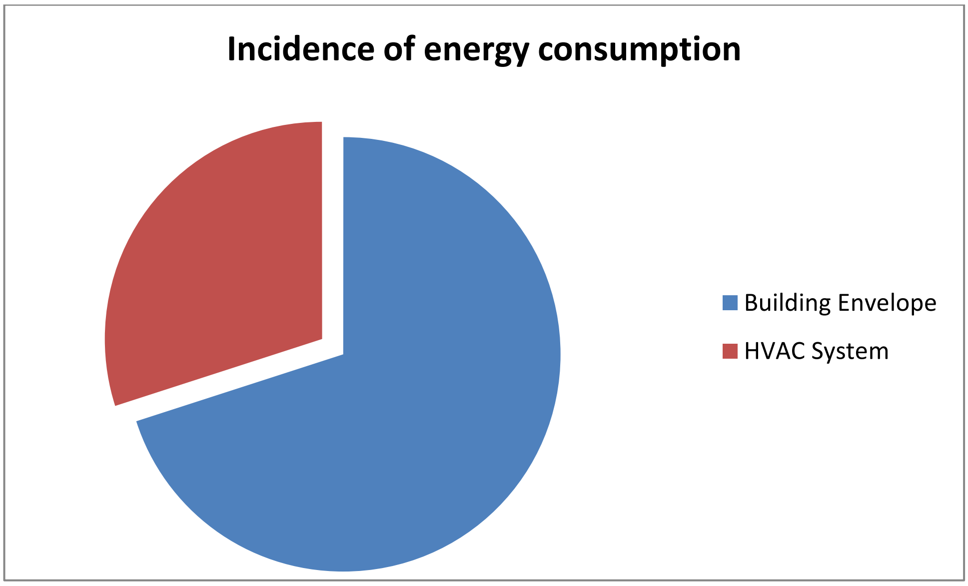



*Fig.7.20 – Incidence of the energy consumption*

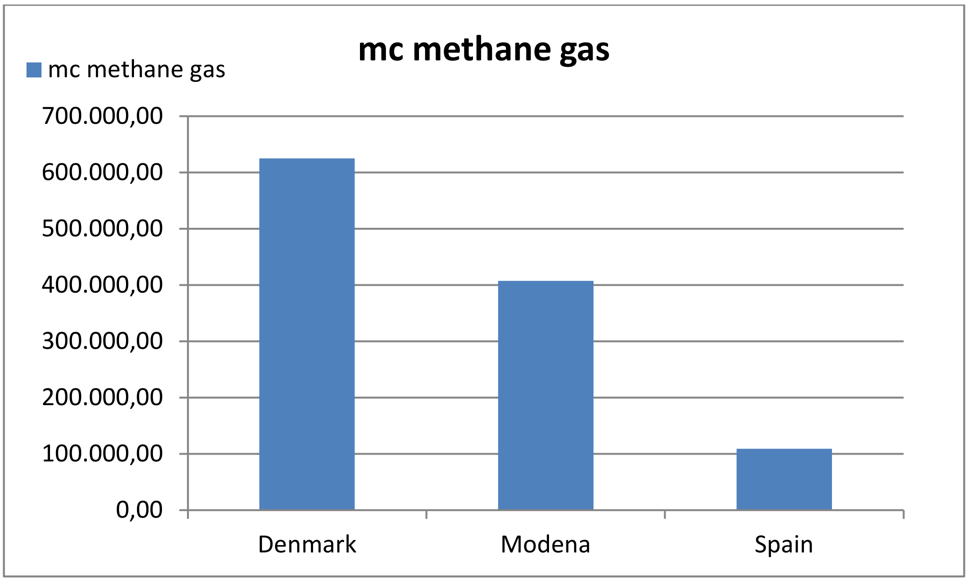



*Fig.7.21 – Annual consumptions of methane gas*

The energy saving measures of windows and insulation for this case study are evaluated below.

### 7.5.1 Windows Retrofitting Solutions

The first simulation consists in applying the windows retrofitting solution described in the chapter 5.1 of the thesis at this case study where the HVAC system is more performant.

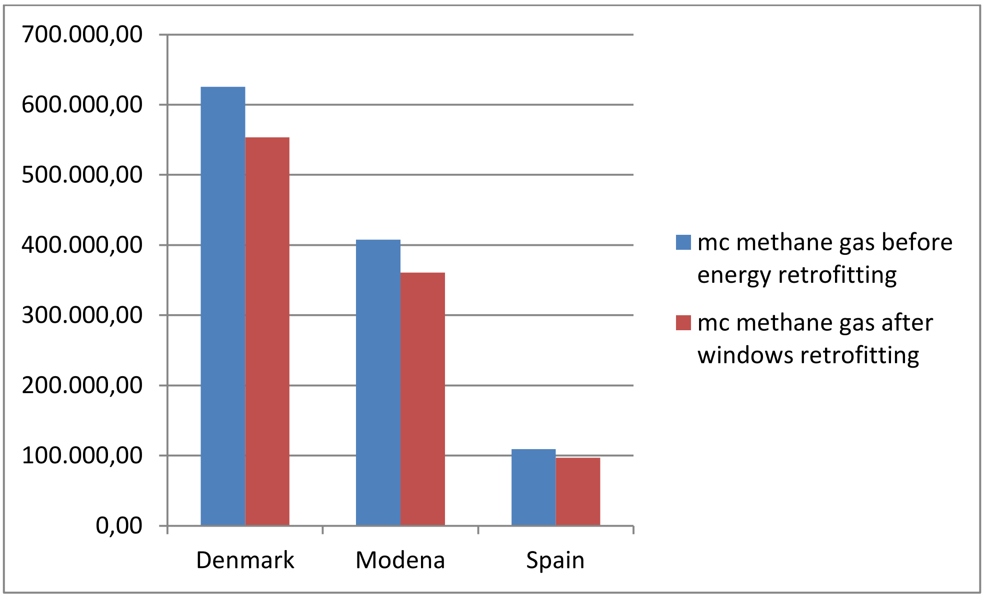



*Fig.7.22 – Annual consumptions of methane gas before / after windows retrofitting of the different thermal zones*

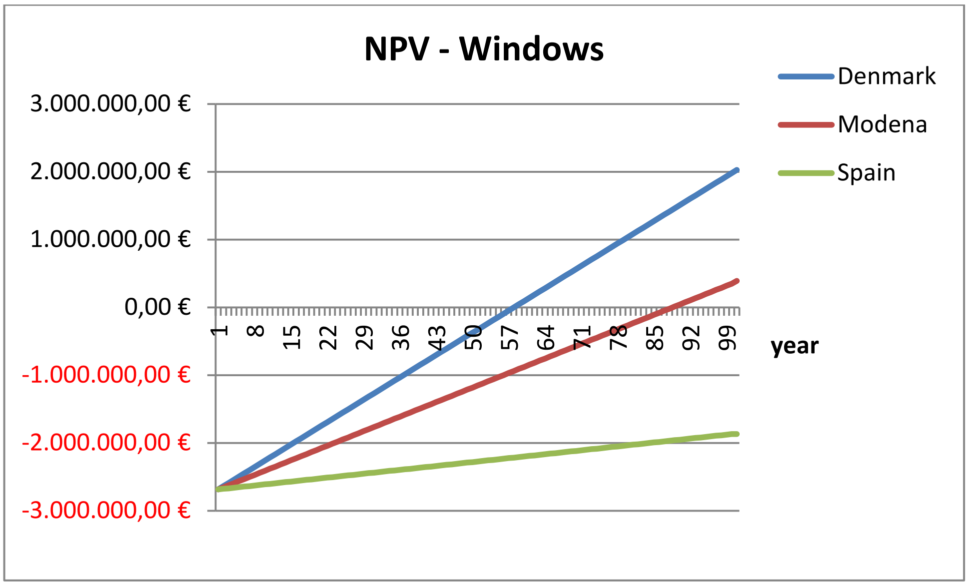



*Fig.7.23 – NPV of windows retrofitting for different thermal zones*

The graphs show how increasing the efficiency of the HVAC system, the payback time of the investment increased and the energy saving of the intervention decreases.

### 7.5.2 Insulation Retrofitting Solutions

The second simulation consists in applying the insulation retrofitting solution described in the chapter 5.2 of the thesis at this case study where the HVAC system is more performant.

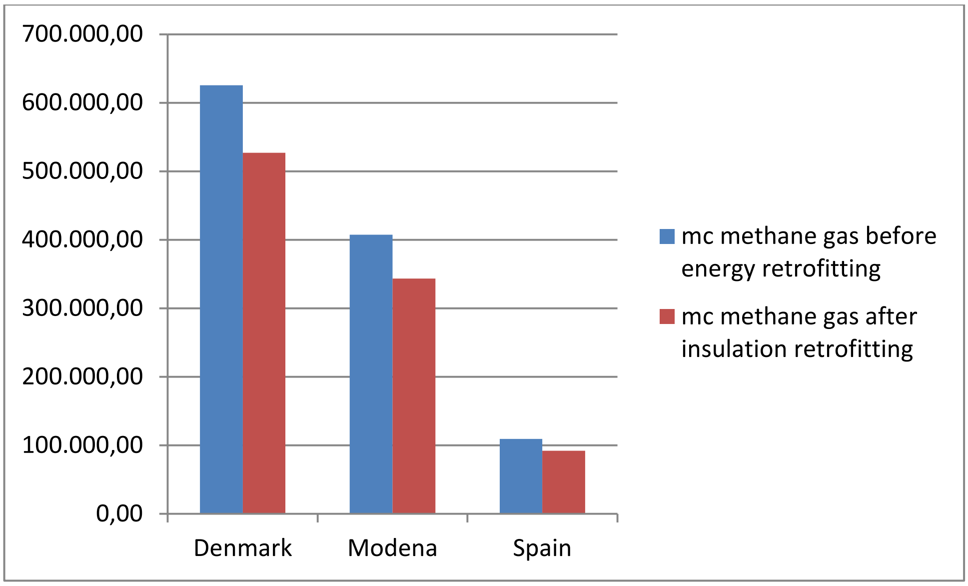



*Fig.7.24 – Annual consumptions of methane gas before / after insulations retrofitting for different thermal zones*

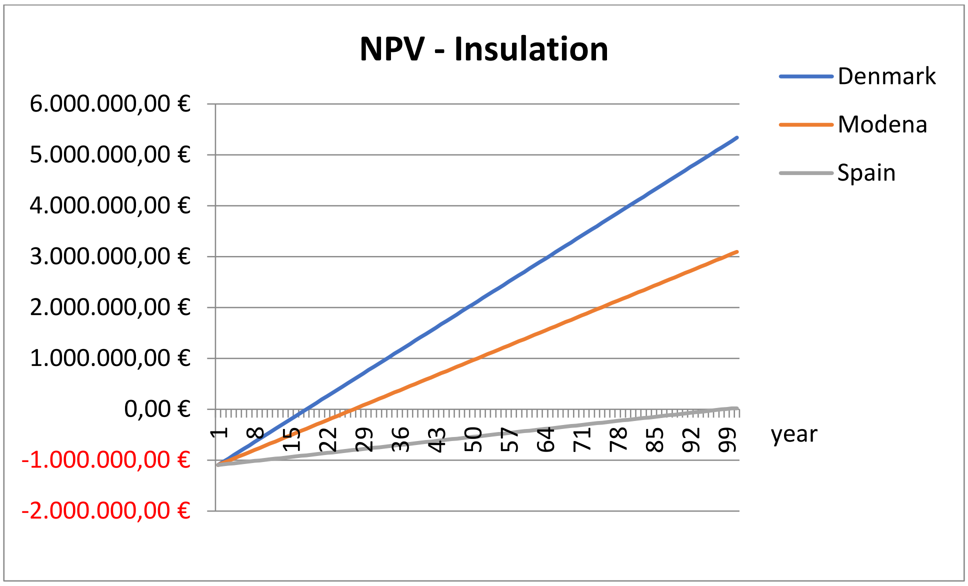



*Fig.7.25 – NPV of insulations retrofitting of the different thermal zones*

Also in this case the graphs show how increasing the efficiency of the HVAC system, the payback time of the investment increased and the energy saving of the intervention decreases.

### 7.5.3 Trend of the payback times of the building envelope energy retrofitting solutions with variation of the climatic zones and HVAC efficiency

The following analysis shows the trend of the payback time of the building envelope energy retrofitting with the variation of the climatic zone and the variation of the efficiency of the HVAC system. Two retrofitting solutions were evaluated: insulation (figure 7.26 and 7.27) and windows (figure 7.28 and 7.29).

The parametric variables relating to the climatic zone and the efficiency of the HVAC system (from a good system with n=69,3% to a system in bad condition n=49,1%) have been varied.

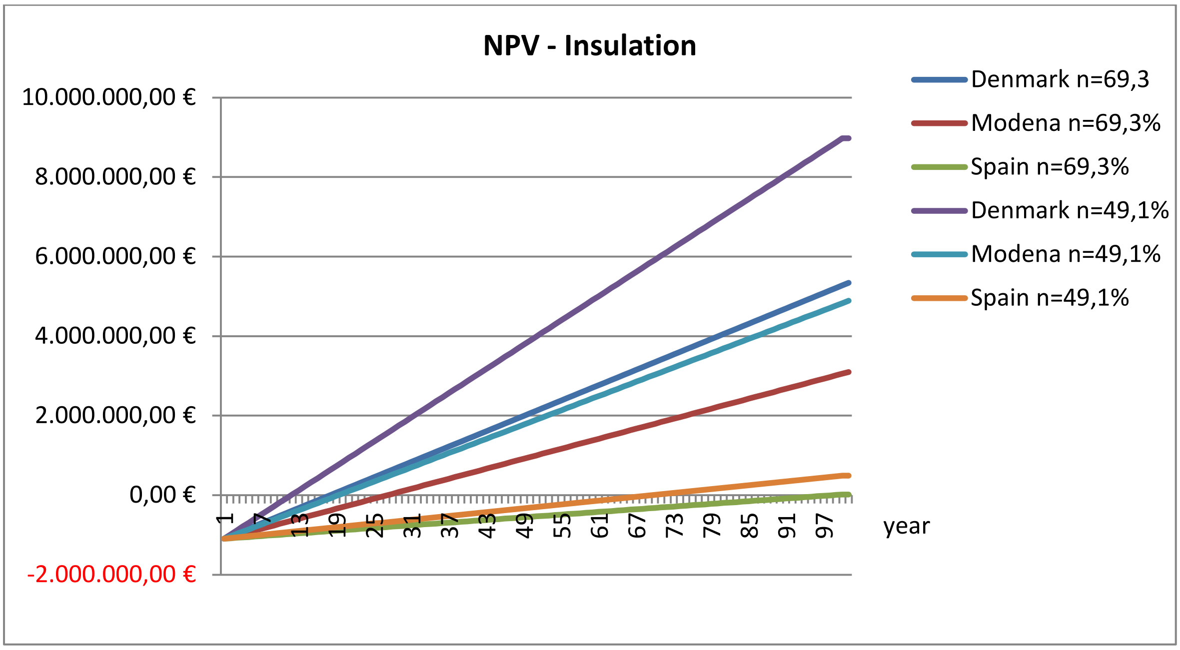



*Fig.7.26 – NPV of insulations retrofitting of the different thermal zones and HVAC efficiency*

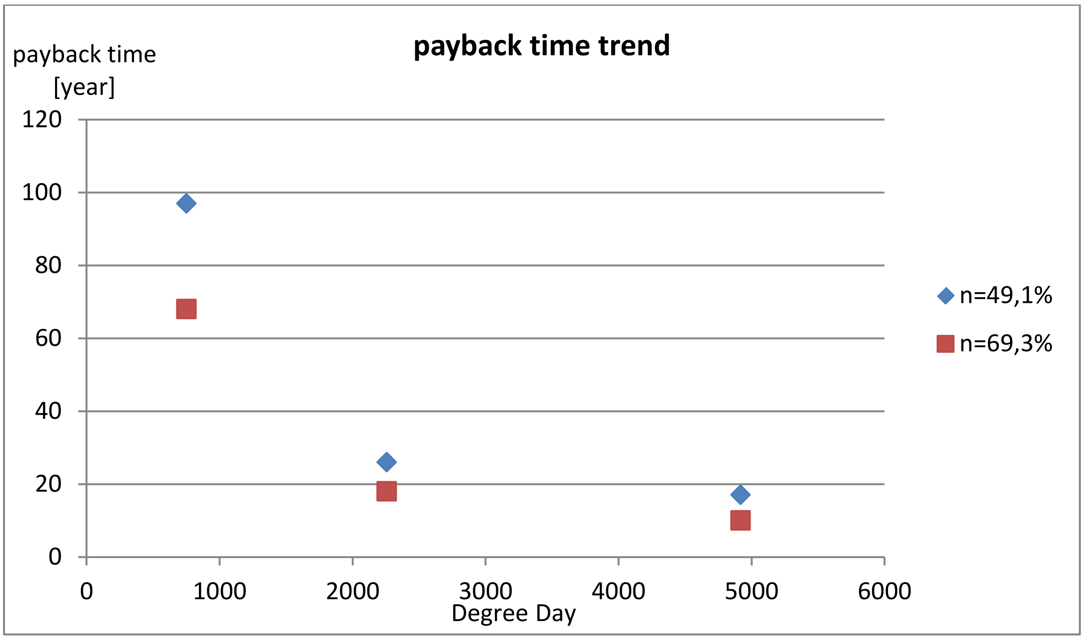



*Fig.7.27 – payback time trend of insulation retrofitting of the different thermal zones and HVAC efficiency*

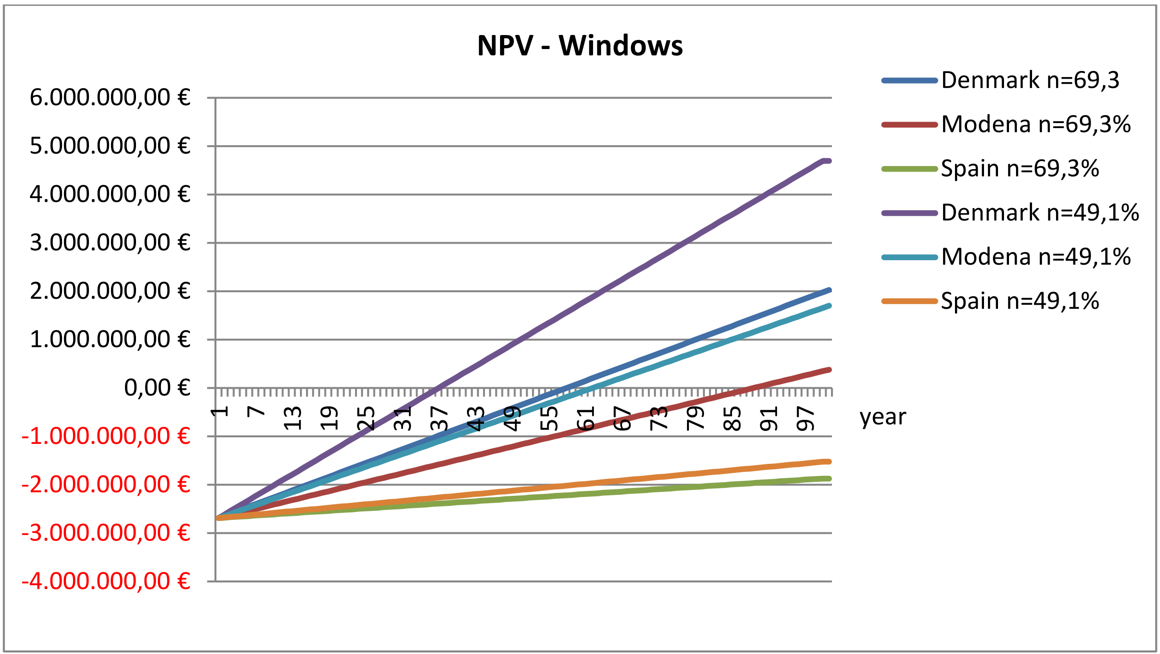



*Fig.7.28 – NPV of windows retrofitting of the different thermal zones and HVAC efficiency*

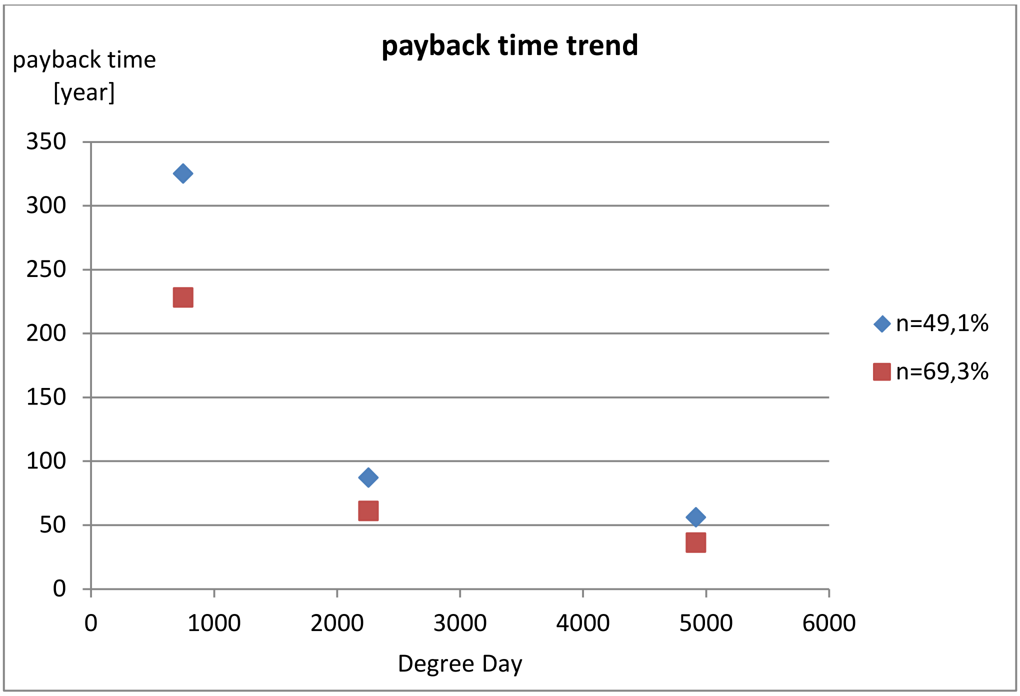



*Fig.7.29 – payback time trend of windows retrofitting of the different thermal zones and HVAC efficiency*

These parametric analyzes in which different factors vary, such as day degrees (therefore the climatic zone in which the building is located) or the performance of the building envelope and HVAC system, allow to understand effectively which retrofitting interventions are really convenient and guide the designer towards the best energy solutions.

Through this parametric analysis methodology it is possible to study all the characteristics of a building, in addition to the heating system, for example, the summer cooling system could be analyzed or further system variables could be taken into consideration.

# 8. CONCLUSION

This PhD thesis focuses on energy efficiency in historical-constrained buildings.

The thesis demonstrates through the use of a case study, the Ducal palace of Modena, the applicability of a comprehensive methodology for the energy retrofitting of historic buildings. The analysis covers energy performance of building envelope and HVAC system.

The analysis of the regulations of the main European countries regarding the protection of historic buildings has shown that at European and National level the laws have a general nature while the evaluation of the feasibility of the interventions are entrusted to local institutions. Ever considering the specificities of the intervention and the local regulatory framework, a common line of intervention for this type of building can be identified and based on two main principles: reversibility and non-invasiveness.

In the literature there are numerous examples of retrofitting of historic buildings and several European and National projects studied the conservation of heritage and its energy redevelopment. This thesis integrates what is present in the literature with the presentation of a methodology for energy retrofitting. The methodology takes into account different identifying factors of the historical buildings, such as the importance of the calibration of the energy model, the thermal inertia and the respect of the architectural constraints.

The retrofitting methodology presented for the Ducal Palace can be used for each historic building in Europe, althought the identification of the most suitable retrofitting solutions has to be developed on a case-by-case basis, according to the architectural constraints and the climatic zone. An analysis was performed to understand the role of the climatic zone in which the historic building is located with respect to the cost-benefit analysis of the energy retrofit interventions. The results also shown how the payback time of the energy retrofitting solutions varies according to the climatic zone and the impact of the energy consumption for building envelope and HVAC system.

The case study of the Ducal Palace of Modena obtained various European and National economic funding to implement energy efficiency measures, becoming an example of best practice in the sector.

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