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Research Doctorate Program in Mechanical System Engineering

Title

MULTI-OBJECTIVE OPTIMIZATION FOR ENERGY-EFFICIENT AND COST-EFFECTIVE HOSPITALS

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Summary

Introduction

Among civil buildings, hospitals are the most energy-intensive. This mainly depends on the specific activities carried out in them, which require big amounts of energy in order to guarantee the best service's quality to users and to fulfill the electricity demand of devices and diagnostic tools. Another important item that affects the energy balance of a hospital is environments' air-conditioning, related to the achievement and maintenance of the high air quality required to carry out healthcare activities, for example the specific aseptic conditions required in operating theatres or in the environments where patients with critical diseases are taken care of. Moreover the approach with which the majority of hospitals nowadays present in Italy were built should also be taken into account. In the previous decades, thanks to low energy costs and especially to a lower political and social attention to human activities' economic and environmental sustainability, the design and construction of healthcare facilities was aimed at fulfilling the required healthcare standards, ignoring the efficiency of the interaction building-system.

From these premises it is clear how energy balances of hospitals, and generally of healthcare settings, show high thermal and electricity consumptions the costs of which fall on profit and loss accounts of hospitals, and consequently, given the high incidence of the public health system's costs, on citizens-taxpayers. In this period of economic crisis, when facing the constantly more compelling need to limit public expenditure and the cost of services to citizens, without affecting the quality level of offered services, hospitals' energy management is one of the many item of expenditure which rationalization is de facto mandatory. The conflict between the request to limit expenditure and the maintenance of qualitative standards can be resolved only by upgrading the efficiency of the examined system, and with specific reference to the problem that it is here addressed, by optimizing the energy management of hospitals. The solution of this problem requires new tools and knowledge, as well as a different approach compared to the one used in the past, which should pay more attention to economic, energy and environmental sustainability.

The observation that each measure in the field of energy saving cannot overlook the fact that, in Europe, the energy used by residential and tertiary sectors represents about a third of the final energy consumption, a decade ago led to the Directive 2002/91/CE, "*Energy Performance of Buildings*" (*EPBD*) [1]. This Directive was aimed at the improvement of energy performance in the construction industry ,integrated and updated by the Directive 2010/31/EU, "*EPBD* recast" of 19th May 2010 [2], to which this thesis will refer, since it is considered as the cornerstone of the current objectives for energy efficiency in the construction industry.

Italy aligned itself to such policy starting from the legislative decree n. 192 of 19th August 2005 [3] (*Implementation of the Directive 2002/91/EC related to energy performance in the construction industry*), as integrated and modified by the D. Lgs. 311/2006 and which was enacted, in its main aspects, by the Presidential Decree 59/2009 and by the Interministerial Decree 26.06.2009 [4] (including National Guidelines for the energy certification of buildings).

The work reported in this thesis is included in this context, it was wrote at the end of a PhD course in “Mechanical Systems Engineering" at the Department of Industrial Engineering of the University of Naples Federico II.

The research carried out aimed at developing an original methodology to define a hospital reference building and at evaluating, through a multi-objective approach, optimal energy performance levels linked to different refurbishment scenarios with the goal of increasing the efficiency of the architectural envelope, of energy conversion systems and integration with renewable sources.

The performed study can be basically subdivided into three parts: construction of the hospital reference building; energy refurbishment of the existing hospital stock through a multi-objective optimization approach; energy diagnosis of a hospital case study and comparison with the reference building.

Essentially, starting from the construction of models for dynamic energy simulation of building-system interaction in hospitals, calibrated basing on monitoring data, it was possible, for buildings representative of Italian hospitals, to develop performance scenarios related to the current status, which can be used to test energy efficiency solutions.

Complying with international and EU orientations and guidelines in the field of energy sustainability in civil construction industry, both for energy refurbishment of existing building and for an energy aware design of new constructions, the dynamic energy analysis, in the context of cost-optimal methodology, was used as an instrument to integrate statistical, archive and analytical data aimed at the definition of the Reference Building.

This thesis is organized in five chapters plus one where the conclusions of the research carried out are reported.

The first chapter is focused on European policies in the field of energy efficiency and on the development of the Italian legislative framework with specific reference to the enactment of the EPBD recast Directive.

In the second chapter the approach used to develop reference buildings at European and USA levels is illustrated. The Reference Building developed by the USA Energy

Department (DOE) [5] is described in more detail since it represented a fundamental reference for the construction of the hospital Reference Building.

The methodology developed to define the hospital reference building, representative of the existing building stock or of new constructions, is reported in the third chapter. Moreover the results of the analysis of energy performances obtained through dynamic thermal-energy simulation of energy models built in Energy Plus are also showed.

Once the scenario of the current status is built, concerning the reference building representative of the existing stock, in the fourth chapter the problem of energy refurbishment was addressed. Different energy efficiency solutions were investigated through the development and the application of a cost-optimal methodology for the evaluation of optimal energy performance's levels.

In the fifth chapter the analysis of energy performances of a real hospital case study is reported: the D pavilion of the "Azienda ospedaliera" A. Cardarelli of Naples. The energy model built in Energy plus [5] was experimentally validated and primary energy consumptions were compared with those obtained for the reference building representative of the existing stock.

Chapter 1. Energy efficiency in the construction industry

The communication "Two times 20 for 2020 [7]**: The opportunity of climate change for Europe" of the Commission to the European Parliament, Council, to the European Economic and Social Committee and to the Committee of the Regions ends with a thought pointed toward the future: *Europe in 2050 will be significantly different from today, this difference will be more clear here depending on how we will face our energy demand and on how we will respect the world around us*.**

The first chapter of this thesis expands and further analyzes this thought which can be considered as the center of the current international economic and social policies.

In the first section the main international actions for energy efficiency are illustrated. **After that, in the second paragraph, the regulatory and legislative context concerning energy efficiency in the construction industry is critically analyzed, highlighting the potentialities of this field referring both to new constructions and, especially, to the energy requalification of the emerging building heritage. Finally in the third section the financial funding established for "sustainable development" will be analyzed in detail.**

1.1 International policies for energy efficiency

The scientific consensus on the evidence of climate change and its causes is by now general: the current dependence of the global energy system on primary sources of fossil origin combusted to satisfy about 80% of the global demand, is the main source of carbon dioxide emissions which are rapidly and dangerously modifying the Earth's climate.

Keeping the rate of the emission of greenhouse gases equal or superior to the actual one will cause a further warming and will cause many changes in the global climate system of the XXI century: this is the conclusion of the IV report "*Climate Change 2007*" [8]. The Intergovernmental Panel on Climate Change (IPCC), while confirming the general indications already included in the previous report released in 2001, has raised the evaluation of the incidence of the anthropic factor on the increase of greenhouse gases' concentration in the atmosphere from 66% to 90%. To keep the increase in warming in the limit of 2°C, beyond which the risk of an ecosystems collapse is really high, reductions of the emission of greenhouse gases between 60-80% need to be made in this century.

This means that extending in the future the actual energy structure, with the predictable consumptions and emissions increase, is simply incompatible with the future of the planet and, only with the adoption of adequate technical solutions supported by appropriate political decisions, it will be possible to reverse the actual tendency and ensure a sustainable development.

The concept of “*sustainable development*”, can be found for the first time inside the Brundtland Report titled “*Our Common Future*” developed in 1987 by the World Commission on Environment and Development (WCED), established in 1983 by the United Nations. Inside the report a guideline for sustainable development is expressed, which is still valid, and the definition to which we currently refer is also reported: “*a development which guarantees the needs of the actual generations without compromising the possibility of future generations of satisfying theirs*”. This does not mean to give up wellbeing and cultural and technological development but allowing it without critically endangering the resources of the planet.

In the international context, the concern on climate change and the awareness of the dependence on exhaustible energy sources led to the *United Nations Conference on Environment and Development* (UNFCC), known as “*Earth Summit*”, held in Rio de Janeiro in 1992, where the participating Countries rated an *action plan for the fulfillment of sustainable development projected in the XXI century.* In this action plan, named “Agenda 21” (Agenda of actions for the XXI century), programmatic indications were included which, in addition to illustrating the great environmental problems, tried to formulate recommendations which could bring together the so-called "three pillars of development": economy, environment and society. The last act of the programmatic line established by the UNFCC was the United Nations Summit on climate change, held in Doha (December 2012), which ended with a prolongation of Kyoto obligations until 2020. Moreover, it was established the commitment to develop, within 2015, a new global agreement that, starting from 2020, will determine a commitment common to all the Countries to solve causes and consequences of climate change. Substantially in this last meeting governments take on the effort to find an agreement wider than the *Kyoto Protocol* rated in 1997, the first real act of the new international strategy.

The topic of energy efficiency has a constantly growing importance for Europe, from the climate energy package 20-20-20 for 2020 and the following programmatic and legislative acts, to the recent directive on energy efficiency (Directive 2012/27/EU [9]). With its approval a framework of very demanding prescriptions and restrictions is set up with the aim of achieving a decisive change in the process of efficiency and reduction of environmental impact with actions that involve in an important way the different fields of efficiency. Each action in the field of energy saving cannot overlook the fact that the energy used in the residential and tertiary sectors represents about a third of the final energy consumption. This is the main legislative framework at European level:

- European directive 2002/91/EC - *Energy Performance of Buildings, EPBD* [1].
- Recently, it was replaced by the Directive 2010/31/EC (EPBD recast,[2]).

In Italy, the EU guidelines were enacted by: the legislative decree n. 192 of 19th August 2005 [3] (*Actualization of the Directive 2002/91/CE concerning the energy performance in the construction industry*).

According to the EPBD Recast, the D.Lgs. 192 was modified and repeatedly integrated until the recent text of the legislative decree n. 63, of 4th June 2013, in coordination with the conversion law of the 3rd, n. 90 [10], titled: "*Urgent instructions for the transposition of the Directive 2010/31/UE of the European Parliament and Council of 19th May 2010, on the energy performance in the construction industry for the definition of the infraction procedures established by the European Commission, and additional instructions on social cohesion*".

The general goal is to improve buildings' energy performance with an accurate design of the envelope and with the integrated use of renewable sources, and also through the energy requalification of the existing buildings. This last point has a strategic importance if we consider that 40% of the Italian building heritage was built before 1976, when the first law (the *373,* [11]) on energy saving in the construction industry became effective, with which minimum limits on buildings' thermal insulation were established.

For this reason the energy quality of the majority of the Italian architecture, both for the state of conservation and for the old construction techniques, is really far from the pursued standards.

The primary energy saving related to the energy requalification interventions that benefit from the tax incentive established by the Budget Law 296/06 (and further modifications) in 2011 was greater than 1'435 GWh/year, with a related reduction of CO_2 emission in the atmosphere equal to 305 kt/year. However, it is essential to extend the scale of the energy requalification interventions if significant goals have to be reached: the interventions on single residences are not sufficient, considering the potentiality and the entity as well as the peculiarity of the Italian building heritage. There is the need to operate on a urban macro-scale level, with an interventions' planning that indicates the territory's potentiality, identifying the possibility of operating on entire complexes (hospitals, schools, etc.) of buildings and/or parts of a city.

To achieve that, a quality upgrade is needed, of which today the first traces can be seen. Indeed referring to the data of the "Interregional operative program (POI) Renewable Energies and Energy Saving 2007-2013" 272 interventions of energy efficiency and energy production from renewable sources on public buildings can be found, in addition to 400 feasibility studies and energy diagnosis. At 30th June 2013, about 930 millions of Euros were assigned to the beneficiaries and about 440 were spent, which are respectively equal to 87% and 44% of the financial supply of the Program.

The legislation on energy saving in the construction industry is affected by a progressive evolution and radical transformation caused by the constantly growing need to establish reference values, *benchmark*, for the evaluation of the real energy performance of analyzed building-system combinations, and to calculate the economic and energy cost of consumptions for the drafting of contracts of energy service management. Concerning the benchmark data, usually the energy consumption of the analyzed building is compared to values found in the international literature, which are hardly fitting to the Italian climate and architectural characteristics. Therefore correction factors for the reference value are used, in order to adapt it to the context where the analyzed building is located.

The definition of a Reference Building is the start-up for the application of the new performances' classification methodology established at European level by the Regulation delegate n. 244/2012 of the European Commission of 16th January 2012 [12].

In Italy, the definition of Reference Building finds some objective difficulties, given the peculiarity of the Italian architectural heritage:

- a great presence of historical buildings;
- a low turn-over in the construction industry;
- a diffuse lack of control on the respect of buildings' energy performance laws;
- significant differences in climate and architectural types between the regions;
- different transmittance values and systems on the national territory, without a precise correlation between the building's age and the level of insulation.

At the present date, the reference is represented by the TABULA project (*Typology Approach for Building Stock Energy Assessment*) but there are still many categories of buildings excluded, mainly in the tertiary sector.

1.2 Energy efficiency in buildings: legislative framework

The publication, on the Official Journal of 3rd August 2013, of the text of the legislative decree n. 63, of 4th June 2013, coordinated with the transposition law 3rd August 2013, n. 90 [10] is the last official act of the Italian legislative process in the field of energy efficiency in the construction industry.

Result of the need of avoiding a worsening of the infraction procedure against Italy, for the missed reception of the Directive 2010/31/EU [2] and to definitely put remedy to the infraction procedure in the field of the certification of energy performance and information to the public in case of transfers and rents, the legislative decree n. 63/2013 intervenes in the field of energy requalification and efficiency of the Italian building heritage, both public and privately owned.

In this section, following the illustration of the EU legislative context in the field of energy efficiency and the related national implications, it is considered appropriate, given the aims of this thesis, to briefly summarize the fundamental legislative steps in the field of energy efficiency which led to the promulgation of the abovementioned decree; pointing out in a detailed way the current obligations and restrictions in this field.

Figure 1.1 reports a summarizing scheme of the main actions related to energy efficiency which will be discussed in this chapter.

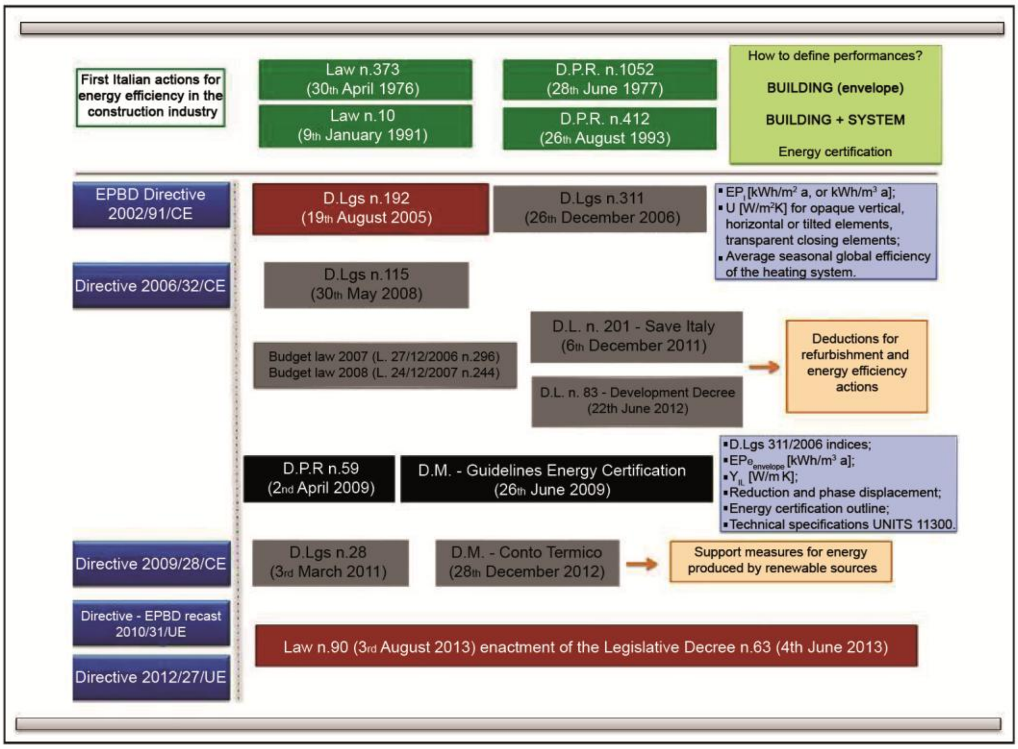

Figure 1. 1: Flow-chart of the main actions related to energy efficiency in the construction industry

1.2.1 The international orientations

In Europe, the Directive 2002/91/EC, "*Energy Performance of Buildings Directive*" (*EPBD*) [1], for the improvement of the energy performance in the construction industry, gave the first input to a community policy aimed at quickening energy saving actions and at reducing the differences among the Nations of the Union. It defines common methodologies with the goal of developing minimum energy performance standards. This Directive, considered as the cornerstone for the goals of energy efficiency in the construction industry, has been recently upgraded and replaced by the Directive

2010/31/EU, "*Energy Performance of Buildings*, *EPBD*- recast" of 19th May 2010 [2], to which this work will therefore refer to.

This Directive established that the Member states have to adopt, at a national or regional level, a calculation methodology of buildings' energy performance[1] which takes into account several aspects, such as thermal characteristics, cooling systems and hot water production, integrated lighting system and the internal climate conditions. In accordance with the abovementioned calculation methodology, the minimum requirements of energy performance to be adopted and revised every 5 years, are aimed at achieving *optimal levels as a function of costs*[2]. In establishing the minimum requirements, the Member states can distinguish between existing buildings and new constructions, as well as between different architectural types.

In more detail, new buildings have to respect the requirements and, before the start of construction works, they have to undergo a feasibility evaluation on the installation of renewable energy supply systems, heat pumps, urban or common district heating or cooling systems and cogeneration systems. On the other hand, existing buildings, destined to undergo important renovations, have to improve their energy performance in order to satisfy the minimum requirements. The architectural elements that are part of the building's envelope and which have a significant impact on its energy performance (for example, windows' fixtures) also have to satisfy the minimum requirements in the field of energy performance when they are renewed or replaced, in order to reach optimal level as a function of costs.

One of the most innovative aspects of the Directive 2010/31/EU [2] is the definition of *Nearly Zero Energy Building* (nZEB), which are buildings with an high energy performance, whose low energy requirement can be satisfied in a significant way by the energy produced using renewable sources. New construction buildings occupied by public institutions and under their propriety should already be nearly zero energy ones starting from 31th December 2018. The obligation for all the new buildings will come in force from 31th December 2020.

In the field of certification of energy performance, the Member states have to adopt a system of buildings' energy performance certification. The certificate has to include information on the buildings' energy consumption, as well as recommendations for improvements as a function of costs. In case of sale or rent of a building or a single unit, the indicator of energy performance which is reported in the certification of energy performance should also be displayed in all the advertisements on commercial

[1] Energy performance: defined as the quantity of energy effectively consumed or which it can be expected to be necessary to satisfy the different need connected to a standard use of the building

[2] Optimal levels as a function of costs are defined by the clause 5 as the levels of energy performance which determine the lowest cost during the estimated economic lifecycle.

communication means. In case of construction, sale or rent of a building or a single unit, the certification has to be shown to the potential buyer or new tenant and delivered to the buyer and new tenant. For buildings in which a total usable area greater than 500 m² is occupied by public institutions and for building with a total area greater than 500 m² usually attended by the public, the certification of energy performance has to be affixed in a place clearly visible by the public (on 9th July 2015 the limit will be lowered to 250 m²).

The most recent action in the field of energy efficiency is the *Directive 2021/27/EU on energy efficiency, which modifies the Directives 2009/125/EC and 2010/30/EU and annuls the Directives 2004/8/EC and 2006/32/EC* [1].

This Directive came into force on 4th December 2012, and its dispositions have to be adopted by 5th June 2014. The new Directive establishes a common framework of actions for the promotion of the energy efficiency in the Union in order to guarantee the fulfillment of the main goal related to energy efficiency of 20% by 2020 and to provide the basis for further improvements of the energy efficiency beyond that date.

Concerning the efficiency in the use of energy, for the first time the problem of the requalification of existing buildings is completely addressed as the main aspect of the energy efficiency interventions in the construction industry. At clause 4, it is indeed established that each Member state should plan "a long run strategy to mobilize investments in the renovation of the national heritage of residential and commercial buildings, both public and private”. In this field, the example role is assigned to public institutions' buildings. Indeed starting from 1st January 2014 and for each year to follow, each Member state should renovate and make energy efficient (satisfying at least the minimum established requirements for energy performance) the 3% of the total covered usable area of heated and/or cooled buildings owned by the central government and occupied by it. The regulation will be applied to buildings with a total covered usable area greater than 550 m² and, by July 2015, to those with an area of 250 m².

In addition to these obligations by 2013 each state should have published an inventory of the heated and/or cooled buildings owned by the central government with a total covered usable area greater than 500 m^2 and, starting from 9 July 2015, greater than 250 m^2. This inventory, which can be considered by all means an energy land register, includes the following data: the covered area; the energy performance of each building or related energy data.

Another relevant aspect, on which the present thesis is indeed centered, is clause 8: *Energy Audit and energy management systems*. In that clause it is established that big companies have to equip themselves of energy audit, by December 2015; such audit has to be performed every 4 years, and has to be carried out in an independent way by qualified experts. Member states should adopt measures to promote *the availability, for all* *final clients, of high quality energy audit, effective in relation with costs*. As regards the economic support, the Commission, directly or through the European financial institutions, plans to help the Member states in the development of funding mechanisms and of technical support regimes to increase the energy efficiency in several fields. In turn the Member states can establish a national fund for the energy efficiency, aimed at supporting the national actions in the field of energy efficiency.

1.2.2 The role of the European Union in the global environmental policies

Following what was announced in the action plan for an European energy policy (approved by the European Council on March 2007), on 23rd January 2008 the Commission presented the communication "*Two times 20 for 2020 - The opportunity of climate change for Europe*". It illustrates a set of actions in the energy and fight against climate change fields, aiming at limiting the planet's warming at 2°C by 2020 [7]. The fulfillment of these goals has to be achieved through a combined system of use of renewable energy and energy rationalization. On a legislative level, the *20-20-20 Package* refers to four Directives and other two community documents:

- Regulation (EC) n. 443/2009 of the European Parliament and Council, of 23rd April 2009, which defines the performance levels in the field of new vehicles emissions as a part of the common integrated approach aimed at reducing light vehicles' CO_2 emission;
- Directive 2009/28/EC of the European Parliament and Council, of 23rd April 2009, on the promotion of the use of energy from renewable sources, which modified and later annulled the Directives 2001/77/EC and 2003/30/EC;
- Directive 2009/29/EC of the European Parliament and Council, of 23rd April 2009, which modifies the Directive 2003/87/EC in order to upgrade and extend the community system of exchange of emission shares of greenhouse gases;
- Directive 2009/30/EC of the European Parliament and Council, of 23rd April 2009, which modifies the Directive 98/70/EC for what concerns the specifications on gasoline, diesel and diesel oil fuels as well as the introduction of a mechanism for the control and reduction of greenhouse gases, it modifies the Directive 1999/32/EC of the Council for what concerns the specifications on the fuel used by ships used for internal navigation and annuls the Directive 93/12/EEC;
- Directive 2009/31/EC of the European Parliament and Council, of 23rd April 2009, on the geological storage of carbon dioxide which modifies the Directive 85/337/EEC of the Council, of the Directives of the European Parliament and

Council 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and of the regulation n. 1013/2006 of the European Parliament and Council;

- Decision n. 406/2009/EC of European Parliament and Council, of 23rd April 2009, concerning the efforts of Member states in the reduction of greenhouse gases emission with the goal of fulfilling the commitment of the Union in the field of greenhouse gases emissions' reduction.

The goals of increasing the global energy production from renewable energy sources and of greenhouse gases emissions' reduction are put into effect in the Directive 2009/28/EC [13] and in the Directive 2009/29/EC [14].

For the goals of this thesis, the main contents of the Directive 2009/28/EC are summarized, before the analysis of the Italian regulatory and legislative system. The Directive 2009/28/EC establishes a common framework for the promotion of energy from renewable sources fixing the mandatory national goals for the global percentage of energy from renewable sources on the final gross consumption of energy and for the amount of energy from renewable sources in the transport field. In more detail, each Member state has to ensure (clause 2) that its percentage of energy from renewable sources on the final gross consumption of energy in 2020, will be at least equal to its general national goal for the energy amount from renewable sources referred to that year. Table 1.1 reports the data referred to Italy.

Percentage of energy from FER on the final gross energy consumption in 2005 (%)	**4.91**
Goal of energy percentage from FER on the final gross energy consumption in 2020 (%)	17.0
Expected total energy consumption, corrected, in 2020 (K_{toe})	131.2
Expected amount of energy from renewable sources for the goal in 2020 (K_{toe})	22.3

Table 1.1: Expected amount of renewable sources on the energy balance in 2020 for Italy.

These mandatory national goals are in line with the aim of an amount at least equal to 20 % of energy from renewable sources on the final gross energy consumption of the Union in 2020. The final gross energy consumption from renewable sources is calculated (clause 5) as the sum of the final gross electricity consumption from renewable sources and of the energy from renewable sources for heating and cooling and for transports.

To easily fulfill the established goals, each state has to promote and encourage energy saving and efficiency. The correct working of the national support regimes is explicitly recognized as an "important mean to reach the goal fixed by the present Directive". In the properly enacting part of the Directive, the national support regime and the mechanisms of trans-border cooperation are expressly identified as means to reach the goals (clause 3). Moreover each Member state (MS) has to ensure that its amount of energy from renewable sources, referring to all the types of transport in 2020, is at least equal to 10% of the final energy consumption in its transport sector.

In agreement with clause 4, each MS had to present by 30th June 2009 a national action plan which established the amount of energy from renewable sources consumed by the transport, electricity and heating sectors for 2020, and also set the reforms' procedure to plan, fix the rates, as well as to regulate the access to the electricity grid, in favor of energy from renewable sources.

When a MS, due to force majeure, presumes to be unable to reach the assigned amount of energy from renewable sources, it informs the Commission which if the impossibility is confirmed has to decide the procedure of adjustment of the final gross consumption of energy from renewable sources of the MS for 2020. The Directive establishes that the MSs can "exchange" an amount of energy from renewable sources through a statistical transfer, start common projects for electricity and heating production from renewable sources and moreover establish a cooperation with third countries .

Another important point of the document is the warranty of origin of the amount of energy produced by renewable sources: each MS should be able to guarantee the origin of electricity, as well as the energy for heating and cooling, from renewable sources. The information included in these origin warranties is normalized and has to be recognized in all MSs. It can also be used to provide information related to the composition of the different electricity sources to consumers. Energy transmission grids should also be updated: MSs will have to build the necessary infrastructures for the energy produced by renewable sources in the transport sector.

The Directive also refers to the energy produced with biofuels and bioliquids (clauses 17, 18 and 19) which have to be made from raw materials coming from inside or outside the community, but they should not be produced from raw materials coming from soils of great value in terms of biological variety or which show a relevant carbon stock. The reduction of greenhouse gases emission thanks to the use of biofuels and bioliquids taken into account, should be at least equal to 35%, percentage that starting from 1st January 2017 will become 50%.

1.2.3 The energy performance in the Italian construction industry

In Italy, the first law to limit energy consumption was the law N. 373 of 30th April 1976 and the related execution regulation D.P.R. 1052 of June 1977 [11] result of the need of containing the costs of energy consumptions also in the construction industry following the Kippur war. The most relevant provision of these two measures was the obligation to calculate thermal dispersions of the envelope (through the C_d[3] coefficient), which should be comprised in a maximum given value, determined by the climate context and by the shape ratio of the building. Ultimately the law aimed at achieving envelopes with a good thermal resistance in order to ensure comfort while reducing heating related energy consumptions (thus only limiting the insulating characteristics of the building, without the evaluation of systems' performance).

Later, the law N.10 of January 1991 - *Rules for the enactment of the National Energy Plan in the field of rational energy use, energy saving and development of renewable energy sources* – [15] and the D.P.R. of June 1993 N.412 [16], annulled the law 373. Starting from these two measures, the goal of energy saving was addressed considering not only the envelope but also the system's efficiency, furthermore, the topic of "certification of energy performance" was introduced for the first time.

The most significant difference, compared with the previous law, concerned the relationship between buildings and systems because the performance of the heating system and the envelope's transmittance together played a role in the determination of a new parameter named FEN (normalized energy demand for winter air-conditioning) which qualified from a performance point of view the entire system. Moreover, to improve the energy transformation processes, reduce energy consumptions and improve the state of environmental compatibility of the use of energy with the same service offer and life quality, the law 10/91 supported and provided incentives, in agreement with the energy policy of the European Economic Community, the use of renewable energy sources. From this brief framework it can be inferred that, if the necessary implementation decree were issued, all the premises were present to realize one of the most advanced and effective regulation in the field of energy saving in the construction industry, since the law 10/91 included the fundamental principles on which the entire international policy on energy efficiency in the construction industry was founded. However the situation evolved in a different way.

The D.Lgs. 19/8/2005 n. 192 "*Implementation of the Directive 2002/91/EC related to energy performance in the construction industry*", represents the Italian legislative instrument for the formal transposition of the EPBD [3]. This introduced the necessary changes and integrations to the already effective discipline in this field, defining the concept of "energy performance of a building" as *the quantity of energy effectively*

[3]The *Thermal dispersion volume coefficient (C_d)* is the ratio between the thermal power dispersed by transmission through the heated envelope in design conditions, and the product of the gross heated volume and the difference between the internal design temperature and the design external temperature.

consumed or that can be expected to be necessary to satisfy the different demands related to a standard use of the building, including among the others, heating, water heating, cooling, ventilation and lighting. Among the introduced provisions, it was already planned that buildings should be equipped, by October 2006, of a certification of energy performance, which had to be attached to all purchase agreements, on pain of the annulment of the purchase itself.

Later, this decree was modified and integrated with the publication of the D.Lgs. N. 311 [4] approved by the Council of ministers on 29/12/2006: "*Corrective and supplementary dispositions of the D.Lgs. n. 192/2005 for the transposition of the Directive 2002/91/EC related to the energy performance in the construction industry*." Among the main changes there was the extension of the obligation to draw up the certification of energy performance also to existing buildings in case of rent or transfer upon payment and the decisive introduction of the goal of energy requalification of existing buildings.

Starting from the D.Lgs 311/2006 [4], the energy performance of a building is expressed by one or two parameters which take into account insulation, technical and installation characteristics, design and location with relation to climate aspects, solar exposure and influence of surrounding buildings, existence of energy transformation systems and other factors, indoor environment's climate included, which affect the energy demand. In addition to the verification of the primary energy demand, the need to carry out the control of the thermal transmittance of the opaque architectural structures and of transparent elements which delimit the buildings was introduced, as well as the verification of the performance of heating systems.

In the attachment C of the D.Lgs 311/2006 [4] the limit values for the parameters necessary for the buildings' energy efficiency definition are listed for each building type and timeline:

- energy performance index for winter air-conditioning (EP_i)[4] [kWh/m^2 a - kWh/m^3 a];
- thermal transmittance[5] (U) of vertical, horizontal or tilted opaque structures [W/m^2 K];
- thermal transmittance of transparent elements [W/m^2 K];
- global average seasonal performance of the heating system (η_g) [%].

For the EP_i parameter, limit values are divided according to the building's type, shape (S/V)[6], climate zone, degree days (DD)[7] and to three deadlines: 2006, 2008 and 2010. In

[4]Quantity of primary energy globally requested during a year , to keep inside the heated volume the internal designed temperature.

[5]Heat flux which passes through a wall for each m^2 of area and for each degree of difference between the temperatures.

[6]Shape factor, in which V (m^3) is the gross volume of the heated parts of the building and S (m^2) is the area of the external surfaces of the elements that delimit the volume.

Table 1.2 are listed, for example, limit values of the energy performance index for winter air-conditioning related to 2010.

S/V	Climate zone									
	A	B		C		D		E		F
	Until 600 DD	A 601 DD	A 900 DD	A 901 DD	A 1400 DD	A 1401 DD	A 2100 DD	A 2101 DD	A 3000 DD	Beyond 3000 DD
<0.2	8.5	8.5	12.8	12.8	21.3	21.3	34	34	46.8	46.8
>0.9	36	36	48	48	68	68	88	88	116	116

Table 1. 2: EPi,lim [kWh/m^2 anno] from 1 January 2010.Residential buildings in E1 class, excluding boarding schools, convents, prisons and barracks.

As regards the limit values for the thermal transmittance of opaque and transparent structures, the tables in the Attachment C, are divided according to the climate zone and timeline. Later these limit values were upgraded by the Ministerial Decree, 26th January 2010 [17]. Table 1.3 lists as an example the updated limits for vertical opaque structures.

A new phase for the energy efficiency of buildings and for the urban planning of Italy started on 10th June 2009 with the publication on the Official Journal of the Decree of the President of the Italian Republic, 2 April 2009, n. 59 :"*Transposition regulation of the clause 4, subsection 1, letters a) and b), of the legislative decree 19th August 2005, n. 192, concerning the transposition of the Directive 2002/91/EC on the energy performance in the construction industry*" in force from 25th June 2009 [18]. The DPR 59/2009 de facto has made mandatory the majority of temporary minimum requirements included in the Attachment I of the D.Lgs 192/2005 and its modifications, with something new.

	Attachment C			Updated limits
Climate zone	**From 1.1.2006 U (W/ m^2 K)**	**From 1.1.2008 U (W/ m^2 K)**	**From 1.1.2010 U (W/ m^2 K)**	**From 1.1.2010 U (W/ m^2 K)**
A	0.85	0.72	0.62	0.54
B	0.64	0.54	0.48	0.41
C	0.57	0.46	0.40	0.34
D	0.50	0.40	0.36	0.29
E	0.46	0.37	0.34	0.27
F	0.44	0.35	0.33	0.26

Table 1.3: Limit transmittance for vertical opaque structures.

[7]The degree days of a location are the sum, extended to all the days of a conventional yearly heating period of only the positive daily differences between the environment's temperature and the average daily external temperature.

Concerning the calculation methods for the energy performance of buildings *clause 3* establishes that the national technical regulations should be used, defined in the context of the EN standards supporting the Directive 2002/91/EC, belonging to the series UNI/TS 11300 and following modifications:

- UNI/TS 11300 - 1 (*Energy performance of buildings – Part 1*): Determination of the heat energy demand of the building for winter and summer air-conditioning [19];
- UNI/TS 11300 - 2 (*Energy performance of buildings – Part 2*): Determination of the primary energy demand and of the performances for winter air-conditioning and for the production of domestic hot water [20];
- UNI TS 11300 - 3 (*Energy performance of buildings – Part 3*): Determination of the primary energy demand and of performances for summer air-conditioning [21];.
- UNI TS 11300 - 4 (*Energy performance of buildings – Part 4*): Use of renewable energy and other methods of production for winter air-conditioning and for the production of domestic hot water [22].

1.2.4 The Italian transposition of the Directive 2010/31/UE

Published on the Official Journal on 3rd August 2013, and in force from the following day, the law 90/2013 which converts with modifications the D.L. 63/2013 [10] is the transposition of the Directive 2010/31/EU [2], establishing new rules on the energy performance of buildings through an upgrade of the D.Lgs. 192/2005 [3].

The provision has the goal of *promoting the upgrade of the energy performance of buildings taking into account the local and external climate conditions, as well as the prescriptions related to indoor environments' climate and the efficacy in terms of costs*. Compared with the previous decrees and putting into action what has been established at an European level, the improvement of energy performances presumes an analysis of the economic lifecycle of a building, selecting for it the best level of energy efficiency as a function of costs. This means that there is a transition toward a design practice aimed at the research of an optimal point between energy efficiency, economic analysis and environmental impact.

The definition of energy performance of a building is modified: *annual quantity of primary energy effectively consumed or that it is expected to be necessary to satisfy, with a standard use of the building, its different demands, the winter and summer air-conditioning, the production of domestic hot water, the ventilation and, for the tertiary sector, the lighting, lift and escalator systems.* This quantity has to be expressed through one or more parameters which take into account the level of insulation of the building and the technical and installation characteristics of systems and its definition can be provided in terms of not renewable, renewable, or total primary energy as the sum of the previous two. What needs to be highlighted, compared to the previous version, is the addition of a paragraph which illustrates the uses to include in the tertiary sector and the particularization in case of demand covered by renewable energy.

This last clarification is necessary to follow up what has been introduced by the Directive 2010/31/EU [2]. It is indeed established (clause 4-bis) that starting from 31st December 2018, new buildings occupied by public administrations and owned by them, and from 1st January 2021 all the new buildings, included educational ones, have to be *nearly zero energy buildings*. A nearly zero energy building is defined as a high energy performance building, in which its really low or almost null energy demand is satisfied in a significant way by energy from renewable sources produced on site, in other words produced, picked up or extracted inside the system's borders (building's energy border)[8].

Moreover, by 30th June 2014, the definition of an Action plan aimed at increasing the number of nearly zero energy buildings is planned even through ad hoc financial measures and policies, thus defining also intermediate goals of improvement of the energy performance of new buildings by 2015. The Action plan should include, in more detail, the following elements:

- ✓ the application of the definition of nearly zero energy buildings to the different building types and primary energy consumption numeric indicators;
- ✓ the selection, on the basis of costs-benefits analysis of particular cases for which the obligation of being nearly zero energy buildings does not apply.

A decisive moment for the upgrade of the legislation in the field of energy efficiency is the issue of transposition decrees anticipated by clause 4, starting from that date the D.P.R. 59/2009 [23] is indeed annulled and the buildings' energy performance calculation method, minimum requirements and interventions fields will change.

As regards the calculation methods and minimum requirements, at the present date, what is established by the clause 3 of the D.P.R 59/2009 [18] remains valid, with the addition of two reference texts: recommendation CTI 14/2013 [23]; UNI EN 15193/2008 [24]. On the other hand, the current system will be permanently upgraded and modified when the transposition decrees related to the paragraphs 1 and 2 of the Attachment I of the Directive 2010/31/EU [2] will be issued. In more detail, the new minimum requirements which will be introduced and upgraded every five years will be based on technical and

[8] System border or energy border of a building is the limit that includes all the area of appurtenance of a building, both inside and outside it, where the energy is produced or consumed, as defined by the clause 2 of the Law 90 of 3rd August 2013.

economic evaluations of convenience, grounded on the costs-benefits analysis of the economic buildings' lifecycle.

When defining these limits, in the document it is stated that in case of new buildings or important renovation, requirements will be determined using the *reference building*. The goal is indeed to move from a legislative system based on normative limits, to a system in which performances (both in the case of design verification or diagnosis) will be compared with those of a “target” building. The latter is identical in terms of geometry (shape, volume, usable area, architectural elements and components area), orientation, territorial location and context and with given thermal and energy parameters. This aspect, absolutely new, clarifies the entity of the transformation that the future (as well as forthcoming) energy legislation will undergo, and given its importance it will be illustrated in an ad hoc section (paragraph 1.3), analyzing in detail all the implications that the transposition of the international orientations in this field will determine.

Concerning the intervention fields, starting from the issue of the abovementioned transposition decrees, previsions should be applied both to public and private buildings, and in a diversified way for new buildings, important renovations and, for the first time in the national legislation in a specific way for energy requalification interventions[9]. The following buildings types are excluded from the decree's application:

- industrial, arts and crafts and agricultural not residential building when the environments are heated for needs connected to the production process or using energy waste of the production process which cannot be used in a different way;
- not residential rural buildings not equipped with air-conditioning systems and those used as places of worship and to carry out religious activities;
- isolated buildings with a total area smaller than 50 square meters;
- building whose use does not presuppose the installation and use of technical systems, such as residential parking spaces, basements, garages, multi-level car park, warehouses, seasonal structures to protect sports facility, etc.

For these the decree is applied only to the parts eventually used as offices or that can be assimilated to them, provided that they can be deducted for the energy efficiency evaluation. At last buildings under artistic restrictions are excluded from the obligation of certifying the energy performance, and from the verifications related to their use, from the maintenance and inspection of technical systems, provided that it is demonstrated that the

9 Definition from clause 2, Law n.90 /2013: an existing building is subjected to energy requalification when interventions, whatever the name, fall into categories different from those indicated as "important renovation of a building " which involve more than 25% of the surface of the envelope of the entire building, including all the units that form it (for example but not in a complete way) in the replacement of external walls, external plasters, of the roof or roof's waterproofing.

respect of prescriptions causes a substantial alterations of their character or aspect, with reference to the historical, artistic and landscape profiles.

Moreover, the transposition decrees will determine the upgrade, in connection with clause 8 and clauses from 14 to 17 of the Directive 2010/31/EU [2], of design, installation, management, maintenance and inspection procedures for buildings' winter and summer air-conditioning systems, as well as professional requirements and accreditation criteria to ensure the qualification and independence of experts and of the bodies to which entrust the certification of energy performance of buildings and the inspection of air-conditioning systems.

Upstream there is the introduction of a new definition of heating system: *technological system for the winter or summer air-conditioning services of environments, with or without production of domestic hot water, independently from the used energy vector, including eventual heat production, distribution and use systems as well as management and regularization bodies*. In more detail, individual heating systems are comprised in the definition whereas stoves, fireplaces, radiant energy localized heating devices are not included; such devices, if fixed, are however assimilated to heat systems when the sum of the nominal powers of the devices' firebox used in the single unit is greater or equal to 5 kW. Systems exclusively dedicated to the production of domestic hot water at the service of single residential units and assimilated are not considered as heating systems. Moreover, in case of new buildings and of buildings subject to important renovation, a technical, environmental and economic feasibility evaluation for the installation of highly efficient alternative systems is expected such as renewable energy supply systems, cogeneration, district heating and cooling, heat pumps and consumptions active monitoring and control systems. The evaluation of technical feasibility of alternative systems has to be documented and available for verification purposes.

Before the end of this section the immediate effects of the law 90 of 2013 will be highlighted; these effects concern the legislation in the field of energy certification, the sanctions for the failed fulfillment of the imposed obligations and the development of financial instruments for the promotion of buildings' energy efficiency.

In the field of energy certification many things change: first of all the definition, which changes from certification of energy performance to *certification of intended energy performance* (APE), a document drawn up respecting the provisions included in the decree and released by qualified and independent experts which certifies the energy performance of a building through the use of specific parameters and provides recommendations for the improvement of energy efficiency. Furthermore, with a new Decree, the adaptation of the energy certification guidelines [25] will be realized in order to introduce:

- simplified calculation methods for buildings with reduced dimensions and energy performances of low quality, aimed at reducing the costs for citizens;
- definition of a certification of energy performance that includes all the data related to the energy efficiency of the building, which will allow to evaluate and compare different buildings;
- a template of sale or rent announcement, to be displayed in estate agencies, which will make uniform the information on the buildings' energy quality provided to the citizens;
- definition of a common information system for the entire national territory, of mandatory use for regions and independent provinces, which includes the management of a buildings, certifications of energy performance and related public inspections land register.

As regards the application field, the most important news are the obligation of providing new or subject to important renovations buildings with the APE before the release of the certificate of use and occupancy. Moreover the obligation to release the APE is mandatory also in case of free transfer of the unit/building, as well as the obligation to attach it to sale agreements, to the acts of units/buildings free transfer or to new rent agreements, on pain of their annulment. In case of sale or rent offer, the corresponding announcements through all commercial communication means have to show the indices of energy performance of the envelope and of the whole building or of the unit and the related energy class. For buildings used by public administrations and open to the public with a total usable area greater than 500 m^2 (starting from 9th July 2015, the limit is lowered to 250 m^2), the owner or the subject responsible of the management, has to arrange for the release of the performance certification. This document has to be displayed at the entrance of the building or in another clearly visible location. For educational buildings these obligations fall on the ownership body.

The clause 15 of the legislative decree n. 192/2005 [18] is deeply modified, in the field of sanctions. In more detail, the expert who releases the technical report or a certification of energy performance not following the template and the procedures established in the decree, is punished with an administrative sanction not lower than 700 Euros and not greater than 4’200 Euros. The construction manager who fails to show to the municipality the compliance certificate in accordance with the certification of energy performance, before the release of the certificate of use and occupancy, is punished with an administrative sanction not lower than 1’000 Euros and not greater than 6’000 Euros. The owner or the landlord of the unit, the building administrator, or the third part who took responsibility, if he does not arrange control and maintenance operations of the air-conditioning systems is punished with an administrative sanction not lower than 500 Euros and not greater than 3’000 Euros. In all the cases, the body that applies the sanctions is obliged to inform the related guild or professional associations for the resulting disciplinary actions.

The operator charged for the control and maintenance who fails to release and rate the technical control report is punished with an administrative sanction not lower than 1’000 Euros and not greater than 6’000 Euros. In case of violation of the obligation to provide new buildings and those subject to important renovations with a certification of energy performance, the contractor or the owner are punished with an administrative sanction not lower than 3’000 Euros and not greater than 18’000 Euros. In case of rent, the owner is instead punished with an administrative sanction not lower than 300 Euros and not greater than 1’800 Euros and in case of sale, the administrative sanction is not lower than 3’000 Euros and not greater than 18’000 Euros.

In case of violation of the obligation of displaying the energy parameters in the sale or rent offer announcement, the person in charge of the announcement is punished with an administrative sanction not lower than 500 Euros and not greater than 3’000 Euros.

1.2.5 Financial support instruments

The Stability law 2015 [26] extended the tax credit IRPEF (Tax on the incomes of natural person) and IRES (Tax on the earnings of companies) for the energy requalification interventions on buildings. The deduction was confirmed in as much as 65% for the expenses incurred from 6th June 2013 to 31st December 2015. Concerning the interventions on the common parts of buildings and on each unit of an apartment building, the deduction is 65%, if the expense incurred in the period comprised between 6th June 2013 and 30th June 2015, and 50%, for the expenses that will incur from 1st July 2015 to 30th June 2016. Starting from 1st January 2016 (1st July 2016 for apartment building) the benefit will be instead replaced by a 36% deduction established for the expenses related to renovations. For the application of the rate it is necessary to refer to two different criteria, independently from the start of works, according to the nature of the subject that accesses to the benefit:

- cash-basis (date of the effective payment) for natural person, artisans, experts and non commercial bodies;
- accrual-basis (date of the conclusion of the intervention, independently from the payment date) for individual companies, societies and commercial bodies.

The benefit is granted when interventions that increase the level of energy efficiency of existing buildings are carried out inside the maximum limit reported in Table 1.4.

	Maximum deduction
Energy requalification of existing buildings	100’000 Euros
Building envelope (example walls, windows, windows' fixtures on existing buildings)	60’000 Euros
Installation of solar panels	60’000 Euros
Replacement of winter air-conditioning systems	30’000 Euros

Table 1. 4: Maximum deduction for intervention type.

Expenses made during the construction of the building cannot receive benefits in accordance with the legislation in this field adopted at community level on which basis all new buildings are subject to minimum energy performance prescriptions. The 55% (65%) deduction cannot be summed with other benefits established for the same interventions by other national laws or recognized by the European Union, by regions or local institutions. If the realized interventions fall both into the established benefits for energy saving and architectural renovations, for the same expenses, only one or the other benefit can be obtained.

All resident or not resident taxpayers can benefit from the deduction, even if holders of business incomes, which own, with any title, the building object of the intervention. In more detail, the benefit can be granted to:

- natural person, artisans included;
- taxpayers who are holders of business incomes (natural person, associations or corporations);
- professional associations;
- public and privately held institutions which do not carry out commercial activities.

In more detail, deductions, are granted if the expenses were met for:

× reduction of the heating energy demand;
× efficiency interventions on the building's envelope;
× installation of solar panels;
× replacement of winter air-conditioning systems.

These benefits essentially concern investments made by private subjects. In the field of public administration, the reference is instead represented by the Ministerial Decree of 28th December 2012 [27].

1.3 Structural funds for energy efficiency

The whole investment established for all EU countries in the new planning of Structural Funds 2007-2013, distributed on a seven years period, amounts to 308 billion of Euros. The three structural funds included in the general regulation are: the European Regional Development Fund (FESR), the European Social Fund (FSE) and the Cohesion Fund.

The FESR defines its role and interventions field in the promotion of public and private investments with the goal of reducing the regional differences in the Union with programs in the fields of regional development, economic change, of competitiveness increase and territorial cooperation on the whole EU territory. The FSE supports the employment and helps citizens improving their education and area of expertise, in order to increase job opportunities. The Cohesion Fund contributes to interventions in the fields of environment and transport networks inside Europe. The last one is activated for Member states with a national gross income lower than 90% of the community average, thus covering new Member states and on a temporary basis also Greece, Portugal and Spain.

The Structural Funds planning 2007-2013 highlight the importance of the energy topic in the Union's politics. The whole financial resources allotment for all 27 EU countries, on each intervention type concerning renewable energy sources and energy efficiency, is almost 9 billion of Euros, of which a little less than 50% for energy efficiency. Among the renewable sources, biomass stands out (20% of the resources); each of the remaining technologies (solar, wind, hydroelectric and geothermal) absorbs about 10% of the resources. As regards the distribution among the different goals, almost 7 billion are dedicated to Convergence areas, about 1.75 to the objective “Regional competitiveness and employment” and 325 millions to territorial Cooperation. About 22% of the whole EU appropriation is destined to transports.

In Italy, the *National Strategic Reference Framework* (QSN) for the period 2007-2013 [28] was organized through Regional Operational Programmes with FESR community contributions and Regional Operational Programmes with FSE community contributions and, for the regions of the Convergence objective and for the South area, through five National Operational Programmes with FESR community contributions, three National Operational Programmes with FSE community contributions and two Interregional Operational Programmes (with ERDF community contribution).

In more detail, the choice of the two Interregional Programmes “Renewable energy and energy saving” and “Cultural, natural and tourism attraction potential" answer the need, signaled by the regions themselves, to promote a common action in those "policy" fields that offer the opportunity, on one hand, to catch the energy systemic nature, and on the other hand, to emphasize contiguous assets not sufficiently recognizable in a separate way.

The main part of the QSN strategy, put into action with national and community resources, will be activated through Regional Operational Programmes funded with FESR contribution or with FSE contribution. In more detail the planned interventions for the CO_2 emission reduction are illustrated in the FESR Regional Operational Programmes, in the POIN “Renewable energy and energy saving” and in the PON “Networks and mobility” also funded by FESR.

Table 1.5 lists financial resources (community and national) for greenhouse gases reduction interventions divided for planning document and topic. From the analysis of these data it is clear that the transport sector has the greater available financial resources, which amount to 5.8 billion of Euros from POR FESR and 2.71 billion of Euros from the PON “Networks and mobility”, for a total amount of the whole transport sector equal to 8.51 billion of Euros. Financial resources for renewable sources and energy saving are also relevant, and together they amount to about 3'882 millions of Euros.

Resources [Millions of Euros]	POR FESR Convergence	POR FESR Competitiveness	POIN Energy	PON Transports	Total
Renewable sources	833.0	617.9	780.0		2'230.9
Energy saving	460.2	426.8	763.8		1'650.8
Transports	4'679.8	1'119.4		2'711.0	8'510.2
Wastes	617.2	68.1			685.3
Total	6'590.2	2'302.2	1'543.8	2'711.0	13'097.2

Table 1. 5: Financial resources for interventions affecting polluting emissions.
Source: QSN 2007-2013

Among those, the Interregional Operational Program for Renewable Energy and Energy saving 2007-2013 (POI Energy), supports efficiency interventions, energy saving an energy production from renewable sources in Calabria, Campania, Puglia, Sicily (Regions “Convergence” Objective). The POI is funded by national and community funds, and it is the outcome of an intense planning work between the Ministry of Economic Development (MSE), Ministry of the Environment (MATTM), Italian Objective "Convergence" regions and a large economic and social partnership. There are three intervention lines in the POI, defined as *Axis I* “Energy production from renewable sources”, *Axis II* “Energy efficiency and optimization of the energy system”, *Axis III* “Technical assistance and backing actions”. Interventions are aimed at:

- public administrations, to develop the culture of renewable energy and energy saving through funding of investments on buildings owned by the administrations themselves;

- to private citizens, with benefits supporting investments aimed at companies producing components for the renewable energy sector, or belonging to the energy saving industry;
- to public administrations or private citizens to reinforce the energy supply network. The financial envelope 2007- 2013 is about 1’103 millions of Euros, of which 72.83% co-funded by the European Union– ERDF.

Referring to the data published by the ministry and updated at 30th June 2013 [29], the “*Interregional Operational Programme (POI) Renewable Energy and Energy saving 2007-2013*” put into effect interventions which involve:

- ✓ public buildings;
- ✓ companies active in the field of renewable energy;
- ✓ public institutions and private sector for the improvement of the energy supply network;
- ✓ research institutes for the development and the arrangement of the knowledge of the geothermal potential of Convergence Regions.

Concerning public buildings, there were 272 funding for energy efficiency and energy production from renewable sources interventions of which 100 are completed. In more detail:

- 10 projects involved Local Health Authorities and Hospitals;
- 14 projects are intended for educational structures;
- 84 interventions for the energy efficiency of 183 buildings located in municipalities with up to 15.000 citizens, including old and valuable villages;
- 19 projects depend on the State administrations which defend legality and safety in the Convergence areas regions;
- More than 140 involved central and local administrations' buildings relevant for citizenship.

Many feasibility studies and energy diagnosis were funded: 25 feasibility studies were carried out to select and design interventions in example areas of minor islands and natural protected areas (23) and on airport facilities in minor islands (2). Moreover 359 energy diagnosis are underway on airport facilities (15), museums and archeological sites (20), judicial buildings (3), municipal heritage facilities (134), heritage buildings in single or associated and in mountain and peripheral villages (40) and province facilities (147).

Furthermore, 45 projects were approved to support productive investments in the biomass industry, in more detail "short distribution chain" and to develop the enterprise related to components for energy production and energy efficiency.

In addition there are 11 projects for the upgrade and adjustment of the electricity grid aimed at spreading renewable sources and micro combined heat and power, for an amount of 208 M€.

In conclusion, as regards the use of geothermal sources within the VIGOR[10] project (Evaluation of the Geothermal potential of Convergence Regions), the knowledge of the geothermal energy potential in the Convergence regions was widened and organized, and 8 feasibility studies were carried out for example projects aimed at realizing interventions for an innovative enhancement and use of this energy source.

From the reported data it can be inferred that the complex financial framework related to energy efficiency promoted many interventions in different fields.

Among the case studies illustrated in this thesis, there will be the requalification of the D pavilion of the Nationally Relevant Hospital Antonio Cardarelli. The hospital recently started a requalification process of its buildings and systems, aimed at improving the occupancy conditions, reducing energy consumption from traditional sources related to the buildings' use and to employees' and users' safety. In more detail, this requalification is included in a structural interventions plan selected by the Hospital for the two-year period 2010-2011. Inside these activities, within a research and technical scientific support agreement, a cooperation agreement was signed between the Hospital and the Department of Industrial Engineering (DII) of the University of Naples Federico II. In more detail the reported project was awarded as example interventions by the public funding plan POIN Energy.

1.3.1 Energy requalification of buildings: results and potentialities

In the last 10 years 58.6% of residences undergo at least one, architectural or systems, extraordinary maintenance or modernization intervention (Table 1.5). This means a number of involved residences equal to 17.6 millions, on a total a little greater than 30 millions of units . There were different elements that confirmed, and solicited, the use of resources in real estate requalification: the old age of the architectural heritage; interventions on just bought residences (the sale volume until 2010 was high); the

10 The VIGOR project (Evaluation of the Geothermal potential of Convergence Regions) has the goal of providing analytical information to start activities to prospect and use the energy from geothermal sources, through the realization of a precise investigation, analysis and study activity aimed at organizing and widen the knowledge of the natural potential and of the possibility of emphasizing the geothermal resource in the territories of Campania, Calabria, Puglia and Sicily regions (Convergence regions).

adjustment to European rules in some fields; the short lifecycle of air-conditioning systems; benefits policies.

	2001		2011	
	thousands	%	thousands	%
Existing residences	27'269	100.0	30'038	100.0
Interventions in the previous 10 years	11'871	43.5	17'613	58.6
– Systems	9'729	35.7	12'524	41.7
– Structures	1'833	6.7	2'756	9.2
– Aesthetics	7'825	28.7	9'214	30.7

Table 1. 3: Stock and requalification activities in residences in 2001 and in 2011.

From the data of the ISTAT 2011 census [30], it results a national stock of buildings greater than 14 millions, a plus 11% compared to 2001. In more detail the number of residential buildings increased by 4.3% during the course of the decade, reaching a number equal to 11'714'262. Residences are instead 28'863'604, an extra 5.8% compared to 2001. If the construction industry is nowadays, after the expansion lasted until 2006, characterized by a general crisis, especially for the new residences and for public works, the recovery and maintenance sectors, on the contrary, show a substantial hold and confirm the constant or slightly increasing trend of the last decades. Indeed, between 2008 and 2012, investments in residences decreased by 21 % in real terms (ANCE[11] evaluations), with a 47.3% reduction for new residential buildings, but with a 9.3% increase for the real expense in renovations.

On the other hand the energy quality of a building largely depend also on its conservation state and construction period. As it can be inferred from the diagram in Figure 1.2, the construction stock is made of a significant number of buildings built before the second world war (30.1%).

Between the postwar period and the nineties the Italian residential heritage hugely increased (70% of the buildings and 78% of residences were built during that period) with an increase of the average number of accommodations for building, which remains relatively low.

Only the last construction industry cycle (after 2001) shows a higher concentration on buildings with greater dimensions (4.5% of buildings and 9.2% of residences were built after 2001) reaching 5.2 accommodations for building.

If the different architectural types as a function of the construction period are taken into account it can be observed that:

- until 1910 there are structures made of bearing walls built with different technologies;

[11]ANCE: National Association Building Contractors

- between 1910 and 1970 bearing walls and reinforced concrete structures with external infill walls coexist, in the majority of cases made of a double platform with hollow bricks;
- after 1970 there is a predominance of reinforced concrete structures; during the last years there was a new interest toward bearing walls structures, even if reinforced concrete continues to numerically prevail.

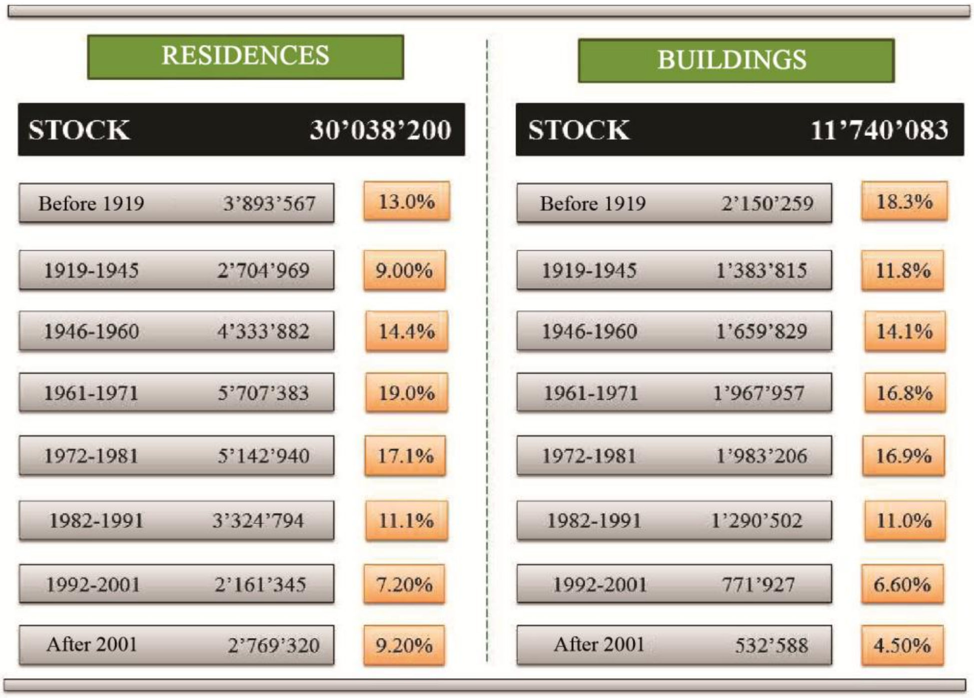

Figure 1. 2: Stock for construction period. *Source CRESME*

However it has to be highlighted that the current energy inefficiency of Italian buildings derives not only from technical solutions that were not characterized by energy saving goals when they were built, but also from buildings' time related decay caused by the absence of maintenance which increased the low efficiency of envelopes and systems in guaranteeing a good indoor air-conditioning.

As reported in Table 1.6, the maintenance state of the architectural heritage shows that more than 22% of buildings is in a mediocre (19.9%) or poor (2.2%) state of conservation; globally there are about 2.6 millions of buildings clearly in need of requalification.

	Excellent		***Good***		***Mediocre***		***Poor***	
	Num.	*%*	*Num.*	*%*	*Num.*	*%*	*Num.*	*%*
Before 1919	316’700	14.7	1’049’615	48.8	680’381	31.6	103’563	4.8
Between 1919 and 1945	193’696	14.0	691’480	50.0	436’613	31.6	62’026	4.5
Between 1946 and 1961	279’450	16.8	913’295	55.0	425’106	25.6	41’978	2.5
Between 1962 and	444’051	22.6	1’142’554	58.1	357’587	18.2	23’765	1.2

1971								
Between 1972 and 1981	619’516	31.2	1’114’754	56.2	237’164	12.0	11’772	0.6
Between 1982 and 1991	450’912	34.9	709’981	55.0	123’812	9.6	5’797	0.4
Between 1992 and 2001	367’438	47.6	346’595	44.9	54’807	7.1	3’087	0.4
After 2001	382’931	71.9	133’147	25.0	15’445	2.9	1’065	0.2
Total	**3’054’694**	**25.9**	**6’101’421**	**52.0**	**2’330’915**	**19.9**	**253’053**	**2.2**

Table 1. 4: Buildings for construction period and maintenance level.
Source CRESME

Indeed the strong relationship between the age of the building and its maintenance state is clear since over 30% of the buildings in poor conditions were built before 1919. In the same way, until the seventies high percentages of buildings in need of requalification can be observed [31].

In such situations, interventions on the architectural envelope are desiderable, but energy requalification frequently involves invasive interventions which are not bearable or compatible with users' presence. Moreover, frequently there is the need of dealing with historical buildings in which the insulation and the replacement of architectural elements is not possible. In these cases a different management of the building-system complex together with a better technology for heat production and its wise management can determine a satisfying thermal comfort level with a lower use of installed power and above all a lower primary energy consumption.

Following the physiological renovation rate of the construction industry, the levels of energy goals fixed by the EU and at a national level will be reached in periods largely exciding the fixed deadlines. Indeed in agreement with the CRESME's data transformations in the EU's architectural heritage follow:

- an annual rate of new buildings' realization equal to 1-1.5%;
- an annual rate of execution of ordinary and extraordinary maintenance interventions equal to 2.0%;
- an annual rate of renovation of the technological system fleet equal to 5.0%;
- an annual demolition rate equal to 0.2-0.5%.

Italy does not differ from this behavior, with a too low dynamics in respect to the "commitments 20-20-20". Therefore it is not enough to concentrate the efforts on new buildings but it is necessary to stimulate and help the energy requalification of existing structures. In a context of dramatic crisis of new buildings, the potential market of residential buildings' energy requalification showed a lively dynamic: + 6.0% in 2008, +2.5% in 2009 and +9.8% in 2010 and +6.2% in 2011. Actually only a part of this activity was translated into interventions aimed at restraining energy consumptions. As it can be inferred from the data developed by CRESME (Table 1.7), the weight of families' expense for energy efficiency interventions, compared to the whole amount of architectural requalification, changed from 25.8% in 2007 to 32.0% in 2011.

	2007	2008	2009	2010	2011
Total requalification (millions of Euros)	40’632	41’134	41’215	43’319	44’716
Interventions EE[1](millions of Euros)	10’480	11’476	11’843	13’264	14’325
Incidence %	25.8%	27.9%	28.7%	30.6%	32.0%

Table 1. 5: Investments in requalification in the construction industry.
Source CRESME
(1 Interventions potentially functional to energy efficiency)

To contextualize these data with relation to interventions strictly aimed at energy efficiency, the reference could be the data published in the ENEA Report on *55% tax credit for energy requalification of the existing architectural heritage in 2011* [32]. This Report summarized the results of the application of the Budget Law 27th December 2006 n. 296 (upgraded and modified by following normative provisions), which funded energy efficiency measures. Specifically, it disposed the possibility to obtain a 55% tax credit (65% for expenses met from 6th June 2013 to 31st December 2014) of the expense incurred for the realization of energy saving interventions on the existing national architectural heritage. In detail clause 1 lists intervention types:

- *Subsection 344:* global energy requalification of the building;
- *Subsection 345*: interventions on horizontal and vertical opaque structures and on windows including fixtures;
- *Subsection 346*: solar panels installation for the production of hot water;
- *Subsection 347*: replacement of winter air-conditioning systems with systems equipped with condensing boilers or, as an alternative, with high efficiency heat pumps or with low enthalpy geothermal systems.

Moreover from 1st January 2012, the deduction was extended to expenses for the replacement of traditional water heating systems with heat pumps dedicated to the production of domestic hot water.

From Figure 1.3 it can be inferred that the greatest increase in the use of the tax credit instrument was registered between 2007 (start year) and 2008 with a +134% and between 2009 (year of the expected conclusion of the provision) and 2010 with an impressive +70% compared to 2009. In more detail the number of files sent to ENEA to access the deductions was 280’700, for total investments greater than 3’300 millions of Euros.

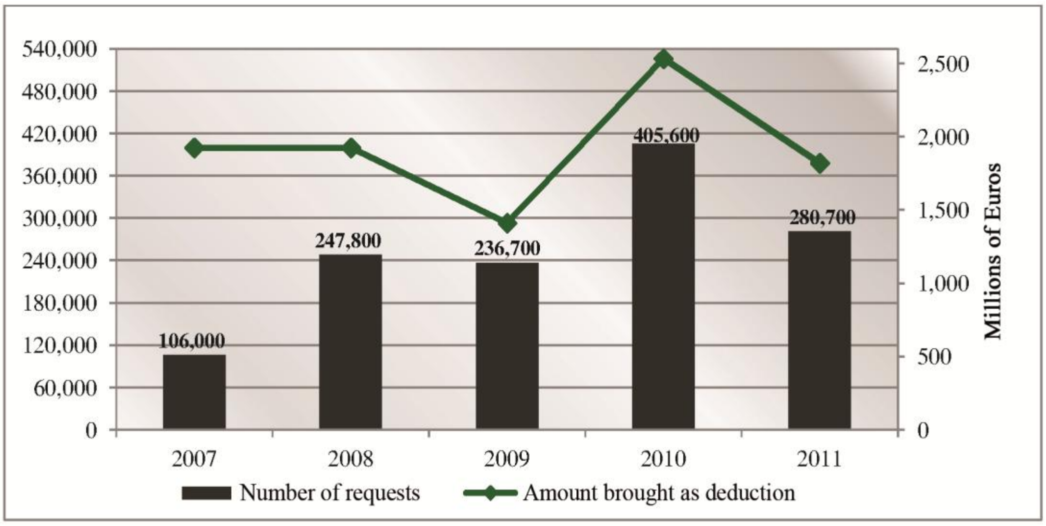

Figure 1. 3: Data related to the documentations received by ENEA for the 55% deduction.

Therefore overall, from 2007, requalification interventions (at least those registered for deductions) allowed a total energy saving almost equal to 8’000 GWh which correspond to an environmental benefit in terms of CO_2 not released in the atmosphere equal to over 1’600 kt. Partial data related to each year are listed in Figure 1.4.

From a quantitative analysis of energy requalification interventions for which a request of tax credit was issued in 2011 [25] it results that the greatest part of files concerns window fixtures replacement (59%). It means more than 165’000 interventions that represent 95% of the files related to subsection 345 in addition to which there are about 9’000 requests (3% of the total) for the insulation of vertical and horizontal opaque structures. About 28% of the total, involve the replacement of winter air-conditioning (80’000 files) and the remaining 11% is for the installation of solar panels for the production of domestic hot water (almost 30’000 files).

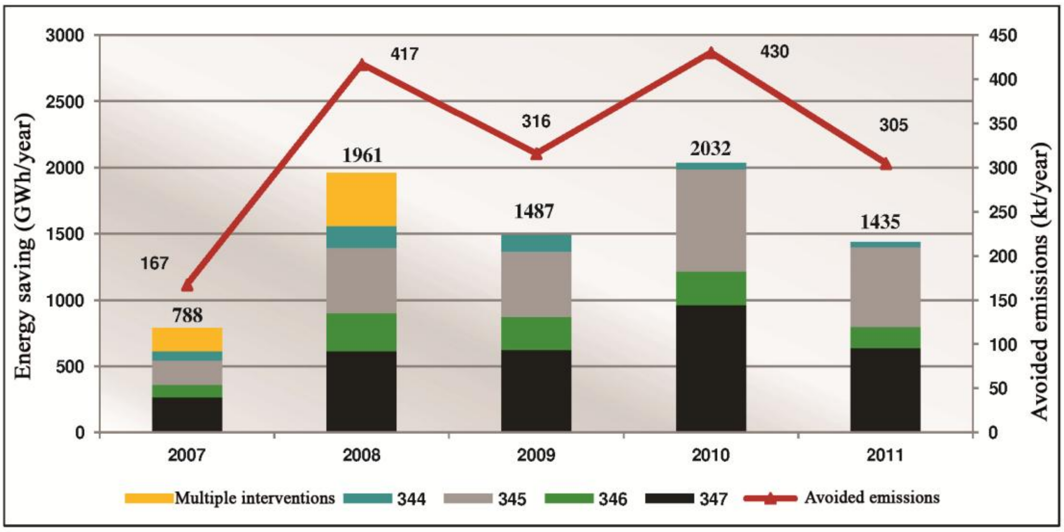

Figure 1. 4: Energy saving and polluting emissions; cumulative results for different years.

However it has to be observed that the diffusion of energy requalification interventions eligible for tax credit is not homogeneous on the national territory. 60% concern only Lombardy, Veneto, Piedmont and Emilia-Romagna. Concerning the effects on each citizen (per capita energy saving, per capita carbon dioxide) the greatest benefits are concentrated in alpine area regions (Valle D’Aosta, Trentino-Alto Adige, Piedmont) whereas minimum values are found in southern regions (Campania, Sicily e Calabria).

In terms of energy saving, available data show that, in a general way, really interesting average values of energy saving are associated to requalification interventions (comprised between 17.5 and 25.0 MWh/year for average intervention). Winter air-conditioning systems' replacement are also rather effective, and among these especially geothermal systems (17.8 MWh/year average) and biomass boilers (16.2 MWh/year average). The lowest energy saving value is instead found for the average installation of thermal solar panels (about 5.3 MWh/year) and for the example interventions of windows' fixtures replacement (average declared savings lower than 3.0 MWh/year).

If these values are compared with what is reported in the CRESME survey it can be noticed that there are still great potentials that can be used. The dimensions of the architectural heritage (tertiary and residential) and its arrangement according to architectural types and age represent important elements in the evaluation of reality and perspectives in the field of energy efficiency.

Even if it is difficult to trace the scenario due to many internal and external variables, concerning the political-economic situation, however it can be hypothesized that the energy requalification field will continue to grow and, starting from 2020, it will involve 80% of the market. These data are of great interest especially in relation with consumptions reduction, because the low rate of buildings' *turn-over* (lifecycle that goes from 50 to more than 100 years). It is clear that in the short and medium term, if it is possible, energy performances of existing buildings have to improve using a different approach compared to the one used for new buildings, which represent a small percentage of the Italian architectural heritage.

Chapter 2. Calculation methodology to define cost optimal levels for buildings' national energy performance

2.1 From the prescriptive limit to the "cost optimal" analysis

The delegated regulation n. 244/2012 of the European Commission [12], of 16th January 2012, supplemented the Directive 2010/31/EU of the European Council and Parliament on energy performance in the construction industry [2]. It establishes, in agreement with clause 5, a methodological comparative framework for the calculation of the optimal levels, as a function of costs, for the minimum energy performance requirements of new and existing buildings and of architectural elements.

The methodological framework specifies the rules with which compare the energy efficiency measures, including those regarding the use of renewable sources and the combination or the variations of the individual simpler adopted measures, on the basis of their primary energy performance and of the cost assigned to their fulfillment.

In more detail, the procedures to calculate the optimal levels as a function of costs are defined both on the basis of the macroeconomics point of view (which takes into account the energy efficiency investments' costs and benefits for the whole society) and of the financial one (which only considers the investment itself). Thus leaving to each State the task of determining which calculation should become the national reference for the evaluation of the minimum national requirements for energy performance. However such requirements should not be lower than 15% compared with the results of the calculations of costs optimality chosen as national reference. The optimal level as a function of costs is therefore placed inside the range of performance levels for which the costs-benefits analysis on the lifecycle is positive. In more detail, the methodology, defined by the *Cost Optimal*, is organized in six phases, described below:

I. definition of reference buildings;
II. identification of energy efficiency measures;
III. calculation of the primary energy demand;
IV. calculation of the global cost in terms of net present value;
V. sensitivity analysis for calculations that include energy prices;
VI. derivation of the optimal performances' level as a function of costs.

2.2 The Reference Building

The definition of representative reference buildings (RBs) by all Member States (MSs) is a fundamental step of the methodology to calculate cost-optimal levels of minimum energy performance requirements for buildings and buildings' elements established by the Energy Performance of Buildings Directive (EPBD) recast [2].

This section defines the concept of ‘‘reference buildings’’ and the methodologies used to characterize it.

The evaluation of the economic potential of renewable energy [33], the cost-benefit of solar heat exchangers [34], the optimal allocation [35] and uncertainty model analysis [36], which take into account specific cases of building stocks, were the basis of other methodologies that have been used to select energy efficiency measures [37]. Moreover choosing and assessing different RBs determines multiple curves in the results of the cost-optimal methodology. This may lead to different recommendations for energy-efficient measures, according to the reference building (RB) type chosen in a given situation [38-40].

There is no standard definition of ‘‘reference building’’ shared by the different MSs. According to the revised EPBD (annex III) [2], RBs are defined as ‘‘buildings that are characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions’’. In addition, for the accompanying guidelines of the EPBD [12], ‘‘the main purpose of a RB is to represent the typical and average building stock in a certain MS’’.

Basically each state has to define its reference buildings, one for new buildings and at least two for existing ones which undergo a complete renovation, for the following categories:

- single-family residences;
- apartment and multifamily buildings;
- office buildings.

The selected buildings can also be classified and differentiated according to their dimensions, age, costs' structure, architectural materials, use models or climate zone, in order to build a reliable framework of the considered construction context. Other categories, for which specific energy performance requirements exist, can be added to the abovementioned ones such as: educational buildings; hospitals; hotels and restaurants; sport facilities; commercial enterprises dealing with retail and wholesale; other types of buildings that use energy.

Moreover, for existing buildings (residential or non-residential), the analysis has to be performed taking into account the application of at least one measure/package/variation representative of a standard renovation, namely necessary to make the building fulfill the energy efficiency limits prescribed by national regulations. On the other hand, for new buildings (residential or non-residential), the minimum energy performance requirements nowadays in effect are the basic requirement that has to be satisfied.

Even if exemplifying sheets for the definition of a Reference Building can be found as an attachment of the Decree, the collected information are not exhaustive for use classifications different from the residential one. Moreover the lack of an unambiguous internationally shared methodology determines many problems and uncertainties especially related to the retrieval and accuracy of the information (both architectural and system related) necessary to define the building's type. The most common approach is based on the use of data obtained from statistical processing or sector studies, and when those are not available the information used have an heterogeneous origin and are generally based on the experience of the person whom is carrying out the analysis.

It is also important to highlight another aspect, which is the dependence of the level of detail of the information that describes the building on the type of analysis that has to be carried out. In other words based on a nearly stationary calculation method, the information necessary to perform the analysis are considerably less compared to those that would be required for the analysis of the building's behavior in real conditions. Concerning this, the Directive 2010/31/EU [2] suggests the analysis of the energy performance through dynamic methods to achieve a greater results' accuracy. However a dynamic thermo-energetic simulation of a building's behavior requires a high number of information compared to simplified methods such as the nearly stationary one. This means that also the definition of the reference building would require an accurate energy diagnosis of the architectural heritage in order to collect detailed information on the characteristics of the building-system interaction and on the real operating conditions as a function of the use classification of the building itself.

This aspect highlights the need to dispose of computer systems to acquire and collect data both at a single building scale and on a macro-scale, in order to develop shared and easily manageable platforms through which collect the necessary information and that would be the starting point for the elaboration of accurate data on the existing architectural heritage. This thesis will also deal with this aspect through a case study.

Generally, referring to the USA's *Benchmark Models* [41], the essential data for the models' definition, can be organized into four main sub-set of information:

- Function: use classifications of the different parts of the building, occupancy and use schedules, location description and determination of the internal thermal loads;
- Shape: type-shape related and geometrical characteristics of the building;
- Architectural Envelope: thermo-physics properties of the envelope's elements;
- System: size and type of air-conditioning system.

As reported by Corgnati et al. [42,43], different models of reference buildings can be defined as a function of the origin and type of collected data:

- *Example Building*: building model defined basing on experience;
- *Real Building*: existing building, selected as representative of a specific building type as a function of the construction period and dimension.
- *Theoretical Building*: simulated building, defined through statistical data.

The Example Building is not a real building but it is a fictitious one, defined by experts through the use of design handbooks and regulatory documents. On the contrary, the *Real Building* and the *Theoretical Building* are defined basing on elaborations of statistical analysis of the architectural heritage. Generally these are not able to include the whole architectural heritage but only a part of this "architectural sample". The latter, analyzed through specific research projects, national census and energy performance certifications, is therefore synthetically described. Data derived from these analysis are processed and used for the definition of buildings' models in two ways: aggregated or disaggregated. Hence, in the former case a real building is selected from the sample which should be the most representative, since it possesses characteristics equal to the average ones of the buildings' sample, as inferred from statistical analysis. On the other hand if data are “aggregated again” to define a building model, which does not correspond to a real building as for the previous case, but rather to a fictitious one, it takes the name of *Theoretical Building*. Although the use of the three methodological approaches allows to pursue the same result, each of the models is different from the others exactly as a function of the type of input data used.

2.2.1 European Framework: TABULA and ASIEPI

At European level, while studying the viability of the definition of Nearly Zero Energy Building (nZEB), the Building Performance Institute Europe [44] proposed two reference buildings that were simulated in three climate locations (Madrid, Copenhagen and Stuttgart). These are included in the category of Example Buildings for new buildings since they are not real ones but the result of a series of assumptions made by experts. The parameters that define the thermal performance of architectural elements and the efficiency of a building's technical systems were selected in order to be significantly better than the minimum limits prescribed by the regulations of each state, and at the same time to remain above the best available technology and to be relatively close to economic feasibility. In other words, the aim was to place the energy performance of reference buildings in the range between the optimal level required by the Directive 2010/31/EU [2] and that of the best technology available.

In more detail the first one, a single-family building (Figure 2.1), is an independent bungalow with a net area of 129 m^2. This type of building was selected because it was deemed as belonging to the most critical ones, in the achievement of the principles of a nZEB design for its high shape ratio (S/V) and therefore for its high heat-wasting surface.

The second one is a four floor building, with a gross area of 1653 m^2 which can be assimilated both to a tertiary building (hotels, schools, hospitals, offices) and to a multifamily residential building. On each floor, there are two Open Offices and a central meeting room, for a total of 96 workspaces (24 for each floor).

It is important to observe that the definition of a reference building for the tertiary is rather complicated, because there is a great variety of architectural types inside the non-residential sector, both in Italy and in Europe, from offices to healthcare, from educational buildings to industrial or commercial ones. Also taking into account the amount of data necessary for the different use classifications, the definition of a Reference Building therefore turns out to be a remarkable challenge.

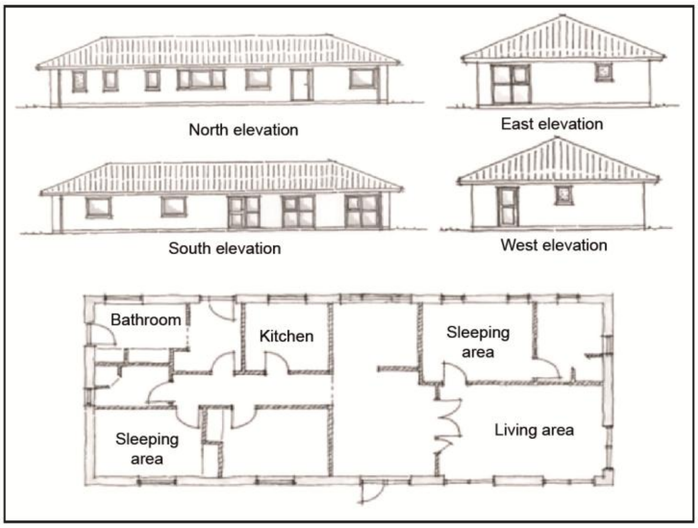

Figure 2. 1: Plan and side elevations of the reference residential building.

There are other noteworthy studies at European level, such as the two projects TABULA and ASIEPI, realized within the program *Intelligent Energy Europe* (IEE), with the goal of developing an harmonized structure for architectural types in Europe. In more detail, the project TABULA – *Typology approach for building stock energy assessment* – which saw the participation of 13 countries including Italy, was aimed at developing an harmonized structure for residential reference buildings. The proposed classification of the residential architectural heritage is based on the definition of national "buildings' models", as a function of the construction period, geometry and of climate conditions. Dimensions, shape factors, thermo-physical properties, heating systems' efficiency and other energy indicators characterize each architectural typology. A fundamental goal of the project was to evaluate the energy consumption of the national architectural heritage and, consequently, to predict the potential impact of energy efficiency measures, in order to select the effective strategies for the requalification of existing buildings.

Of particular interest are the national files on architectural typology [45]. The *Reference Buildings* developed by the Italian section of the TABULA project are mainly Real Buildings from the point of view of geometrical characteristics and Example and Theoretical Buildings as regards the construction period and the considered architectural typology (see figure 2.2). The defined buildings (one new and two existing ones belonging to different periods), were placed in two climate zones (B and E, according to the D.P.R. 412/93[16]), for four architectural typologies (single-family residence, small and big apartment buildings, office building), for a total of 24 reference buildings.

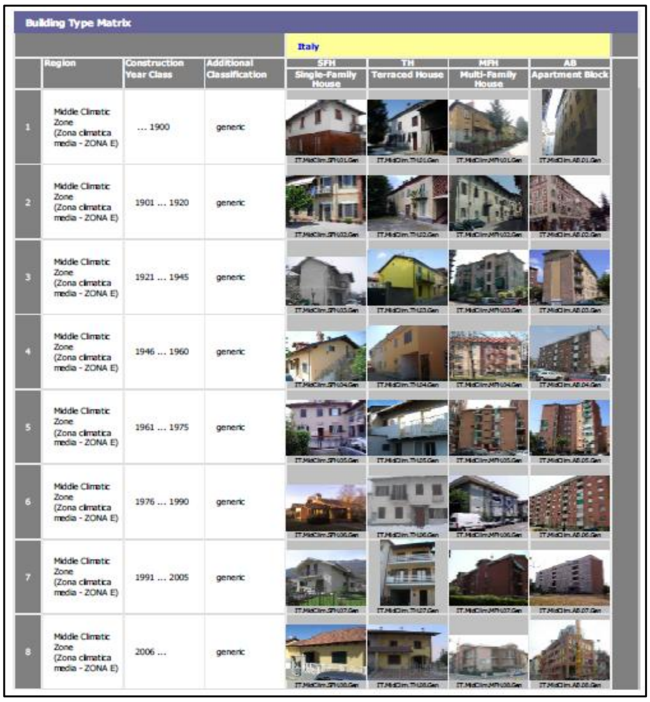

Figure 2. 2: Architectural typology's matrix of the E climate zone (TABULA project).

The ASIEPI (Assessment and Improvement of the EPBD Impact) project has instead developed within a pilot study, a series of 12 reference buildings for single-family residences which fall into the category of Example Buildings since they are defined basing on experience [46]. The aim of the project was to develop and test a tool for the comparison between Member states related to the application of the minimum energy requirements introduced with the Directive EPBD 2002/91/EC [1].

2.2.2 USA Framework: DOE

At the present time there are many international studies and research projects for the development of shared definition of reference buildings. The first and most complete study in this field is the one carried out by the U.S. Department of Energy (DOE) within the *Building Technologies* program. The goal of this project was to develop energy reference models for the most common standard or tertiary buildings which would serve as reference points for the analysis related to energy efficiency in the construction industry. The defined models show realistic architectural characteristics and are representative of the American construction practice. In more detail 15 types of commercial buildings were developed (in Figure 2.3 the geometry of a hospital model is reported) and a multifamily residential building whose energy behavior was simulated with a dynamic analysis in 16 locations which represent all the USA climate zones.

Reference building models were developed to characterize the energy performance of building types under typical operating conditions. Standard data sources do not provide the required information for the development of detailed building energy models; therefore, in order to represent a “typical” performance, information obtained from several sources were combined in a sensible way. To better organize the efforts, according to DOE Reference Building, the model inputs were grouped into program, form, fabric, and equipment (see Table 2.1).

PROGRAM	FORM	FABRIC	EQUIPMENT
Location	Number of floors	Exterior walls	Lighting
Total floor area	Aspect ratio	Roof	HVAC system
Plug and Process loads	Window fraction	Floors	Refrigeration
Ventilation requirements	Window locations	Windows	Efficiency
Occupancy	Shading	Interior partitions	Control settings
Space environmental conditions	Floor height	Internal mass	
Space DHW	Orientation	Infiltration	
Operating schedules			

Table 2. 1: Building energy model input categories.

For each building type, there are three versions of the reference model: new construction, building erected after 1980 or before 1980. All versions have the same shape, same thermal zones, occupancy and operating schedules, instead insulating values, lighting levels and type and efficiency of air-conditioning systems vary. New construction models are in compliance with the minimum requirements of the ANSI/ASHRAE/IESNA 90.1/2004 standard [47], after 1980 models satisfy the minimum requirements of the 90.1/1989 standard [48], whereas before 1980 models were developed through sector studies.

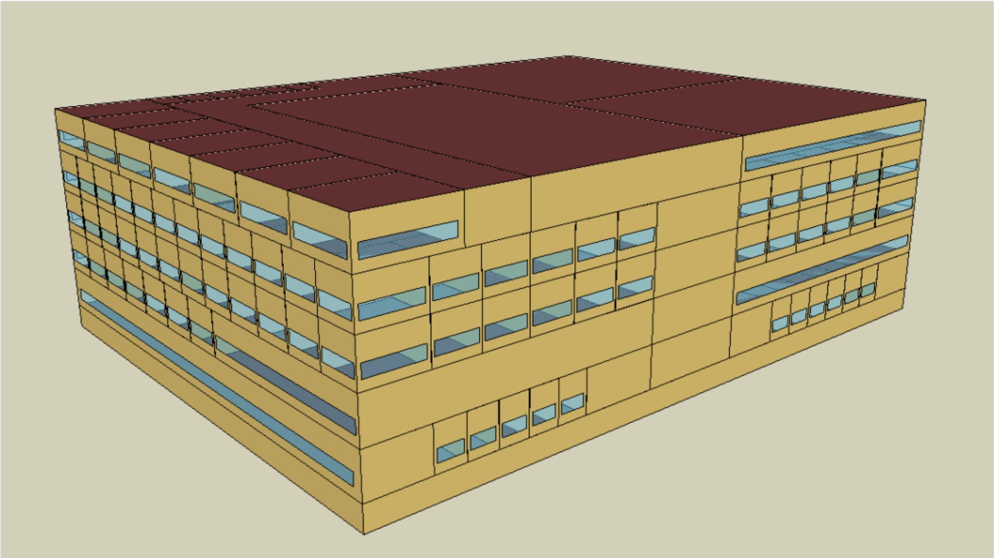

Figure 2. 3: Building model for an hospital.

The different models are described in the report [41] and are available on the page http://commercialbuildings.energy.gov/reference_buildings.html, as input files for EnergyPlus.

2.3 Definition of the energy efficiency measures

Energy efficiency measures for new and existing buildings have to include all the parameters that have a direct or indirect impact on the building's energy performance, and can be consolidated into packages of measures or variations which have to include, among other things, the energy production from renewable sources. Regarding this, the binding obligations established in the national application of the clause 13 of the Directive 2009/28/EC [13] are considered as a single measure/package/variation.

The selected measure have to include the necessary actions to satisfy the current minimum energy performance requirements as well as the eventual national support systems and have also to include solutions capable of fulfilling the minimum energy performance requirements for nearly zero energy buildings in the case of new constructions and eventually also for the retrofit of existing buildings. Such measures have also to be compatible with the levels of air quality and indoor environment's comfort, complying with the current European or equivalent national regulations on indoor air quality.

2.4 Calculation of the primary energy demand

The energy performance of a building is determined basing on the quantity of energy, real or calculated, yearly consumed to satisfy the different needs related to a normal use of the building and it corresponds to the energy demand for heating and cooling which allows to keep the desired temperature inside the building and satisfy the domestic hot water demand. This calculation can be performed on the basis of the general common framework reported in the attachment I of the Directive 2010/31/EU[2] or in the pertinent existing CEN regulations for the energy performance calculation or with an equivalent national calculation method, provided that it is compliant with the clause 2, paragraph 4, and with the attachment I of the Directive 2010/31/EU [2].

For the calculation of costs' optimality, the results of the energy performance are related to the square meters of useful floor area and they refer to the primary energy demand determined through nationally defined energy conversion factors.

2.5 Calculation of the global cost in terms of *net present value*

The analysis of costs starts from the calculation of the global cost of the building or of the architectural elements. It is represented by the sum of the present value of the costs of the initial investment, of the management and replacement (referred to the starting year) costs, as well as of the disposal costs, if that is the case. For the macroeconomics calculation, in these sums, an additional category of cost is introduced which is related to the cost of greenhouse gases emission e.g. the monetary value of the environmental damage caused by CO_2 emissions connected to buildings' energy consumption. The normative reference for the methodology is represented by the regulation EN 15459 of the year 2008: *Energy performance of buildings - Economic evaluation procedure for energy systems in building* [49].

To ensure a common approach in the application of the comparative methodological framework, in the regulation the main necessary conditions are established to carry out the calculation of the net present value, such as starting year and the calculation period to use.

In more detail, the starting year is the one on which all calculations are based and starting from it the calculation period is determined; instead the calculation period is assumed equal to 30 years for public and residential buildings and to 20 years for non residential commercial buildings. Setting a common calculation period is not in conflict with the right of each state to fix its own duration of the economic lifecycle of buildings and/or architectural elements, since it can be effectively longer or shorter than the fixed one.

Assumed this, the global costs for buildings and architectural elements are calculated by summing up the different types of costs and by applying to them a discount factor, in order to express them in terms of their value at the starting year, with the addition of the discounted residual value, as illustrated below:

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i)) - V_{f,\tau}(j) \right] \quad \text{eq.(2.1)}$$

Where:

- $C_g(\tau)$: global cost (referred to the starting year) during the calculated period;
- τ: calculation period
- C_I: initial cost of the investment for the measure or set of measures j;
- $C_{a,i}(j)$: annual cost during the year i for the measure or set of measures j;
- $V_{f,\tau}(j)$: residual value of the measure or set of measures j at the end of the calculation period (discounted at the starting year);
- $R_d(i)$: discount factor for the year i on the basis of the discount rate “r” to be calculated;

In more detail, the sum of the costs for the design, the purchase of the architectural elements, the connection of supply services, the installation and for the procedures to put them to use are assumed as the cost of the initial investment. Instead the annual costs $C_{a,i}$ can be calculated as the sum:

$$\mathrm{C_{a,i} = C_{e,i} + C_{m,i} + C_{f,i} + C_{so,i}}$$
eq (2.2)

In which:

- $\mathrm{C_{e,i}}$ are the overall energy operating costs, including the energy price, capacity and network fees;
- $\mathrm{C_{m,i}}$ are the costs of the ordinary and extraordinary maintenance and they include the annual costs of inspection, cleaning, setting, repairing and consumer products;
- $\mathrm{C_{f,i}}$ represent all the costs connected to a building's working, among which the annual expenses for insurance policies, public services supply, other permanent burdens and taxation;

- $C_{so,i}$ are the costs for the replacement of envelope's or systems' elements, taken into account starting from the comparison between the timeline of the analysis and the elements' lifecycle.

In the end if it is deemed to consider them, the costs for disposal $C_{sm,i}$ should be added to the annual costs. These include the costs related to the dismantling due to the end of a building's or architectural element's lifecycle, and therefore they are the sum of the costs for the dismantling, the removal of architectural elements which have not yet ended their lifecycle, the transport and recycle.

Data for these types of costs are based on the national market's situation and they have to be expressed as real costs excluding inflation. In other words, the prices that should be taken into account are those to be paid by the client, including all taxes, VAT and other expenses. Ideally, available benefits should also be included in the calculation, but they can be excluded, provided that technologies support systems are also excluded, as well as the eventual existing supports for energy prices.

To discount at the starting year the different costs it is necessary to multiply them by the discount rate R_d or by the discount factor f_{pv}. Specifically, the former is used in case of recurring costs, such as the ones for replacement or as the final value of an architectural or system element, whereas the latter is used in case of yearly repeating costs, such as those related to energy consumption. In more detail they have to be calculated in agreement with the following equations:

- Discount rate: $R_d(p) = \left(\frac{1}{1+R_r}\right)^p$ eq (2.3)
- Real interest rate: $R_r = \frac{R-R_i}{1+R_i}$ eq (2.4)
- Discount factor: $f_{pv}(p) = \frac{(1+R_r)-1}{R_r(1+R_r)^p}$ eq (2.5)

where “p” represents the number of years starting from the initial period, R_r the real interest rate, R_i is the inflation rate, and R is the market interest rate.

The discount rate is a defined value to compare money value at two different times, expressed in real terms. The discount factor is derived from it, a multiplicative coefficient used to convert a financial flow at a given moment into its equivalent value at the starting date. The discount rate that has to be used in the financial calculation is determined after a sensitivity analysis on at least two different rates.

When projecting the evolution of the energy price, the forecasts of the evolution of energy prices for oil, gas, carbon and electricity published by the European Commission can be used. They are updated every two years on the following website:

http://ec.europa.eu/energy/observatory/trends_2030/index_en.htm, basing on the absolute energy prices (expressed in Euros) for those energy sources in the year of the calculation exercise. Similar evaluations can autonomously be made for the forecast of the price evolution of other energy carriers used in a significant way in the regional/local context and, if that is the case, also for the fees applied during peak periods. Moreover it has to be taken into account the effect of the (expected) price evolution on non-energy related costs as a function of the attainable innovation and technological update.

In costs' evaluation, the European regulation suggests to refer to the EN 15459 standard on economic data for architectural elements to define the economic lifecycle estimated for the abovementioned components [49].

In conclusion, the residual value of a building is the sum of its residual value and that of its architectural elements at the end of the calculation period. This is determined by a linear amortization of the initial investment or of the cost of the replacement of a given architectural element until the end of the calculation period, discounted at the start of the calculation period. The amortization's length depends on the economic lifecycle of a building or architectural element. It may be necessary to revise the residual values of architectural elements to take into account the cost of their removal from a building at the end of the estimated economic lifecycle of the building itself.

In the macroeconomics scenario a new category of costs for greenhouse gases emissions should be included, thus obtaining the following fitted methodology of the global cost:

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i) + C_{c,i}(j)) - V_{f,\tau}(j) \right] \quad \text{eq (2.6)}$$

where $C_{c\ i}(j)$ represents the cost of carbon emissions for the measure or set of measures j during the year i. The cost of carbon emissions during the calculation period can be obtained multiplying the sum of yearly greenhouse gases emissions by the expected prices for CO_2 tons equivalent to the emission shares during each year in which they are emitted. An initial minimum threshold of 20 EUR for CO_2 equivalent ton until 2025, 35 EUR until 2030 and of 50 EUR after 2030 is considered, which is consistent with the current forecasts of the Commission on carbon prices of the ETS[12]system (measured at real and constant prices expressed in Euros in 2008, they have to be adjusted to the calculation date and to the chosen methodology).

[12] The UE Trading system of emission shares (European Union Emissions Trading Scheme - EU ETS) is the main action of the European Union for the implementation of the Kyoto Protocol to reduce greenhouse gases emission in the industrial sectors which have the greatest impact on climate change. The System was established by the Directive 2003/87/CE and further modifications (ETS Directive).

Figure 2.4 reports an outline of the main points for the calculation of the global cost, illustrating the different necessary sources.

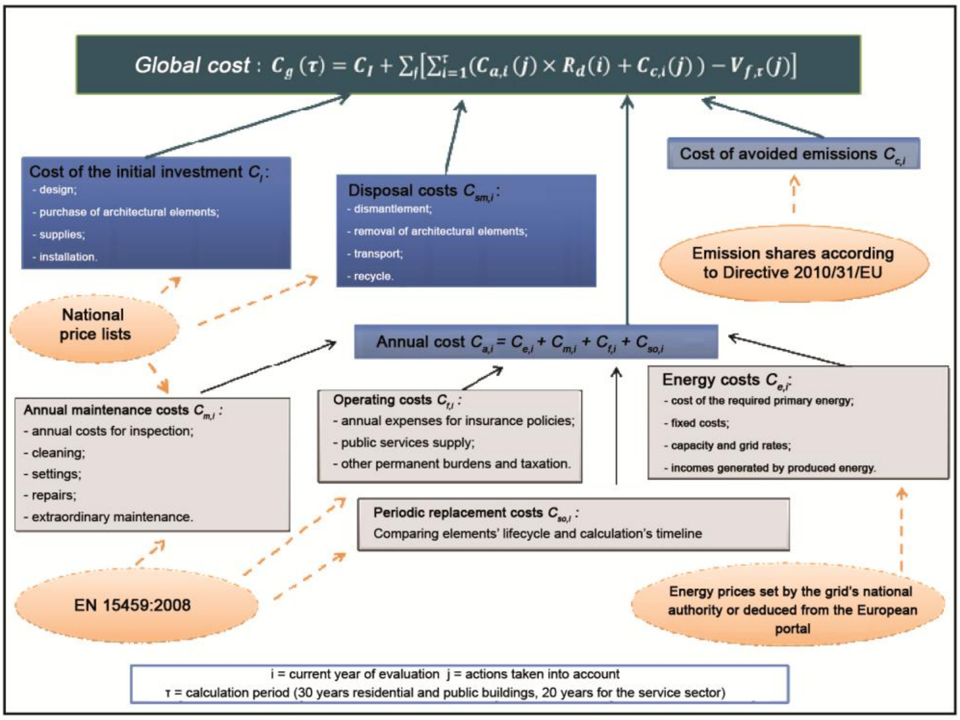

Figure 2. 4: Outline of the main points for the calculation of the global cost.

2.6 Sensitivity analysis for cost data

The calculation and the forecasts of costs that involve several hypothesis and uncertainties, among which for example the evolution of energy prices during time, should be accompanied by a sensitivity analysis to evaluate the firmness of the main parameters used.

In the assessment of results' sensitivity the use of different price scenarios (e.g. high, medium, low)it is recommended. Examples of the global costs and primary energy use of two different packages of measures are illustrated in the following graphs (see Figures 2.5, 2.6, 2.7), considering different energy prices for the same use (new single-family house).

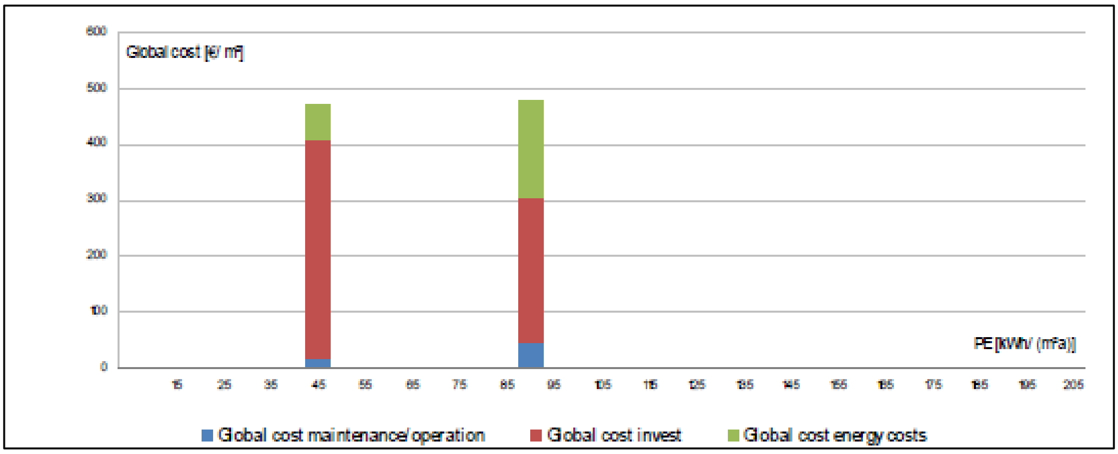

Figure 2. 5: Comparison of two different packages - average energy price equal to 12 cent\kWh gas.

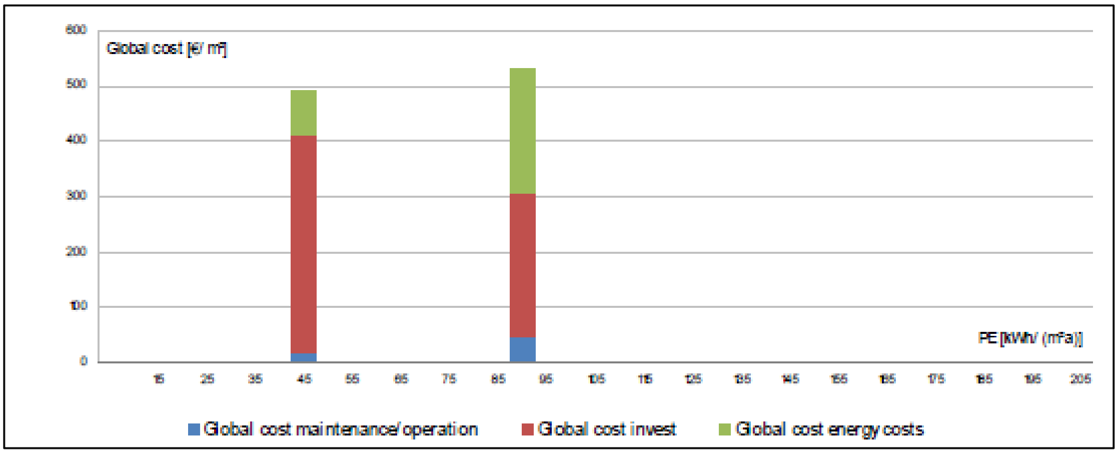

Figure 2. 6: Comparison of two different packages - sensitivity analysis high price (+30%)

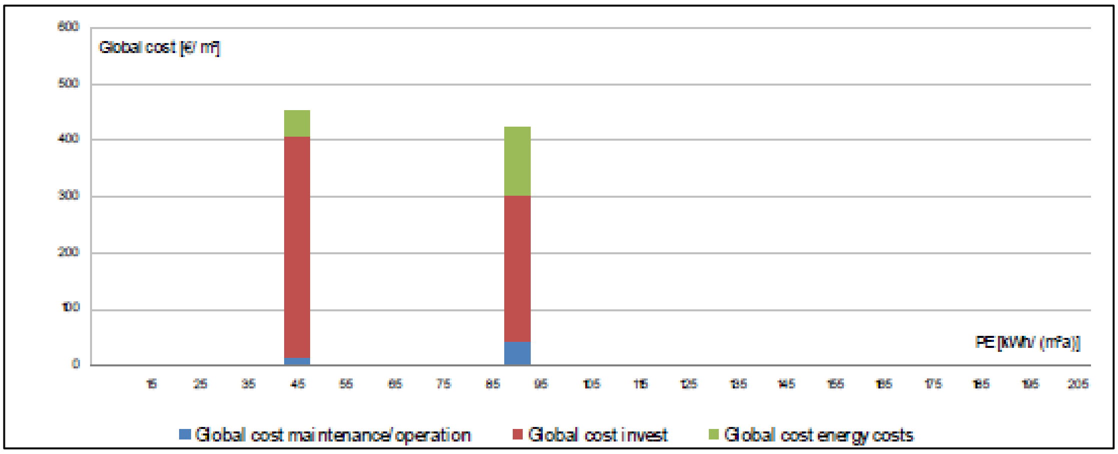

Figure 2. 7: Comparison of two different packages - sensitivity analysis low price (-30%)

It can be observed from the 3 graphs reported before that the energy price is capable of significantly affecting the relative costs of a package and therefore the optimum of a curve (source: European council for an a energy efficient economy).

As regards discount rates, the sensitivity analysis has to be carried out using at least two discount rates both expressed in real terms for the macroeconomics calculation and two for the financial calculation.

According to the EN 15459 [49], the interest rate is derived from market interest rates adjusted for inflation (interest rates offered minus inflation rate). Interest rates are subject to changing market conditions (see Figure 2.8), but they also differ according to whether viewed from a private or society perspective.

Figure 2. 8: Development of interest rates financing (building sector, 10 years fixed interest, source interhyp)

One of the discount rates that has to be used in the sensitivity analysis of the macroeconomics calculation should be equal to 3% expressed in real terms.

2.7 Derivation of an optimal level of performance as a function of costs

The last part of the analysis concerns the comparison between the results of the global cost calculated for the different hypothesized measures of energy efficiency and for their combinations. If the outcome of the calculations of costs optimality determines the same global costs for different levels of energy performance, the requirements that result in the lowest primary energy consumption should be used as a comparative basis with the existing minimum requirements for energy performance.

The determination of the range of minimum values between the interventions applied to a building is not an easily resolved operation, since it is not always possible to select a minimum among the interventions. Indeed Some of them may appear optimal for the improvement of energy performance but they may require really high investment costs and therefore they may not represent an optimal value, such as intervention 1 in Figure 2.9.

Some interventions may require a high global cost and have high consumptions in terms of primary energy, therefore placing themselves on the upper right corner (interventions 5 and 6) in Figure 2.9.

The range of optimal energy performance level therefore corresponds to the combination of energy efficiency measures (interventions 2, 3 and 4) with the lowest global cost.

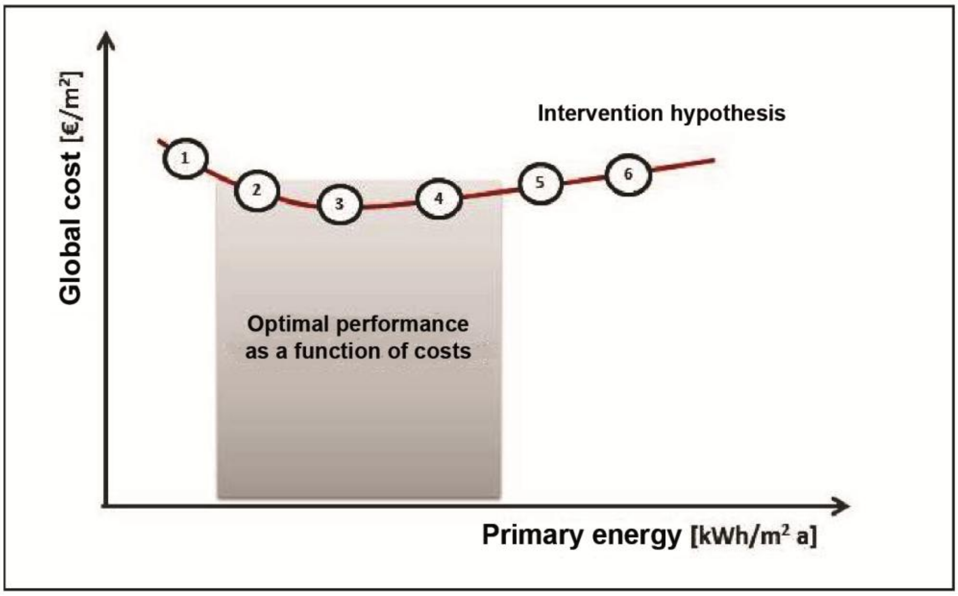

Figure 2. 9: Example of the determination of the optimal performance as a function of costs.

Once it has been decided which calculation — macroeconomics or financial — should be selected as the national reference, the calculation of the averages of the optimal energy performance levels as a function of costs for all the used reference buildings, taken as a whole, is performed. This calculation allows to compare them with the averages of the existing energy requirements for the same reference buildings, in order to allow the calculation of the gap between the existing energy requirements and the optimal levels calculated as a function of costs.

Further observations can be made comparing the ambitious goals (for 2020) set by the nZEB standard with the optimal performance levels for the Cost- Optimal methodology. There are three main differences that can be observed in Figure 2.10:

- ✓ financial gap: difference between the real cost of the optimal solutions and the solutions complying with the nZEB definition;
- ✓ energy performance gap: difference between the primary energy demand at optimal levels and the solutions complying with the nZEB definition;

- ✓ environmental gap: difference between the polluting emissions related to the need of primary energy at optimal levels and the solutions complying with the nZEB definition, the latter aims at emission levels <3 kg [CO_2/m^2/year].

The gap between the attainable levels and the goals that will be imposed starting from 2020 should be conveniently evaluated to guarantee the consistency between European and national policies in the field of energy efficiency. The energy and environmental gap to bridge will tend to cancel themselves when the requirements for "zero energy" buildings will become binding for all new buildings.

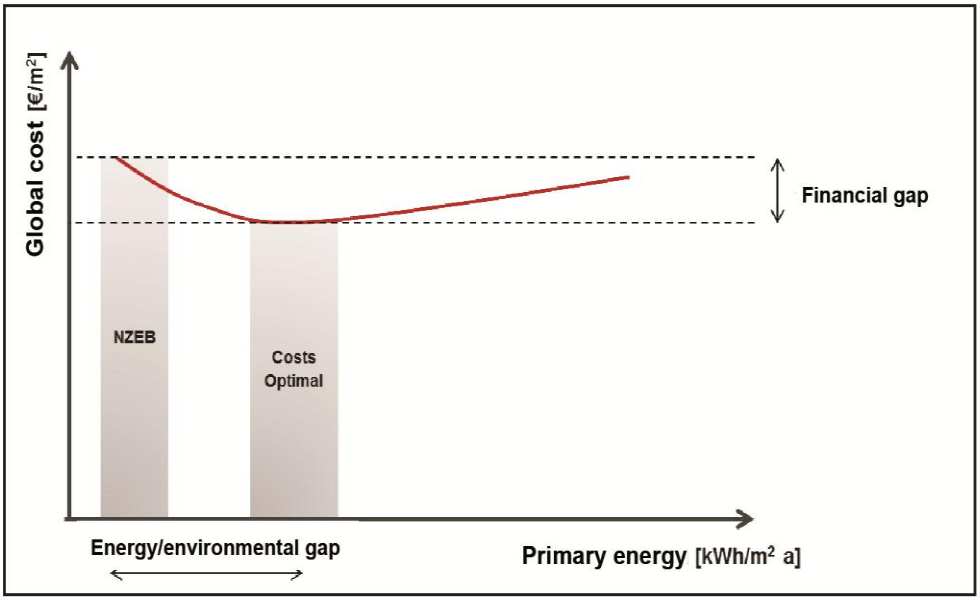

Figure 2. 10: Link between the Cost Optimal and energy target in 2020 (nZEB)

As regards the financial gap, it may be different due to several factors that can be subject to changes such as technology prices (as a reaction to more mature markets and to a greater diffusion of innovative technologies for efficiency), or the variation of the energy price.

2.8 *Summary of the application of the "Cost Optimal" methodology*

The following chart summarizes all the required steps for the implementation of the methodology with specific reference to the Italian context (Figure 2.11).

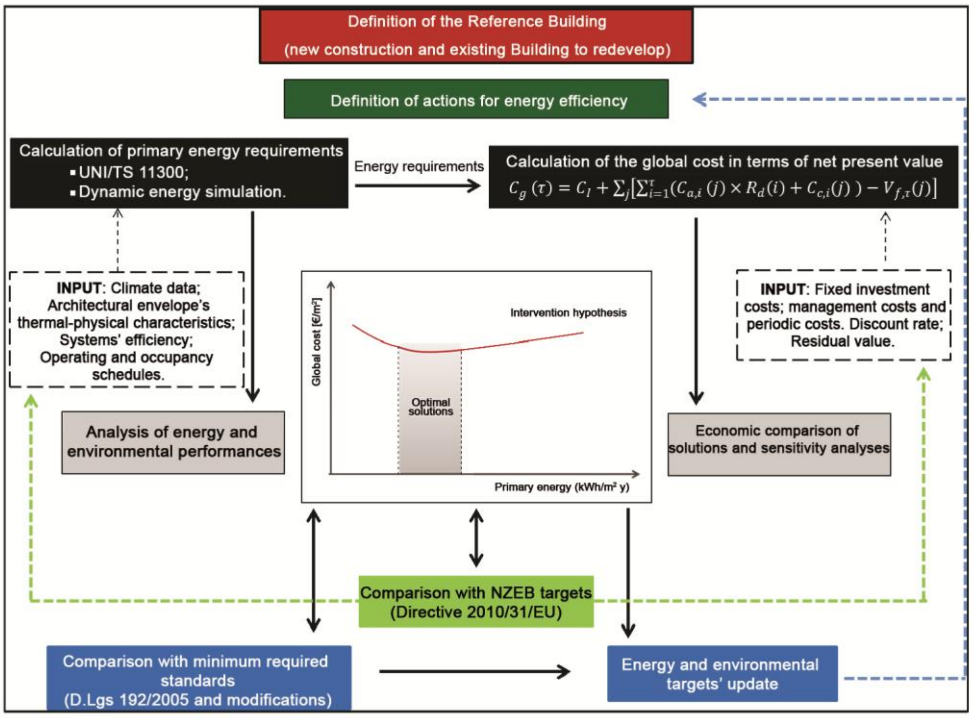

Figure 2. 11: Flowchart of the methodology, with specific reference to the Italian context.

It has to be highlighted that at international level several studies were carried out on the calculation of optimal levels of energy performance as a function of costs based on the calculation procedure recommended by the Directive.

The most influential scientific reference in this field is the BPIE (*Buildings Performance Institute Europe*) document, titled "*Implementing the cost optimal methodology in EU countries. Lessons learned from three case studies*" [50]. In this document, to highlight the consequences of the choice of different values for the key factors (for example, discount rates, types of intervention/set of interventions, costs, energy prices) which concur to the national actualization of the Cost Optimal methodology, the results for three case studies located in Austria, Germany and Poland are reported. For each location, the evaluation was performed only for one or two types of new residential buildings, more precisely for single-family and/or multifamily residences.

In "*Cost Optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation*" [51] instead, the determination of the optimal levels of energy performance are illustrated as a function of costs for nearly zero energy buildings. Through the application of the calculation procedure reported by the Directive, the study, organized in seven phases, defines different intervention hypothesis, especially at systems' level, on a single-family building, selected as reference building for new constructions in Estonia.

Similarly, in [52], a case study was developed for a Reference Building selected within the TABULA project, and located in the urban area of Turin. For this Reference Building, an apartment building built during the period 1946-1960, different hypothesis for energy efficiency were analyzed, both at the level of the architectural envelope and at systems' one, and the global cost corresponding to each hypothesis was calculated and in this way the optimal levels of energy performance as a function of costs were identified. Using the same approach, instead, Fabbri et al. reported the results of the retrofit of a two-family house located in Ravenna [53].

Moreover the author participated in the development of a new methodology for the cost-optimal analysis based on the multi-objective optimization of energy demand for microclimatic control and indoor thermal comfort [54].

Using the proposed method, it is possible to identify the cost optimal package of energy efficiency measures (EEMs) to be applied to new or existing buildings.

Chapter 3. A new Methodology to define a Reference Hospital Building

3.1 Introduction

The Energy Performance of Buildings Directive (EPBD) recast [2] established that all Member States have to define representative reference buildings, this is a fundamental step to develop a methodology to calculate cost-optimal levels related to minimum energy performance requirements for buildings and buildings' elements.

This section provides the definitions of RB and of the methodologies used to characterize it; moreover it also proposes a methodology to define reference buildings in the national hospital building stock.

The useful parameters to define a RB, as previously reported in the paragraph 2.2, can be classified in four macro-categories (function, shape, envelope, system). For each of them it is possible to characterize the parameters through different approaches based on the knowledge of the existing building stock (real building), on the experience of qualified experts (example building) or on statistical analyses (theoretical building).

In this chapter, once fixed the location (Naples, 1034 DD), an original methodology to characterize a hospital reference building (RBh) is explained; in more detail two versions of the reference building will be characterized, the first one representative of hospitals built between 1991 and 2005 and the second representative of new buildings.

It is worth to highlight that the aim is to define a RBh representative of a hospital's pavilion or a hospital centre where there are all the main typical use classifications: operating theatre, emergency room, diagnostics, generic ward, etc.

The developed RBh establish the use of a theoretical approach to characterize the geometry, the subdivision into thermal zones and the transparent and opaque architectural envelope. In more detail the geometry and shape were deduced, on a statistical basis, from the analysis of plans and elevations of hospital buildings managed by the *Azienda Sanitaria Locale* of Naples (ASLNAP1).

In order to characterize the percentage distribution of the different use classifications on the useful floor area and the type of heating and cooling system which supplies them the file related to the census of systems and buildings that is the basis of the "Centralized Community tender aimed at the entrustment of the technological multiservice and of the supply of energy vectors to buildings owned by the *Aziende Sanitarie Locali* of the Lazio Region (ASLRLAZIO).

The definition of the architectural envelope was achieved choosing a configuration aimed at the achievement of the limit energy, referring to the standards in force during the construction period taken into account.

For the definition of the reference building, representative of the hospital building stock between 1991 and 2005, the n.10-1991 [15] law was considered as regulatory reference.

For new buildings the necessary parameters to define the architectural envelope were deduced from normative limits established by the current regulation in the field of energy efficiency: legislative decree 192/2005 [3].

Systems for the production of domestic hot water and thermal fluids for summer and winter air-conditioning were defined basing on the experience acquired through the analyses of energy performances of different hospitals carried out during the PhD course.

It is recurring the scientific community to develop reference buildings' models using different approaches for the definition of typical parameters.

Such circumstance especially occurs when complete documentations for parameters' definition are not available; in this case it is indeed unavoidable to gain information from several studies or resort to professionals' expertise [55].

The core of this methodology is the development of a virtual building based on statistical data and, exceptionally, on experts' knowledge and other sources of information. The definition and the list of both the parameters necessary to distinguish buildings and the detailed ones that help to characterize each building are included.

The methodology is organized in different phases listed below:

i. Definition of the geometry
ii. Subdivision into thermal zones
iii. Definition of the architectural envelope
iv. Development of the geometric model
v. Systems' characterization
vi. Dynamic thermal-energy simulation and analysis of energy performances

3.2 Definition of the geometry by means of a Theoretical Approach

The geometry of the RBh was defined on a statistical basis through a study carried out on some of the main hospitals managed by the ASLNAP1.

The documents provided are related to plans and elevations of the hospital centers listed in Table 3.1. Overall the analyzed hospital surfaces is equal to 183 378 m^2.

HOSPITALS	TOTAL FLOOR AREA [m^2]
Hospital S.Paolo	26'195
Hospital Frullone	9'255
Hospital Loreto Mare	17'344
Hospital Ascalesi	24'941
Hospital Pellegrini	18'497
Hospital San Gennaro	29'448
Hospital Napoli EAST	11'614
Hospital Loreto Crispi	5'895
Hospital Incurabili	15'889
Hospital S.G. Bosco	24'297

Table 3. 1: Hospitals of ASL-NAP1

The geometry's characterization concerned the definition of the following shape and geometry parameters listed in the following table.

PARAMETERS	REFERENCE HOSPITAL
Total Floor Area (m^2)	22709
Building Shape	Rectangle
Aspect Ratio	0.2
Number of Floors	6
Window Fraction (Window to Wall Ratio)	
South	0.26
East	0.24
North	0.15
West	0.23
Total	0.23
Skylight/TDD Percentage	0
Shading Geometry	None
Azimuth	0
Floor to Ceiling Height (m)	3.96
Floor to Floor Height (m)	3.96

Table 3. 2: Reference Building's geometrical characteristics

The evaluation of each parameter was performed averaging the typical values of each structure to the useful floor area.

It is worth to highlight that the choice of parameters that characterize the shape and geometry was made according to studies carried out by DOE about the characterization of the USA hospital reference building [41].

3.3 Thermal zoning by means of a Theoretical Approach

The evaluation of energy performances of a hospital is influenced in a significant way by the percentage distribution of use classifications on the useful floor area [56;57].

The current system type and the quality level of indoor air are strictly related to the use classification taken into account [58].

The subdivision, expressed in percentages, with relation to the entire volume was determined on a statistical basis through an in depth study of the file related to the census of systems and buildings that is the basis of the "Centralized Community tender aimed at the entrustment of the technological multiservice and of the supply of energy vectors to buildings owned by ASLRLAZIO".

The ASLRLAZIO is subdivided into 12 provincial ASL and 4 Aziende Ospedaliere (AO); overall 50 hospitals were analyzed for a total surface equal to 1'275'676 m^2 .

For each ASL, only the hospital centers representative of the type of hospital that the RBh is aimed to represent.

All hospitals, reported in Table 3.3, show the contemporary presence of all the main use classifications divided into "high tech" (operating theatre, emergency room, diagnostics ,etc), generic wards, ambulatories and offices.

ASL	HOSPITALS	[m^2]
"ROME A"	Hospital Regina Margherita	42'491
	Hospital George Eastman	38'657
"ROME B"	Hospital Sandro Pertini	43250
"ROME C"	Hospital "C.T.O. Andrea Alesini"	43180
	Hospital "S. EUGENIO"	69566
"ROME E"	Hospital Oftalmico	9688
	Hospital S.M. della Pietà	142'712
"ROME F"	Hospital San Paolo Civitavecchia	13966
	Hospital P. Pio di Bracciano	9110
"ROME G"	Hospital Colleferro - Parodi Delfino	13477
	Hospital Monterotondo - Gonfalone	6058
	Hospital Palestrina - coniugi Bernardini	4'319
	Hospital Subiaco - A. Angelucci	14'648
	Hospital Tivoli	29'405
	Hospital Zagarolo - S. G. Battista	1'881
"ROME H"	Hospital "S. Giuseppe" ALBANO LAZIALE	11417
	Hospital OO.RR. Anzio - Nettuno	16993
	Hospital "De Santis" GENZANO	8'170
	Hospital "S. Giuseppe" MARINO	13'466
	Hospital "L. Spolverini" ARICCIA	12'938
	Hospital "S. Sebastiano" FRASCATI	13'698
	Hospital "A. C. Cartoni" ROCCA PRIORA	11'867
	Hospital "P. Colombo" VELLETRI	11'671
"ASL FROSINONE"	Hospital ALATRI	20049
	Hospital ANAGNI	10'926

	Hospital CASSINO	39'538
	Hospital SORA	56'570
	Hospital SPAZIANI FROSINONE	34'723
"ASL LATINA"	Hospital FONDI	13'396
	Hospital FORMIA	13751
	Hospital GAETA	11'524
	Hospital S. MARIA GORETTI	43'259
	Hospital TERRACINA	19'963
"ASL RIETI"	Hospital Magliano Sabina	11009
	Hospital Rieti	54320
	Hospital Amatrice	6276
"ASL VITERBO"	Hospital Acquapendente	3'684
	Hospital MONTEFIASCONE	6097
	Hospital SANT'ANNA RONCIGLIONE	4'987
	Hospital in CIVITA CASTELLANA	3'434
	Hospital in BELCOLLE	44'347
	Hospital in TARQUINIA	10'687
"A.OSPEDALIERA S.ANDREA"	Hospital in SANT'ANDREA	57373
"A. OSPEDALIERA S.F.NERI"	Hospital San Filippo Neri	52283
"A. OSPEDALIERA S.G.ADDOLORATA"	Hospital Addolorata	15204
"A. OSPEDALIERA TORVERGATA"	Hospital Britannico	8594
	Hospital San Giovanni	57064
	Hospital Policlinico Tor Vergata	93990
		1'275'676

Table 3. 3: Hospitals of ASL-Regione Lazio

The percentage evaluation of each use classification was performed averaging the mean values of each use classification evaluated for each ASL or AO to the total volume.

The results of the statistical analysis are reported in the following figure (see Figure 3.1).

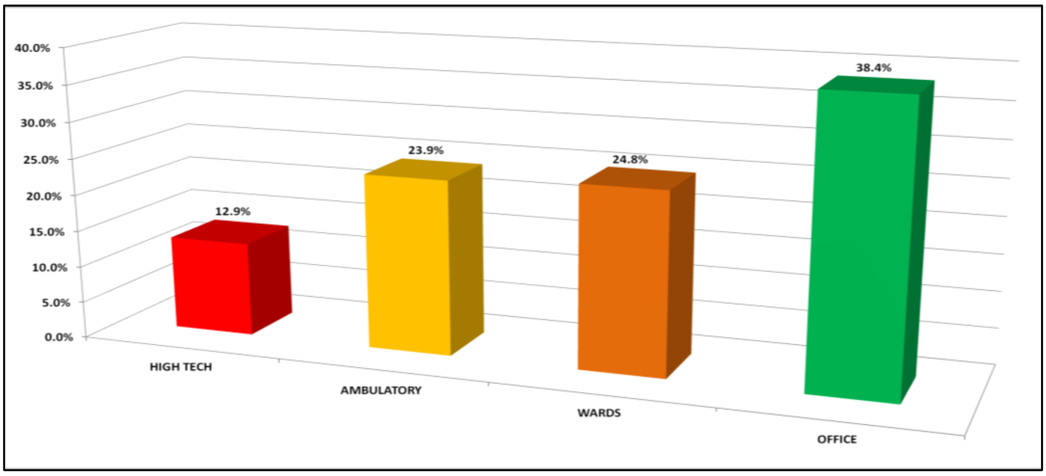

Figure 3. 1: Percentage distribution of use classifications

Is it possible to observe a predominance of the office use classification which is equal to 38.4%; "high tech" use classifications, characterized by higher comfort levels, are equal to 12.9%. Generic wards and ambulatories use classifications respectively occupy 23.9% and 24.8% of the useful floor area.

It is worth highlighting that it is a preliminary percentage distribution which does not directly allow the subdivision into thermal zones; it is indeed necessary a further subdivision into thermal zones according to the type of air conditioning system installed in the environment.

3.3.1 Thermal zoning characterization

Once defined in terms of percentages the distribution of use classifications on the useful floor area it was then possible to make, on a statistical basis, a further subdivision into thermal zones according to the type of installed air-conditioning system (see Figure 3.2).

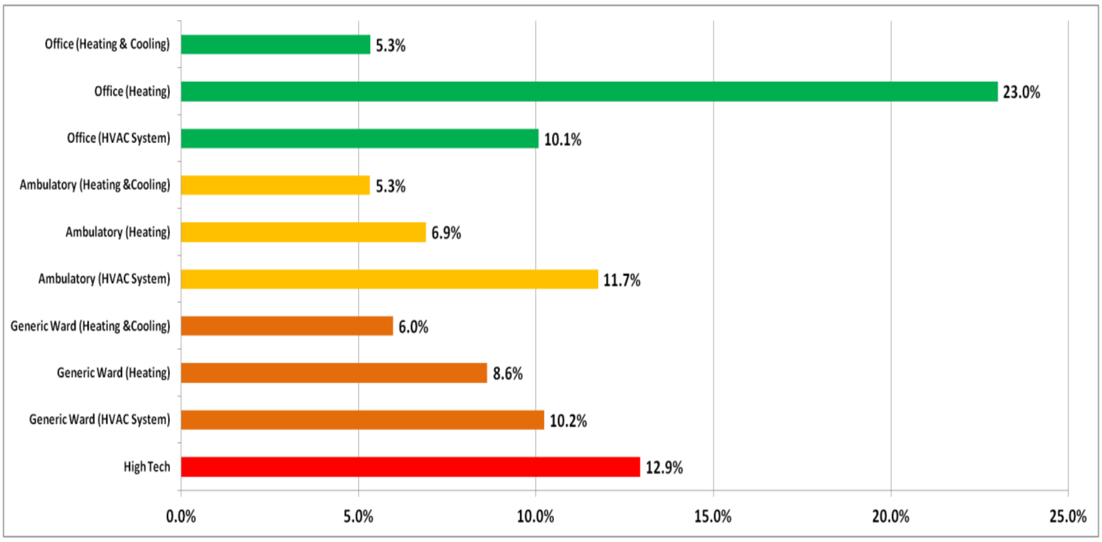

Figure 3. 2: Subdivision in thermal zones depending on use classifications and air-conditioning system type

All High Tech zones and a share of the other use classifications are considered as supplied by an air-conditioning system ("HVAC System") with the possibility to control Temperature and Humidity inside the range of set point temperature and humidity.

The "Heating" system type includes the possibility to control only the Temperature during winter, and involved all use classifications excluding High Tech zones.

"Heating & Cooling" system type only allows the control of the Temperature during winter and summer, and involves all use classifications excluding High Tech zones.

Temperature and Relative Humidity set point values and the volume/hour of air change were chosen in compliance with regulatory references in the field of hospitals' air-conditioning (see Table 3.4).

A directly binding legislative/regulatory framework in the field of hospitals' air-conditioning does not exist in Italy, but there is only an old Ministerial Circular, a guide lines, and some general UNI standards.

Ultimately the main references are: Ministerial Circular LL.PP. n.13011/22.11.1974 [59], UNI 10339 Standard [60], UNI 8199 Standard [61] , ISPESL's Guide line [62].

	T [°C]	U.R. %	ACH [Vol/h]
Operating Theatre	24	50	15
Intensive Care Unit	24	50	6
Sterilization Room	24	50	15
Radiology	20-26	40-60	6
Post Mortem Facility	20-26	40-60	6
Generic Ward (HVAC System)	20-26	40-60	3
Generic Ward (Heating)	20	-	-
Generic Ward (Heating &Cooling)	20-26	-	-
Ambulatory (HVAC System)	20-26	40-60	6
Ambulatory (Heating)	20	-	-
Ambulatory (Heating &Cooling)	20-26	-	-
Office (HVAC System)	20-26	40-60	3
Office (Heating)	20	-	-
Office (Heating & Cooling)	20-26	-	-

Table 3. 4: Micro-climate characterization for each use classification referred to the air-conditioning system type

Moreover thermal zones were defined in terms of occupants' number, lighting and devices' presence.

Working schedules for each use classification were selected from the library of Design Builder with which the geometrical model was developed.

The source used to define the typical parameters of each use classification and each type of load is represented by the database of the "National Calculation Method for the EPBD (Energy Performance of Buildings Directive)", defined by the Department for Communities and Local Government (DCLG) of the United Kingdom .

The typical parameters taken into account are reported below:

	Density of People [person/m²]	Interior Lighting [lux]	Equipment [W/m²]	DHW [l/m²day]
Operating Theatre	0.125	1000	75	1.3
Intensive Care Unit	0.125	1000	75	1.3
Sterilization Room	0.125	1000	75	1.3
Radiology	0.100	1000	150	0.6
Post Mortem Facility	0.050	1000	75	1.3
Generic Ward	0.175	150	13	1.3
Ambulatory	0.195	350	27	0.17
Office	0.195	350	27	0.17

Table 3. 5: Typical internal gains for each use classification

Working hours are defined basing on the experience acquired in the analysis of energy performances of other hospitals. Table 3.6 lists, for each use classification, the schedules taken into account .

	Operating Hours	Operating Days
Operating Theatre	8am - 1pm	Workdays
Intensive Care Unit	Always	Always
Sterilization Room	8am - 1pm	Workdays
Radiology	8am - 5pm	Workdays
Post Mortem Facility	8am - 1pm	Workdays
Generic Ward	Always	Always
Ambulatory	8am - 5pm	Workdays
Office	8am - 5pm	Workdays

Table 3. 6: Schedules for each use classification

3.4 Envelope characterization in compliance with normative limits for different construction period

The definition of the architectural envelope (vertical, horizontal and transparent walls' transmittances) was deduced from the main regulatory references in the field of energy efficiency which characterized the Italian regulatory context of this field: law 10/91[15] (calculation of losses and evaluation of the FEN index) and D.lgs 192/2005 [3] (listed limit values) .

Ultimately the opaque and transparent architectural envelope was defined so that it verifies the limit energy performance according to the legislation in force during the construction period taken into account.

In the following paragraphs performance limits used for the definition of the architectural envelope before 2005 (existing hospital stock) and after 2005 (hospital newly built) will be reported.

3.4.1 Hospital Reference Building for the existing building stock - BEFORE 2005

With the 10/91 law the building's energy losses are evaluated and limited (FEN), evaluating the energy lost for: transmission, ventilation, emission, control, distribution and production.

The FEN (eq. 3.1) derives from the definition of the conventional energy requirement (Q) and it is defined as the quantity of primary energy usually necessary during a year for winter air-conditioning, to keep heated environments at a constant temperature of 20°C, with an adequate air change.

$$FEN = \frac{Q}{GG*V} \qquad \text{eq (3.1)}$$

The FEN_{lim}, represents a limit performance condition of the system building set. It depends on the climate zone, on the shape ratio, on the included use classifications and on the type of production systems and it is evaluated through the following expression,

$$FEN\lim = \left\{ c_{d_{\lim}} + 0.34*n - K_u * \left[\frac{0.01*I}{\Delta\theta_m} + \frac{a}{\Delta\theta_m} \right] \right\} * \frac{86.4}{\eta_g} \qquad \text{eq. (3.2)}$$

where:

- $C_{d,lim}$ represents the thermal power dispersed for transmission compared to the total volume of the building and to the difference between internal and external Temperatures (design data);
- n is the number of hourly air changes
- $\Delta\theta_m$ represents the difference between internal and external design temperatures;
- K_u is the dimensionless use coefficient of heat gains
- I is the average solar irradiance [W]
- a represents internal heat gains [W/m^3]
- η_g average seasonal efficiency of the thermal system

The definition of the architectural envelope was performed by selecting the envelope's and system's characteristics which comply with the conditions:

I. $FEN = FEN\lim$

II. $c_d \le c_{d,\lim}$

III. $\eta_g \leq \eta_{g,\lim}$

In the following table the typical parameters useful for FENlim evaluation are reported:

Parameters	Regulatory references	Value	
$C_{d,lim}$	Law 373\76	0.45	[W/m^{3}K]
n	UNI 10379	2.7	
K_u	UNI 10379	0.79	
$\Delta\theta_m$	UNI 10379	8.0	[K]
I	UNI 10349	9.6	[W/m^2]
η_g	UNI10348	68%	
a	UNI EN 832	4.55	[W/m^3]

Table 3. 7: Parameters and regulatory references for the evaluation of FEN_{lim}

Replacing the values inside the eq.3.2 it is thus deduced that:

$$FEN_{\lim} = 113 \quad \left[\frac{KJ}{GGm^3}\right]$$

The FEN (eq.3.1), defined in the article 8 of the D.P.R. 412/1993 [16], whereas its calculation can be found in the UNI 13790 [63]. The calculation of energy requirement for heating of buildings (Q) was performed on a monthly basis; for each month during the heating period the energy exchanged by transmission and ventilation through the architectural envelope which encloses an environment heated at an homogeneous temperature (thermal zone) is considered as the sum of five terms (see eq.3.3). These are:

- energy exchanged by transmission with the external environment, QT, and with the ground, QG;
- energy exchanged by ventilation, QV;
- energy exchanged by transmission and ventilation with not heated environments, QU,
- and with zones with a previously fixed temperature, QA.

$$Q_L = Q_T + Q_G + Q_V + Q_U + Q_A \qquad \text{eq. (3.3)}$$

In Figure 3.2 is reported the logical scheme for the use of UNI standards involved in the evaluation of the FEN.

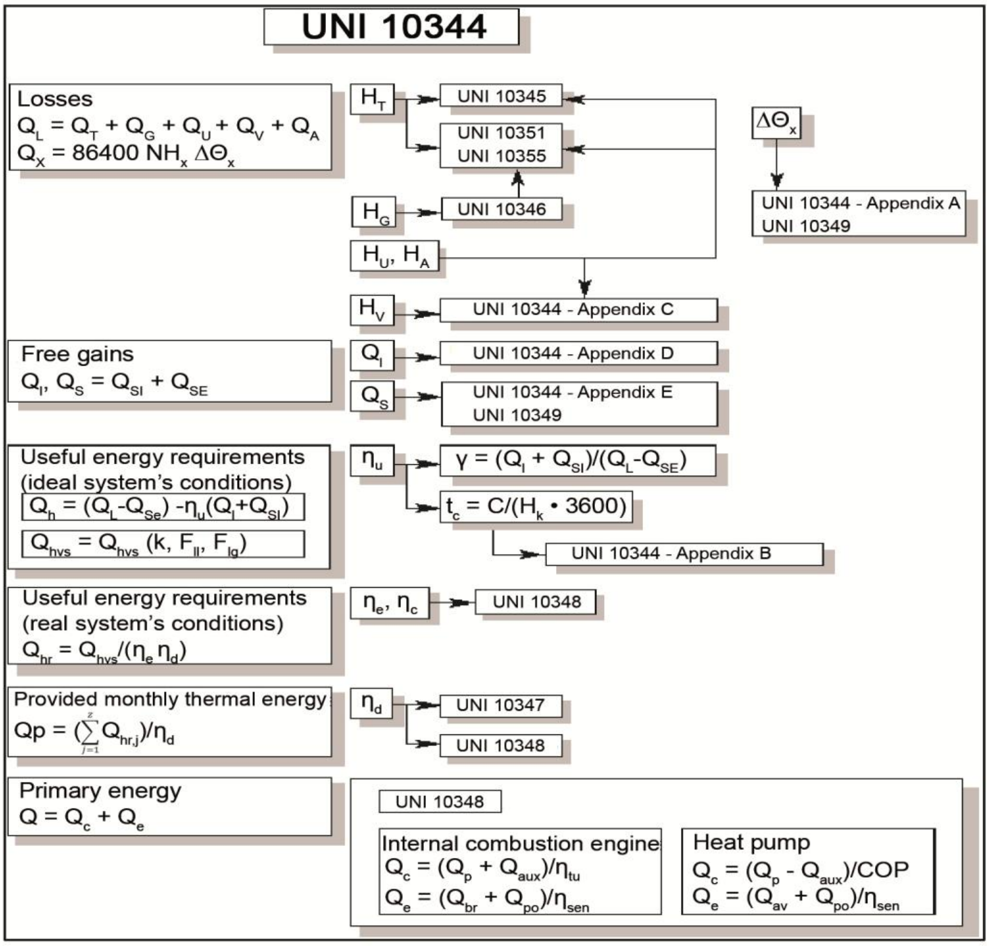

Figure 3. 3: Regulatory references for the evaluation of Q

Essentially, starting from the geometrical model a system-building configuration was established which determines a FEN equal to 113 KJ/DDm^3 (FENlim) (see Table 3.8).

In more detail all the parameters which characterize the envelope and systems were defined, except the transmittance of the opaque vertical envelope which was instead evaluated in compliance with the equivalence between FEN and FENlim.

The characteristics of the architectural envelope and of systems which are typical of the RBh BEFORE-2005 are reported.

ARCHITECTURAL ENVELOPE		HVAC	
U_{VERT}	0.717 W m^{-2}K^{-1}	η_p	0.9
U_{ROOF}	1.5 W m^{-2}K^{-1}	η_c	0.98
$U_{BASE\ PLATE}$	1.5 W m^{-2}K^{-1}	η_d	0.89
$U_{WINDOWS}$	3.2 W m^{-2}K^{-1}	η_e	0.88

Table 3. 8: Main parameters for the evaluation of FEN

3.4.2 Hospital Reference Building for new constructions - AFTER 2005

The architectural envelope of the RBh representative of new hospitals was defined taking into account the transmittance values of the opaque and transparent architectural envelope equal to the limit ones established by the legislation in force in the field of energy efficiency (Dlgs 192/2005 [3] and following integrations or modifications).

The values used to define the architectural envelope are listed in the following table:

ARCHITECTURAL ENVELOPE	
U_{VERT}	0.34 W $m^{-2}K^{-1}$
U_{ROOF}	0.32 W $m^{-2}K^{-1}$
$U_{BASE\ PLATE}$	0.40 W $m^{-2}K^{-1}$
$U_{WINDOWS}$	2.1 W $m^{-2}K^{-1}$

Table 3. 9: Architectural envelope's definition

3.5 Development of the Geometric Model

The geometrical model (see Figure 3.3) was developed through the Design Builder software [64] thanks to which it was possible to define the architectural envelope (paragraph 3.4.1), the subdivision into thermal zones and the definition of use classifications in terms of internal loads (Interior Lighting, density of people and equipment).

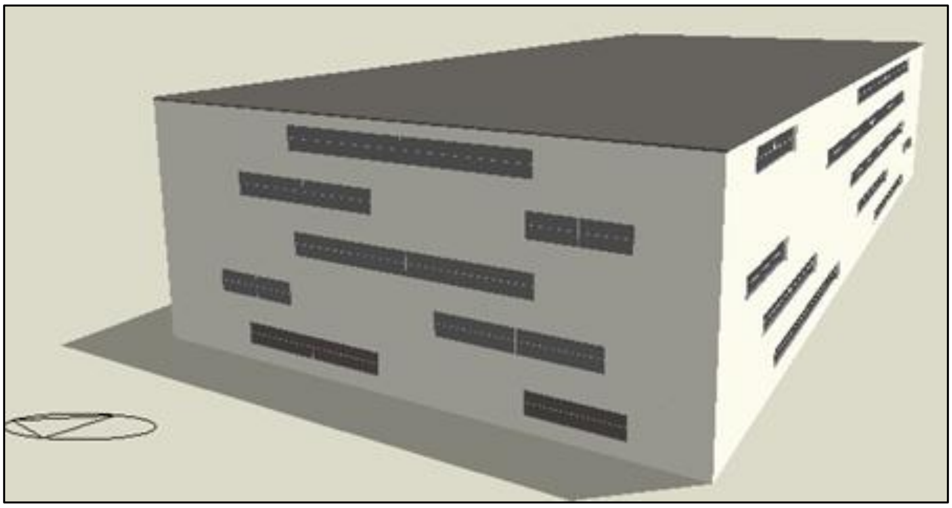

Figure 3. 4: Rendering of the geometrical model - EAST elevation

26 thermal zones were created in order to model real loads. In Figures from 3.4 to 3.8, the subdivision in thermal zones for each of the building's floors is reported.

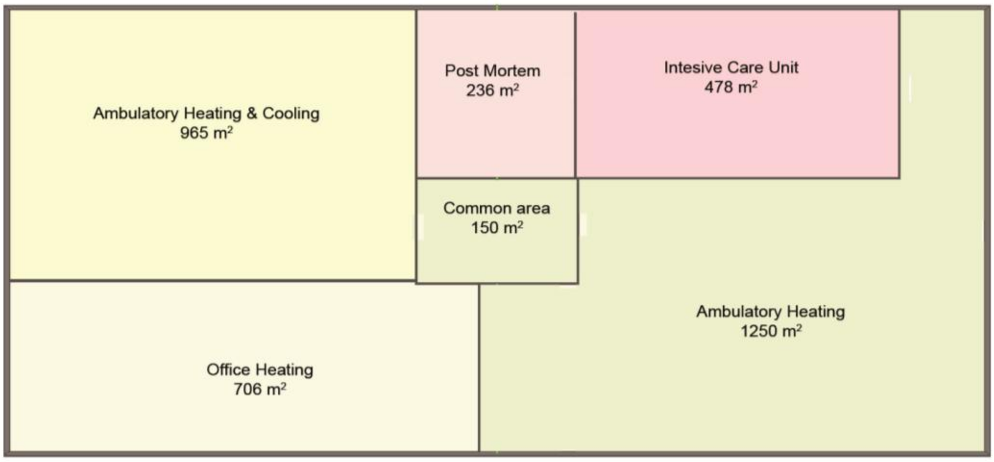

Figure 3. 4: Subdivision into thermal zones ground floor

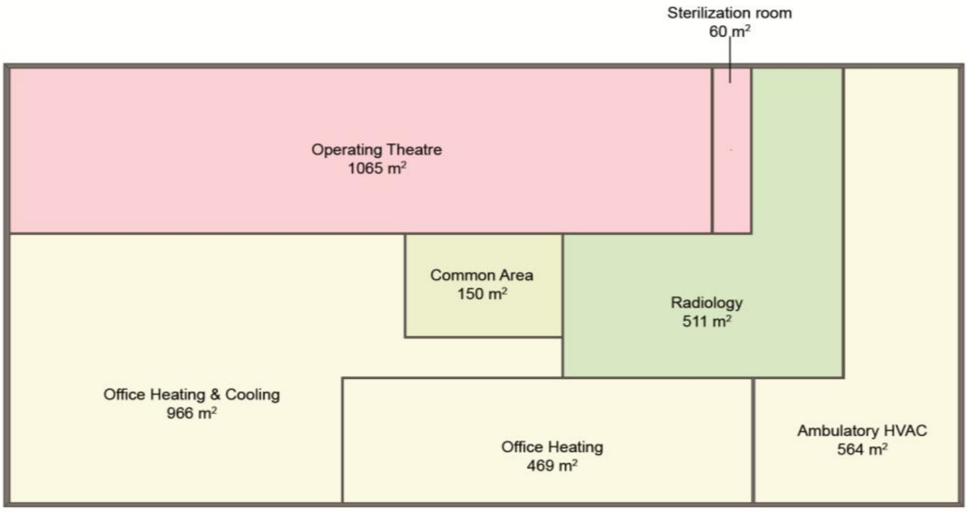

Figure 3. 5: Subdivision into thermal zones first floor

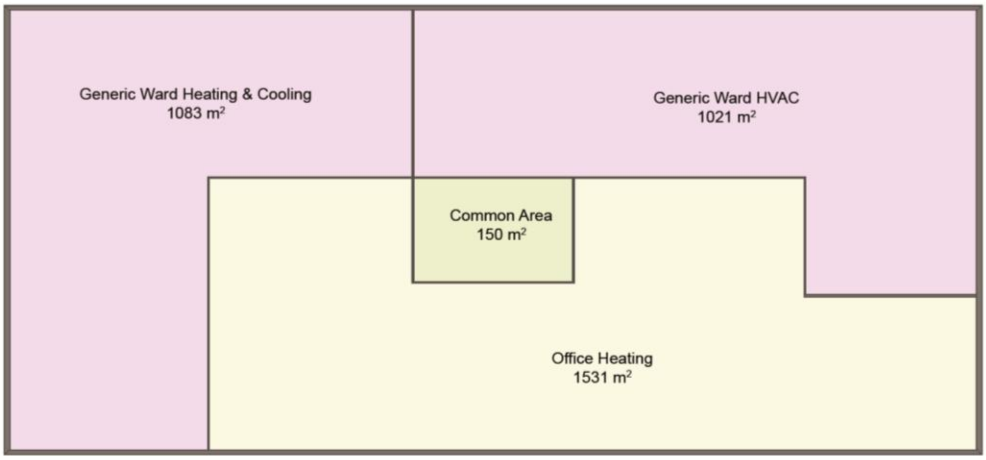

Figure 3. 6: Subdivision into thermal zones second floor

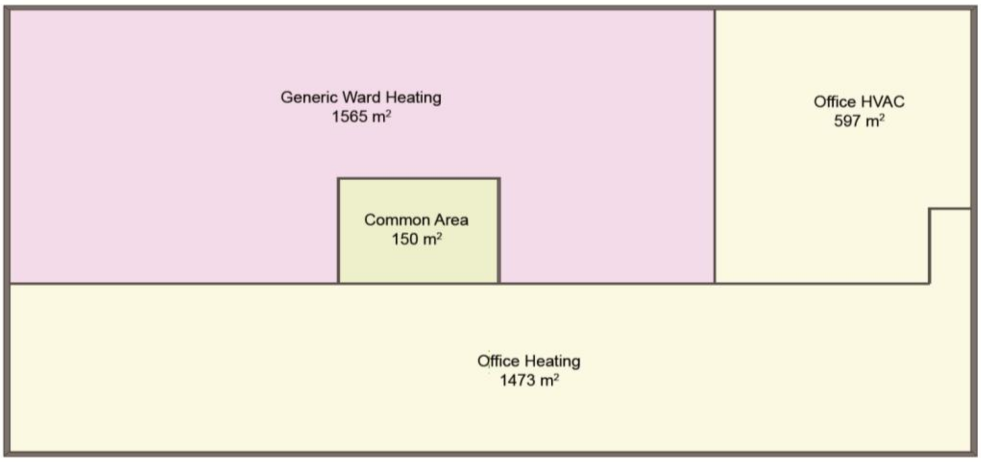

Figure 3. 7: Subdivision into thermal zones third floor

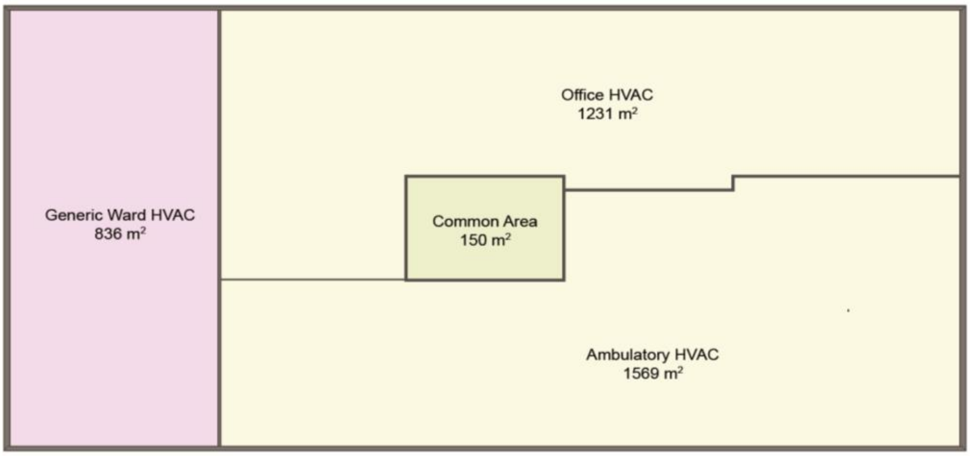

Figure 3. 8: Subdivision into thermal zones fourth floor

3.6 Characterization of the plant systems: Example Approach

Systems of the RBh were defined with an "Example" type of approach, basing on the experience acquired from the analysis of energy performances of hospitals carried out during the PhD course.

Energy sources required by an hospital are: thermal energy for winter air-conditioning and domestic hot water production, cooling energy for summer air-conditioning and electricity for lighting and equipments. Moreover it is worth to highlight that hospital consumptions require simultaneously all energy sources.

The thermal energy supply is performed through district heating at building level (Primary Distribution), then through a secondary distribution there is a subdivision of the required thermal load according to the system types present in the environment. In order to evaluate the primary energy consumption, connected both to heating and DHW's production, a global efficiency of the District Heating (η_{DH}) was considered. In more detail η_{DH} for RBh referred to existing stock and to new construction is equal respectively to 0.72 and 0.80.

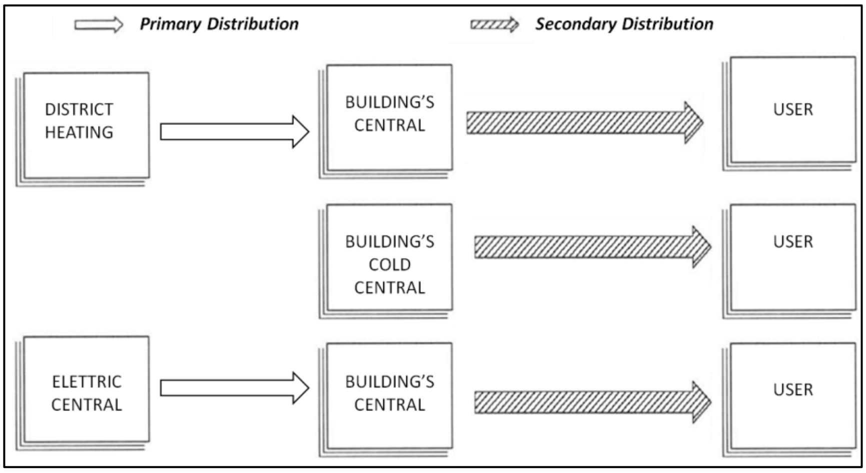

Figure 3. 9: Plant systems' configuration Reference Building

For summer air-conditioning a central production of chilled water was considered, the COP and capacity of air-cooled chillers are reported for both RBs in the following table 3.10.

RBh for existing stock	RBh for new construction
COP= 2.7	COP= 3.1
Capacity=3371 MW	Capacity=3408 MW

Table 3. 10: Architectural envelope's definition

A secondary distribution is exclusively present for the subdivision of cooling load according to the different types of system present in the environment (see Figure 3.9).

The electricity required for all uses is directly taken from the national electricity grid (η_{eg}=0.46).

In the environment three system types for air-conditioning were considered:

- Air systems without recycle with the possibility to control temperature and relative humidity;
- Fan-coil systems for winter air-conditioning with only the possibility to control the temperature;
- Fan-coil systems for winter and summer air-conditioning with only the possibility to control the temperature.

As previously stated in the paragraph 3.3.1, air-conditioning systems (HVAC) supply all High-Tech zones; the required indoor air quality (IAQ) is performed through the inlet supply temperature whereas the supply air flow in the environment is constant. The fan coil system type is present in the majority of cases in other thermal zones (generic wards, offices, ambulatories) and the control type taken into account is ON/OFF.

3.7 Analysis of the energy performance by means of BPS tool "Energy Plus"

In this PhD thesis, to simulate the energy behavior of the building/systems interaction in the case studies reported in this chapter and in the following ones, EnergyPlus v.8.1.0 [6] was used. It is a simulation engine based on the transfer function method and which features a modular structure encoded in Fortran 90, an evolution of the synergy between the different technical bases DOE-2 [65] and BLAST [66] respectively developed by the USA Departments of Energy (DOE) and of Defence (DOD), with the ASHRAE contribution (Technical Committee 4.7 Energy calculation).

EnergyPlus consists in a complex system of several modules and numerical solvers, which cooperate to evaluate the necessary energy for buildings' heating, ventilation and cooling, both if produced by traditional systems or by innovative systems and energy sources, solving energy balances when the system is exposed to different environmental and operating conditions. The iterative procedure includes a continuous exchange of information between the different modules in parallel, so that calculated loads, referring to time steps specified by the user, are sent to the simulating module of the building system, referring to the same time step.

The geometrical model, built in DesignBuilder (see paragraph 3.6), was imported into EnergyPlus [6], where the air-conditioning system was defined. It is worth highlighting that to achieve reliable results a detailed definition of all boundary conditions is necessary, since the interactive architecture is rather complex.

In this paragraph the results of the energy analysis carried out for the before-2005 RBh (representative of the existing building stock) and for the after-2005 one (representative of newly built hospitals) will be reported.

3.7.1 Results - Reference Building before 2005

Following the geometrical modeling, the definition of the stratigraphy and of subdivision in thermal zones and the setting of micro-climate parameters for both summer and winter, a dynamic simulation of the building was carried out, using EnergyPlus 8.0 [6].

A yearlong simulation period was chosen, with a monthly and hourly results' subdivision, in order to have a global vision of the building's performances.

In Table 3.11 the values of the annual demand of primary energy for heating, domestic hot water, cooling and the total electricity demand are reported.

Primary energy [MWh]	
Thermal energy for heating	2657
Thermal energy for DHW	892
Total electricity	11110
Electricity for cooling	2875

Table 3. 11: Total annual demand of primary energy

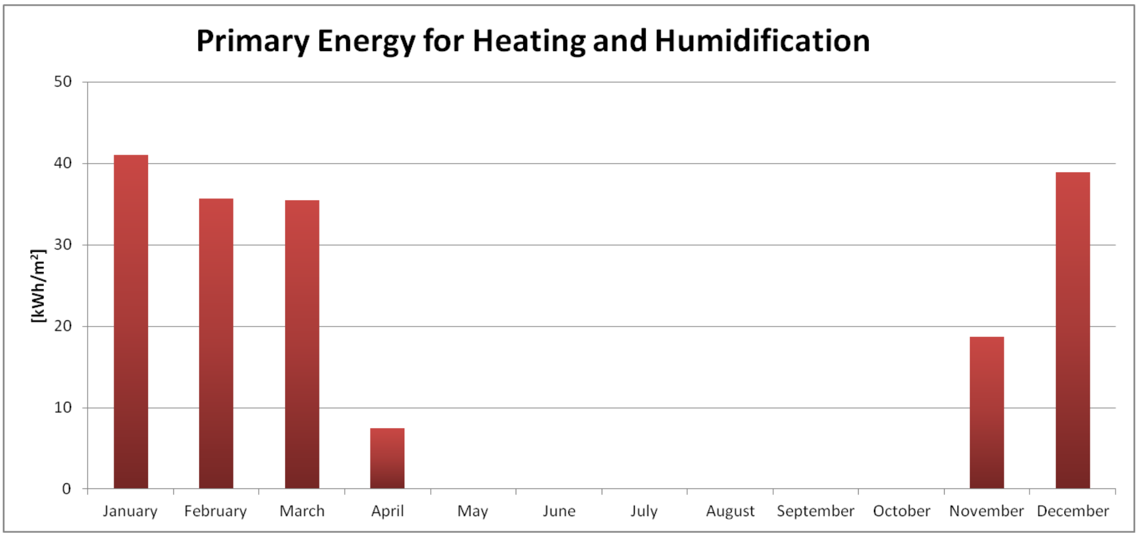

Figure 3. 10: Monthly demand of primary energy for heating and humidification

From the graph related to the annual demand of primary energy for heating and humidification per square meter, reported in Figure 3.10, it can be observed that the examined building shows a demand only in the heating period between 1st November and 15th April. This does not coincide with the conventional heating period, which for the C zone identified in the D.P.R. 412/93 [13] starts on 16th November and finishes on 31th March. Indeed hospitals, for the users type they represent, are not obliged to comply with the abovementioned obligation. The trend of the annual demand of primary energy for domestic hot water production per square meter is illustrated in Figure 3.11. Also in this case, as for heating demand, the thermal energy demand supplied through district heating. The trend, as it can be observed, is rather constant during all months.

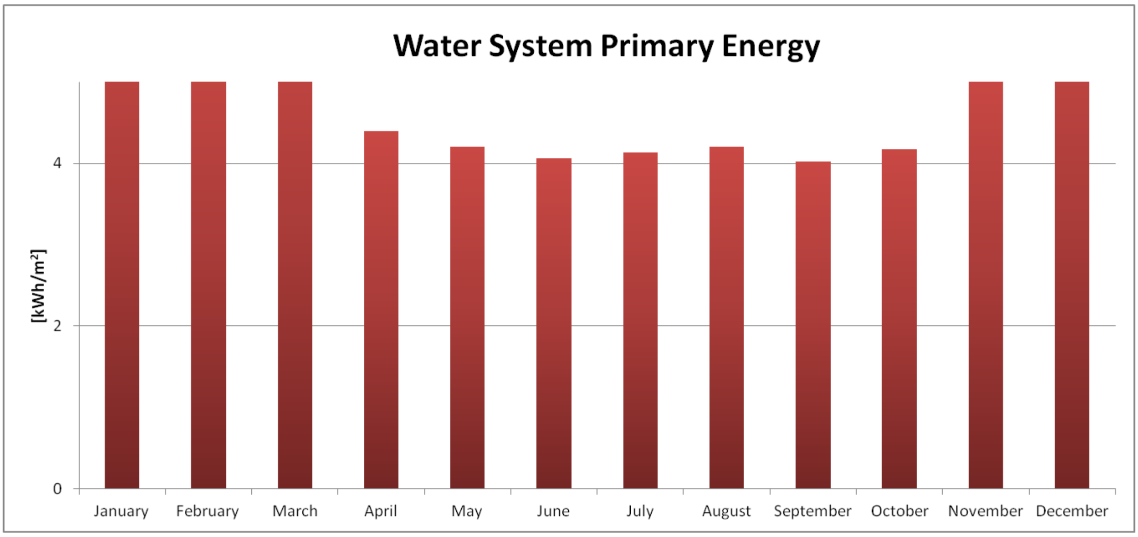

Figure 3. 11: Monthly demand of primary energy for domestic hot water

The total demand of electricity obviously includes pure electric loads (lamps and equipments), electricity for summer cooling and for the activation of auxiliaries. As it can be observed in Figure 3.12, it is almost constant during winter, it grows during intermediate months, to then reach a peak during July and August, up until values greater than 80 kWh per square meter. This is clear looking at Figures 3.13 and 3.14, in which the unbundled trends of electricity for pure loads and for summer air-conditioning are reported.

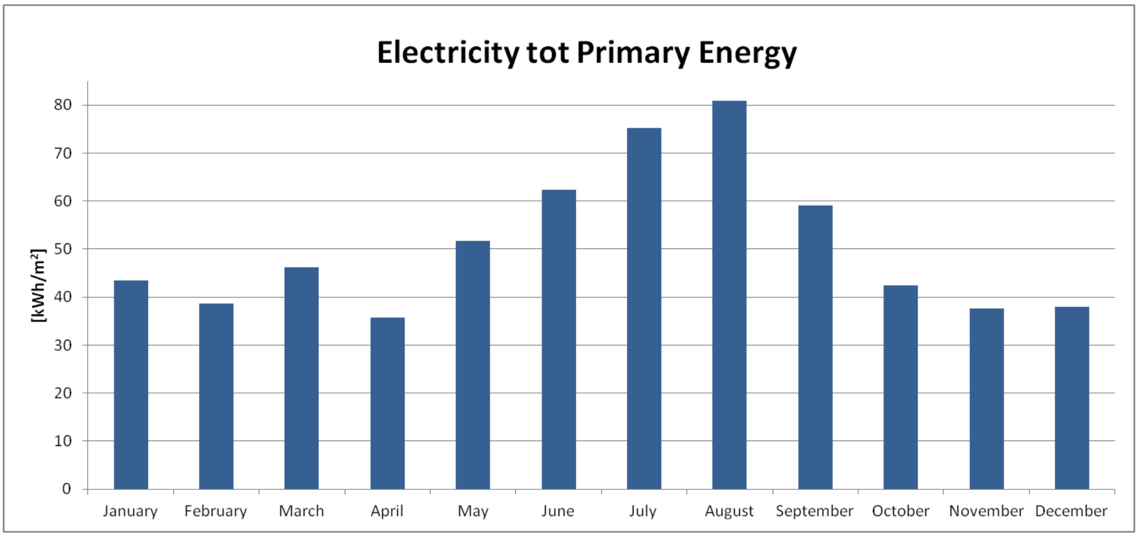

Figure 3. 12: Monthly demand of primary energy, to satisfy all electric uses

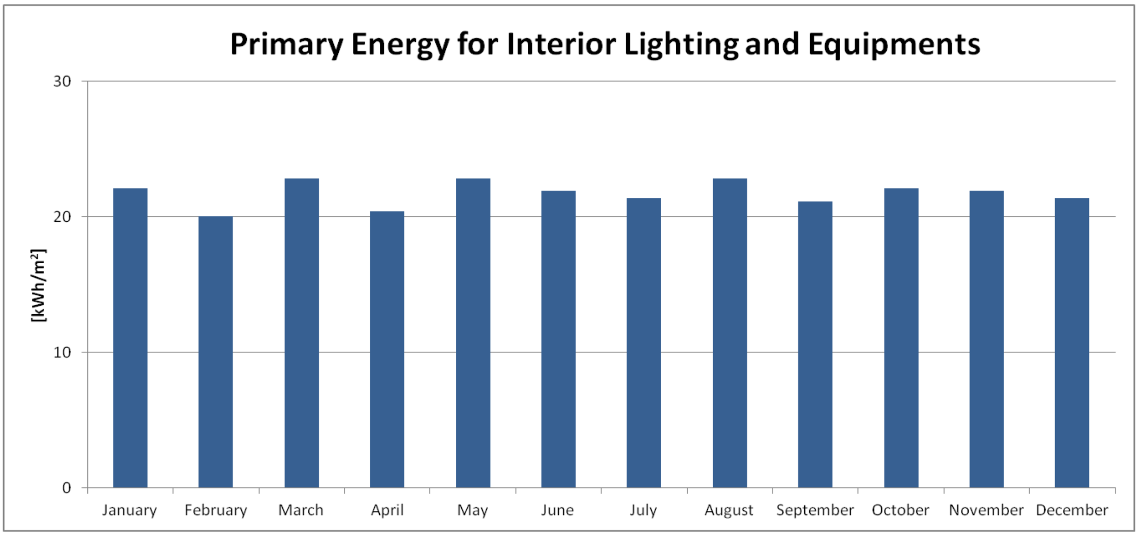

Figure 3. 13: Monthly demand of primary energy for interior lighting and equipments

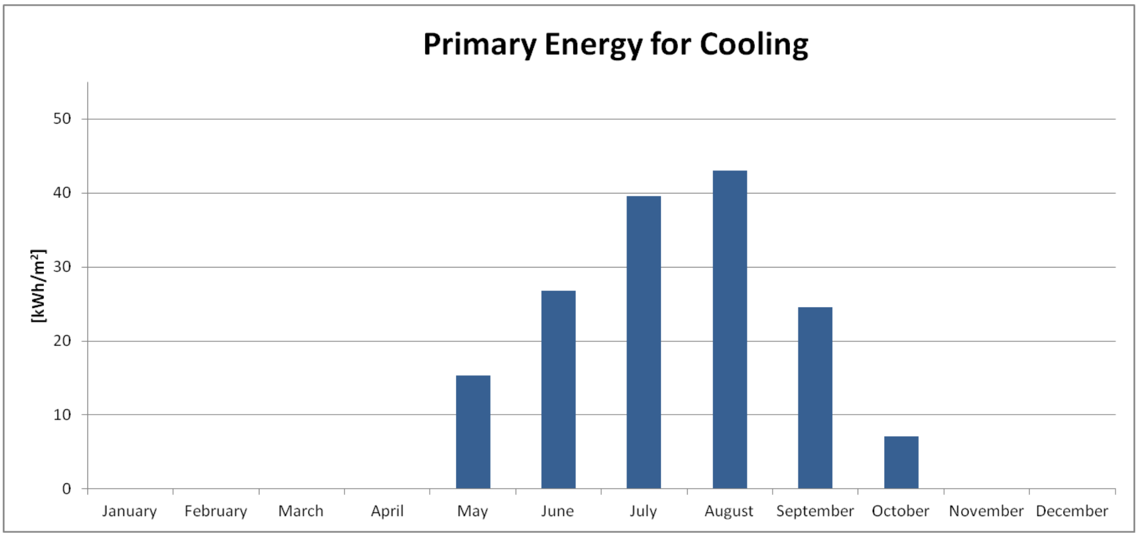

Figure 3. 14: Monthly demand of primary energy for cooling

Considering the BEFORE-2005 RBh the entire electricity demand is fulfilled by the national electricity grid. Therefore, in Figures 3.12÷3.14 the average efficiency of the national thermal-electric system was taken into account which is equal to η_{EG} = 0.46.

Referring to the energy demand for micro-climate control and production of domestic hot water, Figure 3.15 reports, on a monthly basis, primary energy demands for:

- Heating, production of domestic hot water;
- working of the cooling plant;
- humidification (with steam, through electrical resistance)
- auxiliaries working, and therefore pumps and fans.

It can be noted how, at least referring to peak months during winter and summer, the demand for summer air-conditioning is greater than the winter one. During winter, also the consumption of energy for humidification is significant. Finally, also the energy demand for auxiliaries' working is not negligible, representing, during the warmest and coolest months, about a sixth of the primary demand for air-conditioning.

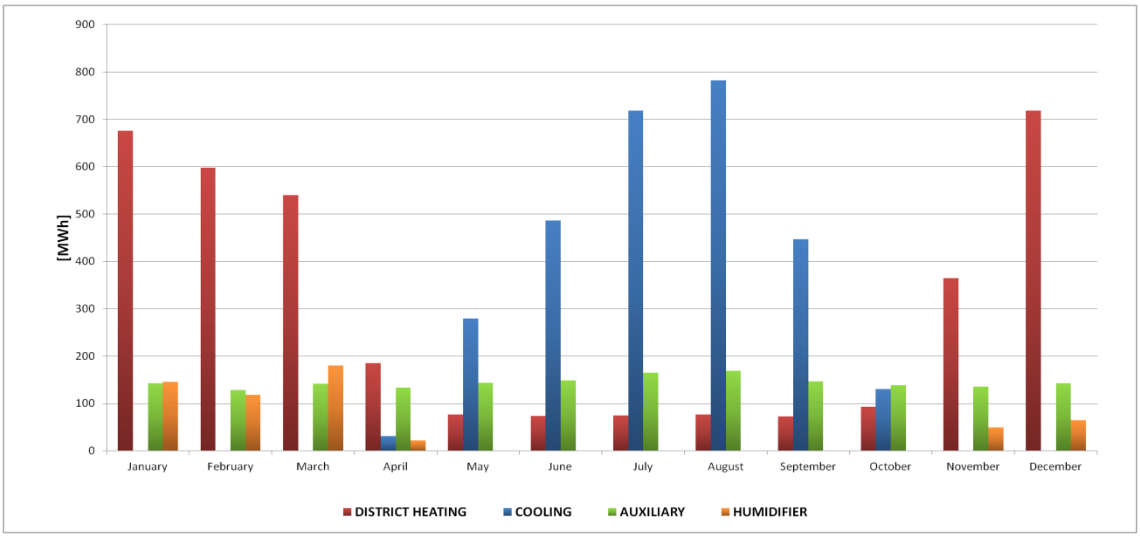

Figure 3. 15: Monthly demand of primary energy for environmental air-conditioning (all uses)

3.7.2 Results - Reference Building for new constructions

Following the geometrical modeling, the definition of the stratigraphy and of subdivision in thermal zones and the setting of micro-climate parameters for both summer and winter, a dynamic simulation of the building was carried out, using EnergyPlus 7.2.

A yearlong simulation period was chosen, with a monthly and hourly results' subdivision, in order to have a global vision of the building's performances.

In table 3.12 the values of the annual demand of primary energy for heating, domestic hot water, cooling and the total electricity demand are reported.

Primary energy [MWh]	
Thermal energy for heating	2250
Thermal energy for DHW	804
Total electricity	10796
Electricity for cooling	2574

Table 3. 12: Total annual demand for primary energy

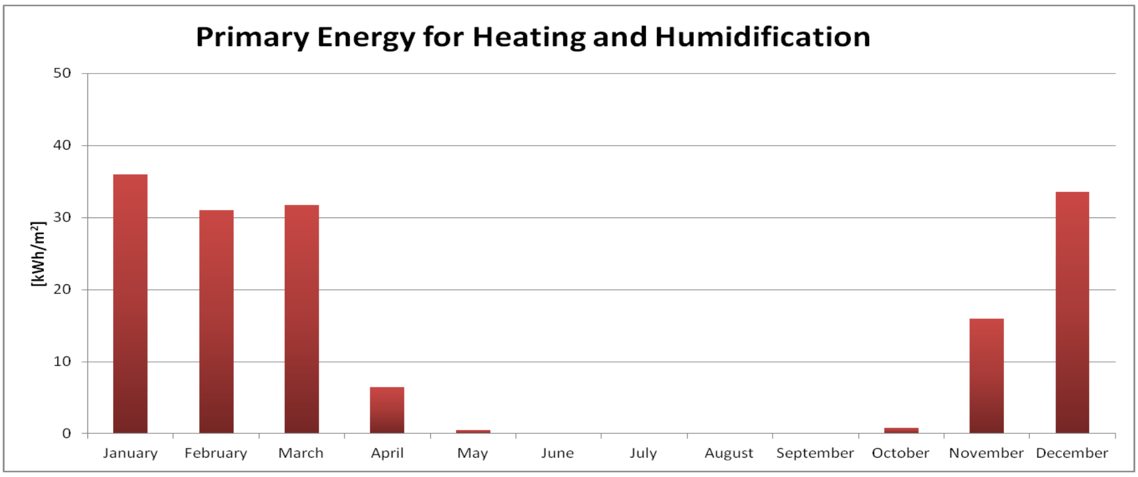

Figure 3. 16: Monthly demand of primary energy for heating

From the graph related to the annual demand of energy for heating and humidification per square meter, reported in Figure 3.16, it can be observed that the examined building shows a demand only in the heating period between 1st November and 15th April. This does not coincide with the conventional heating period, which for the C zone identified in the D.P.R. 412/93 [13] starts on 16th November and finishes on 31th March. Indeed hospitals, for the users type they represent, are not obliged to comply with the abovementioned obligation.

The trend of the annual demand of primary energy for domestic hot water production per square meter is illustrated in Figure 3.17. Also in this case, as for heating demand, the thermal energy demand supplied through district heating. The trend, as it can be observed, is rather constant during all months.

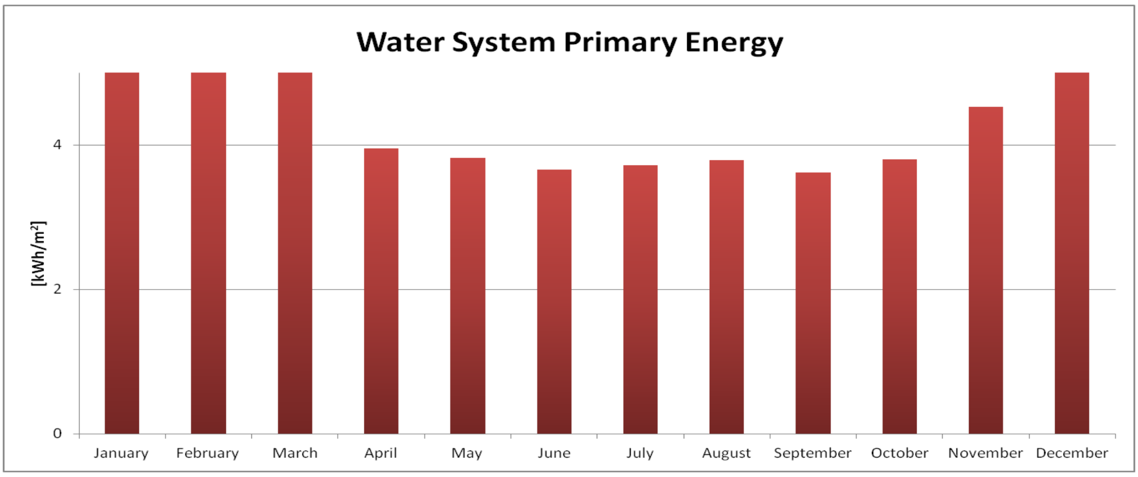

Figure 3. 17: Monthly demand of primary energy for domestic hot water

The total demand of electricity obviously includes pure electric loads (lamps and equipments), electricity for summer cooling and for the auxiliaries' working. As it can be observed in Figure 3.18, it is almost constant during winter, it grows during intermediate months, to then reach a peak during July and August, up until values lower than 80 kWh per square meter. This is clear looking at Figures 3.19 and 3.20, in which the unbundled trends of electricity for pure loads and for summer air-conditioning are reported.

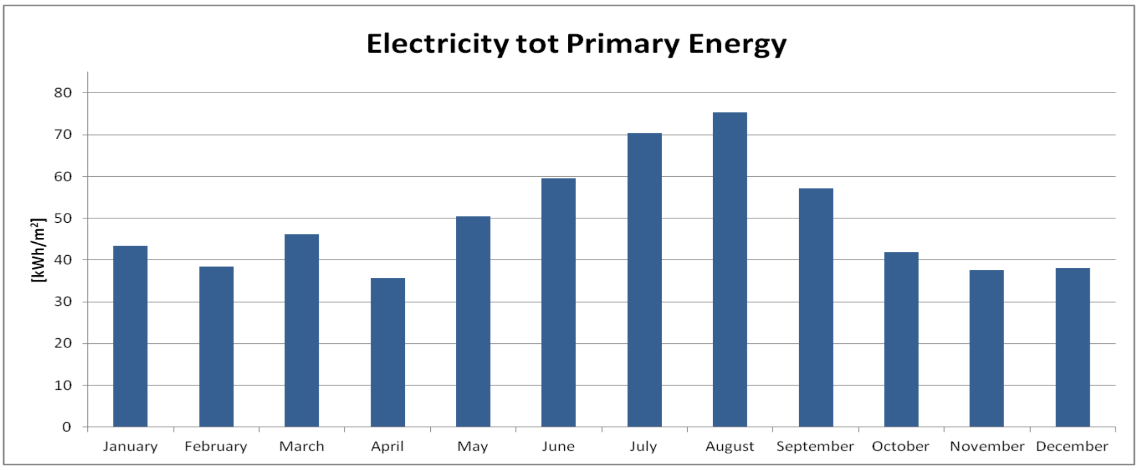

Figure 3. 18: Monthly demand of primary energy, to satisfy all electric uses

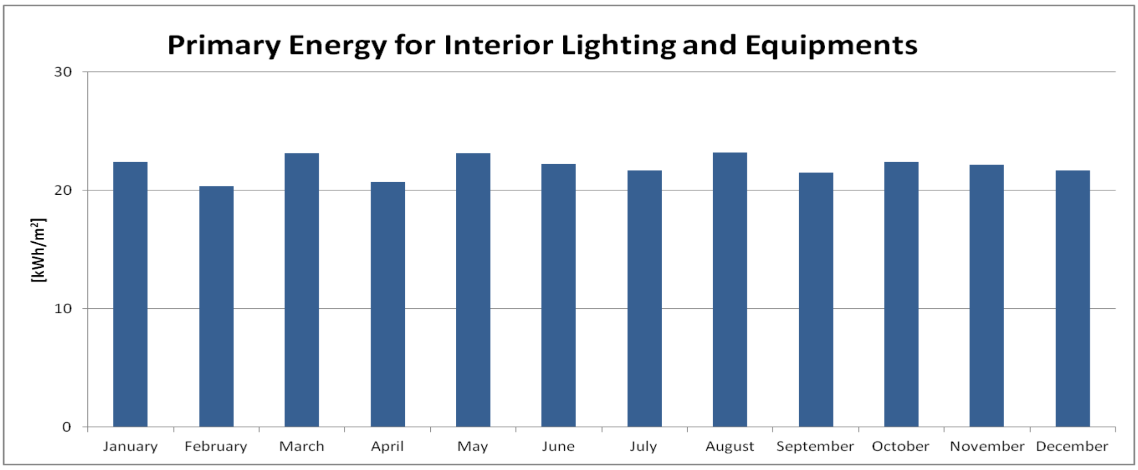

Figure 3. 19: Monthly demand of primary energy for interior lighting and equipments

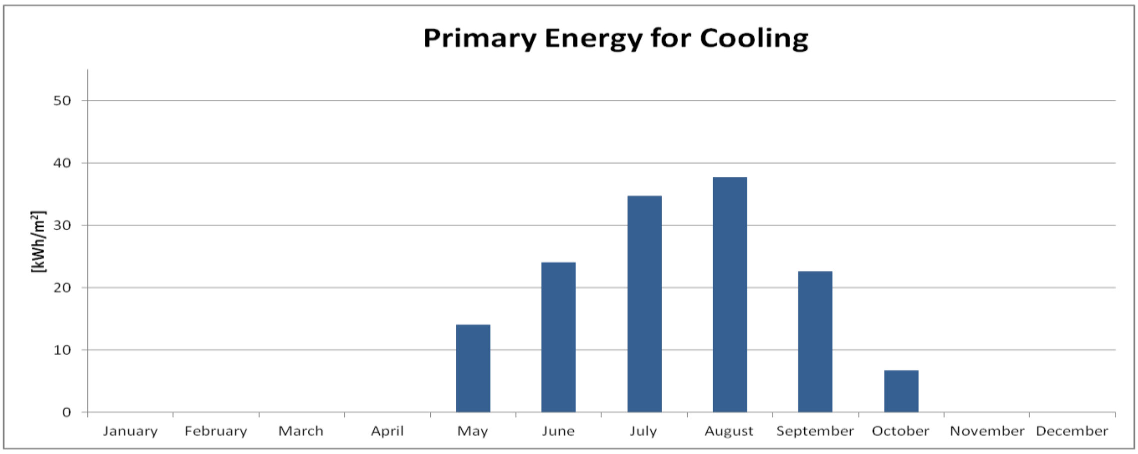

Figure 3. 20: Monthly demand of primary energy for cooling

Considering the RBh, representative of new constructions, the entire electricity demand is fulfilled by the national electricity grid. Therefore, in Figures 3.18÷3.20 the average efficiency of the national thermal-electric system was taken into account which is equal to $\eta_{EG} = 0.46$.

Referring to the energy demand for micro-climate control and production of domestic hot water - bringing thermal and electricity demands upstream production and conversion systems - Figure 3.21 reports, on a monthly basis, energy demands for:

- Heating, production of domestic hot water;
- working of the cooling plant;
- humidification (with steam, through electrical resistance)
- auxiliaries working, and therefore pumps and fans.

It can be noted how, at least referring to peak months during winter and summer, the demand for summer air-conditioning is greater than the winter one. During winter, also the consumption of energy for humidification is significant. Finally, also the energy demand for auxiliaries' working is not negligible, representing, during the warmest and coolest months, about a eighth of the primary energy demand for air-conditioning.

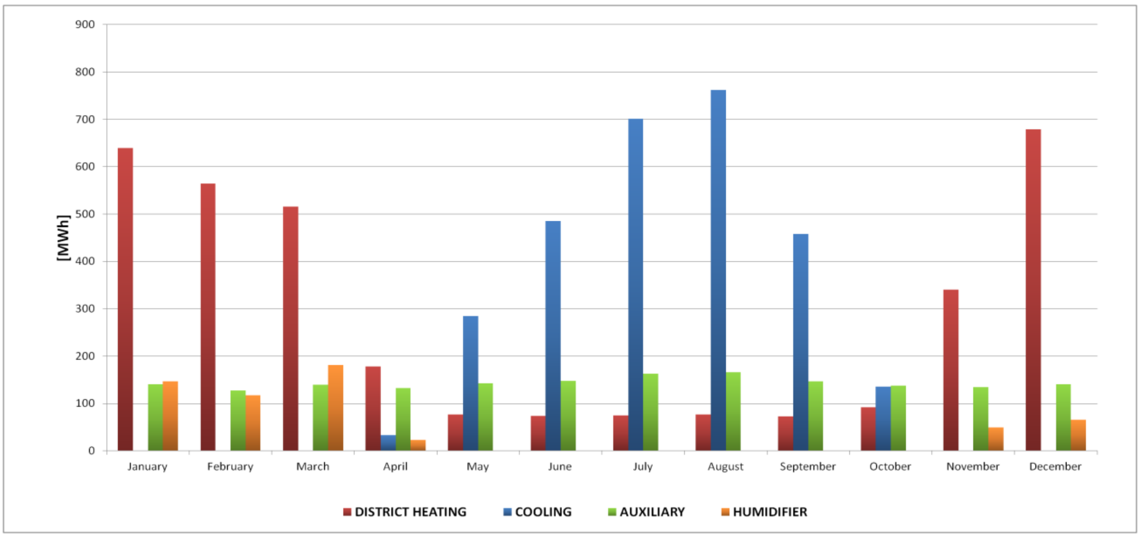

Figure 3. 21: Monthly demand of primary energy for environmental air-conditioning (all uses)

Chapter 4. Reference Building: Cost optimal analysis

4.1 Introduction

An efficient architectural envelope (in containing heat losses, reducing the effects of impulsive variability in external and endogenous loads, in limiting temperature's variation), adequate air-conditioning systems (in the functions of required micro-climate stability, quality and quantity of ventilation, filtration efficacy and treatment of adequate flow rate to guarantee healthiness), energy conversion systems and proper transport of thermal fluids are all fundamental aspects for energy saving and the micro-climate control requested by hospital construction industry.

As highlighted by the results reported by [57], the energy requalification of the architectural envelope is the starting point of the optimization of an existing hospital's energy performances. Indeed the envelope's resistance and thermal inertia contribute to the determination of stable and controllable indoor micro-climate conditions, they also energy savings that can even be significant, especially in case of architectural obsolescence. However the key for energy saving is an accurate design of the air-conditioning system, since the mainly "energy-intensive" aspect in this sector is the high ventilation load and the related humidity control, due to high air changes which are also strongly different according to the use classification that can be identified in a hospital.

As regards the architectural envelope, the use of traditional technologies - such as external wall insulation and the adoption of better performing transparent elements - may be a good solution, both for energy saving and the achievement of a greater micro-climate stability. However, the achievable energy savings are significant only if referred to the demand related to the architectural envelope and to the infiltration load, whereas, also taking into account the ventilation load, the main role is played by air-conditioning systems' requalification.

Therefore, referring to the existing hospital stock, it is rather difficult to understand which energy efficiency solutions have to be investigated in order to achieve energy savings. What is more convenient from an energy and economic point of view? How optimize the architectural envelope if poorly performing? How energy production systems can be improved? To what extent evaluate possible integrations with renewable sources?

In this section an original methodology to identify optimal performance levels with a multi-objective approach will be explained, referring to different packages of energy efficiency. Overall nine requalification interventions will be analyzed which involve the integration of existing systems with renewable sources, the optimization of the architectural envelope's and systems' performances.

4.2 Multi-objective Optimization

The building sector represents, at EU level, about 32% of the final energy demand and almost 40% of the primary energy request and thus it is very energy-intensive. In this scenario, the recast version of the Energy Performance of Buildings Directive 2010/31/EU [5] establishes a general framework to evaluate buildings' energy performances, and it introduces a comparative methodology “with a view to achieving cost-optimal levels” [9]. In more detail, packages of energy efficiency measures (EEMs) that minimize the global cost should be selected through cost-optimal analysis, considering a building's entire lifecycle. It is not possible to apply this type of analysis to each single building, therefore there is the need to define a set of reference buildings (RBs) [60] that represent the national stock, as it was previously done but with different aims [61, 62].

Within this context, the scientific community involved in buildings' energy modeling is trying to answer a new question, which concerns how to perform the cost-optimal study in order to obtain rigorous outcomes.

In recent years, the combination of BPS tools and optimization programs has been the topic of many studies, which aimed at improving optimization algorithms, above all to decrease the required computational time and CPU resources. At the present date, there are several algorithms available, which are usually classified as local or global methods, heuristic or meta-heuristic methods, derivative-based or derivative-free methods, deterministic or stochastic methods, single-objective or multi-objective algorithms and many more. Researchers involved in buildings' energy performance tend to favor the use of derivative-free optimization routines [63], considering that a continuous or differentiable objective function does not exist and that, in many cases, the gradient information, even if obtained numerically from the model, is not accurate. Referring to derivative-free methods, the most widespread ones are genetic algorithms (GAs). Indeed, such method involves a class of mathematical optimization approaches that reproduce the natural biological evolution, as long as the processes of inheritance, selection, mutation and crossover provide an optimal population after a number of iterations (generations). The use of genetic algorithms has spread in the building simulation community, because these are capable of managing black box functions as BPS tools' ones. Moreover, there is a quite low probability that these methods converge to local minima, without ensuring the optimal solution, but producing, in a reasonable time, a good solution (sub-optimal) which is also close to the optimal one. In addition, referring to the building sector, GAs allow more appropriate multi-objective optimizations compared to single-objective's ones. Indeed, there is often the need of dealing with conflicting goals at the same time; for this reason, a holistic and integrated team approach is required for high performance buildings [64]. The multi-objective optimization is usually necessary in building applications because, even with well-coordinated researches, it is difficult to find the optimal solution that allows to perfectly satisfy all identified necessities.

The main goal is the identification of the so-called ‘Pareto front’, and thus the set of non-dominated solutions. Referring to buildings' efficiency, usually only two objective functions are defined by researchers in order to avoid problems that are too complex, such as carbon dioxide equivalent emissions and investment cost [65], carbon dioxide equivalent emissions and life cycle cost [66], energy demand and thermal comfort [67-70]. In few cases, three objectives are defined, such as energy demand, carbon dioxide equivalent emissions, investment cost [71], or energy demand, thermal comfort and investment cost [72].

This chapter illustrates a new methodology to perform the cost-optimal analysis of EEMs, which can be applied to new or existing buildings. The study is based on a multi-objective optimization procedure (energy demand and cost of investment) which implements a GA and combines EnergyPlus [73] and MatLab [74]. The coupling strategy will also be illustrated, after that the methodology is applied to the evaluation of the cost-optimal solution in the design of the refurbishment of the Hospital Reference Building representative of Italian hospitals built before-2005.

4.3 Metodology

The new proposed approach, based on the multi-objective optimization, can be used both for the evaluation of the cost-optimal solution referring to the energy refurbishment of existing hospital or, by considering RBs, it can also be applied to new ones. This method combines EnergyPlus and MatLab. The former has been chosen as BPS tool for two main reasons: a) on one hand, this program allows to model both building and HVAC systems in a reliable way, and, on the other hand, b) EnergyPlus works with text-based inputs and outputs, which make the interaction with optimization algorithms easier. According to [75], EnergyPlus is probably the most used “whole building energy simulation program” [73] for research on buildings' optimization. There are several studies proving its reliability in predicting buildings' and facilities' energy performance. Obviously, to achieve reliable results, it necessary to properly define models and also to possess expertise in the assignment of all boundary conditions (starting from the selection of the heat transfer's solution algorithms). In a similar way, MatLab was selected as the optimization ‘engine’ for the following two main reasons: a) it has a remarkable capability, which allows to carry out the multi-objective optimization using GAs and, moreover, b) it can automatically launch EnergyPlus as well as manage both input and output files.

The following paragraphs fully describe the methodology which, as a generic optimization process [75], can be subdivided in three main phases: 1) formulation of the optimization problem, 2) optimization phase and 3) post-processing phase.

4.3.1 The formulation of the optimization problem

The current paragraph describes the combination of the BPS tool and the optimization program and it also defines the formulation of the optimization problem. The latter is really significant since it involves the boundaries between building science and mathematical optimization and therefore it requires a satisfactory expertise in both fields. First of all, by creating a text-based format input file (.idf), the existing building or the reference building (i.e., in case of new constructions) is defined in EnergyPlus, both for what concerns the thermal envelope and the HVAC system. Then, after a proper sensitivity analysis [76] or a detailed study of the system, the parameters that affect the most the energy performance can be identified as design variables. However, to perform this selection a satisfactory expertise in matter of energy efficiency in buildings is required.

Each variable assumes a value that corresponds to a design decision and this can be related to the envelope (e.g., insulation thickness, type of windows), the heating and cooling systems (e.g., kind of heat emitters, boilers, chillers) or the operation (e.g., usage of the building, defined through a set of schedules)..

Afterwards, by replacing the current unique value, defined for the base building, with a set of values depending on the designer's decisions, each selected design variable is parameterized in the aforementioned .idf file. The proper coupling between EnergyPlus and MatLab is ensured by enconding the i-th parameter with a string of ni bits, in this way it can assume 2ni different discrete values. For example, if a design variable is represented by the thickness of a vertical wall's insulation which can assume four values, this variable will be encoded with a string of two bits. Therefore, a generic configuration of the system, which is defined by a number of values of the parameters, can be represented by a vector x of $\sum_{\mathbf{i=1}}^{\mathbf{N}} \mathbf{n_i}$ bits, where N is the number of design variables. The formulation is reported in equation (4.1).

$$\underline{\mathbf{x}} = \Big[\underbrace{x_1, \dots, x_{n_1}}_{\substack{\textit{encoding of the} \\ \textit{first decision variable}}}, \dots\dots, \underbrace{x_{(\sum_{i=1}^{N} n_i)-n_N+1}, \dots, x_{\sum_{i=1}^{N} n_i}}_{\substack{\textit{encoding of the} \\ \textit{last decision variable}}}\Big] \quad \textit{with } x_j = \begin{cases} 0 \\ 1 \end{cases} \textit{for} \quad j = 1, \dots\dots, \sum_{i=1}^{N} n_i$$

eq.(4.1)

It is extremely important to highlight that the discrete values, that can be assumed by the chosen parameters, must be carefully selected, basing on energy and economic considerations that derive from an appropriate expertise. Using proper discrete variables allows the optimization algorithm to converge quickly, without affecting the accuracy and the generality of the method. Moreover, the adoption of discrete values is more realistic, considering that the construction industry is usually characterized by a limited number of design solutions, depending on commercial availability.

The proposed methodology aims at finding the set of the values that decision variables should assume to optimize various objective functions. Considering that a building's design has to take into account, simultaneously, different competitive criteria, such as the demand, the thermal comfort, the investment costs and the emissions of $CO_{2\text{-equivalent}}$ during the building's operation, the multi-objective approach was considered as more suitable and relevant compared to the single-objective one. Some of these objectives are conflicting. In this regard, both the energy requests for the microclimatic control and the investment costs will be considered, even if the developed method can be applied to several other objective functions.

The first objective is the minimization of primary energy required by the air-conditioning system, per unit of floor area, indicated with the acronym EP [kWh/m^{2}a] and calculated through equation (4.2).

$$EP=\frac{E_{heating}+E_{cooling}}{A} \qquad \text{eq.(4.2)}$$

In the equation (4.2), $E_{Heating}$ and $E_{Cooling}$ are the annual primary energy demands respectively for the space's heating and cooling, and A is the conditioned building's area.

Referring to the investment costs, this objective is identified with the acronym C and is calculated using the equation (4.3).

$$\boldsymbol{C} = \sum_{i}^{n} \mathbf{C_i} \qquad \text{eq.(4.3)}$$

In the equation (4.3), Ci is the initial investment cost associated to the value assumed by the i-th decision variable, which is encoded by a string of bits in the vector x.

Therefore - once design variables and objective functions are defined - the proposed multi-objective programming problem assumes the mathematical formulation shown below.

$$\begin{cases} \min \ F(x) = [EP(x), C(x)] \\ \underline{\mathbf{x}} = \left[\mathbf{x_1}, \dots, \mathbf{x_{n_1}}, \dots \dots, \mathbf{x}_{(\sum_{i=1}^{N} n_i) - n_N + 1}, \dots, \mathbf{x}_{\sum_{i=1}^{N} n_i}\right] \quad \text{with} \quad \mathbf{x_j} = \begin{cases} 0 \\ 1 \end{cases} \ \mathbf{for} \ \ \mathbf{j = 1, \dots \dots, \sum_{i=1}^{N} n_i} \end{cases}$$

4.3.2 Optimization phase

The multi-objective programming problem is solved by properly setting and running the optimization program, which provides the Pareto front; this is a very delicate phase because it affects both results' reliability and accuracy.

Since the optimization algorithm is implemented in MatLab whereas objectives' evaluation needs the use of EnergyPlus, a communication between these two programs is required. Therefore, a coupling function was written in MatLab environment, in order to convert the vector of encoded decision variables x into an EnergyPlus input file (.idf) and also to properly convert an EnergyPlus's output file (.csv) into the objectives' vector F. This allows to achieve the communication between the two software and to solve the optimization problem.

It is important to highlight that MatLab sees EnergyPlus as a black box functions' generator, thus the gradient information is not available [77]. For this reason, it is recommended to use heuristic and iterative optimization algorithms. The use of these methods does not guarantee that the true Pareto front will be obtained after a finite number of iterations, even if they allow to obtain a proper sub-optimal Pareto front, with reasonable computational times and required CPU resources. A controlled elitist genetic algorithm is used in the proposed methodology to optimize the aforementioned objective functions. This algorithm is a variant of NSGA II [78] and, since it ensures a higher diversity in the population, it allows a more reliable evaluation of the Pareto front compared to the original one. In more detail, this consists of a stochastic evaluation-based method, which is founded on the iterative evolution of a population of individuals: the so-called chromosomes. Referring to our scopes, these are the several possible configurations of a building. Therefore, each chromosome corresponds to a possible building's layout and it is encoded by a set of values of the vector x, whose components are called ‘genes’. The genes of some chromosomes are combined and/or mutated at each iteration (called ‘generation’), in order to obtain new ones, characterized by improved values of the objective functions. This procedure goes on until ‘a stop criterion’ is satisfied. The ultimate result is the Pareto front. In more detail, the following scheme reports the proposed procedure performed by the optimization algorithm, where τ indicates the number of generations.

τ = 1

Create the initial population P(1) ≡ { xi(1) }i=1, …,s of s individuals

Calculate F(xi(1)) for i=1, …,s

Evaluate the rank value and the average crowding distance for each individual of P(1)

DO UNTIL at least one stop criterion is satisfied

τ = τ + 1

Select the parents from P(τ-1)

Generate P(τ)≡ { xi(τ) }i=1, …,s from crossover and mutation of the parents: elite parents survive

Calculate F(xi(τ)) for i=1, …,s

Evaluate the rank value and the average crowding distance for each individual of P(τ)

END

Return the Pareto front

A creation function randomly generates an initial population of s individuals, then the objective functions related to each individual are evaluated. Each individual is characterized by a non-dominated ranking, based on the values assumed by the objectives, and a mean crowding distance. An individual has a lower ranking compared to another one if the first dominates the second. In addition, the crowding distance of an individual represents a measure of how much it is distant from another one in the space of the objective functions (phenotype): the higher the distance, the higher the diversity in the population. Furthermore, by applying a binary tournament selection that uses the low ranking number as first criterion and the high crowding distance as second one, some individuals are chosen within the population and are called ‘parents’. This procedure allows to ensure the diversity of the population. The next generation of individuals includes the best parents, which are part of the so-called ‘elite’, and by the ‘children’, that derive in part from the crossover and in part from the mutation of the parents. The composition of the new generation derives from a function of the values of the elite count (ce), which is the number of surviving parents, and of the crossover fraction (fc), which is the fraction of the population created using the crossover. In more detail, a crossover function was also written to ensure that each child randomly inherits some design variables (i.e., some strings of bits) from one parent and the other ones from the second parent. In addition, a mutation function was written to obtain a mutated child from a randomly selected parent, by changing each bit with a mutation probability fm. It is important to highlight that the mentioned functions are defined in order to ensure that the offspring respects the budget constraint (which is included in such functions).

Only if one of the following 'stop criteria' is satisfied the 'Darwinian' evolution of the population stops:

- the maximum number of generations (g_{max}) is reached;
- the average change in the spread of the Pareto front is lower than the tolerance (e).

Here the previously discussed GA's control parameters are set as shown in table I. These values were chosen on the basis of expertise, previous authoritative studies [79, 80] and according to some tests carried out to obtain the best trade-off between computational time and reliability of the Pareto front.

s	c_e	f_c	f_m	g_{max}	e
30	2	0.6	0.1	30	0.001

Table 4. 1: Setting of the control parameters of the Genetic Algorithm

4.3.3 Post-processing phase

The next step features the analysis of the Pareto front which also needs to be interpreted in order to select a solution, e.g. the set of values that design variables should assume to satisfy all stakeholders.

In more detail, using the 'multi-criteria decision-making' a recommended solution is identified for the Pareto front obtained through the optimization phase. This process can be carried out using different techniques [75] and in this case the minimum global cost one is used. In more detail, the global cost for the entire building's lifecycle is calculated referring to each package, such calculation is performed according to the European Commission Delegated Regulation [9], which was published after the EPBD recast. For residential buildings, a calculation period of 30 years is used. The cost-optimal solution is identified by the package characterized by the lowest value of the global cost.

In the next section the developed methodology for the cost-optimal evaluation is applied to a case study analyzed as an example.

4.4 Cost Optimal Analysis

In the starting configuration (before the energy retrofit) the Reference Building is characterized by a value of the primary energy useful to environments' micro-climate control equal to 481.6 kWh/m^{2}a. It is therefore clear that the investment cost in the basic configuration is equal to zero.

Later, the previously illustrated methodology was used to identify the cost-optimal solution, in case of an energy-oriented refurbishment. After a preliminary study of the existing hospital building and of the possible EEMs [53,55], the following energy refurbishment measures were considered in the optimization study, because they are the ones that mainly affect the energy performance of the building:

- Installation of a low-absorptance (low-a) roof's external coating (i.e., high-reflective), in order to reduce heat gains by changing radiative characteristics.
- Installation of a vertical walls' low-absorptance (low-a) external coating (i.e., high-reflective), in order to reduce heat gains by changing radiative characteristics,.
- Installation of a roof's external insulation, using rockwool panels.
- Installation of a vertical envelope's external insulation, using expanded polystyrene (EPS).
- Replacement of the single glazed windows with low-emissive double glazed ones.
- Replacement of the air-cooled chiller with a water-cooled one (COP = 4.0), with the consequent installation of a well-sized cooling tower.
- Installation of a photovoltaic collectors field.
- Installation of a thermal solar collectors field.
- Installation of heat recovery systems in the HVAC systems.

The design choices comply with local construction standards. Therefore, the following design variables were identified (please note that, as recommended by Wetter [32], the number is in the range of 10):

1. roof's solar radiation absorption coefficient (ar)
2. vertical walls' solar radiation absorption coefficient (av);
3. thickness of roof's insulation (t_r);
4. thickness of vertical walls' insulation (t_v);
5. window: single/double glazed (w_t);
6. chiller: air- or water-cooled (CH_t);
7. size of PV collectors (Pv_s);
8. size of solar collectors (Ps_s);

9. heat recovery system ($HR_{\%}$).

The values that each variable may assume and the related investment costs (if present) are reported in table 4.2, which also shows the configuration of the base building. Investment costs values were obtained through quotations from suppliers and according to the typical Italian market.

It is important to note that, as known, a building's energy efficiency can be achieved through: a) a proper design of the thermal envelope, b) efficient systems and equipment for micro-climate's control (equipped with suitable thermal generation devices for both heating and cooling) and c) using a proper on-site energy conversion by renewable sources.

For an existing building, the third strategy which is the installation of renewable energy systems, is referred to the refurbishment of the building's envelope and of the heating/cooling system. Indeed, the use of renewable sources would represent a way to compensate for the high energy demand of the current building, using a clean energy conversion but not erasing the waste of energy due to the poor performance of the building itself.

On the other hand, in the case of refurbished architectures, the clean energy conversion from renewable sources could have other uses, such as indoor lighting or electrical devices' operation. For this reason, in the present case study, the attention was aimed at the architectural envelope's and HVAC system's renovation, which represented a priority also for its effect on thermal comfort. In any case, a following optimization of renewable sources that is possible to install is recommended and the methodology here proposed can be also used for this scope.

	Design Variables	Option Values	Base Building	Investment Costs [€]
1	a_r	0.05		77841
		0.70	●	-
2	a_v	0.05		147916
		0.70	●	-
3	t_r	0 cm (U_r = 1.5 W/m^{2}K)	●	-
		1 cm (U_r = 0.951W/m^{2}K)		52396
		2 cm (U_r = 0.696 W/m^{2}K)		44311
		3 cm (U_r = 0.549 W/m^{2}K)		56637
		4 cm (U_r = 0.453 W/m^{2}K)		68963
		5 cm (U_r = 0.386 W/m^{2}K)		81290
		6 cm (U_r = 0.336 W/m^{2}K)		84965
		7 cm (U_r = 0.298 W/m^{2}K)		88640
		8 cm (U_r = 0.267 W/m^{2}K)		92316
		9 cm (U_r = 0.242 W/m^{2}K)		95991
		10 cm (U_r = 0.222 W/m^{2}K)		99666
		11 cm (U_r = 0.204 W/m^{2}K)		103342
		12 cm (U_r = 0.189 W/m^{2}K)		107017
		13 cm (U_r = 0.176 W/m^{2}K)		110692
		14 cm (U_r = 0.165 W/m^{2}K)		114367
		15 cm (U_r = 0.155 W/m^{2}K)		118043
4	t_v	0 cm (U_v = 0.717 W/m^{2}K)	●	-
		1 cm (U_v = 0.567 W/m^{2}K)		139760
		2 cm (U_v = 0.471 W/m^{2}K)		144890
		3 cm (U_v = 0.404 W/m^{2}K)		150020
		4 cm (U_v = 0.353 W/m^{2}K)		155151
		5 cm (U_v = 0.313 W/m^{2}K)		160281

		6 cm (U_v = 0.282 W/m^{2}K)		165411
		7 cm (U_v = 0.256 W/m^{2}K)		170541
		8 cm (U_v = 0.235 W/m^{2}K)		175672
		9 cm (U_v = 0.216 W/m^{2}K)		180802
		10 cm (U_v = 0.201 W/m^{2}K)		185932
		11 cm (U_v = 0.187 W/m^{2}K)		191062
		12 cm (U_v = 0.176 W/m^{2}K)		196193
		13 cm (U_v = 0.165 W/m^{2}K)		201323
		14 cm (U_v = 0.156 W/m^{2}K)		206453
		15 cm (U_v = 0.148 W/m^{2}K)		211583
5	W_t	Double glazed (Uw = 3.2 W/m2K)	●	-
		double glazed low-e (Uw = 1.69 W/m2K)		168904
6	CH_t	air-cooled (COP=2.7)	●	-
		water-cooled (COP=4)		793533
7	Pv_s	0 kW	●	-
		26 kW		32523
		53 kW		65045
		79 kW		97568
		106 kW		130091
		132 kW		162613
		159 kW		195136
		185 kW		227659
		212 kW		260181
		238 kW		292704
		265 kW		325227
8	Ps_s	0 kW	●	-
		38 kW		30156
		76 kW		60312
		114 kW		90469
		151 kW		120625
		189 kW		150781
		227 kW		180937
		265 kW		211093
		303 kW		241250
		341 kW		271406
		378 kW		301562
9	$HR_{\%}$	no heat recovery (%rec.=0)	●	-
		heat recovery (%rec.=100)		100000

Table 4. 2: Option values and associated design variables' investment costs

For an existing building another possible strategy is the installation of renewable energy systems which is referred to the refurbishment of the building's envelope and of the heating/cooling system. Indeed, the use of renewable sources would represent a way to compensate for the high energy demand of the current building, using a clean energy conversion but not erasing the waste of energy due its poor performance.

On the other hand, in case of refurbished buildings, the clean energy conversion from renewable sources may have other uses, such as indoor lighting or electrical devices' operation. For this reason, in the present case study, the attention was focused on the architectural envelope's and HVAC system's renovation, which represented a priority also for its effect on thermal comfort. In any case, a following optimization of renewable sources that is possible to install is recommended and the methodology here proposed can be also used for this purpose.

4.4.1 Results and Discussions

In figure 4.1, the Pareto front is reported which is characterized by 16 not dominated optimal solutions. The values assumed (x_i) by the design variables corresponding to these recommended packages are reported in table 4.3.

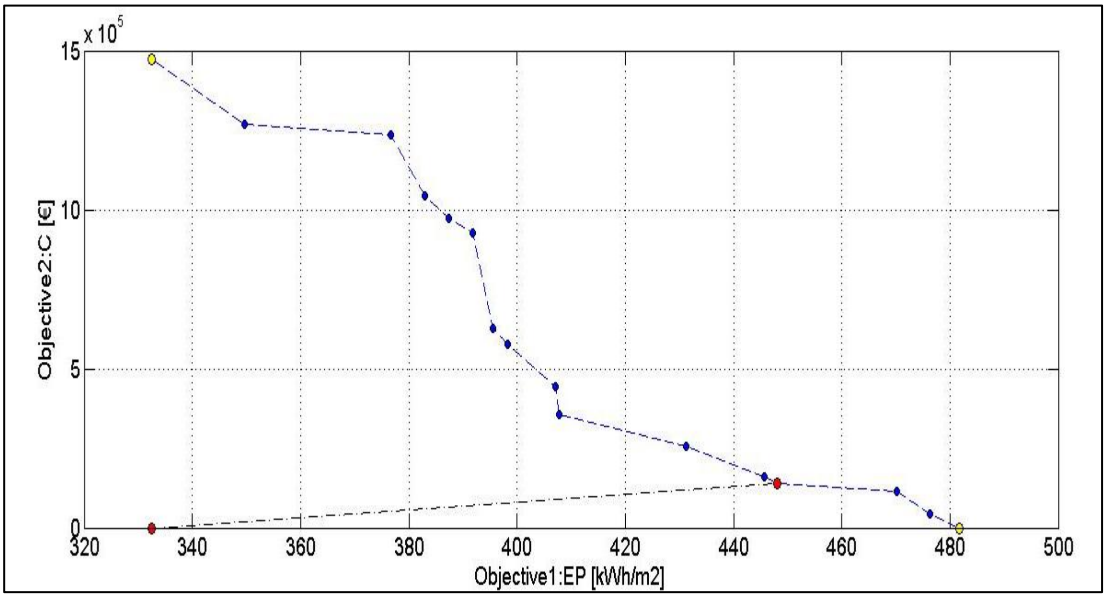

Figure 4.1: Pareto's front

x_i	t_r [cm]	t_v [cm]	a_r [cm]	a_v [cm]	w_t	CH_t (COP)	$HR_{\%}$	Pv_s [kW]	PS_s [kW]
1	14	0	0.7	0.7	1	4	0	0	215.7
2	14	0	0.7	0.7	0	2.7	0	0	0
3	0	0	0.7	0.7	0	2.7	0	0	189.2
4	2	0	0.7	0.7	0	2.7	1	74.2	189.2
5	2	0	0.7	0.7	0	2.7	0	74.2	189.2
6	0	0	0.7	0.7	0	2.7	0	0	215.7
7	0	0	0.7	0.7	0	4	1	37.1	0
8	14	0	0.7	0.7	0	4	1	37.1	0
9	2	0	0.7	0.7	0	4	1	37.1	0
10	0	2	0.7	0.7	0	4	1	74.2	215.7
11	11	8	0.7	0.7	0	2.7	1	74.2	242.2
12	4	0	0.05	0.7	0	2.7	1	0	268.7
13	2	0	0.7	0.7	0	2.7	0	0	0
14	11	2	0.7	0.7	0	2.7	1	74.2	215.7
15	4	6	0.05	0.7	0	4	1	111.2	215.7
16	0	0	0.7	0.7	0	2.7	0	0	0

Table 4. 3: Optimal design variables' values

It is possible to observe (see table 4.4) that all the solutions – points on the Pareto front – determine a significant improvement compared to the base building's conditions (EP_{BB} = 481.6 kWh/m^{2}a).

x_i	Investment Costs [€]	EP [kWh/m^2]	EEMs'Global Cost [€/m^2]
BB	0	481.6	1005
1	1'236'547	376.6	956
2	114'367	470.2	986
3	140'125	448.0	970
4	354'996	407.7	940
5	254'996	431.2	949
6	159'743	445.7	970
7	928'813	391.7	945
8	1'043'180	383.0	951
9	973'124	387.4	948
10	1'268'726	349.6	958
11	628'934	395.5	934
12	445'782	407.1	937
13	44'311	476.2	996
14	578'535	398.3	934
15	1'471'331	332.5	966

Table 4. 4: Objective functions and global cost values for each Pareto' point

As reported in paragraph 4.3.3, once the Pareto points are known, it is necessary to identify the optimal solution among them: in the examined case it was decided to consider the minimum global cost calculated in compliance with the European guidelines [9] and related to the different Pareto's EEMs. Investment costs were defined according to the current market (national reference price lists) and national financial incentives [26].

In figure 4.2 the results of the cost optimal analysis are reported and it is possible to observe the optimal solution which determines the minimum global cost calculated on a 30 years period.

The optimal solution - indicated in the table as P14 - includes an improvement of both the architectural envelope's and systems' performances. To this end, it was possible to identify the presence of both the roof's and vertical envelope's insulation (respectively 11 cm and 2 cm); moreover, as regards the improvement of systems' efficiency, the optimal solution suggests the installation of both photovoltaic (74.2kW) and solar collectors (215.7 kW). The results obtained are consistent with [57,58], indeed due to investment cost it is better to insulate the roof, obviously such circumstance loses its relevance when the shape ratio increases, in which case it is more convenient to insulate the vertical envelope.

From a system point of view, starting from the assumption that a hospital requires during a year always thermal energy for the production of DHW and electricity, it is appropriate the presence in the optimal solution of a photovoltaic and a solar thermal plants which reduce the required loads.

Moreover, it was right to expect the presence of heat recovery systems coherently with high ventilation loads which characterize hospitals.

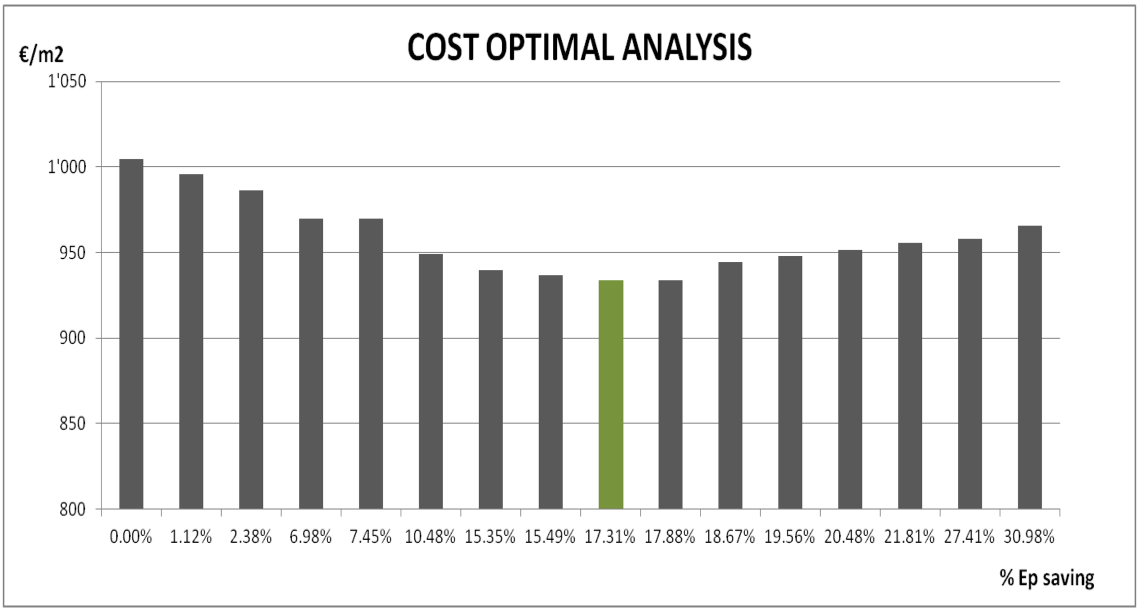

Figure 4.2: Cost optimal analysis: choice of best solution

Referring to figure 4.2 the optimal solution involves a global cost per square meter equal to 934 € and a percentage reduction of primary energy for winter and summer air-conditioning equal to 17.31%.

Chapter 5. A real hospital case study: " D Pavilion - A.Cardarelli"

5.1 Introduction

In this chapter, the analisys of D Pavilion's energy performances is described, which houses the Department of Gastro-enterology of the Nationally Relevant Hospital "A. Cardarelli".

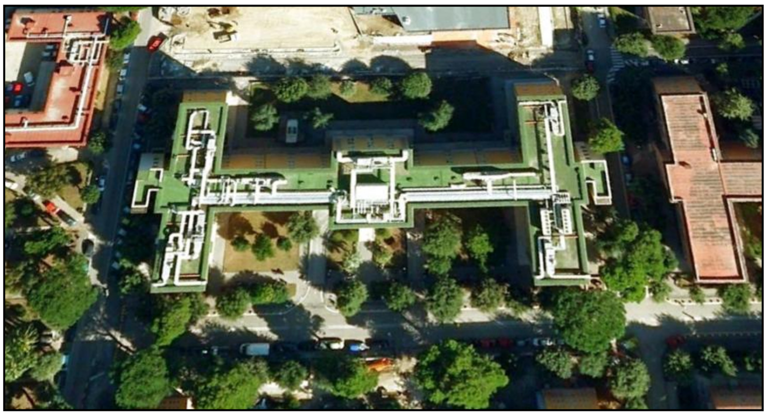

Figure 5. 1: Top view of the D Pavilion

It is characterized by a H shape (figure 5.1) and side wings oriented along the North-South axis. it consists of a 4 floors above-ground and one basement floor. In table 5.1 information related to the subdivision of wards on each floor are reported.

FLOOR	D PAVILION' S WARDS
-1	Gastrointestinal Endoscopy, Treatment Rooms, Day Hospital, Transplanted Treatment Rooms, Changing Rooms, Technical Rooms
0	Hepatology, Multimedia room
1	Gastro-enterology, Gastro-enterology Surgery
2	Laparoscopic Surgery, Hepatic Specialized and Liver Transplantation Centre, Hepatobiliary Surgery and Liver Transplantation Centre
3	Anesthesia and General Post-Operative Intensive Care, Anesthesia and Liver Transplantation Centre Post-Operative Intensive Care, Operating Block

Table 5. 1: Subdivision of floors and wards of the D Pavilion

Figure 5. 2: SOUTH Elevation of the D Pavilion

Figure 5. 3: NORTH Elevation of the D Pavilion

The building has a gross projection on the ground of about 2026 m^2, for a total useful floor area (taking into account the 4 above-ground floors and one partly buried) equal to 8886 m^2. The maximum height of the building is about 21 m and the gross volume is 42'140 m^3. The South and North elevations are showed in 5.3 and 5.4.

5.2 Energy Audit

In the current section, the set of documentary, on-site and experimental studies carried out on the envelope and systems of the D Pavilion will be reported, starting from the thermo-physical characteristics of boundary elements to get to the description of active systems, including both short accounts on production substations and on processes and devices for microclimate's control.

5.2.1 Thermo-physics of the architectural envelope

In the following paragraph, thermo-physical characteristics of the vertical and horizontal architectural envelopes are illustrated, firstly through the evaluation of the their stratigraphy, then using heat flux meters and infrared thermography, on the abovementioned elements.

a) Envelope composition

The current architectural envelope of the D Pavilion consists of opaque and transparent elements, which main geometrical- thermo-physical characteristics are described in the following list:

External wall: single layer tuff brickwall variable between 0.60 m and 0.75 m; the wall is plastered on its internal and external sides and the plaster's thickness is respectively 0.015 m and .0.04 m (figure 5.4);

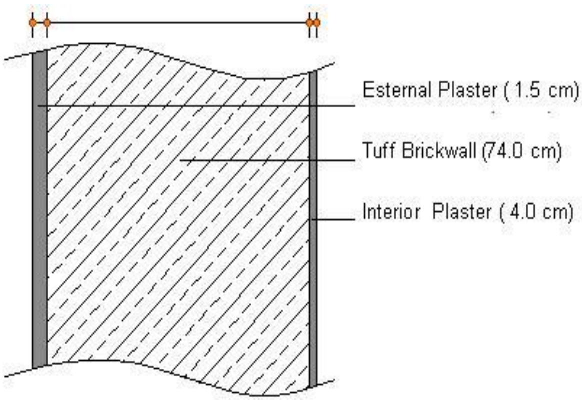

Figure 5. 4: External wall's section

Structure in reinforced concrete: the network of beams and pillars, immediately visible in the external elevation of the building, features a framework in reinforced concrete. The pillars' thickness is 50 cm, they are also plastered. Load-bearing structures reach the same thickness of tuff claddings. The network of beams and pillars do not show any type of thermal insulation and, in its current state, it therefore represents a significant element of heat loss, showing widespread thermal bridges that strongly influence energy demand.

Under window compartments: The current under window compartments are made of tuff cladding, they show a thickness reduction of about 20 cm compared to the current cladding.

Floor on the ground: not insulated concrete and masonry structure.

Roof structure: load-bearing element made of concrete and masonry, without thermal insulation. Presence, from the inside, of interior plaster 2 cm thick made of gypsum mortar and concrete, concrete and masonry layer with a structural interstice 6cm thick, screed bed and slopes. The overall calculated heat transfer coefficient is equal to 1.502 W/m^2K (figure 5.5).

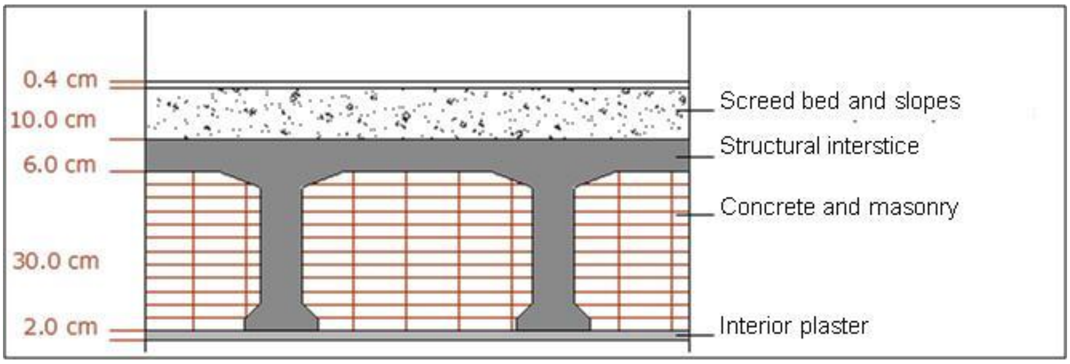

Figure 5. 5: Section of the structure of the concrete and masonry roof

The physical characteristics of the materials that constitute the roof of the D Pavilion are reported below:

Layer	λ (W/m^2K)	s (m)	R (m^2K/W)
Interior plaster	0.25	0.02	0.080
Concrete and masonry	---	0.30	0.410
Structural interstice 6 cm thick	2.50	0.06	0.024
Screed bed and slopes	0.65	0.10	0.154
Waterproof sheet	---	0.005	---
TOTAL		0.485	0.668

Table 5. 2: Characteristics of the D Pavilion's roof

Windows: clear double glazing 3/6/3, with air-filled chamber; aluminum frames without thermal break.

b) Heat flux measurements

Concerning the method used to measure the thermal transmittance of perimeter walls, tests were carried out with a heat flux meter, which is an instrument capable of providing reliable values of thermal conductivity, from which the required values of thermal transmittance can be derived.

The analyzed wall is illustrated in figure 5.6, it is located on the North side of the D Pavilion, and it was chosen to represent the building's perimeter. The measurement was performed inside an office located on the third floor of the building. The environment is air-conditioned both during daytime and nighttime, to allow the optimal working of the heat flux meter, which performances improve when ΔT between inside and outside increases. Temperature sensors were conveniently placed, so that direct solar radiation does not fall on them, since it would have invalidated the measurement's results.

Figure 5. 6: North side of the D Pavilion where the heat flux meter was placed

As it can be noted in picture, the measurement was performed on the wall and the heat flux meter was mounted on a section of the wall that was deemed suitable since it is representative of the whole room's state.

The duration of the measurements was about 3 days, from 11:00 of 18/01/2013 to 13.00 of 21/01/2013, with a data capture interval equal to 30 minutes, and, therefore, a number of measurements equal to 150. In the following table (Tab. 5.3) the measured values of heat flux, inside and outside temperatures are reported.

In figure 5.7, the trends inside of outside temperatures are showed; in figure 2.8 the heat flux's trend is illustrated.

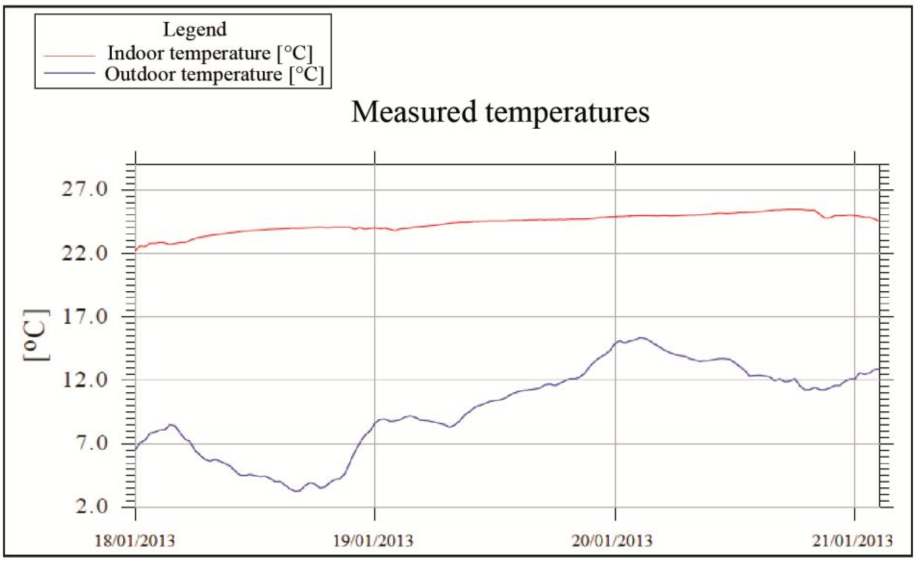

Figure 5. 7: Measured inside and outside termperatures' trends (measurement on the wall)

Q [W/m^2]	T_{ins}	T_{out}
1.04	22.22	6.49
3.72	22.57	7.08
2.61	22.53	7.29
8.21	22.78	7.81
4.92	22.78	7.93
8.74	22.86	8.07
4.94	22.81	8.11
4.06	22.68	8.5
7.49	22.77	8.41
6.65	22.85	7.85
7.41	22.85	7.37
10.4	23.02	7.16
11.53	23.17	6.47
11.32	23.26	6.1
11.05	23.33	5.76
11.1	23.4	5.62
11.2	23.45	5.76
11.35	23.5	5.62
11.52	23.55	5.45
11.7	23.6	5.26
11.71	23.65	4.87
12.04	23.71	4.53

Q [W/m^2]	T_{ins}	T_{out}
8.68	24.57	10.83
9	24.59	11.02
8.26	24.58	11.15
8.7	24.6	11.21
8.72	24.62	11.25
8.36	24.62	11.31
9.13	24.65	11.39
8.89	24.63	11.63
8.48	24.65	11.7
8.22	24.65	11.58
8.32	24.66	11.74
7.97	24.65	11.95
8.95	24.68	12.11
8.38	24.69	12.1
8.4	24.69	12.24
8.29	24.69	12.55
8.29	24.72	13.08
8.51	24.75	13.48
9.28	24.8	13.79
9.34	24.82	14.02
8.95	24.86	14.32
8.96	24.87	14.87

11.57	23.75	4.5
11.35	23.77	4.58
11.13	23.8	4.48
10.88	23.82	4.42
11.21	23.85	4.45
11.24	23.89	4.28
10.84	23.9	4.02
10.78	23.92	4.03
10.81	23.94	3.75
10.68	23.96	3.44
10.28	23.96	3.26
10.36	23.97	3.29
10.74	23.99	3.68
10.83	24.01	3.95
10.72	24.03	3.82
10.07	24.03	3.51
9.93	24.02	3.59
9.94	24.02	3.95
9.77	24.03	4.19
9.93	24.03	4.24

8.89	24.9	15.1
8.68	24.91	14.92
9.4	24.93	15.08
9.38	24.95	15.16
8.98	24.97	15.34
9.22	24.97	15.29
8.15	24.96	15.1
8.29	24.95	14.84
8.52	24.95	14.6
8.23	24.96	14.37
8.52	24.95	14.19
8.85	24.94	14.04
9.11	24.97	13.95
9.29	24.98	13.9
9.06	25.01	13.7
9.52	25.01	13.59
9.52	25.03	13.5
9.36	25.05	13.54
9.31	25.07	13.56
8.9	25.12	13.63

Q [W/m^2]	T_{ins}	T_{out}
10.11	24.04	4.65
9.55	24.04	5.51
7.41	23.9	6.37
10.52	24.02	7.07
6.59	23.9	7.67
9.8	23.96	8.01
9.96	23.99	8.61
7.93	23.95	8.9
9.22	23.97	8.94
5.62	23.89	8.76
6.28	23.77	8.79
8.21	23.91	8.88
8.89	23.95	9.09
9.19	23.99	9.19
9.58	24.05	9.09

Q [W/m^2]	T_{ins}	T_{out}
8.69	25.16	13.7
8.89	25.14	13.69
9.16	25.14	13.64
9.97	25.16	13.4
9.89	25.21	13.08
9.58	25.21	12.77
9.82	25.24	12.32
10.01	25.24	12.37
10.65	25.28	12.39
10.8	25.31	12.33
11.14	25.36	12.26
10.88	25.4	11.97
10.72	25.41	12.1
10.76	25.43	11.88
10.52	25.45	11.92

10.22	24.08	8.87
10.49	24.12	8.82
10.68	24.16	8.78
10.79	24.19	8.68
11.12	24.25	8.6
11.47	24.3	8.49
11.99	24.37	8.3
11.62	24.4	8.49
11.15	24.43	8.8
10.46	24.43	9.28
9.94	24.46	9.53
9.69	24.5	9.88
9.41	24.51	10.02
9.26	24.52	10.16
9.66	24.54	10.33
9.19	24.55	10.41
8.62	24.53	10.45
8.98	24.54	10.58
9.82	25.45	12.12
8.93	25.46	11.6
8.56	25.41	11.25
8.1	25.38	11.25
8.41	25.38	11.46
0.78	25.07	11.26
-0.51	24.77	11.24
3.63	24.78	11.4
6.69	24.95	11.58
6.03	24.97	11.58
6.01	24.96	11.89
7	25.01	12.08
6.48	24.96	12.09
4.82	24.92	12.58
3.73	24.82	12.47
5.34	24.82	12.57
2.84	24.7	12.84
1.14	24.51	12.89

Table 5. 3: Measured values of heat flux, inside and outside temperatures (under the window)

From the graphs and reports obtained from the processing software, it can be observed how the outside temperature's trend reproduces Naples' typical winter day: the outside temperature shows peaks greater than 12 °C, with minimum values of about 3 °C during nighttime. The average inside temperature is about 24 °C.

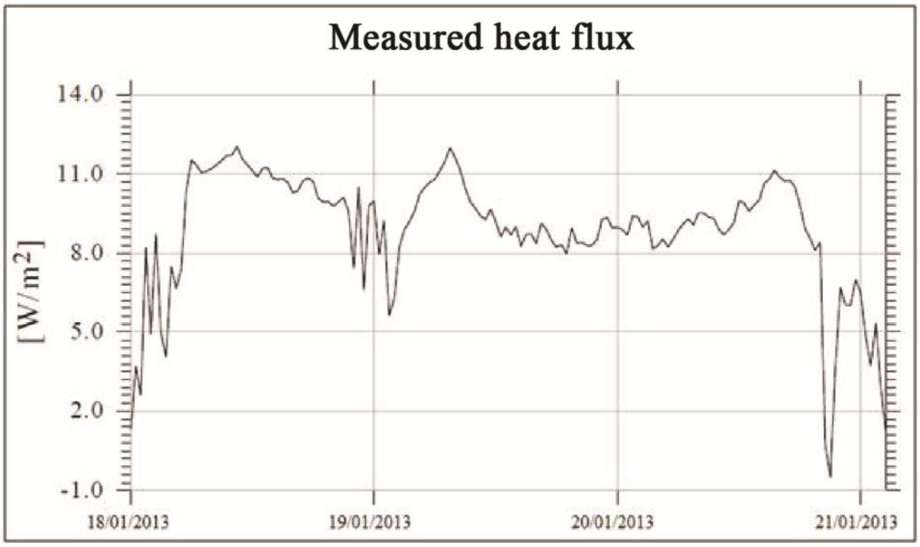

Figure 5. 8: Heat flux's trend

The high inside temperature, which deviates from the usual 20-21 °C in the civil construction industry, is related to the fact that the environment used to perform the measurement has a very reduced volume. Moreover, it was made impermeable to air infiltrations, both from outside, closing windows and venetian blinds, and from indoor environments, since it is not used by employees. The average outside temperature is about 10 °C. The average ΔT between inside and outside keeps itself around 15 °C, thus complying with the standard.

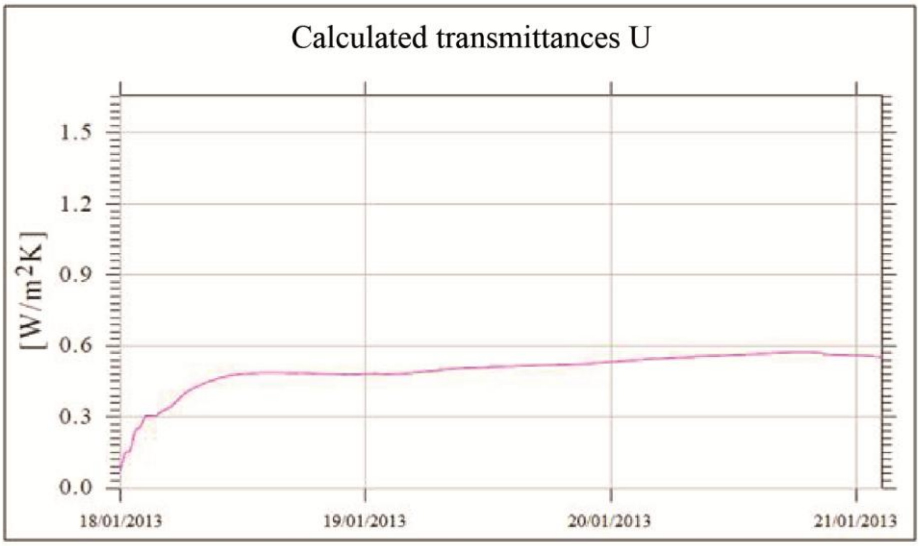

Figure 5. 9: Thermal transmittance U's trend

In figure 5.9, it is reported the trend of the calculated thermal transmittance which resulted equal to 0.553 W/m^{2}K; from the graph it is possible to observe how, even from the first day of measurement, this value converges.

As regards the other elements of the examined building, similar buildings were considered, built at the end of the eighties and located in the C climate zone, to which Naples belongs. In more detail, for the *roof* a thermal transmittance value equal to 1.171 W/m^{2}K was taken into account; and respectively equal to 3.159 W/m^{2}K and 9.5 W/m^{2}K for *glazings* and for the frames.

c) Infrared Thermography

In January 2013, a thermography of the D Pavilion was carried out, even if exclusively qualitative, aimed at identifying discontinuities of the architectural envelope.

The thermography technique allows, without contact, to acquire and analyze thermal/radiation related information of architectural elements. Therefore, thermography allows the two-dimensional "qualitative" visualization of the measurement of infrared radiation emitted by a surface and consequently the thermal distribution of analyzed objects and also possible irregularities.

The result of infrared photos is reported in figures 5.10 and 5.11, referred to front and rear elevations of the D Pavilion of the A. Cardarelli Hospital.

The heat loss bridge determined by the structural framework clearly emerges from the studies. Further reductions of thermal resistance can be found in the under-window compartments. Also in this case, as it will be showed for the L-DEA Pavilion, it the need to equip the building with an exterior insulation finishing system, not so much to reduce the overall thermal transmittance value, but rather to "homogenize", from a thermal point of view, heat transfer through the envelope.

Figure 5. 10: Photo of the thermography of the front elevation of the D Pavilion

Figure 5. 11: Photo of the thermography of the rear elevation of the D Pavilion

5.2.2 Register of systems

During surveys, the building-system interaction was characterized through the collection of the envelope's technical-architectural characteristics, of information on the different systems' technologies and on distribution grids as well as through the census of air-conditioning systems' terminals and of electric devices.

With specific reference to each thermal zone a census of installed luminaires and heat transfer terminals for environments' heating and cooling was carried out.

As an example in the following table are reported the results of the census and rationalization of the data collected in the field.

Thermal zone	Total floor area [m²]	ID Code	Number	Capacity [kcal/h]
Common area	878.13	RAD(01-07)-CORR-A-0-D	7	1097
		RAD(08-15)-CORR-A-0-D	8	853
		RAD(16-17)-CORR-A-0-D	2	610
		RAD(18)-CORR-A-0-D	1	523
		RAD(19)-CORR-A-0-D	1	488
		RAD(20-21)-CORR-A-0-D	2	610
		Tot	**21**	**17954**
Office	185.33	RAD(01)-DOCT-B-0-D	1	1097
		RAD(02)-DOCT-B-0-D	1	366
		RAD(03)-WC01-B-0-D	1	523
		RAD(04)-WC01-B-0-D	1	366
		RAD(05)-PHARM-B-0-D	1	628
		RAD(06)-AMB01-B-0-D	1	523
		RAD(07)-AMB02-B-0-D	1	628
		RAD(08)-WC02-B-0-D	1	366
		Tot	**8**	**4497**
Generic Ward	143.98	RAD(01)-WARD01-D-0-D	1	523
		RAD(02)-WARD01-D-0-D	1	366
		RAD(03)-WARD02-D-0-D	1	628
		RAD(04)-WARD02-D-0-D	1	366
		RAD(05)-WARD03-D-0-D	1	523
		RAD(06)-WARD03-D-0-D	1	366
		RAD(07)-WARD04-D-0-D	1	523
		RAD(08)-WARD04-D-0-D	1	366
		RAD(09-10)-WC-D-0-D	2	1097
		Tot	**10**	**5855**

Table 5. 4: Radiators' census

5.3 Modeling of the complex interaction building/system

The modeling of the interaction building-systems, in order to retrace energy demands for the space heating and cooling, can be performed through two different calculation methodologies: steady state and dynamic. Simulations that use a steady state approach refer to typical climate conditions of the examined location, and to average internal loads and solar radiation contributions.

On the contrary, the dynamic approach takes into account hourly climate variations, in addition to internal loads and solar radiation changes. In more detail, the accurate evaluation of the performances of the building-systems interaction, especially during summer, can only be performed referring to dynamic simulations; indeed, this tool is the only one that can take into account a building's thermal inertia and, therefore, its delayed response to changes in the outside climate.

The software EnergyPlus was chosen, to perform dynamic simulations of the building that is the target of this study. Such code, previously described, was used through an external graphic interface, to model the geometry, which is called Design Builder.

The modeling and the following simulation with EnergyPlus, can be subdivided in the following phases:

- choice of the location and of the building's orientation;
- development of the geometrical model and of the envelope's elements;
- definition of activity and operation parameters in the different zones of the building;
- choice of the period of time to use to perform the dynamic simulation.

Climate data are those reported in the ASHRAE database for Naples, completed by Italian standards' information/requirements. They are listed in table 5.5

Location	NAPLES
Latitude	40° 50’
Longitude	14° 18’
Altitude	72
Degree days	1034
Climate zone	C
Minimum Winter outside temperature	2
Conventional heating period	15 November- 31 March
Conventional heating period	As a function of internal and external loads

Table 5. 5: Naples' geographic and climate data

After the selection of climate and of the related parameters that describe the location, it was necessary to geometrically model the building and to characterize types and materials of the envelope's elements. In order to develop a model as accurate as possible, the plans of the different floors of the building were used; moreover, to precisely define the dimension and shape of all glazed surfaces, the elevations referred to the different exposures of the building were taken as reference.

The choice of types and materials of opaque and transparent elements was made easier by the presence, in Design Builder, of a well-provided database of every type of architectural elements. Moreover, it was possible, when necessary, to also include inside the database other materials, knowing their thermal conductivity, specific heat and density. In more detail, for perimeter walls the thermal resistance measured with the heat flux meter was used, whereas for other elements (roof and ground floor) the stratifications reported in the previous report delivered as a part of the activities established in the agreement were included. The same as been done for windows, which type was known as a result of surveys.

After completing the geometric modeling and the construction of the building's stratification, the parameters that characterize the activities carried out inside the different environments were set. The use classifications of the D pavilion are different, given the complexity of the functions carried out inside a health care facility. Therefore indoor environments were divided into different *thermal zones*, which differ between each other depending on the following parameters:

- density of people;
- type of activity carried out inside;
- set-point temperature (heating and cooling);
- air infiltration;
- lighting;
- presence of electro-medical equipment and devices.

To model the real loads, 48 thermal zones were created. In Figures from 5.12 to 5.15, the subdivision in zones of the building's floors is reported.

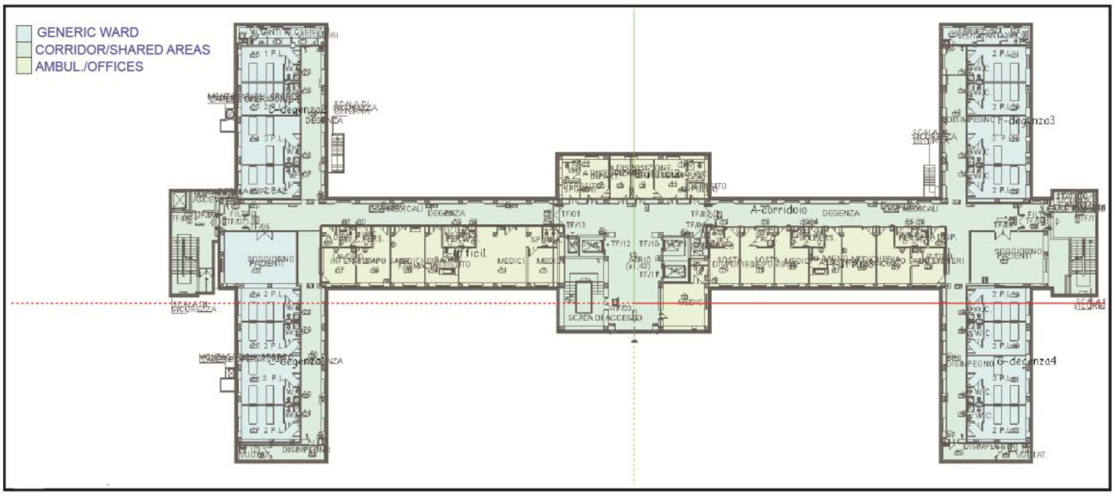

Figure 5. 12: Example of subdivision into zones in Design Builder. Ground floor

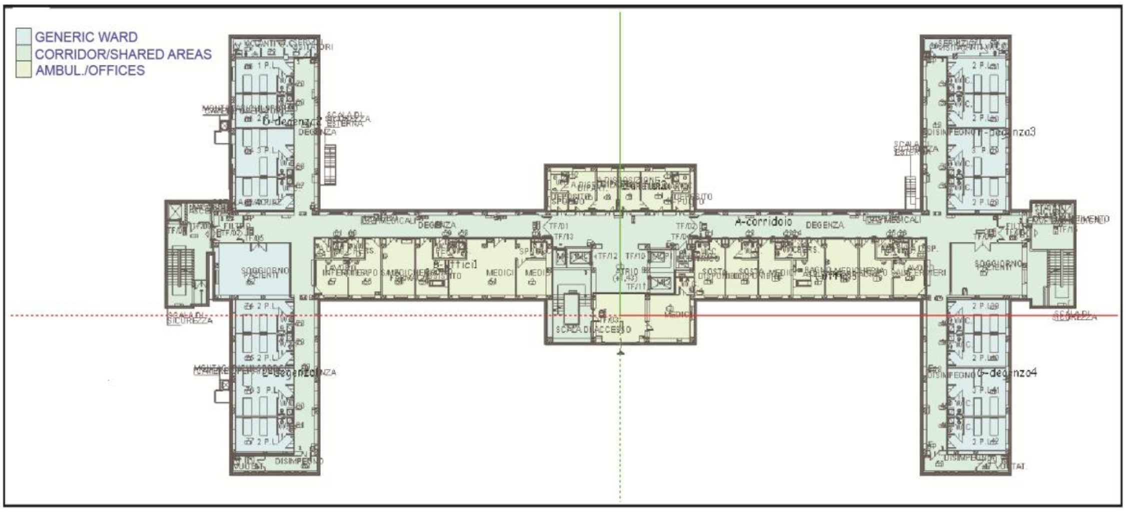

Figure 5. 13: Example of subdivision into zones in Design Builder. First floor

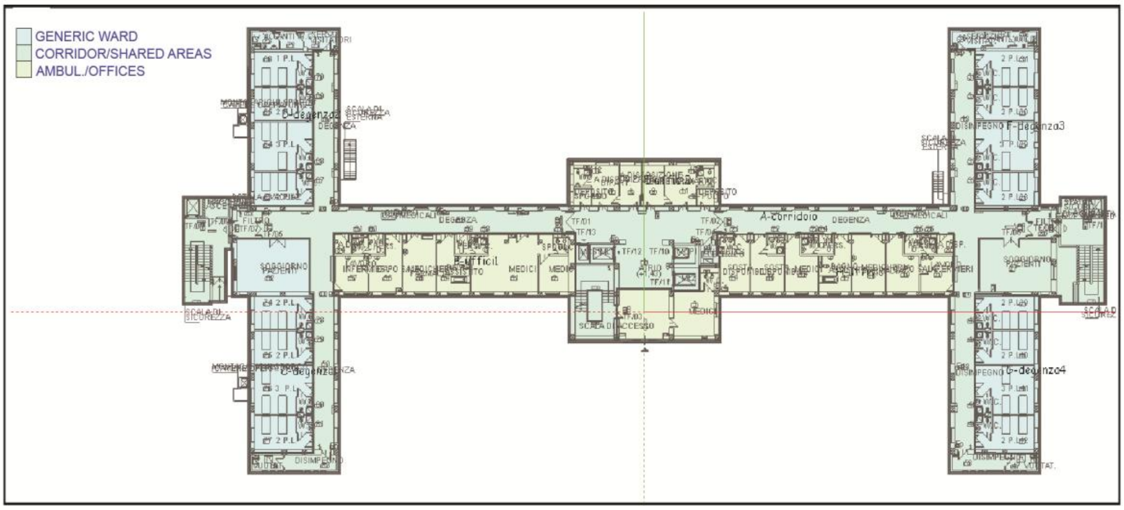

Figure 5. 14: Example of subdivision into zones in Design Builder. Second floor

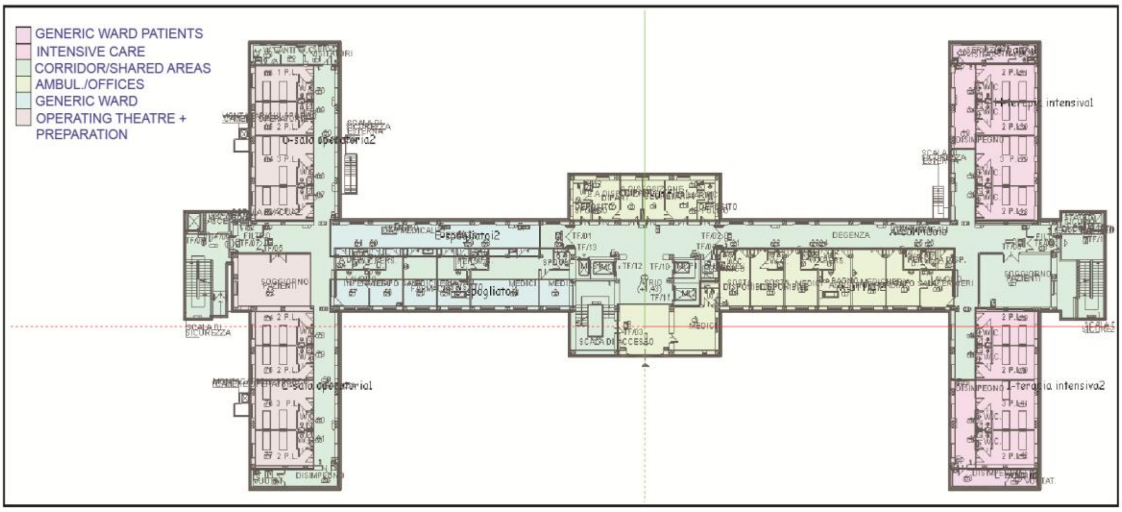

Figure 5. 15: Example of subdivision into zones in Design Builder. Third floor

Concerning the assignment of specific characteristics to the different environments, seven typical thermal zones were created, each of them recurring in the analyzed building:

- thermal zone *corridor*;
- thermal zone *generic ward*;
- thermal zone *surgery*;
- thermal zone *intensive care*;
- thermal zone *ambulatory/office*;
- thermal zone *consulting room*;
- thermal zone *changing room*.

Occupancy density was established basing on use classification of thermal zones. For example, it was considered 0.20 people/m^2 in offices, 0.17 people/m^2 in generic wards, 0.125 people/m^2 in surgery, 0.25 people/m^2 in intensive care to also take into account the personnel responsible for patients.

The thermal contribution related to the lighting system and to electro-medical devices was evaluated taking into account powers detected during on-site census. In more detail technical sheets later used for the energy audit were added to the report object of the agreement's first delivery.

Passage and facilities areas, as *isolated areas* and *technical rooms*, were not considered as air-conditioned, neither in heating or cooling states.

Set-point temperatures, both in heating and cooling state, were set up considering the ASHRAE standard for similar hospital use classifications; the same was done for the definition of the amount of external fresh air, which constitutes a relevant thermal load, especially in hospitals. Both for inside temperatures and fresh air, slightly increased values were set, of about 10-15%, in order to take into account users' behavior. Moreover, systems' working schedules were defined, adding information on their operating ways and hours, obtained both from surveys and average data found in the literature.

The heating period was not a priori defined in simulations, since hospitals, which fall in the E3 category, are not subject to operating limits for heating systems, as established by the D.P.R. 412/93 and later modified by the D.P.R. 551/99, neither for what concerns the yearly operating period nor for what concerns daily operating hours. In table 5.6 the boundary conditions used for representative thermal zones are listed.

BOUNDARY CONDITIONS					
Thermal zone	Density of people [people/m^2]	Setpoint Heating / Cooling [C°]	Infiltration rate [vol/h]	Lighting [W/m^2]	Equipments' contribution [W/m^2]
Corridor	*0.11*	*No air conditioned*	*1*	*From census*	*From census*
Generic ward	*0.17*	*22/28*	*0.7*	*From census*	*From census*
Operating theatre	*0.125*	*23/24*	*0.00*	*From census*	*From census*
Intensive care	*0.25*	*22/25*	*0.00*	*From census*	*From census*
Ambulatory/Offices	*0.20*	*21/26*	*0.7*	*From census*	*From census*
Consulting room	*0.20*	*21/26*	*0.7*	*From census*	*From census*
Rest/ Changing room	*0.50*	*21/26*	*0.7*	*From census*	*From census*

Table 5. 6: Boundary conditions applied to thermal zones.

In figures 5.16 and 5.17, some images of the building's rendering achieved with *Design Builder* are reported.

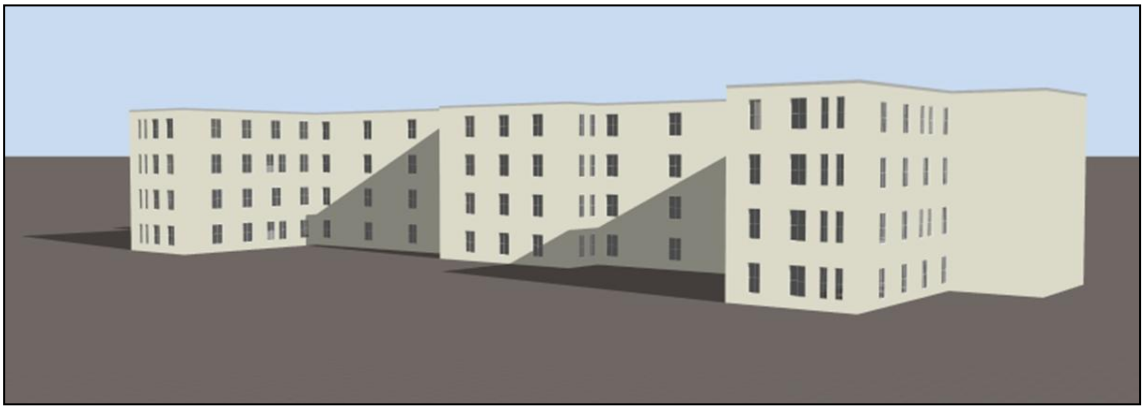

Figure 5. 16: View of the North side of the rendering of the D Pavilion

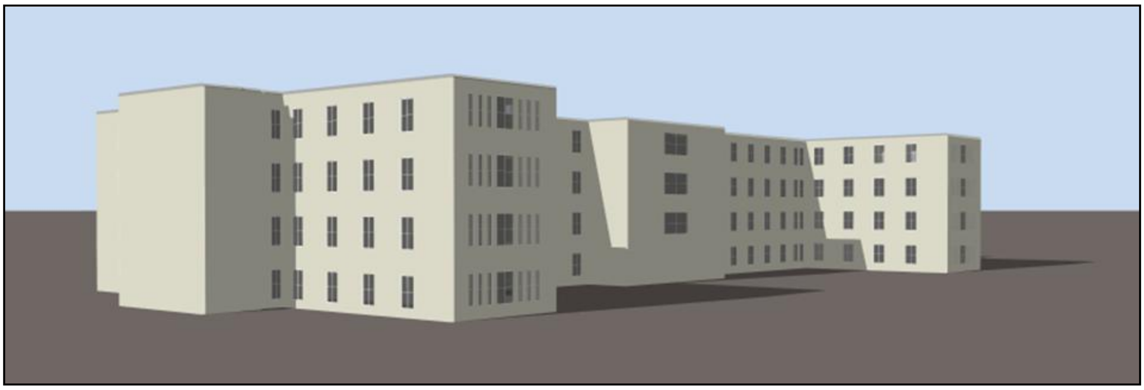

Figure 5. 17: View of the South side of the rendering of the D Pavilion

The so-called "conduction transfer functions method" (CTF) was selected as resolution algorithm, since it is reliable and less onerous from a computational point of view compared to finite-difference methods, which, instead, are necessary in specific cases not present in this study, such as, for example, changing phase elements inside walls or inertias of the envelope beyond ordinary ones.

Concerning weather data files, ASHRAE data for Naples were used, in the IWEC format (*i.e., International Weather Data for Energy Calculation*), downloaded from the EnergyPlus's website.

5.4 Analysis of energy performances

Following the modeling of the geometry, the definition of stratifications and use classification of the different environments and the set up of environmental heating, cooling and air-conditioning systems' set-point values, a simulation of the dynamic behavior of the building was performed, using *EnergyPlus 7.2*.

The chosen simulation period is one year, with monthly and hourly results' subdivision, in order to achieve a global view of the building's performances.

Table 5.7 reports the values of the annual demand of primary energy for heating, domestic hot water, cooling and the total electricity demand.

Primary energy[MWh]	
Heating thermal energy	731.3
Thermal energy for DHW	927.2
Total electricity	3315.7
Electricity for cooling	966.6

Table 5. 7: Total annual demand of thermal energy and electricity

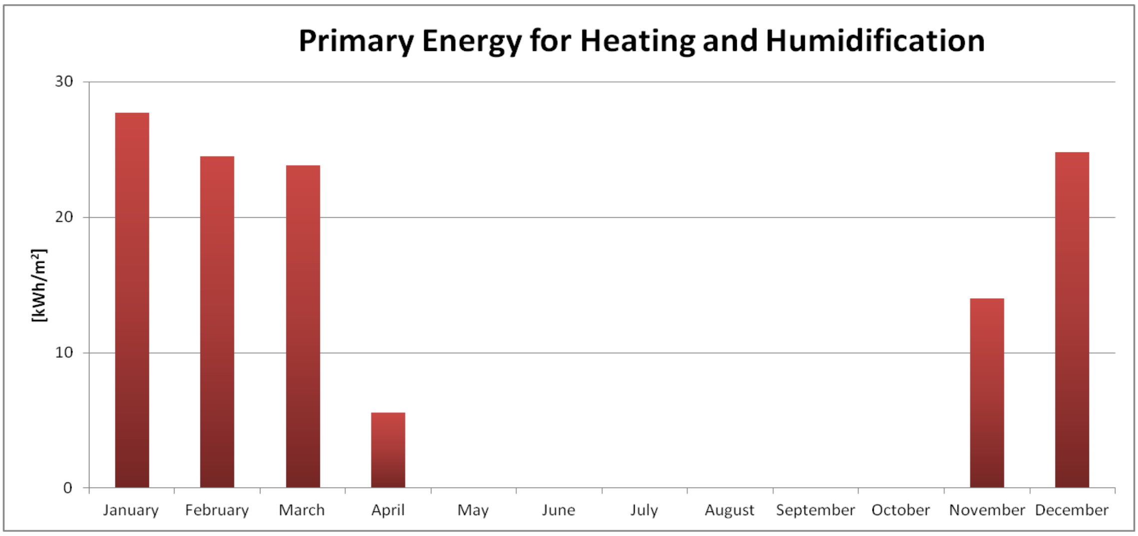

Figure 5. 18: Monthly demand of primary energy for environmental heating and humidification

From the graph of the annual energy demand for heating per square meter, reported in figure 5.18, it can be observed that the building in exam shows a thermal energy demand for heating only in the usual heating period according to the use of the Cardarelli Hospital, from 1 November to 15 April. This does not correspond to the conventional heating period, that for the C zone identified in the D.P.R. 412/93 [16] starts on 16 November and finishes on 31 March. Indeed, as previously anticipated, hospitals, for their users' type, are not subject to respect this restriction.

The trend of the annual demand of primary energy for domestic hot water production per square meter is reported in figure 5.19. Also in this case, as for environmental heating, the function is guaranteed through the use of thermal energy coming from the thermal station through the ring. About it, a district heating system supply hot water to the entire hospital. The trend, as it can be observed, is rather constant in all months.

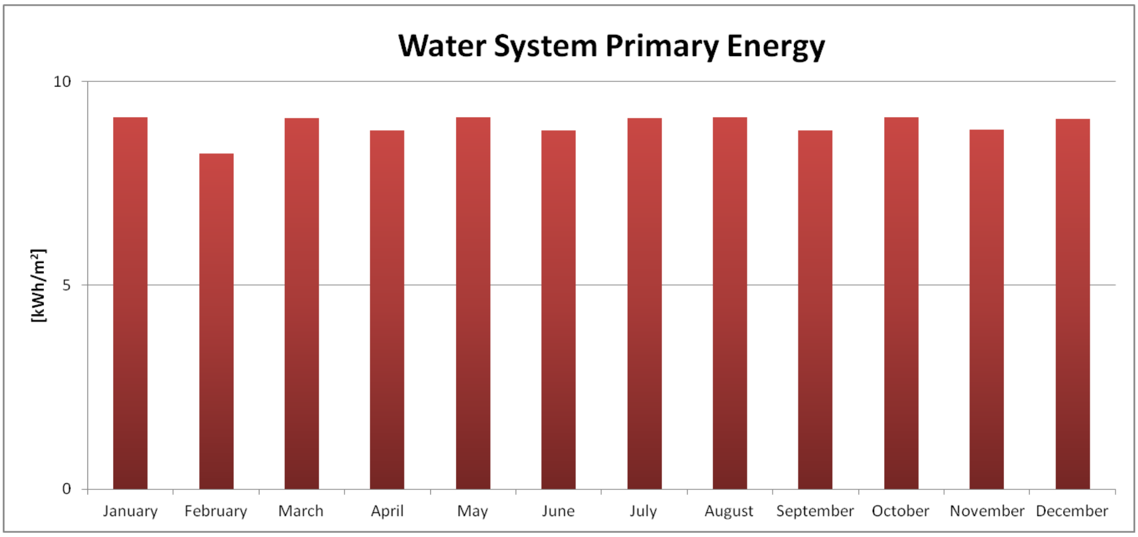

Figure 5. 19: Monthly demand of primary energy for domestic hot water

The total demand of electricity includes, obviously, pure electric loads (luminaires and devices), the electricity for summer cooling and for the activation of auxiliary. As it can be observed from the graph in figure 5.20, it is nearly constant during winter, it increases during intermediate months, and it reaches a peak during July and August, until values greater than 45 KWh per square meter. This is particularly clear looking at the graphs in figures 5.21 and 5.22, in which the disaggregated trends of electricity for pure loads and summer cooling are reported.

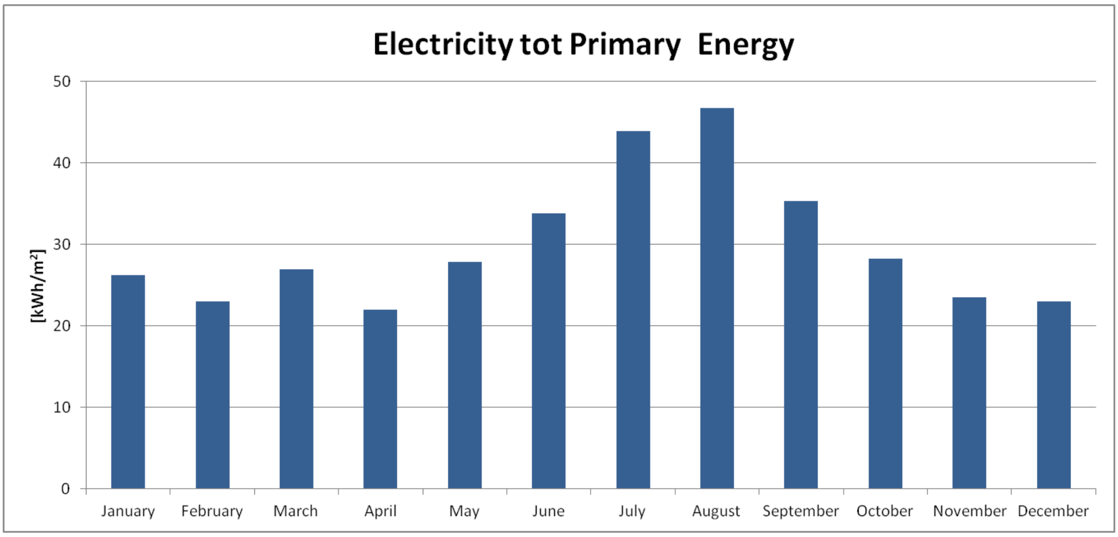

Figure 5. 20: Monthly demand of primary energy, to satisfy all electric uses

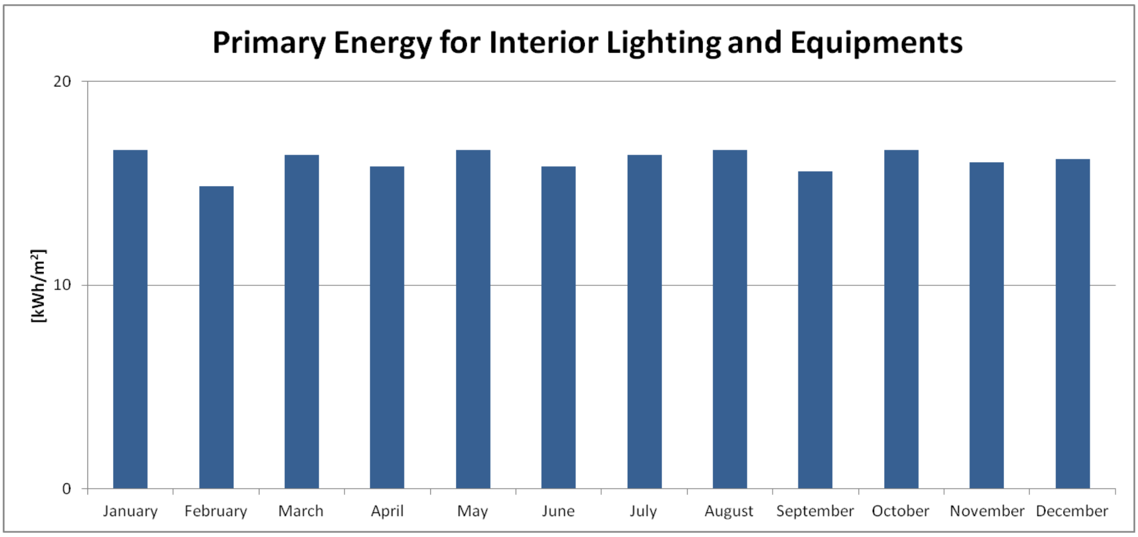

Figure 5. 21: Monthly demand of energy for interior lighting and equipment (primary energy, from electricity demand)

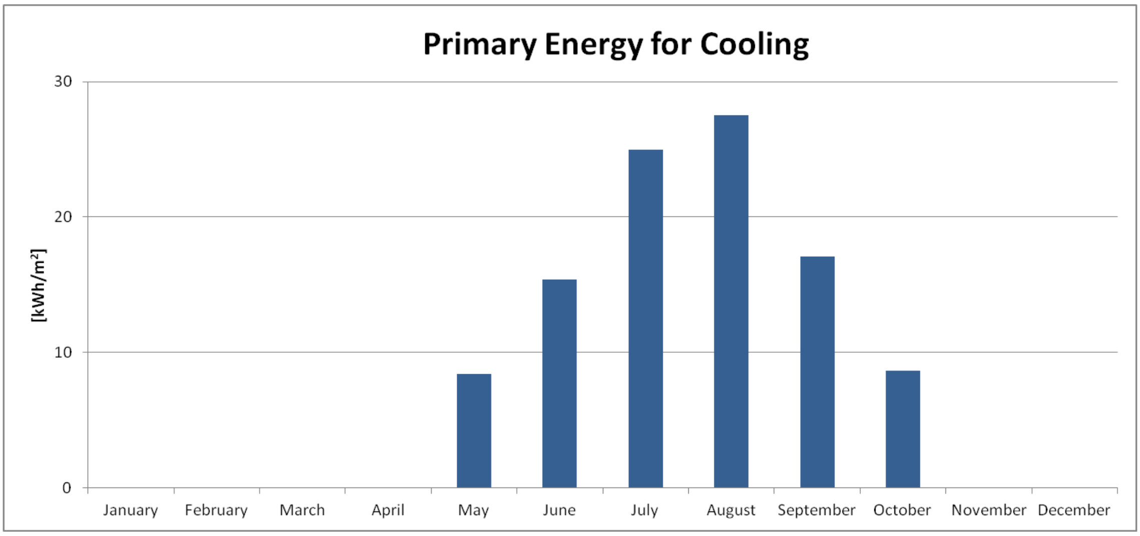

Figure 5. 22: Monthly demand of energy for cooling (primary energy, from electricity demand)

Referring to the D Pavilion, the entire electricity demand is satisfied by the national electricity grid. Therefore, in figures 5.20÷5.22 the average efficiency of the national thermal-electric stock was considered equal to $\eta_{EG} = 0.46$.

Considering the energy demand for microclimate's control and domestic hot water production - reporting thermal and electricity demands upstream of generation and conversion systems - in figure 5.23 are illustrated, on a monthly base, energy demands for:

- heating, post-heating, domestic hot water production;
- the operation of chiller;
- humidification needs (using steam, through electric devices)
- auxiliary's working, and therefore pumps and fans.

It can be noted how, at least referring to peak months during winter and summer, the refrigerating demand are equivalent. During winter, the energy absorption for humidification devices' working is also significant. In conclusion, the energy demand for auxiliary's working is also not negligible, representing, in the coolest and warmest months, about a tenth of the primary demand of thermal and refrigerating energy.

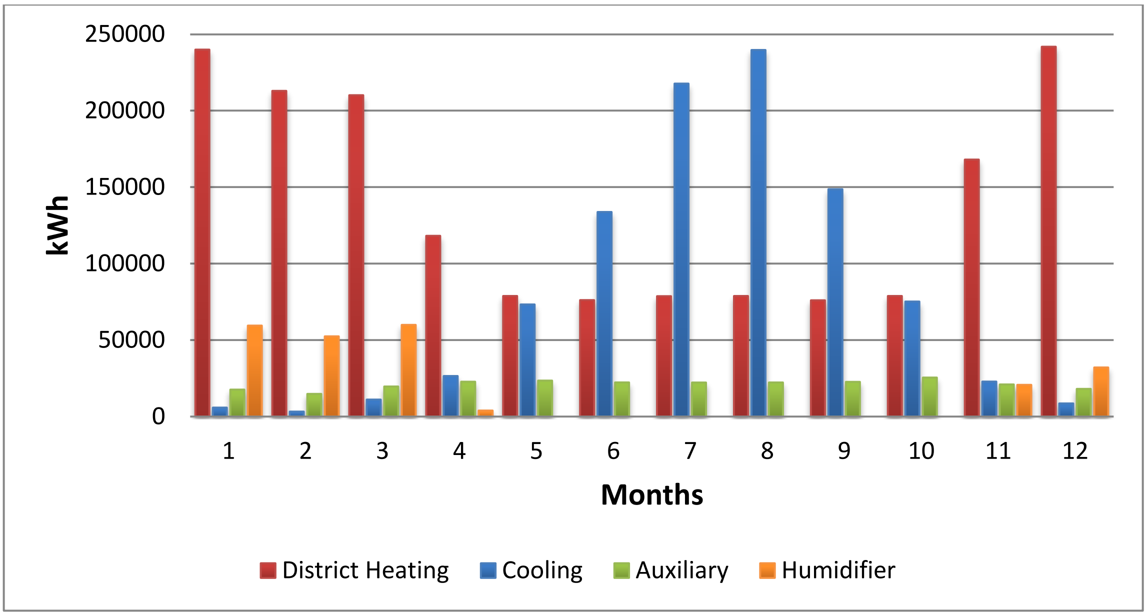

Figure 5. 23: Monthly demand of primary energy for environmental air-conditioning (all uses)

5.5 Comfort analysis

In this paragraph, referring to central days during heating and cooling seasons as well as to the entire periods, the following evaluations will be performed:

- the trends of thermal levels and humidity degree that are found in environments;
- the adequacy of temperature and relative indoor humidity in guaranteeing, according to the different use classifications, comfort conditions for work activities and/or related to generic wards.

In more detail three thermal zones were selected which require different control levels:

- Ambulatories;
- Generic wards;
- Intensive care wards.

For each of them, not hypothesizing adaptive comfort conditions, and thus remaining close to the consolidated O. Fanger's theory, reported in the UNI 7730/2006 standard [88], acceptability ranges were identified linked to the occupancy type of the environment taken into account.

Winter conditions:

- ambulatories: temperature comprised between 18.5 ÷ 24 °C (not occupied overnight), relative humidity ranging between 35 ÷ 55% (not occupied overnight);

- generic wards: temperature comprised between 20 ÷ 24 °C (continuous occupancy 24/7), relative humidity ranging between 40 ÷ 55% (continuous occupancy 24/7);
- intensive care and/or special wards: temperature comprised between 22 ÷ 25 °C (continuous occupancy 24/7), relative humidity ranging between 50 ÷ 60% (continuous occupancy 24/7).

Summer conditions:

- ambulatories: temperature comprised between 23 ÷ 28 °C, relative humidity ranging between 40 ÷ 65% (not occupied overnight);
- generic wards: temperature comprised between 24 ÷ 28 °C (continuous occupancy 24/7), relative humidity ranging between 40 ÷ 65% (continuous occupancy 24/7);
- intensive care and/or special wards: temperature comprised between 21 ÷ 26 °C (continuous occupancy 24/7), relative humidity ranging between 45 ÷ 55% (continuous occupancy 24/7).

In the list reported above, it can be noted how the indoor control is gradually more restrictive. The chosen values come from an intersection of national and international standards and national laws. In some cases, especially referring to the summer state, systems will show limits in the control. In this regard, it has to be taken into account hat installed systems belong to different types, in many zones they belong to the mixed air-water type, but in most cases, hydronic terminals (radiators) only works during winter.

It is worth to highlight that it was not deemed necessary to report in detail what happens inside operating theatres. Such choice derives from the optimal control that was observed in operating blocks, the only ones equipped with air systems capable of introducing in the environments high amount of air. Therefore these are capable of rapidly balancing thermal and humidity loads in both seasons, significantly limiting temporal variations of humidity and temperature when loads impulsively change . In this regard, it has to be taken into account that the high endogenous power density induces instantaneous loads in starting transients to which systems have to rapidly react.

In the following pages, for each use classification, the trends of temperature and humidity are reported referring to the day between 08 ÷ 11 January and 23 ÷27 July.

Ambulatories

Figures 5.24 and 5.25 respectively report temperatures and indoor air's relative humidity for ambulatories. It can be observed how winter temperature range between 20 ÷ 24 °C during operating hours: such values are influenced by the high endogenous powers. Substantially air-conditioning systems work during the first hours of the morning, then thermal trends are essentially controlled by endogenous load. The registered relative humidity ranges between 35 ÷ 45%, thus resulting consistent with the activity carried out in the environment.

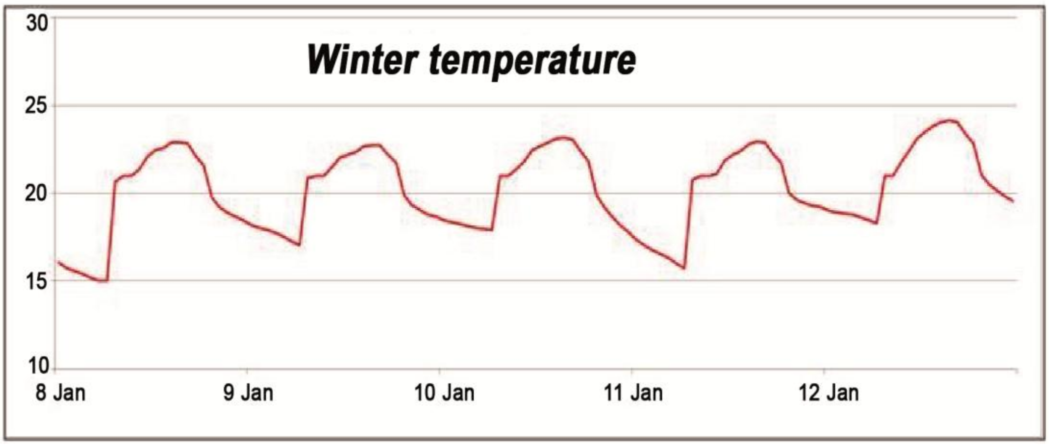

Figure 5. 24: Temperature's trend during winter state

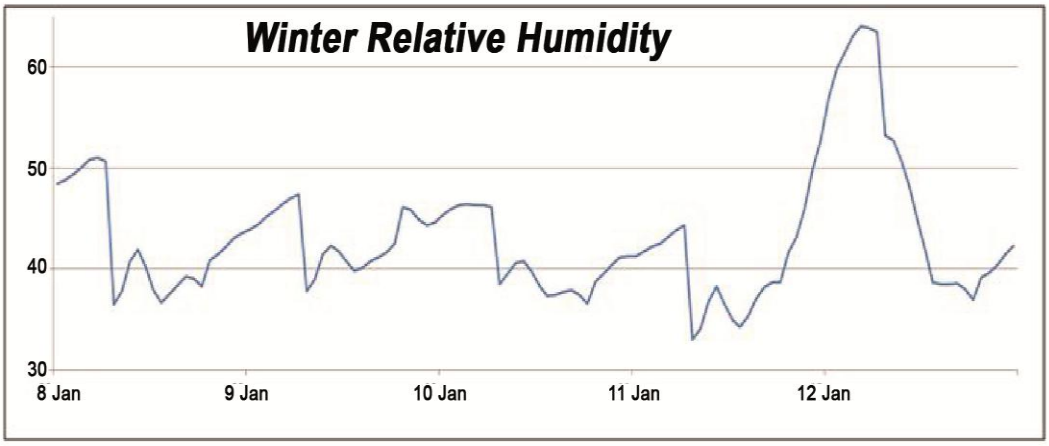

Figure 5. 25: Relative humidity's trend during winter state

In figures 5.26 and 5.27 the summer trends of temperature and relative humidity are illustrated. Daytime temperature do not exceed 27.5 °C. Relative humidity, significantly higher than during winter, range between 35 ÷ 45%.

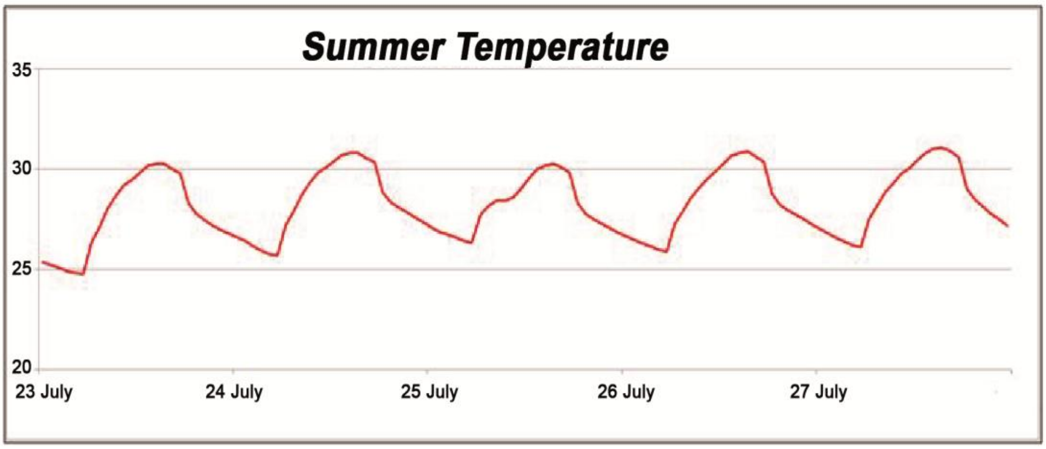

Figure 5. 26: Temperature's trend in summer state

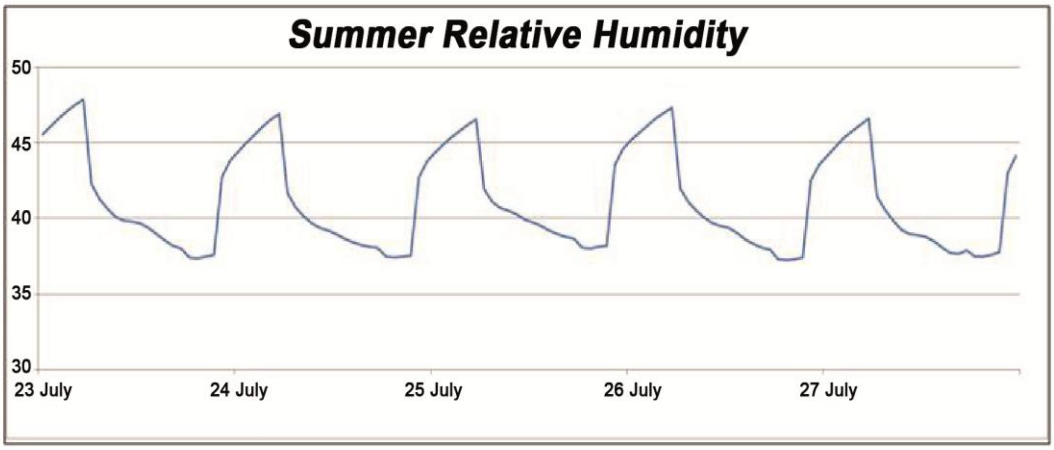

Figure 5. 27: Relative humidity's trend in summer state

Generic wards

In figures 5.28 and 5.29, referred to winter, the trends of temperature and relative humidity of the current building are reported. The perfect control of the temperature that ranges between 22 ÷23 °C, determines an easy control of the humidity degree which, with the same amount of humidity in the air, is essentially linked to the thermal level.

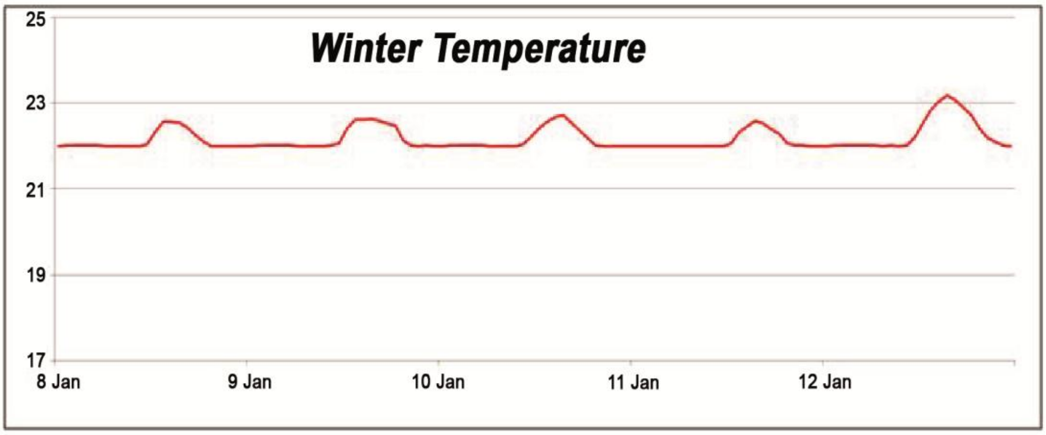

Figure 5. 28: Temperature's trend in winter state

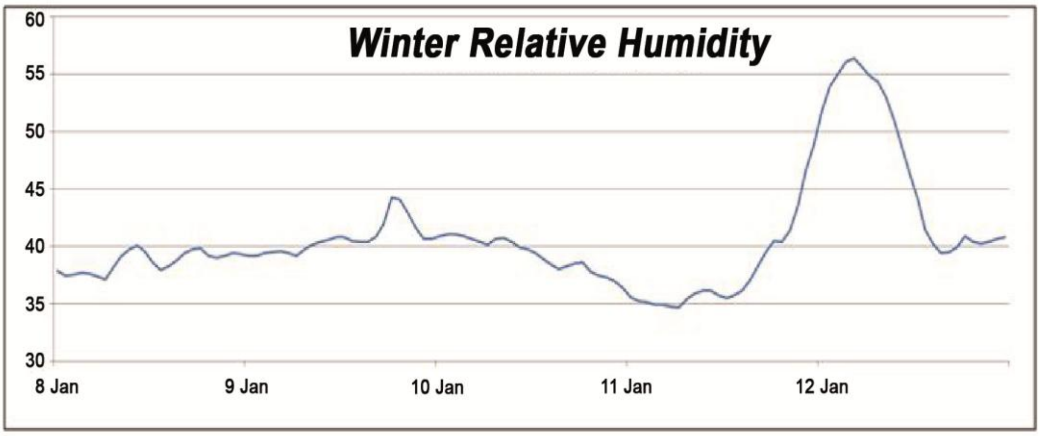

Figure 5. 29: Relative humidity's trend in winter state

In contrast to summer (figures 5.30 and 5.31), trends show more variations for both parameters. It has to be kept in mind that the system (in this case only the air system is active, since hydronic terminals are radiators which are activated only during winter) is controlled referring to a reference thermal zone. Therefore, the microclimate parameters' control fluctuates in the other environments, since the system is not equipped with post heating batteries. In any case, acceptability levels are guaranteed with temperatures that are always comprise into the 24 ÷ 28°C range. Relative humidity values are also acceptable, not exceeding 48%.

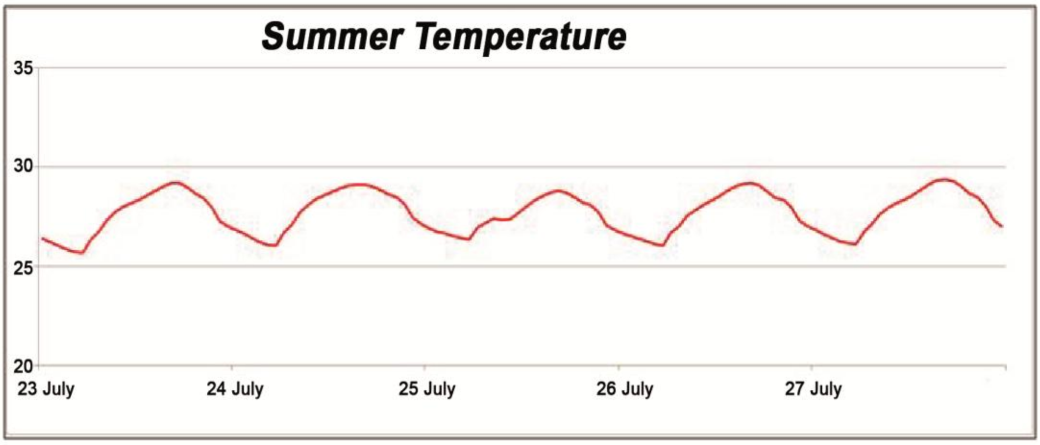

Figure 5. 30: Temperature's trend in summer state

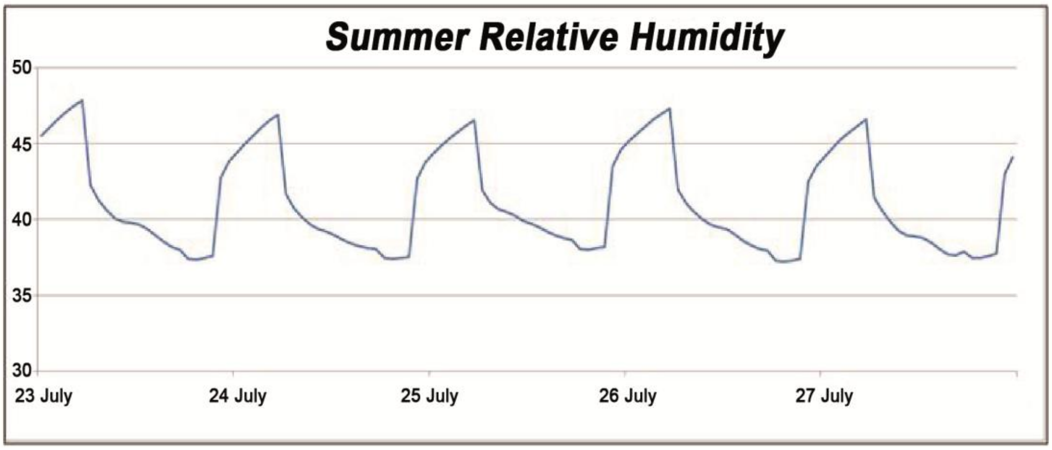

Figure 5. 31: Relative humidity trend in summer state

Intensive care and/or special wards

Similarly to what has been previously seen, in figures 5.32 and 5.33, a winter temperatures' trend is illustrated. For this purpose, it has to be remembered that, also in intensive care wards, the control of the sensible load is centralized referring to a reference zone and therefore it is not possible to locally control the temperature. The relative humidity, is never lower than 35%, with average values around 40%.

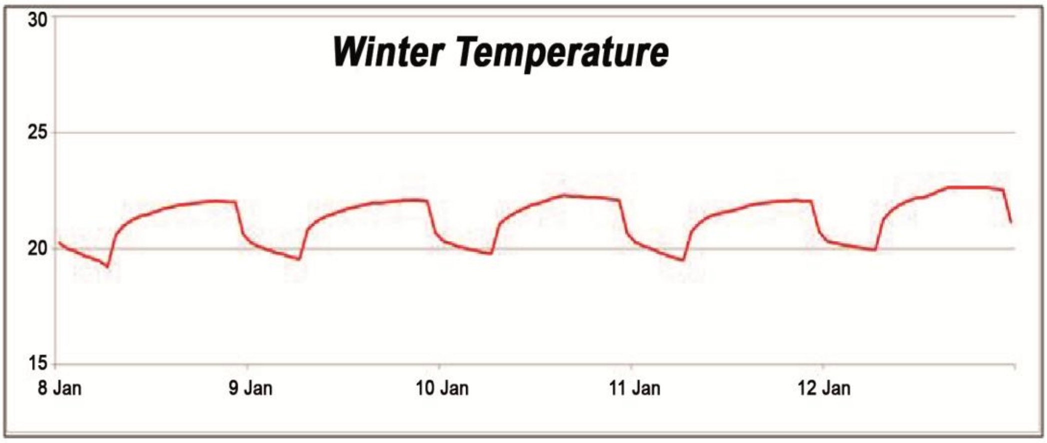

Figure 5. 32: Temperaure's trend in winter state

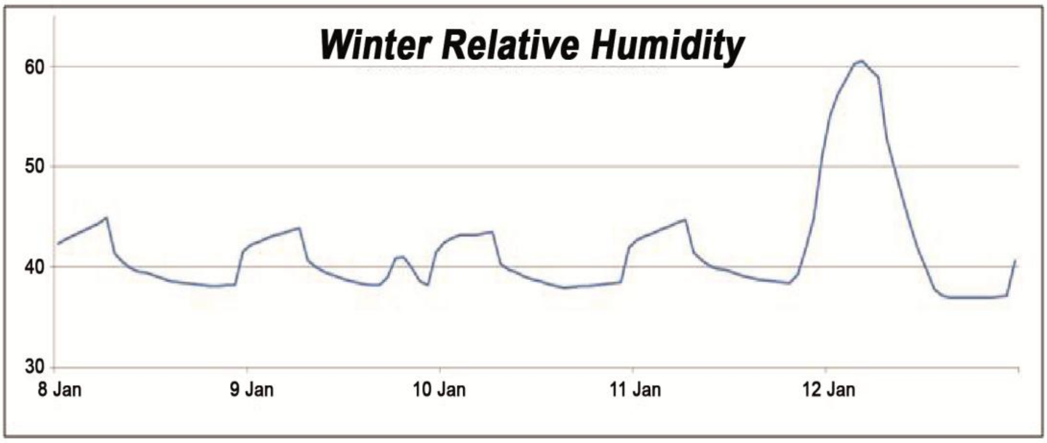

Figure 5. 33: Relative humidity's trend in winter state

In summer, the high endogenous loads (which are useful during winter) determine a really significant environmental cooling load. In this case, as it is clear in figures 5.34 and 5.35, the heavy use of systems happens during daytime, when the starting of electro-medical devices causes an increase of air temperatures, only partially balanced by air-conditioning systems. Also in this case, high indoor temperatures determine low relative humidity values, which result optimal in the range between 38% and 48%.

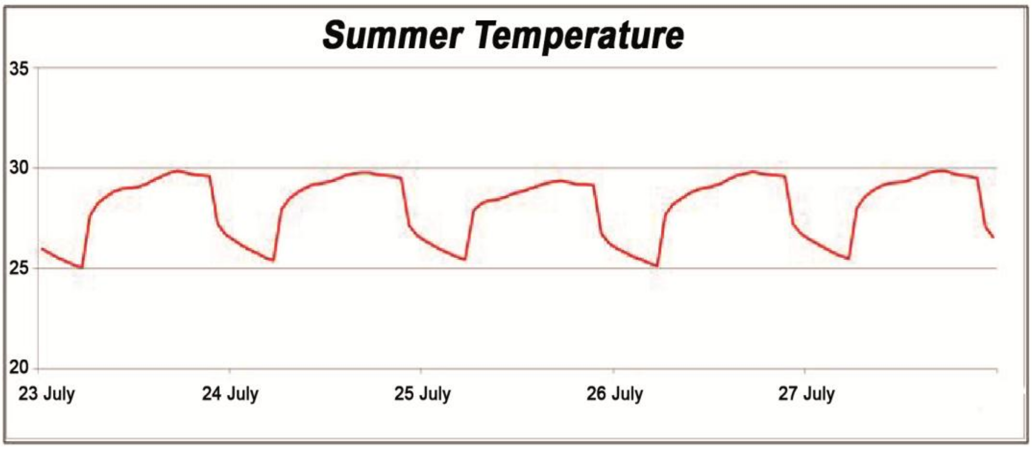

Figure 5. 34: Temperature's trend in summer state

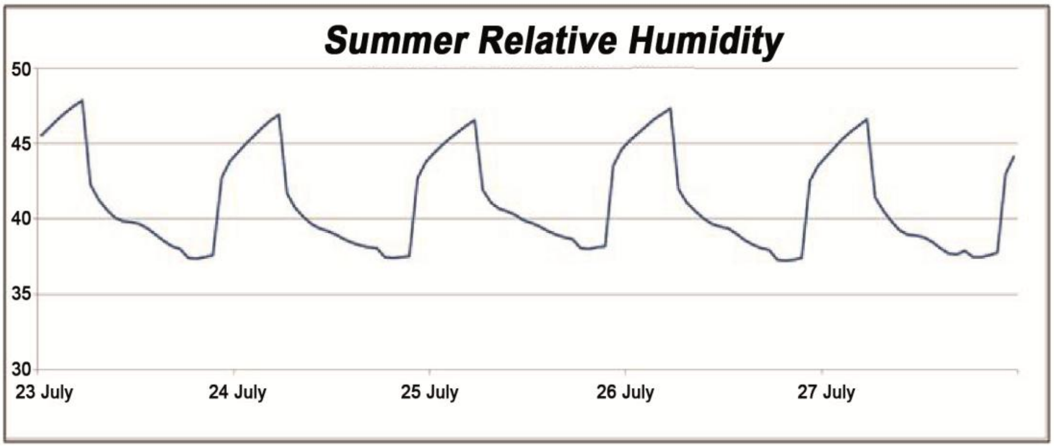

Figure 5. 35: Relative humidity's trend in summer state

5.6 Model's calibration on consumptions detected on site

The A.Cardarelli Hospital within the "POIN" funding planned the installation of a centralized measurement system to acquire thermal energy and electricity consumptions referred to each energy sub-service of each pavilion.

It is important to highlight that the installation of the equipment is still in a star up phase, therefore the model was exclusively validated referring to available thermal energy measurements for winter air-conditioning for November and December 2014.

The "original" model shows a reasonable coherence with total consumptions for winter air-conditioning; in more detail the percentage deviation is respectively equal to 5% and 2% for November and December 2014 (see fig.5.36 and fig.5.37).

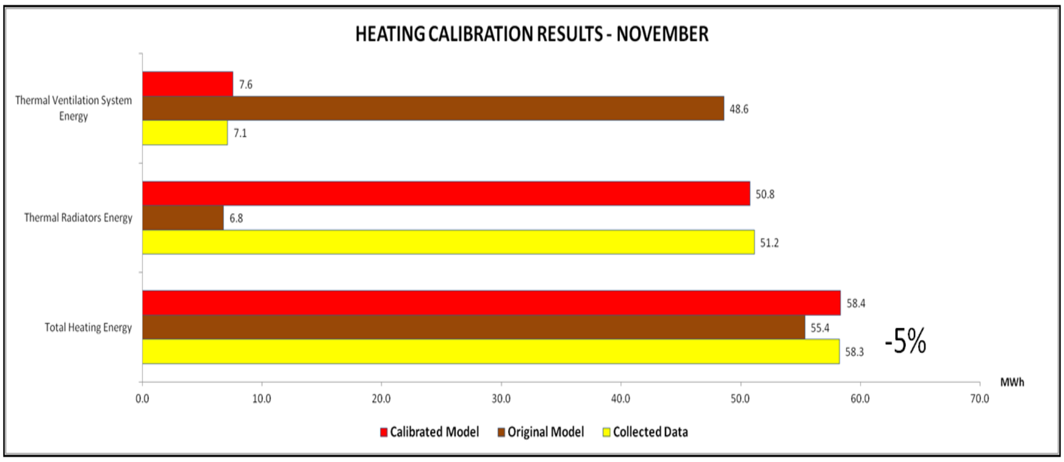

Figure 5. 36: Model's calibration according to energy consumptions for heating in November

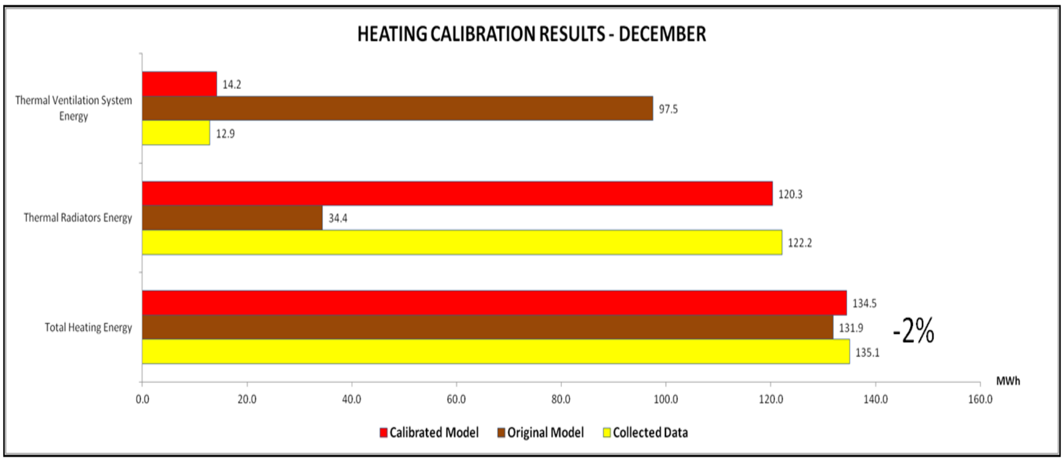

Figure 5.37: Model's calibration according to energy consumptions for heating in December

From the disaggregated analysis of consumptions for the different systems, used for environments' winter air-conditioning, it was possible to observe an overestimation, in terms of use, of radiators compared to air systems. Such circumstance is a direct consequence of the fact the systems' type, featuring manual control rules (on/off), cannot be accurately defined in terms of priority inside the energy model.

Downstream the consumptions' collection, in the calibrated model systems' operating and control rules were conveniently defined to achieve values similar to those detected on site.

5.7 Comparison with the Reference Building representative of the existing stock

As previously anticipated the D pavilion for its architectural envelope's characteristics, for systems' configuration and percentage distribution of use classifications that characterize it surely represents an healthcare facility which characteristics make it suitable to be compared with the RBh developed for the existing stock in the third chapter.

It is worth to clarify that the comparison is anything but a mere numerical exercise; indeed an attempt will be made to explain eventual differences with the reference case by identifying the main influence parameters. First of all it is helpful to compare the two buildings in terms of shape and geometry (see table 5.8).

PARAMETERS	PAD D	REFERENCE HOSPITAL
Total Floor Area (m^2)	9'736	22'709
Net Conditioned Area (m^2)	8'653	18'176
Building Shape	Rectangle	Rectangle
Aspect Ratio	0.21	0.2
Number of Floors	5	6
Window Fraction	0.13	0.23
Floor to Ceiling Height (m)	3.7	3.96
Floor to Floor Height (m)	3.7	3.96

Table 5. 8: Comparison with the Reference Building- Geometrical and shape characteristics

It is possible to observe a reasonable similarity in terms of shape ratio and a relevant difference in terms of the ratio between glazed and opaque surfaces.

As widely discussed and analyzed in depth in the third chapter, primary energy consumptions for the production of domestic hot water, winter and summer air-conditioning are greatly influenced by the distribution of use classifications on useful floor area. Such circumstance depend on the fact that internal gains (interior lighting, density of people, specific DHW's consumption and equipments) and typical comfort level required in the environments are associated to each use classification.

The distribution of use classifications considered for the two hospitals (High tech, Generic Wards, Offices and Ambulatories) is reported in the following graph:

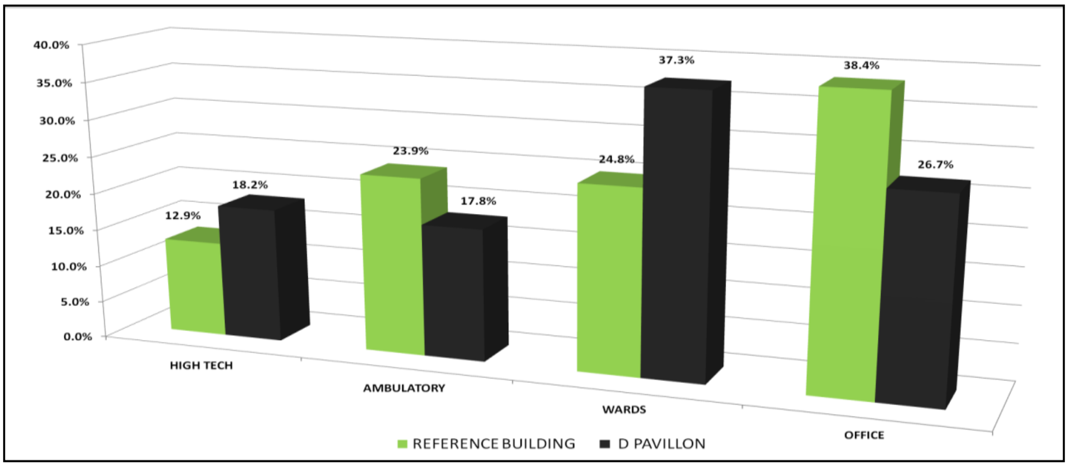

Figure 5.38: Comparison with the Reference Building- Distribution of use classifications

At this point after the comparisons useful to understand similarities and differences that characterize the examined hospitals, the results of the energy performances' analysis carried out in chapters 3 and in this section are reported in the following table.

Primary energy [KWh/m^2]	**D Pavillon**	**Reference Building**
Heating and Humidification	120	177
DHW'production	107	59
Pure Electric Load	194	261
Cooling	102	157

Table 5. 8: Comparison with the Reference Building- Geometrical and shape characteristics

A relevant difference can be observed in terms of primary energy consumption for winter and cooling air-conditioning which is mainly due to the different architectural envelope's quality in terms of vertical opaque envelope's transmittance (see table 5.9).

	D Pavillon	**Reference Building**
U_{VERT}	0.553 W m^{-2}K^{-1}	0.717 W m^{-2}K^{-1}
U_{ROOF}	1.5 W m^{-2}K^{-1}	1.5 W m^{-2}K^{-1}
$U_{BASE\ PLATE}$	1.5 W m^{-2}K^{-1}	1.5 W m^{-2}K^{-1}
$U_{WINDOWS}$	3.2 W m^{-2}K^{-1}	3.2 W m^{-2}K^{-1}

Table 5. 9: Comparison with the Reference Building- Architectural envelope

The D pavilion's measured transmittance is rather low consistently with the fact that the building was recently refurbished; therefore the comparison with the reference building inevitably determines significant differences.

Finally, it is possible to observe a different primary energy consumption for DHW's production and for the pure electric load which, as it could be expected, directly depends on the percentage distribution of use classifications.

It is clear that the D pavilion is characterized by an higher number of generic wards which inevitably determines an higher consumption for DHW production. At the same time it includes a lower number of ambulatories and offices with internal gains related to electric devices greater than generic wards' ones.

Therefore, the comparison between indices of primary energy consumption shows variations that are coherent with the differences that may be found in terms of architectural envelope's quality and of use classifications' distribution on the useful floor area. Furthermore, it is worth to highlight that the comparison in terms of geometry and shape between the reference building and the D pavilion determines really interesting results.

Chapter 6. Conclusions

The thesis titled "*Multi-objective optimization for energy-efficient and cost-effective hospitals*"- is placed in the field of the research on energy saving related to micro-climate control in hospitals. The starting point was the placement of the research activity inside the European and Italian legislative framework in the field of energy efficiency in the construction industry.

Indeed regulations on energy saving in the construction industry are undergoing a progressive and radical transformation, due to the ever increasing need to establish reference values (benchmark) for the evaluation of real energy performances of buildings/systems interactions.

The delegated regulation n. 244/2012 of the European Commission [2], of 16th January 2012, integrated the Directive 2010/31/EU of the European Parliament and Council on energy performance in the construction industry [12], establishing, in agreement with the clause 5, a methodological comparative framework for the calculation of optimal levels as a function of costs for minimum energy performance requirements for both new and existing buildings and architectural elements. In more detail, the procedures for the calculation of optimal levels as a function of costs are defined basing on both the macroeconomics (which considers costs and benefits for the entire society of the investments in energy efficiency) and financial (which only takes into account the investment itself) point of views. Each country has the task to determine which calculation should become the national reference for the evaluation of minimum energy performance national requirements. In this sense, the definition of a Reference Building represents the start-up for the application of the new performances' classification methodology established at European level.

Within this context the modeling and numerical research activity, illustrated in this PhD thesis, was carried out by following three convergent macro-planes:

- [a] development of an original methodology for the construction of a hospital Reference Building representative of the existing building stock and of another one representative of new buildings.
- [b] Analysis of elements and technologies for the reduction of the energy demand of the building-system interaction, with an approach first focused on the detailed study of the single design element and then on the global analysis of the efficacy of "energy efficiency packages". Morevoer, the development and application of a new methodology for cost-optimal analysis by means of the multi-objective optimization of hospitals energy performance are proposed too.

[c] Dynamic analysis of energy performances of a hospital case study representative of the existing stock, calibration of the energy model on monitoring data and comparison with the Reference Building.

Development of an original methodology for the construction of a hospital Reference Building

The definition of a Reference Building, representative of a stock of existing buildings, requires the knowledge on a statistical basis of many parameters that are necessary for the definition of the geometry, of the architectural envelope's quality, of internal gains and of the type of installed systems.

Referring to hospitals it is not possible to develop Reference Buildings' models starting from accurate statistical studies on the entire national hospital stock. To solve this problem in the context of the methodology, described in chapter 3, different documents strategically interconnected were used (Theoretical approach) and conveniently integrated by information derived from professionals' expertise in this field (Example Approach).

Typical parameters useful for the characterization of the **geometry** and **shape** of the Reference Building were defined through the analysis, on a statistical basis (Theoretical Building), of plans and elevations of all the hospitals managed by the ASLNAP1. After the analysis a basic rectangular shape was taken into account, with 5 floors, a total useful floor area equal to 22707 m^2, an S/V ratio equal to 0.2, an azimuth angle equal to zero and a ratio between transparent and opaque surface equal to 0.23.

The **definition of the architectural envelope** was deduced from the main legislative references (Theoretical Building) in the field on energy efficiency which characterized the Italian legislative framework: law 10/91 [15] (calculation of energy losses and evaluation of the FEN index) for the Reference Building representative of the existing stock and Dlgs 192/2005 (limit values) for new hospitals [3]. The transmittance values of the opaque and transparent architectural envelope are listed in tables 3.8 and 3.9.

The **subdivision in thermal zones** was developed taking into account the percentage distribution of use classifications and of the type of air-conditioning system related to them. The evaluation of percentage distributions which characterize in a relevant way the ventilation load, which is significantly higher than transmission one, was performed on a statistical basis (Theoretical Building) properly using data found in the census file at the base of the " Centralized Community tender aimed at the entrustment of the technological multiservice and of the supply of energy vectors to buildings owned by ASLRLAZIO". The analysis involved 50 hospitals for a total hospital floor area equal to 1'275'676 m^2.

High Tech zones occupy 12.9% of the useful floor area whereas ambulatories, offices, and generic wards are respectively equal to 23.9%, 38.4% and 24.8%. Taking into account the system type installed in the environment the **geometrical model** was built considering 26 thermal zones.

Moreover in the geometrical model, developed in Design Builder, the stratigraphy of the opaque and transparent architectural envelope, operating schedules internal gains were defined. The system was directly specified in Energy plus (Example Building), energy performances calculation engine. As regards the Reference Building representative of the existing building stock it was calculated, on an annual and per square meter basis, a primary energy consumption for heating and humidification equal to 177 kWh, to 59 kWh for domestic hot water production and to 157 kWh for cooling.

As regards the hospital, Reference Building representative of new constructions it was calculated, on an annual and per square meter basis, a primary energy consumption for heating and humidification equal to 156 kWh, to 53 kWh for domestic hot water production and to 140 kWh for cooling.

Development of a methodology for cost-optimal analysis by means of the multi-objective optimization of RB hospitals energy performance

Considering different types of energy retrofit, an original methodology to identify RBh's optimal performance levels with a multi-objective approach was applied. Overall nine requalification interventions will be analyzed which involve the integration of existing systems with renewable sources, the optimization of the architectural envelope's and systems' performances.

The proposed methodology aims at finding the set of the values that decision variables should assume to optimize various objective functions. Considering that a building's design has to take into account, simultaneously, different competitive criteria, such as the demand, the thermal comfort, the investment costs and the emissions of $CO_{2\text{-equivalent}}$ during the building's operation, the multi-objective approach was considered as more suitable and relevant compared to the single-objective one. Some of these objectives are conflicting. In this regard, both the energy requests for the microclimatic control (first objective function) and the investment costs (second objective function) will be considered, even if the developed method can be applied to several other objective functions.

A controlled elitist genetic algorithm is used in the proposed methodology to optimize the aforementioned objective functions. This algorithm is a variant of NSGA II [78] and, since it ensures a higher diversity in the population, it allows a more reliable evaluation of the Pareto front compared to the original one. The GA was applied considering a random initial population of 30 of individuals (s), a fraction of the population generated by crossover (fc) equal to 0.6 and a maximum number of generations equal to 30.

Overall the Pareto front showed 16 optimal solutions (not dominated points), the corresponding retrofit configurations are listed in table 4 .3. For the choice of the optimal solution the minimum global cost criterion was used, which was calculated separately for each of the Pareto front's points. The optimal solution has a global cost per square meter equal to 934 € and includes, compared to the reference system, the insulation of both roof (11 cm) and vertical envelope (2 cm), the installation of heat recovery systems and the installation of both photovoltaic and solar collectors whose powers are respectively equal to 74.2 and 215.7 kW.

The investment cost related to the optimal solution is equal to 578'535 € with a percentage reduction in terms of primary energy for environmental air-conditioning equal to 17.31%.

Dynamic energy analysis of a real hospital case study, D pavilion, model's calibration and comparison with the hospital Reference Building

The dynamic analysis of the energy performances of the hospital A.Cardarelli's D pavilion in Naples is reported in Chapter 5. To characterize the energy model Design Builder was used as graphic interface whereas the energy performances were evaluated through Energy plus. Each envelope's element and system were defined into the model data deduced from official documents or collected on site.

Only the vertical architectural envelope was characterized through heat flux's measurement using an heat flux meter which allowed to calculate a transmittance Uv equal to 0.553 W/m^2K. The results of dynamic simulation show, on an annual and per square meter basis, a primary energy consumption for heating and humidification equal to 120 kWh, to 107 kWh for domestic hot water production and to 102 kWh for cooling.

The original model was calibrated according to the primary energy consumption for winter air-conditioning, which is currently made available by the monitoring system only for November and December.

The "original" model shows a reasonable coherence with total consumptions for winter air-conditioning; in more detail the percentage deviation is respectively equal to 5% and 2% for November and December 2014.

From the disaggregated analysis of consumptions for the different systems, used for environments' winter air-conditioning, it was possible to observe an overestimation, in terms of use, of radiators compared to air systems. Such circumstance is a direct consequence of the fact the systems' type, featuring manual control rules (on/off), cannot be accurately defined in terms of priority inside the energy model.

Downstream the consumptions' collection, in the calibrated model systems' operating and control rules were conveniently defined to achieve values similar to those detected on site (see fig.5.36 and fig.5.37).

Energy performances of the original model were also compared with those calculated for the reference building representative of the existing hospital stock (see par.3.7). The comparison was performed in terms of primary energy for heating and humidification, for the production of DHW and cooling.

Referring to primary energy consumptions it was possible to observe variations mainly due to the higher quality of the vertical architectural envelope of the D pavilion, recently refurbished. The transmittance Uv is 21% lower than the one evaluated for the reference building. A different percentage distribution of use classifications determines, as it was expected, differences in terms of primary energy for DHW production.

Nomenclature

a_r	roof's solar radiation absorption coefficient	---
a_v	vertical walls' solar radiation absorption coefficient	---
ANCE	National Association Building Contractors	---
AO	Azienda Ospedaliera	---
APE	Certification of intended energy performance	---
ASLNAP1	Azienda Sanitaria Locale of Naples	---
ASLRLAZIO	Aziende Sanitarie Locali of the Lazio Region	---
CRESME	Center for Economical and Social Market Researches for the construction industry and the territory	---
BB	Base Building	---
C	Investment's cost	€
C_i	Initial investment cost associated to the value assumed by the i-th decision variable	%
c_e	elite count	---
CH_t	Chiller's type	---
COP	Coefficient Of Performance	---
DD	Degree Days	°
DHW	Domestic Hot Water	---
e	tolerance	---
$E_{heating}$	Primary Energy for Heating	kWh/m^2a
$E_{cooling}$	Primary Energy for Cooling	kWh/m^2a
EP	Primary Energy for environmental air-conditioning	kWh/m^2a
EPi	Energy performance index for winter air-conditioning	kWh/m^2a
EEMs	energy efficiency measures	---

f_c	Crossover fraction	---
f_m	Mutation probability	---
FEN	Normalized energy demand for winter air-conditioning	kJ/DDm^3
FESR	European Regional Development Fund	---
FSE	European Social Fund	---
g_{max}	maximum number of generation	---
GA	Genetic Algorithm	---
$HR_{\%}$	Heat recovery's percentage	%
MATTM	Ministry of the Environment	---
MSs	Member States	---
MSE	Ministry of Economic Development	---
nZEB	nearly Zero Energy Building	---
POI	Interregional Operative Program	---
PON	National Operative Program	---
POR	Regional Operative Program	---
Pv_s	Photovoltaic system's size	[kW]
Ps_s	Solar system's size	[kW]
Q	Energy requirement for heating of buildings	---
QSN	National Strategic Reference Framework	---
RB	Reference Building	---
RBh	Hospital Reference Building	---
RBs	Reference Buildings	---
S/V	Shape factor	

tr	thickness of roof's insulation	cm
tv	thickness of vertical walls insulation	cm
U	Thermal transmittance	W/m^2K
U_r	Roof's thermal transmittance	W/m^2K
U_w	Vertical walls' thermal transmittance	W/m^2K
VIGOR	Evaluation of the Geothermal potential of Convergence Regions	---
w_t	Window's type	---
ηc	efficiency of control	---
ηd	efficiency of distribution	---
ηDH	efficiency of district heating	---
ηe	emission efficiency	---
ηeg	efficiency of Italian electricity grid	---
ηp	efficiency of production	---

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