THE REPUBLIC OF TURKEY
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A METHODOLOGY TOWARDS COST-OPTIMAL AND ENERGY EFFICIENT RETROFITTING OF HISTORIC BUILDINGS: A CASE STUDY OF ISTANBUL UNIVERSITY

Master's Thesis

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ABSTRACT

A METHODOLOGY TOWARDS COST-OPTIMAL AND ENERGY EFFICIENT RETROFITTING OF HISTORIC BUILDINGS: A CASE STUDY OF ISTANBUL UNIVERSITY

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Preservation keeps the nation's history and culture alive and promotes the transfer of methods and practices for several generations. Alongside climate change and the threatened environment, sustainability became a crucial way of living. Original passive sustainable features were realized in historic buildings which responded to micro-climate and site. With regard to historic buildings' original sustainable features, active sustainable techniques can enhance the buildings' energy efficiency without affecting its unique historic character. Thus preserving an existing building is considered the greatest recycling project. The present thesis attempts to examine and assess sustainable retrofitting of a historic building in order to maximize energy efficiency, hence with the aim to meet the terms of EPBD Recast. In this framework, Hasan Ali Yücel Eğitim Faculty (A-block & B-block) located in Istanbul University, Beyazit campus, will be analyzed in the framework of a case study. The study will evaluate the implementation of several retrofit techniques, active and passive, in the mentioned building using the energy software DesignBuilder. Later, the implemented retrofit strategies will be implemented in terms of a Life Cycle Cost evaluation with the aim of determining the cost-optimal energy efficient solution. The research will look at how preservation and green goals overlap, transforming historic building into a high-performance building. The resulted improvements in energy consumption can serve as a model for forthcoming historic retrofitting project taking into consideration the historic value and the economic feasibility.

Keywords: Sustainable Retrofitting, Historic Building, Life Cycle Cost, Energy Efficiency, Cost Optimal Solution.

ÖZET

TARİHİ BİNALARIN ENERJİ ETKİN VE MALİYET OPTİMUM YENİLENMESİNE YÖNELİK BİR METODOLOJİ: İSTANBUL ÜNİVERSİTESİ'NDE BİR ÖRNEKLEM

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Tarihi binaların korunması, ulusun tarihini ve kültürünü canlı tutmakta ve kuşaklar boyunca metotların ve uygulamaların aktarımını sağlamaktadır. Günümüzde iklim değişikliği ve tehdit altındaki doğal çevre ile birlikte sürdürülebilirlik konuları insan hayatında kritik hale gelmektedir. Mevcut tarihi binalarda, binanın mikro iklimi ve bulunduğu alana özgü özgün pasif sürdürülebilir özellikleri görülmektedir. Tarihi binalar pasif sürdürülebilir özellikler ile mikro iklime ve fiziksel çevresine yanıt vermektedirler. Tarihi binaların sürdürülebilir özelliklerine ek olarak aktif sürdürülebilir teknikler, binanın benzersiz tarihi karakterini etkilemeden binaların enerji verimliliğini artırabilmektedir. Dolayısıyla mevcut bir binanın korunması, en büyük geri dönüşüm projesi olduğu düşünülmektedir. Tez çalışmasında, enerji verimliliğini en üst düzeye çıkarmak amacıyla tarihi bir binanın sürdürülebilir yenilenmesi için yöntemler geliştirilmekte, böylece Bina Enerji Performans Direktifi'nin (EPBD) öne sürdüğü koşulları yerine getirmesi amaçlanmaktadır. Bu çerçevede, İstanbul Üniversitesi Beyazıt kampüsünde bulunan Hasan Ali Yücel Eğitim Fakültesi (B-blok), örneklem bina olarak ele alınmıştır. Bu çalışmada, söz konusu örneklem bina için geliştirilen aktif ve pasif enerji etkin yenileme stratejilerinin DesignBuilder simulasyon programını kullanılarak değerlendirilmesi yapılmıştır. Daha sonra, enerji etkin yenileme stratejileri enerji ve maliyet etkin çözümleri belirlemek amacıyla, Yaşam Döngüsü Maliyeti açısından değerlendirilmiştir. Araştırma, tarihi bina koruma ve yeşil bina hedeflerinin nasıl üst üste gelerek tarihi bir binanın yüksek performanslı bir binaya dönüştüreleceğini analiz etmektedir. Sonuç olarak, geliştirilen tez çalışması, tarihi binaların tarihi değeri göz önünde bulundurularak, maliyet etkin enerji performans iyileştirmelerinde gelecekteki çalışmalara örnek model teşkil etmesi hedeflenmiştir.

Anahtar Kelimeler: Sürdürülebilir Yenileme, Tarihi Bina, Yaşam Döngüsü Maliyeti, Enerji Verimliliği, Maliyet Optimum Çözüm.

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1. INTRODUCTION

Cities around the world are facing social and economic difficulties which have directly affected the maintenance of national heritage. Many considerable historic buildings and districts are destroyed, others just die of desertion and decay and others are transformed into slums. Moreover, historic buildings are facing several pressures. As known, pollution and neglect are the main factors causing their decline. Moreover, the requirements of contemporary facilities such as water, electricity and HVAC conflict with the need of preservation of their historic integrity. Thus preservationists commonly argue that historic buildings are inefficient and require major corrective measures. Yet, Serageldin, et al. (2001) claim that the rehabilitation of historic buildings is not an addition, it is a part of a communal responsibility to recognize and protect history, tradition and cultural diversity. Such difficulties have brought the attention of new ways to revive historic fabric at a low maintenance and operational cost.

Moreover, the concept of sustainability, due to the constant climate change effect, has been a major priority in the agenda of numerous countries and organizations. In this framework, the built environment is the main targeted area, due to its high effect on energy depletion. With the increasing pressure on ecological balance, the United Nations Sustainable Development Goals (UN SDG) 2019 summit emphasized the completion of "2030 Agenda for Sustainable Development" with the "17 Sustainable Development Goals" (UN, 2015). This agenda was adopted for the first time in September 2015, and each year the summit checks the progress of its implementation. From these goals, three of them are connected to the built environment, which are to "ensure access to affordable, reliable, sustainable and modern energy for all" (goal 7), "make cities and human settlements inclusive, safe, resilient and sustainable" (goal 11), and "take urgent action to combat climate change and its impacts" (goal 13) (UN, 2015).

The unification of these two concepts together shaped the idea of energy conservation of already erected buildings. A common saying in the green building movement states that "the greenest building is the one that is already built", (Elefante, 2012). The idea of energy savings in buildings is not novel. Throughout history, builders have dealt with changing fuel supplies and the need for efficient use of these fuels. Nowadays with energy resources

being depleted and the rising concerns over the effect of greenhouse gases on climate change, historic buildings became a great asset for energy savings given all the embodied energy found in their built-up materials. Energy efficiency is the key component of sustainability—a term that generally implies the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment Development, 1987).

Historic conservation and sustainable design are two fields that shouldn't be conflicting but can actually be combined together to enhance the effectiveness of buildings (Green, 2011). Existing materials and infrastructure are utilized by the act of preservation, it also diminishes waste production, and preserves the remarkable character of historic buildings and cities. Preserving an existing building is considered, by itself, as the greatest recycling project, hence when effectively retrofitted with energy-saving devices and systems, historic buildings can achieve substantial energy savings.

According to Cambridge dictionary, the word 'Retrofit' (verb) means "to provide a machine with a part, or a place with equipment, that it did not originally have when it was built". Jay Dolmage provided a vital explanation of retrofitting. He wrote, "to retrofit is to add a component or accessory to something that has already been manufactured or built. This retrofit does not necessarily make the product function, does not necessarily fix a faulty product, but it acts as a sort of correction – it adds a modernized part in place of, or in addition to, an older part" (Dolmage, 2008). Hence retrofitting historic buildings with sustainable equipment is a corrective and reactive approach responding to the problems of decay and energy efficiency.

From another point of view, the Energy Performance of Buildings Directive (EPBD) proposed a set of guidelines to improve the energy performance of existing and new construction, in reaction to the increasing global warming and greenhouse gas emissions. These guidelines urge every participating Member State to set minimum prerequisites for energy performance for their building stock. It also promotes having a stable environment for investment for decision-making. This main legislative instrument is only outlining the main concepts and later it is transposed into national legislations according to each Member State. The Recast of this Directive, in 2010, also introduced the 20-20-20 policy to be achieved by 2020. It requires a 20% decrease of energy consumptions, 20% decrease

in CO2 emissions, and 20% introduction of renewable energy. It stresses as well the need to develop Near to Zero Energy Buildings with high energy performance. However, the current stand of this directive regarding historic listed buildings is still ambiguous, causing arguments to whether or not comply with the requirements. The law states that an assessment of the building must be done prior to decision regarding compliance. If complying with the defined prerequisites for energy performance would "unacceptably alter the character or appearance" (European Commission, 2010) of the building, then only in this case it is exempt from the regulation. Otherwise listed building should comply with minimum performance requirements. In this way the exemption may be mistakenly received, but a thorough assessment should be performed firstly (Michelmores, 2016). The ambiguity of the earlier statement along with an ineffective assessment could lead conflicts between related authorities over the right of exemption. As a result, the refurbishment of existing historic buildings constitutes a major challenge in the construction sector.

1.1 PURPOSE OF THE STUDY

Historic buildings have a large embodied energy in their built-up materials, therefore they create a great asset for energy savings. Hence retrofitting historic buildings ensures the livability and survival of old structure through time.

In reference to the above hypothesis, the purpose of this study is to develop a methodology for retrofitting historic buildings to maximize their energy efficiency and thus comply with EPBD Recast. In this context, the representative case study is evaluated with the purpose of achieving energy consumption values beyond the baseline values. The study aims at proposing a holistically sustainable intervention strengthened by a LCC analysis, identifying the optimal solution in terms of economic and energy impacts.

This approach is novel in the preservation arena, as it is not restrained by specific rules and regulations to regulate their energy consumption. Yet the intervention on historic buildings is constrained by local conservation principles. The present investigation takes into account these principles when providing data-driven strategies for sustainable retrofit interventions.

In the framework of this investigation, the research will look into the subject according to these questions: How to identify in a historic building its already existing energy-efficient features? And how to retrofit while maintaining its character-defining features? What are the guidelines for effective sustainable retrofitting? What are the opportunities and limits of retrofitting historic buildings?

1.2 SCOPE OF THE STUDY

This study targets historic buildings which are utilized for higher education purpose, due to their widespread in Istanbul. In particular, it investigates the retrofitting approach, in the scope of attaining energy efficiency, of Hasan Ali Yücel Eğitim Faculty (B-block) located in Istanbul University, Beyazit campus. Although B-block building underwent a recent renovation, yet there was no concern regarding its energy consumption. Thus this retrofitting will be an additional enhancement proposing a new strategy for sustainable retrofit which considers the historical value of buildings and serves as a model for sustainable urban development. Within this scope of study, Istanbul is selected as a pilot city. It is located in a temperate-humid climatic region that is assumed representative due to its dominancy in the country.

The scope of the study was limited by the denied access to data related with the energy bills, which resulted in the elimination of model calibration. Such step is needed in future researches in order to simulate a model which is conform and truthful to reality. Moreover, the limited time of the study and the complexity of the simulation software constituted a barrier to the detailed modeling of internal components such as HVAC system. Thus the acquisition of all related data prior to modeling is a vital step for the smooth progression of the study.

1.3 METHODOLOGY

The study is based on quantitative research techniques as its methodological framework. Firstly, a region / pilot city is designated due to its effect on the climatic conditions, necessitating different interventions for different climates. From this region a building type is selected based on the involved user's schedule, occupancy number and different

energy usage. Then a case building is designated based on the availability, accessibility, durability of its related data. These data involve the building's drawings (plans, sections, and elevations), details about walls, roof, and floors layers, windows type and schedule, the operation schedule of users, heating & cooling systems details, natural & mechanical ventilation details, and energy bills. Next, from the broad variation of modeling software, the most suitable one for the scope of the study is selected. Later an energy model is simulated using the selected modeling software, where the collected building's data are inserted. After which the model is calibrated using the energy bills and the weather data. Then the building is analyzed in terms of end-use energy consumption, and the compatibility of the results is assessed based on local and international legislations, thus the need for retrofit interventions. According to the energy simulation results, the deficiencies noted in the system, the broad variety of interventions techniques collected from the literature, and the local preservation guidelines, retrofit strategies are designated and applied to the model. Subsequently, calculation regarding energy performance and Life Cycle Cost are carried out, according to the most suitable calculation method. Finally, cost optimal point or range is designated, representing the optimum retrofit scenario. Results are drawn from numerical data and energy simulation model about energy and cost efficiency of the retrofitting project. In brief, the paper analyzes the challenges in incorporating sustainable technologies into historic buildings, while providing guidelines for a comprehensive intervention, integrating energy efficient measures at a cost optimum while respecting the historic character.

1.4 LITERATURE REVIEW

In this introductory chapter, a synopsis of state of the art literature represents the general context in which the work of this thesis is conducted. The following sub-chapters are divided in such a way to link between the energy problems on one hand and the building sector on the other, providing cases from Turkey and the world, with similar climatic region. The sub-chapters are divided in terms of followed energy efficient approaches for retrofitting, inclusive retrofitting of conventional buildings, and historical buildings, and lastly a synopsis of rating systems supporting such interventions.

1.4.1 Integration of Energy Efficient Approaches

In the article "*Integration of passive PCM technologies for net-zero energy buildings"*, the authors Stritih et al. (2018) examine the use of Phase Change Materials (PCM) as a passive technique for Thermal Energy Storage (TES) aiming at attaining net-zero energy buildings. PCM is a material with a great heat of fusion, it melts and solidifies at specific temperatures, meanwhile in this process it stores and releases a significant amount of energy. PCM is considered a latent heat storage unit since thermal energy is released and absorbed with the constant change in substance's state, from liquid to solid and vice versa. The researchers tested the efficiency of PCM through designing a concrete wall filled with different types of microencapsulated PCM (mPCM) and analyzed its different performance using TRNSYS software. The researchers chose a new strong mPCM that is durable enough to resist smashing during the mixing process with concrete. Additionally, this new mPCM increased the thermal mass of concrete. The composite wall is composed of two layers adjacent to each other, one layer of concrete only and a second layer of concrete mixed with mPCM. Parametric analysis was conducted in order to test different parameters each one separately, such as the material of wall, the type of PCM and the percentage of PCM. This analysis helped the selection of the optimum PCM configuration for the case study designated by researchers. The appropriate type was selected based on a consideration of the meteorological conditions. In this case, PCM SP22A4 is the one which saved the highest amount of cooling energy. This option is characterized by the highest melting temperature (24^{o}) which allows the material to cool down at night, along with a large storage capacity (latent heat 165 kJ/kg).

The article "*Renewable energy technologies for sustainable development of energy efficient building"*, written by Chel et al. (2017), investigates different passive strategies coupled with several renewable energy technologies with the purpose of achieving nZEB. The authors discuss energy conservation from four main aspects, firstly the passive building design strategies, secondly the use of materials with low embodied energy, thirdly the use of low operational energy efficient equipment and lastly the addition of renewable energy sources (RES). Energy conservation measures are acquiring great importance in the arena of new building construction as well as in the refurbishment of

existing ones. Therefore the authors inspect several passive techniques for solar heating, such as the thermal mass, thermal storage wall (Trombe wall), water wall, roof pond system, sunroom, and solar collectors. Besides, they consider the passive solar cooling methods, for instance, natural ventilation, operable windows, wing walls, and thermal chimney. Any passive strategy implemented in buildings requires a great understanding of the technique of heat exchange and a knowledge of the suitable building materials for the local climatic conditions. Subsequently, a series of RES is reviewed based on their efficiency and their suitability for the local conditions in India. For example, the hybrid Photovoltaic/Thermal (PV/T) system provides electricity as well as the chimney effect. It is a novel adaptation of the Trombe wall with PV module. Another example is the combination of photovoltaic panels with small wind turbines that can perform efficiently in regions with adequate sunshine and wind conditions. Additionally, the researchers developed numerous unit cost tables of different RES. Finally, they compared a building's energy consumption before and after retrofitting with Trombe wall. The results were highly in favor of the retrofitting strategy in terms of energy reduction and cost-effectiveness which have a payback period of less than one year. In conclusion, the integration of passive techniques with renewable energy technologies can achieve tremendous outcomes in energy conservation.

In the article "*Assessment of residential building performances for the different climate zones of Turkey in terms of life cycle energy and cost efficiency"*, the researchers, Mangan et al. (2016), assess residential building performance in different climatic zones of Turkey, like Istanbul, Ankara, Antalya, Diyarbakir, and Erzurum, with regards to energy as well as cost efficiency. The researchers selected a reference residential building representing the bulk of investment put for residential construction, accomplished nationwide by TOKI (Housing Development Administration of Turkey). Subsequently, they developed several measures with the intent to improve building energy performance. The methods targeted the building envelope including energy-saving measures as thermic insulation (including external wall, ground floor, and roof), improvement of U-value of the window's glass and introducing green roof technology. Additionally, the methods included energy producing systems as the photovoltaic systems. Successively, the researchers evaluated the life cycle of the reference building in terms of the developed

measures according to energy, financial and environmental performances. The reference building's current energy consumptions along with the energy saving practices were calculated using DesignBuilder modeling and simulation software. Later the LCC was calculated including both the primary investment costs as well as the operational costs, according to a Net Present Value discount rate. Therefore reducing the future expenses to its equivalence in present day. The LCC was calculated along with a sensitivity analysis to determine the impact of the changing values on the overall results. At last, the researchers determined the optimum enhancement combinations for each climatic zone that has the optimum execution as regards of life cycle energy and life cycle cost. In conclusion, this study provided a compilation of standards aiming at improving the energy performance of the newly designed housing typology of TOKI along with the country's energy economy.

In the article "*Passive design strategies and performance of Net EnergyPlus Houses"*, Rodriguez-Ubinas et al. (2014) discuss several passive design strategies implemented in houses to reach Net EnergyPlus Building (PEB) and to meet the terms of the EPBD goals. This research studies the Solar Decathlon Europe (SDE) 2012 houses designed to achieve sustainable goals and high energy performance. This competition emphasizes on the diminution of energy demand and the production of renewable energy to cover the energy demands. Moreover, it encourages the use of passive strategies by demanding a two-days Passive Monitoring Period. SDE 2012 was set in Madrid, therefore the study included the analysis of the microclimatic conditions of the city. The researchers analyzed in depth the strategies used by the houses to achieve thermal comfort with a specific attention to the passive strategies. These strategies were analyzed according to five criteria: envelope, orientation, geometric aspects, and other passive and hybrid strategies. Findings were organized into tables and graphs comparing different results achieved by each design strategy. These strategies include but not limited to: effective insulation, great glazing performance, envelope air-tightness, evaporative cooling, nocturnal ventilation, and night sky radiant cooling. As a result, all houses achieved a positive energy sum-up in both the two-weeks monitoring and the annual energy simulations provided by the contestants. Several recommendations were provided by the authors at the end of the study concerning a better monitoring performance, such as the limitation of public accessibility to the

houses due to their effect house thermal performance, the addition of radiant temperature measurement which is a key parameter of thermal sensation, the creation of solar protection solutions that balance thermal and lighting comfort. Nevertheless, one of them is related to the actual economic feasibility of these strategies and their payback period which I believe is an essential consideration in a globally troubled economic situation.

In brief, the integration of energy efficient approaches ranges from passive strategies to active ones, including the development of novel materials or the integration of renewable energy, can assist the building to reach energy efficient goals set by local or international standards.

1.4.2 Retrofitting of Conventional Buildings

In the article "*An approach for an educational building stock energy retrofits through life-cycle cost optimization"*, the researchers Yılmaz et al. (2018) assess the improvements in energy saving through retrofitting certain appliances in order to reach the optimal value combining energy efficiency and life-cycle cost. The research investigates education building stock (48 buildings) in the districts of Beşiktaş and Şişli in Istanbul. The researchers started by classifying these buildings into categories in order to define the lower limit of energy requirement for the stock as a threshold value using the clustering method. The required data for classification were collected through field studies and the threshold value was determined through a mathematical equation established by the researchers to suit the local conditions. A building beyond the threshold value was selected for retrofitting and a 20% reduction of total energy consumption was targeted, in order to comply with the EPBD Recast of 2010. The selected base case building was modeled in EnergyPlus simulation tool where calibration method was applied with the intention to minimize the difference of results between measured and simulated energy levels. The calibration by mean bias error (MBE) and coefficient of variation of the root mean square error (CV [RMSE]) is specified in ASHRAE Guideline 14. After determining the input parameters with uncertain value, variants were located in the calibrated range and the best variant in which the difference between measured and

simulated data is minor, was considered subsequently. Several retrofitting scenarios were designated taking into consideration the envelope insulation including roof, ground floor and external walls, alteration of window types, and replacement of condensing boiler and led tubes. For each one of these six parameters, several alternatives were proposed based on the local conditions and life-cycle cost. The LCC calculation for these different scenarios is based on the method provided in the NIST Life-Cycle Costing Manual. LCC calculations require several formulas comprising the annual operation cost, nominal escalation on energy prices and investments costs. With the aim of obtaining an optimum energy performance and cost efficiency, GenOpt tool was used as a stand-alone optimization tool. Involving a Particle Swarm Optimization (PSO) algorithm, GenOpt designated the optimum combination between energy and cost efficiency which is the lowest point on a concave up parabola. Hence this study follows a specific scientific methodology leading to maximizing energy performance of existing building while considering life-cycle optimization. The methodology of this research provides guidelines for my study related to results that comply with the EPBD Recast requirement and to cost-efficient calculations, attaining a cost-optimum..

The paper "*New methodology and tools for retrofit design towards energy efficient and sustainable buildings and districts"*, composed by Ferrando et al. (2016), introduces a new methodology and tool for sustainable retrofit of existing building. NewTREND project proposes a new approach combining energy efficiency retrofit along with a participatory design. Firstly it adopts simulation tool at the early design stage to ensure accurate results, applying simulation and optimization of energy performance. The design process follows three modes of operation, basic, advanced and premium, based on the accuracy of the collected data concerning the building geometry and thermal characteristics. More developed modes allow the user to investigate more detailed aspects and to examine the building post-retrofit. The Data manager is one of its tools that assists users through the entire design process with its easy accessibility from mobile devices. It also helps designers during the data collection phase by providing a checklist of the needed data and the methods to collect it through online questionnaires and surveys. Other tools are Design Hub and the Key Performance Indicators (KPIs) which allow designers to simulate and compare different retrofit scenarios and to identify the optimum solution.

Additionally, NewTREND Technology Library is a comprehensive library of retrofit strategies that retains quantitative information and data on different technologies to be implemented in the simulation. Secondly, the project incorporates participatory design and occupant involvement through a collaborative design platform at each phase of the project, for example, pre-design scoping sessions, co-design workshops, continued two-way dialogue during construction and collaborative post-occupancy evaluation. This approach aims at having better functionality, improved design strategies, greater occupant satisfaction and minimization of conflict between users' comfort and building's energy performance. As a result, the intervention is shaped by the socio-technical systems in which occupants are embedded. Finally, NewTREND project embraces an innovative approach consisting of a design methodology, software tools, and a collaborative design.

The study *"Carbon mapping for residential low carbon retrofitting"*, conducted by Dabaieh et al. (2016), develops a new carbon mapping tool having the purpose of measuring the carbon footprint for residential stock in Egypt. The tool has the purpose of retrofitting carbon alleviation solutions targeting both the building as well as the urban level in order to improve the energy efficiency of the existing stock. This tool is a user-friendly web application that supports not only designers, planners and business developers in the large scale low carbon planning but also homeowners seeking a reduction in energy consumption and house bills. During an extensive literature review, the authors investigated several methodological approaches to calculate carbon footprint with regards to LCA (Life Cycle Assessment). The main two methods are the PA (Process Analysis) and the EIO (Environmental Input-Output) analysis. Additionally, the widespread use of GIS (Geographic Information System) application as an analytical mapping tool for energy consumption is emphasized. As a result, the researchers employed GIS as an auxiliary tool for entering data, analyzing and performing calculation. The study methodology consists of collecting carbon emission data of a pilot neighborhood in Cairo, then testing and validating the data and calculations using GIS application, later uploading the data on an open-access web link as a user-friendly interface, and lastly testing the users' interactions and comments to the designed tool. This project provides guidelines for decision making and design approaches that will reduce CO_2 emissions for running energy of buildings. It also serves as a support for

retrofitting and rehabilitation projects to reach zero carbon emissions and positive energy buildings.

The paper "*Retrofitting an office building towards a net zero energy building"*, created by Pyloudi et al. (2015), investigates an office building's energy retrofit to comply with the goals of the European Directives and to reach net zero energy building. The authors state that in a world with massive energy depletion, it is necessary to adopt smart consumption strategies to reduce energy demands without affecting the occupants' comfort and thus their productivity. The building under study is an office building located in the campus of the Technical University of Crete. Using TRNSYS and HOMER software, the authors examined four retrofit scenarios for energy reduction and three more for energy production technologies. In the aim of minimizing energy consumption, several strategies were implemented. Firstly, concerning the building envelopes, additional insulation layer was added to the walls and ceiling, all windows were substituted with more energy efficient ones, and a layer of cool paint was applied to the external walls. Later, in the framework of building internal conditions, lighting system and the power supply of computers were replaced. Next, heating and cooling thermostat set points were changed along with the ventilation settings in the schema of energy-saving measures. Additionally, due to its location in a mild Mediterranean climate with an intense solar radiation, PV systems were implemented on the roof facing south direction. Furthermore, four wind turbines were examined in the purpose of generating the same quantity of consumed energy. Nevertheless, renewable energy technologies cannot always produce the same amount of energy due to weather conditions, hence the building must be grid connected. Finally, all these scenarios were analyzed separately and in combination using the simulation software. After comparing all different scenarios, the authors concluded that the best retrofit scenario was the one combining energy-efficient measures along with renewable energy production, in order to achieve NZEB.

Retrofitting projects taking place in conventional buildings present a wide range of intervention strategies. These strategies are not limited by any law or regulations. Their main purpose is to achieve energy efficient goals complying with the minimum

requirements. Most of the projects develop a simulation model and optimization of building's energy performance, in order to assess the results and determine the most suitable intervention plan.

1.4.3 Retrofitting of Historic Buildings

The speculative case study "*Energy upgrading of buildings. A holistic approach for the Natural History Museum of Crete, Greece"*, conducted by Al. Katsaprakakis et al. (2017), presents a comprehensive approach regarding the energy upgrading of the NHMC (Natural History Museum of Crete) in Greece, from rank D to A+ under the authority of the Greek Directive on Buildings' Energy Efficiency. The implemented strategies are established after a collection of passive and active approaches. This case study constitutes a pilot and demonstrative project, submitted for funding in April 2016 to the first European call "Interreg Greece - Cyprus, 2014-2020". It aims at providing an inclusive overview of the current energy savings possibilities and their implementation.

The NHMC is situated in Heraklion, Crete, featuring the typical Mediterranean climate conditions. The building was originally an electricity generation power plant, the first in Crete, launched in 1925. Later in time, it housed the central vegetable market before it was abandoned for almost a decade. It is not until 2005 that the Municipality granted it to the University of Crete, to accommodate the largest natural history museum of Greece, after undergoing radical renovation works.

The renovation didn't include any energy efficiency considerations. Therefore, the researchers targeted this issue by implementing primarily passive strategies. These strategies include the application of an expanded polystyrene insulation layer on the outer surface of the walls, in order to prevent any annoyance and nuisance to the working schedule of the museum. Regarding the roof, the classic expanded polystyrene insulation layer will be added along with a waterproofing layer (polyurea spray). Additionally, a semi-intensive green roof is chosen to be mounted in the South above the entrance. Apropos the openings, doors and windows will be replaced with more efficient ones, having an airtight synthetic PVC frame. As an addition to the overall aesthetic and

bioclimatic condition of the building, the outdoor yard will be converted into a planting area increasing the fraction of latent heat from solar radiation.

Furthermore, the application of several active systems was examined. Giving its vicinity to the seaside, the initiation of an open loop geothermal system combined with water-to-water geothermal heat pumps (GHP) was perceived as an ideal resolution. The seawater aquifer acts as a thermal tank, allowing the absorption and discharge of heat according to seasons. An intervention on the lighting system was required, involving the substitution of the existing lamps with new energy efficient ones (LED). It also included the inauguration of a central system for lighting management in order to optimize its operation. An advance measure proposed the installation of a reactive power recompense panel, to reduce the reactive electricity demend. Concerning the renewable energy sources, connecting the building with PV station (10 kW) and four wind turbines (5 kW each) was proposed due to the climatic features of the site.

In conclusion, the proposed interventions led to a 93.29% reduction in energy consumption, from 273.65 kWh/m^2 to 18.36 kWh/m^2. Moreover, they demonstrated a technical feasibility and an easy installment process. This investigation provided a clear methodology for prospect energy upgrade studies on historic buildings. The researchers believe that such documentation contributes to the cultivation of knowledge related to energy conservation, strengthened by the idea that this specific building presents a evolution from conventional fossil fuels to substitute energy sources, and thus it gains a symbolic extension.

In the article "*The assessment of environmental conditioning techniques and their energy performance in historic churches located in Mediterranean climate"*, the researchers Muňoz-González et al. (2017) assess the environmental conditioning techniques in a historical building as a case study. The building selected was the church of Nuestra Seňora de la Merced in Spain, which is characterized by a Mediterranean climate. In the framework of an experimental research, the building was modeled using DesignBuilder and EnergyPlus software and the application of various environmental practices - passive, active and combined - was evaluated. The intention of this experiment is to develop a technique for predicting the indoor environmental behavior prior to the refurbishment of

historical buildings. Firstly, the building's hygrothermal conditions were monitored. Two variables were recorded, which are the air temperature (T) along with relative humidity (RH). Later the building was simulated in DesignBuilder and validated using the onsite measurements carried by sensors. The minor differences between the model and the measurements confirm that the software generated an adequate prediction of the local environment. Subsequently, different environmental scenarios for heating and cooling were simulated based on the ones mostly used in Mediterranean climate. The results of the several simulated scenarios were the inefficiency of passive techniques solitary because they do not guarantee indoor comfort all year long aside from increasing the risk of heritage deterioration. On the other hand, active systems coupled with passive techniques provide better occupants' comfort and by implementing them, the indoor temperature and humidity are maintained therefore the risk of bio-deterioration disappears. Although the energy consumption in these scenarios remains high, but the grouping of active systems with passive techniques improved energy savings from the baseline.

The article "*An overview of energy retrofit actions feasibility on Italian historical buildings"* is a synopsis of the Italian and international literature about different retrofit strategies for historic buildings. The authors, Galatioto et al. (2017), focus on Italian residential building heritage in terms of applicable strategies according to thematic area along with the benefits and shortcomings of each. Their methodology revolves around highlighting the practicability of retrofit actions related to envelope insulation, HVAC system, occupant behavior, control strategies for indoor comfort, RES (Renewable Energy Sources), and Thermal Energy Storage. Since 46% of the building stock in Italy is registered as world architecture heritage by the UNESCO, the Italian energy policy department is recently persuading buildings' owners to apply retrofit actions to reduce their massive energy consumption by means of tax breaks and/or co-funding. However, the authors argue that in order for the buildings' owners to endorse these retrofit actions, the implemented strategies should be feasible and have a low Payback Times, as energy-financial plans are the key factor for execution. In the framework of this evaluation, the authors composed a summary table assembling a wide range of strategies from Italian and International citations with their benefits and shortcomings. Finally, the authors

concluded that case-by-case retrofit strategies should be considered due to the different characteristics of each building in terms of occupancy, usage, envelope types, heating/cooling system performance, microclimatic conditions and regulatory restrictions of the country.

The study "*Energy retrofit of historic buildings in the Mediterranean area: the case of the Palaeontology Museum of Naples"*, written by D'Agostino et al. (2017), aims to assess the energy retrofit strategies of a historic building in Naples, Italy characterized by its Mediterranean climate. The building under investigation is the Paleontology Museum of Naples situated in the ancient city center declared World Heritage by the UNESCO. This refurbishment project presents further difficulty due to the valuable elements comprised inside this type of building that require specific indoor environment. Firstly, through field inspection and photographic documentation, the authors collected data about the building concerning its geometric layout, building materials, and the HVAC system. Consequently, building simulation has been carried out in a dynamic mode using DesignBuilder / EnergyPlus software and several retrofit strategies have been monitored on an hourly basis. During the field inspection, the authors noticed a nonexistence of cooling system inside the museum and a privation of both heating and cooling systems in some halls of the later. Therefore, they proposed several retrofit combinations concerning the integration of these neglected systems, for instance: condensing boiler, heat pump, condensing boiler + chiller, reversible heat pump, condensing boiler + chiller + packaged AC units, and lastly reversible heat pump + packaged AC units. The suggestion of packaged air conditioning units conforms to the preservation regulations because it doesn't include air channels nor water pipes, neither outdoor units to alter the façade's aesthetics. Lastly, these combinations have been assessed with regards to primary energy consumption. As a result, the best outcome regarding primary energy has been achieved with the use of heat pump. On the other hand, the combination of condensing boiler + chiller + packaged systems provided the best aftermath considering electric energy, if together heating and cooling are required for all museum halls. In conclusion, this research stipulated several alternatives for improving the indoor environmental comfort of the museum along with its energy performance depending on the required conditions.

The article "*Energy retrofits in historic and traditional buildings: A review of problems and methods"* is a comprehensive analysis of the growing amount of research conducted on the theme of energy retrofits in historic and traditional buildings (Webb, 2017). Believing that retrofitting historic buildings is a complex act balancing several criteria, the author investigated these criteria, the analysis methods, and decision-making process. Even though historic buildings are, according to each case, exempted from energy regulations, nowadays a growing interest in upgrading and adapting them to meet modern needs is surfacing. However, energy retrofits strategies in modern buildings might not be necessarily applicable to historic buildings, and can produce deficiencies to the structure. Therefore, the author classified the criteria to evaluate the influence of energy retrofits according to four categories: global environment, building structure, indoor comfort, and finances. In the framework of this assessment, the author evaluated several types of research and projects and their different implementation of retrofits strategies. Subsequently, she examined different analysis methods, including field measurements (environmental monitoring and microclimate analysis and on-site measurements of envelope), laboratory examination, performance simulation (including energy and hygrothermal simulation) and damage functions. Lastly, she addressed the recent efforts in providing counseling and decision-making for choosing retrofit strategies. One of the organizations developing long-term researches in this field is the STBA (Sustainable Traditional Buildings Alliance), which has created retrofit guidance. She criticized that most of the guidelines have a generalized approach, only very few take into consideration the climate and the building typology of a specific region. She also noticed that with the presence of a wide range of guidelines for retrofit alternatives, only one or a subgroup is ultimately selected. As a solution, decision analysis such as single-objective and multiple criteria acts as a screening tool to narrow the list of retrofit strategies that comply with the heritage conservation criteria. In brief, energy retrofitting of historic buildings is recently coming into light, from one hand to reduce their energy consumption and from another hand to preserve them for a long-term.

The paper "*Local energy efficiency interventions by the prioritization of thermal zones in an historical university building"*, by Carbonara et al. (2016), discusses local interventions for sustainable retrofits of a historical university building in terms of specific thermal zones. The historic building stock is not concerned with energy performance regulations due to the need for protecting their cultural value and the limited interventions allowed by the preservation authorities. Nevertheless, the authors believe that minimum accurate interventions, that do not affect the building's historic characteristics, can achieve a high decrease of energy consumption along with occupants' thermal comfort improvement. The study is applied to the Physics building of Rome University "La Sapienza", built in 1932. Firstly, the building's second floor, mostly composed of classrooms, is divided into three zones with different surface areas and different orientations (SE, NW, and NE). Later a dynamic simulation was performed using TRNSYS software, where several parameters related to thermal comfort were monitored, for instance the operating temperature, the air relative humidity and the sensible heat load associated with energy consumption. The intervention strategies consisted of the insertion of an internal insulation layer in walls and roof, aiming at preserving the original appearance of the building, in addition to the replacement of glazing with more energy efficient one. Subsequently, the simulation was performed on an hourly basis where the selected parameters were evaluated on a span of a whole year. As a result, all thermal zones exhibited improvements in the thermal comfort ranges, and the SE zone particularly had the best results in this framework. On the other hand, in terms of energy reduction, the NW zone displayed the highest reduction of energy demands per square meter of floor area. The authors conclude that interventions in specific parts of the building are more beneficial and economical than the ones performed on the entire building structure with regards to energy reduction, especially with the limited funds provided for energy improvements of historic buildings.

The article "*Roof top PV retrofitting: a rehabilitation assessment towards nearly zero energy buildings in remote off grid vernacular settlements in Egypt"*, written by Dabaieh et al. (2016), discusses retrofitting off-grid vernacular architecture with renewable energy, its benefits, constraints, and potential opportunities. The authors argue that such hybrid energy efficient retrofitting solution can make vernacular structures reach nearly

zero energy buildings. Two pilot projects in the Egyptian Western Desert served as study cases for the investigation and in order to evaluate them, post-occupancy evaluation (POE) was implemented by the researchers. They believe that passive techniques used in vernacular buildings are being neglected due to modern inventions, therefore it is essential to enrich them with advanced modern technologies in order to reach better energy performance, user comfort and preserve local climate specificity. The two case studies, one in El-Gara and the other in El-Heiz located in Siwa Oasis and Baharia Oasis respectively, include the installation of rooftop PV systems providing adequate levels of power for basic houses' needs. These projects were funded one by the Government and local authorities and the other was a community-driven initiative, both have the aim to develop the primitive lifestyle of these villages while lowering their energy consumption depending solely on the diesel generators. The POE conducted by the researchers included interviews with municipal employees (structured open-ended), questionnaires with villagers from each Oasis, photographs, videos and audio recording, along with site observations. The survey mainly targeted the level of satisfaction of the users post-retrofitting. It provided a methodology on the way to conduct community energy surveys. The findings showed great users satisfaction along with an effective energy reduction in consumption of fossil fuels to reach nearly zero energy building. This retrofitting approach provided an off-grid sustainable energy resolution for unconnected villages. The authors also discussed several barriers and recommendations to the spread of such approach on the financial, governmental, national and awareness levels. In conclusion, with its low maintenance cost, in the long term, and its clean source of energy that isn't noisy nor pollutant, this hybrid system creates an optimal solution for the energy crisis globally and specifically in Egypt, along with reducing the rate of demolition of historical vernacular settlements.

The article "*The energy performance improvement of historic buildings and their environmental sustainability assessment",* written by Magrini et al. (2016), discusses a new methodology for evaluating environmental sustainability and potential energy performance enhancement in historic buildings. The researchers believe that an early assessment of the interventions techniques could occupy a crucial role in highlighting the value of smart energy renovation. A multi-disciplinary investigation was conducted on a

illustrative study case, the historical complex of the Albergo dei Poveri of Genoa in Italy. The complex which served for charitable purposes will be renovated and reclaimed as the campus of the University of Genoa. The field of historic buildings' environmental sustainability lacks the standard methods to assess these buildings. Nevertheless, several local initiatives are emerging, one of them is the new rating system GBC Historic Buildings, developed by GBC-Italia, combining LEED standards with the special requirements of historic buildings complying with the restoration rules of Italy. Even though it appears to be the most specific instrument for assessment, but this rating system can only be applied at the end of the design process. Therefore, in this case study, the Reference Practice developed by the Italian National Standardization Authority, the ITACA (Institute for Innovation and Transparency of Contracts and Environmental Compatibility), was chosen as the sustainability rating system for evaluation. The calculation of the energy score has been conducted for different scenarios, the current situation and two different levels of rehabilitation. The results were a comparison, according to the different categories of the rating system, between the planned refurbishment limited by the restoration constraints and the maximum energy performance improvements. This analysis provided a new methodological approach to adjust the rating system analysis to the specific limitations and constraints of restoration. As this evaluation is novel in the field, the researchers recommend that different rating systems should integrate these new categories, in order to offer a larger choice of techniques within the limits of refurbishment actions.

The study "*Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study"*, achieved by Cornaro et al. (2016), exhibits a methodology for energy retrofit employing in-situ measurements along with dynamic reproduction of the complex historic building of Villa Mondragone, situated in Colli Albani which currently belongs to the University of Rome. In 1573, this Villa was built as a mansion for Cardinal Marco Sitico Altemps over ancient Roman remnants. The complexity of the building resides in the superimposition of different construction technologies and styles that occurred over time on the building's structure causing its peculiar historic stratification. Initially, the researchers conducted a reliable assessment of the building by the review of available historical records, field inspection, visual

examination, and interviews with personnel. This investigation allowed gathering different building's characteristics, such as the envelope, walls and roof details, and levels structures. Subsequently, a whole building simulation was carried out in a dynamic mode using IDA ICE 4.5 software. Additionally, in order to obtain accurate results, one month of air temperature and humidity measurements, on an hourly basis, during the spring season (May-June), was performed by sensors located in three different points. The objective of the monitoring is to calibrate the building envelope in the aim of reducing the variation between measured and simulated data and thus obtain truthful results. The calibration also overcame the lack of technical references regarding the rooftop's former restoration. Ultimately, two retrofit approaches were analyzed, one regarding the windows' refurbishment and in some areas their incorporation, and the other concerns the substitution of the external existing damaged mortar with a high insulating material, Dyatonite Evolution. Both approaches demonstrated an improvement in the energy performance of 40% and 38% respectively. In brief, this analysis proposed two refurbishment interferences with minor impacts, preserving the historical character of the building.

The study "*Retrofitting Solutions for Energy Saving in a Historical Building Lighting System",* conducted by Ciampi et al. (2015), investigates various actions on historic buildings targeting energy savings with focus on lighting system. The office building under assessment is located in Abbey of San Lorenzo, now housing the Second University of Naples. Before being erected in the simulation software DIALux, several experimental measurements were conducted on a prototype office room. These measurements included the height and area of the room, wall thickness, windows dimensions, luminaires details and arrangements, and the reflectance values of the surfaces and furniture. Consequently, without modifying the geometry or aesthetic of the room, five retrofit measures were applied and assessed with regards to Lighting Energy Numeric Indicator (LENI) and the illuminance uniformity. The strategies include (i) the replacement of existing lights with other two types (fluorescent , LED), (ii) the consideration of two different arrangements of the luminaires (vertical and horizontal), (iii) the placement of the luminaires on three different mounting heights (2.5m, 3.3m, 3.5m), (iv) the alteration of the values of wall reflectance (30%, 50%, 88%), and (v) the modification of the ratio of glass area (Ag) to

window area (Aw) for the same window area (0.38, 0.42, 0.78). As a result, all implemented strategies achieved a considerable reduction in the LENI value, which means a reduction in electric energy consumption, except for the alteration of window type, which didn't achieve a significant reduction. For this reason, the Ag to Aw ratio must increase substantially, which is not possible in historic buildings. Likewise, the illuminance uniformity values were greater than 0.6, the reference value for task areas. The authors concluded that the best measures were the replacement of lights, the diminution of mounting height, along with the increase of surfaces' reflectance values.

When reaching historic building, retrofitting projects become limited to local preservation guidelines. Therefore a comprehensive analysis must be conducted prior to intervention. Such analysis provides adequate prediction of the local environment in addition to the effect of retrofit actions on the historic structure. The project becomes a complex act balancing several criteria in order to reach satisfactory decision-making. This type of projects are still being developed worldwide, with case-by-case assessment.

1.4.4 Sustainability through the Application of Rating Systems

The conference paper entitled "*GBC Historic Building: a new certification tool for orienting and assessing environmental sustainability and energy efficiency of historic buildings"* is an overview of the newly launched sustainable rating system in 2015, GBC Historic Building. The authors Lucchi et al. (2016) describe the main features of this pilot environmental certification tool which are the integration of interdisciplinary fields of restoration and energy efficiency, in a holistic manner with a great level of transparency. The certification is a subset of the worldwide well-established LEED rating system. It is also a local adaptation issued by GBC Italia, centering around the building stock erected before 1945, before the industrialization of materials and construction techniques. The protocol contains the same categories within the LEED with an addition of "Historic Value" category. This credit category emphases the principles adopted during the restoration process. It foresees the restoration process as the primary sustainable act by maintaining both the building's physical form and cultural values. It is based on four main

principles, which are “minimal intervention”, “distinguishability”, “reversibility”, and “compatibility”. The principle of “reversibility” is stressed due to the probability of future generations acquiring advanced technologies that will provide a conservation in a more respectful manner. This category also encourages the performance of energy audits (“walk-through audit”, “standard audit”, or “simulation audit”) to acquire adequate information about the current energy state of the building in order to identify the appropriate retrofit interventions. The other categories are equivalent to the ones in LEED New Construction and Major Renovation. In conclusion, this voluntary and third-party certification tool allows the inclusion of historic buildings under the umbrella of sustainability.

The paper entitled “*Sustainability of a Historical Building Renovation Design through the Application of LEED Rating System”*, exhibits a study case of a hypothetical green retrofitting and certification of a historical school building in Treviso, Italy. The researchers, Baggio et al. (2016), implemented a retrofit strategies according to three main purposes: firstly saving energy in the building, secondly preserving its historic character and lastly enhancing the indoor environmental comfort. The researchers chose to use GBC Historic building protocol, proposed by the Italian Green Building Council, as a design tool in order to develop their design strategy and the LEED rating system as an assessment tool to certify the building post-retrofit. After performing a metric survey and archival research, the state of art of the school building was identified filling the preliminary required document the “Historical building Identity Card” and therefore recognizing the historical value of the building. Subsequently, a building simulation was conducted using DesignBuilder software coupled with EnergyPlus engine in order to implement the intervention strategies. For this reason, a restoration plan was carried out along with the intervention on specific parameters as roof and façade insulation, windows and heating system replacement. Finally, an analysis of a cost-optimum was performed to determine the best combination between the four measured parameters, and therefore the optimal retrofit strategy. At last, the building, after intervention, was assessed according to the LEED credits and, as calculated by the researchers, it received 56 points equivalent to a silver level certification. In conclusion, intervention strategies are limited in existing buildings and even more in historical ones. This requires an accurate

assessment of the present building condition and intervention strategies in respect to its historical value and the local regulations.

The article "*Sustainability assessment of historic buildings: lesson learnt from an Italian case study through LEED rating system"* by Boarin et al. (2014), discusses LEED rating system in general and its local Italian version, GBC Historic building, in particular in order to assess of historic buildings with regards to energy efficiency. The building under investigation is an old stable found adjacent to a Middle Age fortress in Perugia, Italy. After renovation, it will be reused as an International research center. All restoration reforms were approved by the Architectural Preservation Office, including the insertion of an external insulation layer that conforms with the ancient structure of the building, which had originally a cement plaster as the outermost layer. The restorative interventions included the design of high-performance envelope, replacement of HVAC system, and reduction of potable water consumption. Additional innovative techniques were integrated to passively reduce the cooling needs, like the innovative reflective clay tiles, which were implemented in a historic building for the first time. Later the authors analyzed the building's energy performance with EnergyPlus simulation software. The authors concluded that in order to apply environmental certification to historic buildings, the gap between sustainable energy reforms and restoration principles must be bridged. Therefore, the novel assessment framework, GBC Historic building, develops a new methodology based on the contrast and unification of these two fields.

In terms of rating systems, historic retrofitting projects lack the comprehensive guidelines for their implementation. Existing rating systems can be applied to historic building nevertheless they are not completely relevant. The recent GBC Historic Buildings initiative is trying to provide these comprehensive and common guidelines for all historic retrofitting interventions.

2. ENERGY EFFICIENT RETROFITTING IN HISTORIC BUILDINGS

2.1 ENERGY EFFICIENCY

During the last decades, the rapid increase of resources depletion, the greenhouse effect and the global warming concerns, led authorities in the energy sector to promote proficient use of the currently available resources while searching for alternatives for energy production from renewable resources. While buildings in general provide shelter for human beings to perform numerous daily activities, they also constitute a major danger to the environment with their high energy consumption. According to the UNEP (2011) around 40% of global energy, 25% of global water and 40% of global resources are consumed by the building sector, in addition to its production of one third of the greenhouse gas emissions.

In the aim of minimizing these global impacts, the concept of energy efficiency is introduced, which means the reduction of energy consumed by a product or a service. When targeting a reduction in energy consumption, cost savings is as well obtained. Likewise energy efficient buildings are entities that exhibit reduced energy needs for heating and cooling. This goal can be achieved through the design of several elements, such as climate responsive architecture, high performance envelope insulation, and high performance mechanical systems.

2.1.1 Energy Efficiency in Buildings

Generally, building's design is one of the key aspects affecting energy consumption during its whole life cycle. Historic buildings, particularly, exhibit a unique character related to their traditional construction techniques, local materials, available technologies and their artistic qualities. Therefore, the designation of these design specificities is vital in understanding their energy consumption and thus providing successful plans for energy conservation. Optimizing the energy consumption in historic buildings, which constitutes a large section in the existing building stock, will also decrease the energy expenditure on the national level. Each of the subsequent mentioned aspects cannot be changed in any

already erected building, however the awareness of the potentials of each aspect can be a great help for designers and planners to improve buildings' energy efficiency.

2.1.1.1 Climate

The climatic condition where the building is located is one of the main parameters affecting its design. For instance, historic buildings are built with special attention to the surrounding climate, due to the nonexistence of mechanical conditioning systems at the time of their construction. Accordingly, their design and the materials' choice was highly responsive to the local environment, trying to maximize indoor thermal comfort. In this manner, several weather parameters can be identified, such as air temperature, air pressure, solar radiation, humidity, precipitation, wind velocity, and wind direction. Air temperature is a parameter that measures the kinetic energy of the air determining how hot or cold it is. Air pressure is the force exerted by the weight of air onto a surface. Solar radiation is the radiant energy emitted by the sun, responsible for heat and natural light. Humidity represents the amount of vapor water in the air, it highly affects the building structures due to corrosion. Precipitation is the amount of rain, snow, sleet, or hail accounted for a specified period and location. Wind velocity is an important weather parameter caused by the air movement from high to low pressure due to changes in temperature. This measure is coupled with wind direction in order to orient different building design elements according to the desired effects. All these weather parameters are essential to be identified in the local milieu in order to conduct a comprehensive retrofitting plan.

2.1.1.2 Location

Additionally, the location of the building defines its natural and artificial surroundings. These aspects affect the heat island levels, the solar radiation and the indoor illumination levels of the building, especially in dense urban areas where the density and the height of buildings is growing. Such features should be defined and modified according to the needed level of heating, cooling and illumination inside the building, depending on the season. Surrounding vegetation also notably influences the external air temperature, humidity, pollution and noise, (Kalaycioğlu, 2010) therefore the investigation of the existing ones and the addition of new ones can have a massive effect on the micro-climatic conditions.

2.1.1.3 Orientation

Defining the building's orientation, the direction of each façade and the presence of any special feature such as internal open courtyard, helps comprehend the levels of solar radiation, heat gain or loss, natural lighting, wind penetration. These factors influence decisions regarding the modification of wall insulation, windows frame, glazing type, or shading devices, in the aim of improving interior lighting, heating or cooling, and natural ventilation, which varies with the variation of location. Moreover the sun path is taken into consideration when orienting the building to achieve energy efficiency levels, in this way it can take advantage of passive and active solar strategies. Ideally, a building in the Northern Hemisphere should have a long East-West axis in order to passively heat and illuminate the inside. Building orientation can also benefit from the prevailing wind for natural ventilation and air exchange.

2.1.1.4 Form

The building's form and the distributions of the different masses, if any, affects the internal conditions such as temperature along with the energy efficiency of the building. The form is determined by the building's footprint, volume, floors height, and compactness ratio (Bayraktar, 2015). The more the building's form is compact, the less heat loss will occur due to the limited surfaces in contact with the external environment. Moreover, the internal distribution of functions can widely improve the energy efficiency. Placing the functions which require similar thermal conditioning in proximity, can diminish the consumption of heating or cooling by reducing the buffer zones in between. The form of the building can also benefit from the cultural and traditional construction customs for the region in study. Since it is built with traditional techniques, it represents an optimum form in its climatic region. Thus the investigation of traditional know-how, local materials, local technology, and labor skills can be an asset for energy efficient and environmental design.

2.1.1.5 Envelope

The envelope of the building is the principal buffer between external and internal atmosphere. It comprises the main features affecting energy efficiency, such as thermo-

physical elements including external walls and their built up materials along with external doors, and optical elements including glazing types.

The U-value and the materials' thermal mass of each of these elements should be designated in the framework of future enhancement. The heavier is the material, for instance bricks, the higher its thermal mass, hence its capability of absorption ant storing heat energy. The recognition of all these factors allows the optimization of the building's existing conditions and thus improve its energy efficiency.

As mentioned previously in the orientation part, the sun path also affect decisions regarding facades' insulation, glazing, solar shading, and window-to-wall ratio (WWR). Their effect on heat absorption, heat transmission, solar reflectivity, and optical transmittance should be taken into consideration for optimizing energy performance of the building.

2.2 OVERVIEW OF HISTORIC BUILDINGS' ENERGY CONSUMPTION

Historical and traditionally constructed buildings represent a unique fragment in the large stock of existing buildings, due to their cultural importance and unique qualities of age, rarity, integrity and significance (Mazzarella, 2015). They are recognized as a significant part of history due to their association with a particular meaning or value related to a historic event, a well-known architect, or a special manner of construction. These traditional and local manners of construction need a comprehensive conservation approach through well-reasoned principles, in order to be transferred correctly and truthfully to future generations. The responsibility of the local authorities in the sensibilization of the local actors is also fundamental in this process.

Historic buildings, solely, approximately occupy 1% to 5% of the total building stock, according to the region in consideration (CIBSE, 2002). As for historic and traditional buildings all together, they constitute 10% to 40% of the existing building stock (CIBSE, 2002). Historic buildings are traditionally constructed buildings, holding a historic-artistic value to the culture they represent and therefore they are 'listed' by the national authorities as Cultural Heritage to be preserved.

As reported in the UNESCO World Heritage List, Turkey has 1.6% of the world architectural heritage with 10 listed historical sites. In the case of Istanbul, four urban areas are inscribed on the WHL, which are the Archaeological Park, Süleymaniye Conservation Area, Zeyrek Conservation Area, and Land Walls of Istanbul (UNESCO, 1985). With more than 8500 years of history, Istanbul comprises 63 museums, 64 historic mosques, 66 historic madrasas, 49 historic churches, 1 historic synagogue, and 4 historical bazaars (Great Istanbul, 2017). Additionally, a large number of historic houses built with timber during the late 19th - early 20th century still exist in many districts of the Historical Peninsula, and they represent the distinctive character of the residential stock in the old city. With its organically shaped streets, responding to the local topography, the Historical Peninsula establishes a unique urban environment in the city.

Built before the designation of energy efficiency codes, historic buildings exhibit poor energy characteristics, due to mainly the high level of air leakage and inadequate insulation. They are defined as "buildings of traditional construction with permeable fabric that both absorbs and readily allows the evaporation of moisture" (English Heritage, 2011). Similarly, the existing outdated windows and doors, composed of a single uninsulated layer with a poor operative material, present incompetent energy performance levels. These setbacks increase the energy needed for heating, cooling, and ventilation while affecting the indoor thermal comfort of occupants.

Due to the absence or low level of wall insulation, which represents the main barrier between inner and outer environment, energy retrofit plans must target therefore this issue primarily. Given that historic buildings are often being adapted reused to host public functions, their energy efficiency constitutes a great challenge for any retrofitting plan. Historic buildings are non-renewable resources in the field of architecture, thus any intervention should be able to achieve the requirements of modern days as well as of energy efficiency without the alteration of their unique historic character guarded by legislations under a 'protected status'.

2.2.1 Guidelines and Regulations for Interventions in Historic Buildings

Due to the ambiguous law concerning minimum energy performance obligations in historic buildings, sustainable interventions should be carefully designed according to a thorough assessment. If the fulfillment of minimum energy requirements wouldn't "unacceptably alter the character or appearance" (European Commission, 2010) of the building, then retrofitting project can be applied. Thus, each country or region has to set guidelines regarding these interventions in the aim to protect the national cultural heritage from inappropriate alterations. Moreover, several international certifications and legislations outline the basic framework for green retrofitting of existing buildings, not necessarily historical. An outline of some of the most important guidelines which can be applied in the context of energy performance calculations, are described in this section.

2.2.1.1 EPBD

The European Directive on Energy Performance of Buildings (European Commission, 2003), published in 2002, has the objective to outline a common practice regarding the energy performance calculations of buildings, to define the lower limit for energy performance of newly built and already existing buildings which undergoes a renovation, and to regulate the standards of energy certification allowing each nation to design their own local certification systems. This directive only identifies a comprehensive methodology for energy calculations, yet each member state should develop its own regional or national based methods. Additionally, with its defined guidelines, control systems such as boiler and air conditioning systems can be regularly examined to test their long time operation. The following criteria are the main ones to be considered by all nations regardless their regional differences (Kalaycioğlu, 2010):

a. Thermal properties of the building's envelope including exterior and interior walls as well as the air-tightness qualities,
b. Heating and hot water supply system, including their insulation properties,
c. Air-conditioning along with ventilation system,
d. Lighting system,
e. Building' location and orientation, considering outdoor macro and micro climate,

f. Passive solar techniques and solar shading,
g. Natural ventilation,
h. Indoor thermal conditions.

As an output of this directive, all member states adjusted their national legislations in accordance to the new energy performance requirements. Turkey, as a candidate to join the European Union, has as well taken this directive into consideration, establishing new Energy Efficiency Law in 2007 (5627 Enerji Verimliliği Kanunu, 2007). This law sets the minimum U-value and condensation control criteria for building's envelope in different climatic zones of Turkey.

In 2010, the EPBD was revised and a recast was published (European Commission, 2010), requesting all the energy performance certifications to be improved according to the new directive. It consists of integrating a global cost calculation methodology setting the cost optimal solution to fulfill the minimum requirements of energy performance. It also involves a 20% reduction of energy consumptions, 20% reduction in CO2 emissions, and 20% introduction of renewable energy. Furthermore, it requires the elaboration of the concept of nZEB in the new legislations.

Concerning the relation of this directive with historic buildings, it sets several requirements for existing buildings which are valid for historical buildings as well if they fulfill the law. Thus when a renovation project is applied, the renovated parts, the building's envelope, or the replaced building systems (if exists) should achieve the minimum energy performance requirements set by the concerned Member State. The addition of smart metering as well as control system is encouraged to regulate energy consumptions. Moreover, "buildings occupied by public authorities and buildings frequently visited by the public should set an example by showing that environmental and energy considerations are being taken into account" (European Commission, 2010), thus energy certification is required and the certificate needs to be exposed to the public.

An additional directive was published in 2012 (European Commission, 2012), requiring member states to determine their 2020 energy efficiency targets, demanding the implementation of supervisory actions, energy audits, and management systems in line with the regular monitoring of buildings, which shouldn't exceed five years. This latest

assessment comprises a cost analysis that respects economic feasibility, local climatic conditions, and technical suitability of each system.

2.2.1.2 GBC Historic Building

Green certification allows the improvement of energy efficiency while ensuring a greater transparency on energy uses. One of the most diffused green building standard in the U.S. and worldwide is the LEED, standing for Leadership in Energy and Environmental Design. It is a rating system developed by U.S. Green Building Council (USGBC, 2009) in 1993, and it was placed into practice in 1998 with its pilot version 1.0. The LEED certification is voluntary, consensus-based, and market-driven. It was firstly designed for new buildings construction, nowadays it comprises five choices of rating systems: Building Design and Construction (BD+C), Interior Design and Construction (ID+C), Building Operations and Maintenance (O+M), Neighborhood Development (ND), and Homes. For each certification a scorecard must be completed consisting of categories and credits, targeting energy reduction, energy production, indoor environmental comfort, environmental justice, and greener economy. Each credit is assigned a number of points related to its environmental impact.

As the USGBC is supported by over 77 local chapters worldwide (USGBC, 2009), one of them is the Italian Green Building Council (GBC Italia, 2013) which developed a local version of the LEED in 2010, and named it LEED Italia. This local rating system is applicable to new buildings or existing buildings with deep renovation. Nevertheless, it does not embrace the sustainable valorization of heritage and cultural characteristics in the massive stock of existing historic buildings. Therefore GBC Italia developed the first rating system targeting sustainability in historic building, the GBC Historic Building in 2015. It is currently under a pilot period for its validation until the verification of its efficacy with the implementation on real case studies in Italy. This new rating system is LEED-based and it has the aim of voluntary certifying the level of sustainability in the restoration project of historic buildings. The innovative assessment framework is established on contrasting and merging two different cultures, the international principles of the LEED and the field of restoration and preservation in the Italian context. It bridges

the gap between two principal domains, environmental sustainability and heritage preservation.

This new protocol refers to historic buildings as “material witness having the force of civilization” (Franceschini, 1967). Accordingly, buildings that will be certified under this protocol should have a construction process marked by a pre-industrial character, thus built before 1945. The year after which the building sector in Europe witnessed major innovations with regards to materials, techniques and technologies.

The structure of this rating system follows the already existing categories within the LEED, along with the addition of a new credit category, ‘Historic Value’ (HV), aiming at valorizing the characteristics of historic buildings by developing specific and considerate methods for the intervention on the latter. The operational principals of this credit category are related to the field of refurbishment, such as least intervention, distinguishability, reversibility, compatibility and durability. ‘Minimal intervention’ has the goal of preserving the material and the historical image while renovating the property. ‘Reversibility’ is related to the possibility of future generations to undo the current restoration in favor of more developed and respectful technological advancement. ‘Compatibility’ concerns the harmonious use of material and technology with the existing configuration. ‘Durability’ of the intervention is associated with the frequently scheduled maintenance plan.

The energy issue is tackled in the other credit categories, emphasizing the identification of an appropriate energy retrofit intervention. The GBC Historic Building adopts an interdisciplinary approach, targeting energy efficiency, restoration and human comfort. It provides a comprehensive guideline assisting planners in the restoration field to renovate historic buildings to meet today’s needs.

2.3 RETROFITTING STRATEGIES FOR HISTORICAL BUILDINGS

Recently, the importance of preserving historic buildings for their cultural and aesthetic dimensions have arisen. Retrofitting does not only reduce environmental impact but also allows the preservation of memories, discovering richer textures and uses of spaces that require innovative design solutions for reuses. It answers one of the biggest challenges

facing today's industry. Therefore, the retrofitting market is expanding at a fast rate requiring research on suitable materials and novel techniques. A specific guideline of retrofitting strategies for historic buildings is not yet defined due to the authenticity and unique character of the valuable buildings and the preservation regulations which differ by region and country. The prime tendency of these strategies is to enhance the energy efficiency. Total energy demand of a building is affected by several components, such as the envelope performance, active systems (HVAC, lighting system) efficiency, adaptation of control systems and the integration of renewable energy to equalize the expenditure. A compilation of scientifically approved retrofit strategies are described subsequently.

2.3.1 Envelope Performance

The performance of the building's envelope is affected by the opaque and the transparent components of the latter. Energy performance of opaque elements is mainly affected by thermal transmittance (U-value), thermal capacity, infiltration and absorption coefficient of the outer surfaces. Concerning the opaque part of the building fabric, most retrofitting scenarios include the addition of an insulation layer that improves its U-value. The U-value is the rate of transfer of heat through a structure, measured in W/m^2K, a lower value indicates better thermal insulation of the material. This insulated layer is not only limited to walls, but it also involves the roof and in some cases the building's floors. The extra layer is added in the interior or the exterior side of the wall depending on the preservation regulations set by the local authorities. If there is no clear regulation concerning the interventions on the exterior façades, the insulation is usually placed on the outer side in order to increase its thermal performance by reducing thermal bridges. These thermal bridges are formed by a large temperature difference between external and internal environment, which encourages the formation of condensation, and thus the slow degradation of the structure. Additionally, historic building structures have huge thermal mass related to the high material density, which causes high time lags in order to change the temperature of the structure, thus requiring more energy loads.

In the example of the Middle Age fortress in Perugia, Italy (Boarin et al., 2014), the Architectural Preservation Office allowed the addition of an external insulation layer, because the building had originally a cement plaster as the outermost layer. On the other

hand, the insulation is placed interiorly in the case where the conservation principles prohibit any alteration to the exterior façades of the historic building. As in the case of La Spienza, Rome University, in which the insulation layer is applied from inside in the context of preserving the outer casing of the listed building (Carbonara et al, 2016). Additionally, the choice of placing the insulated layer on the inner side of the wall is also affected by the function of the historic building. For instance, in the Natural History Museum of Crete, the authors preferred to preserve the original aesthetic of the interior façade due to its contribution to the general ambient of the museum (Katsaprakakis et al., 2017). However, interior insulation have exhibited poorer performance along with probable risks affecting the durability of the building structure, including freeze-thaw damage, interstitial condensation, and masonry's elements deterioration (Webb, 2017). Due to the specificity of each climatic condition and the different thermal behavior of the historic buildings, the nomination of a certain type of insulation is not viable. For each case the designation of the insulation type along with its thickness could follow a "case-by-case" methodology proposed by De Berardinis et al. (2014) depending on several elements. These elements comprise, but not limited to, the material's U-value, compatibility with the original historical material, fire and vapor resistance, availability in the local market, and LCC (described in chapter 3).

Furthermore, energy performance of transparent elements is also affected by thermal transmittance (U-value) and air infiltration. The replacement of ancient ineffective windows is needed to decrese the energy loss, heat and cold, and improve the indoor environmental comfort. Usually alternative glazing is chosen based on the most diffused products in the local market, along with their U-value, Solar Heat Gain Coefficient (SHGC), and light transmittance (Tvis). SHGC is the fraction of admitted solar radiation through a window, conveyed as number between 0-1, the smaller the number the less solar heat is admitted by the glazing. Tvis is the ratio of light transmitted through a material, expressed in percentage. They are typically composed of a double layered glass with an air or argon gap in between. For enhanced performance, triple layered glass windows with argon gap are selected. The thickness of the gap varies according to the window type, as a result, each type displays different U-value, solar heat gain coefficient and visible transmittance. The performance of the wide range of window's types can be evaluated using DesignBuilder simulation software and the results can be compared

according to LCC. The selection of window type depends therefore on the cost efficiency of the latter along its thermal conductivity value. The material of the window's frame is a well a vital aspect to consider in retrofitting. The PVC frame, with 0.17 W/mK thermal conductivity, is most likely used to replace the outdated wooden frames. A critical issue in such intervention is to comply with the original historic aesthetic of the building while inserting high-performance windows. It is necessary to maintain the same shape of windows and therefore the same glass area (Ag) to window area (Aw) ratio, which in some cases may be ineffective to the overall thermal performance, as in the case of the retrofit of an office building in the Abbey of San Lorenzo, Naples (Ciampi et al., 2015).

A further intervention on the building's envelope includes the insertion of an extensive green roof system. Such intervention is not compatible with all climatic and building conditions, thus it must be well investigated in terms of suitability to the microclimate, maintenance, structural load, and LCC prior to implementation. The application of a green roof is mostly effective in temperate climate due to the sufficient amount of precipitation as well as solar exposure, likewise the placement should be made on the Southern edge in order to maximize its performance. The type of structural support depends on two major factors: the human accessibility and the kind of planted vegetation, which define the dynamic and static loads and therefore the nature of reinforcement. Beside the structural support, the roof comprises several insulation membrane, such as vapor sealing, insulation, root barrier, drainage layer, and filter membrane topped with the growing medium (Katsaprakakis et al., 2017). A green roof does not only serve to regulate the heat island effect but also it provides an outdoor recreational space for users. The urban heat island is the increase of temperature in urban areas compared to rural areas due to the continuous human activities that generate extra heat especially with the modification in the natural topography.

2.3.2 Active Systems Efficiency

In contrary to passive systems, which relies on the architectural design of the building, active systems operate with external devices. They are adjusted with the aim to maintain a level of indoor thermal comfort. These external devices lose their effectiveness with time. They require regular maintenance along with periodical replacement. For instance,

the former lighting system in historic buildings is not compatible with modern day's requirements of energy savings, and thus it consumes a large amount of energy that could otherwise be recovered. The substitution of current light bulbs with more energy efficient ones, such as fluorescent or LED, can result in substantial reduction in energy consumption. In most retrofitting cases, this topic is limited to the replacement of existing luminaires, however, as stated by Ciampi et al. (2015), there are more alternative approaches such as, the consideration of different arrangements of the luminaires in vertical and horizontal layout, the positioning of the luminaires on dissimilar mounting heights, and the alteration of the wall reflectance's values, which is the amount of visible light reflected from a painted surface. These interventions can be modeled in building energy software, and then assessed according to the LENI index. The Lighting Energy Numeric Indicator (LENI) measures the efficiency of lighting system, it is indicted in $kWh/m^2/yr$. The greater the value of the index, the larger the electric energy utilization. Additionally, the installation of a central lighting management system is a method aiming at controlling and optimizing the operation schedule. It includes motion sensors, and load actuators which enable the dimming of light bulbs according to the performed tasks. Moreover, the introduction of low-energy appliances which are certified by a local or international green procurement can guarantee energy savings regarding technical devices, such as computers, kitchen and office equipment, etc.

The general building systems' energy performance is influenced enormously by the efficiency of the HVAC system. The intention of this system is to regulate climatic conditions in the aim to ensure occupants' thermal comfort all year long. In modern days, this system constitutes a large amount of local and global energy expenditure. The HVAC system is composed of several components assigned to heat, cool, provide fresh air, humidify, dehumidify, and control air movement and filtration when necessary. In historic building, HVAC system is either not present or outdated, hence its substitution is an essential part of any retrofitting plan. However due to their unique architectural characteristics and legal limitations, such intervention in historic buildings exhibits several constraints. Some limited interventions regarding this matter include the modification of the indoor temperature set-points, to be lower in winter and higher in summer by 2^oC. Even though such strategies affects slightly the occupants' thermal comfort, it has major effects on the energy and economical savings. In addition, the

installation of zone thermostats allows the measurement of each room thermal properties as well as its energy consumption, and this could provide an insight on the possible interventions on a small scale. On the other hand, the integration or the replacement of HVAC systems with the wide range of available technologies, depends highly on the allowed intervention by local authorities and the historic architectural constraints.

2.3.3 Renewable Energy Generating Systems

As it is important to target the reduction in energy use, it is also essential to develop solutions regarding the supply of energy. In parallel with improving the existing conditions of historic buildings, the introduction of energy generating systems could compensate the energy consumption by producing clean energy from renewable resources. There is a wide range of renewable energy which could be applied in conjunction with buildings, such as solar heating, photovoltaic panels, wind turbines, hydroelectricity, micro-hydro, biomass, and geothermal technologies, etc. Renewable Energy Resources (RES) are considered alternatives to conventional energy sources besides, they limit the greenhouse effect. This substitution contributes as well to the cost reduction in the building's energy bills.

Referring to the EPBD Recast (2010), which introduced the 20-20-20 policy, it requires a 20% inauguration of renewable energy to be achieved by 2020. Although historic buildings are not necessarily obliged to follow this policy due to a concern of alteration of their unique features, yet the improvement of their energy performance by inserting RES will compensate their large energy consumption related to their architectural peculiarities. The application of RES in historic structures is thus a controversial issue, due to the risk of altering the façade's aesthetics, especially with solar devices. For this reason, the installation of these active technologies depends highly on the harmonization with the building's architecture and environment. In order to maximize their efficiency, it is essential to place them according to a wise environmental studies. Therefore, an appropriate planning regarding the environmental, local and existing particularities, is needed prior to implementation. An example of technology respecting the architectural attributes of historic buildings is proposed by Bellia et al. (2015). It involves the installation of opaque PV modules in a particular layout considering the physical limits,

waterproofing needs, and daylight integration while generating power. Additionally, the study by Chel and Kaushik (2017) investigated several building integrated RES that can harmoniously be applied to an existing structure. For instance, solar collectors that have different absorber colors other than black, provide novel solutions in terms of aesthetics, they can blend with the architecture style of the building. Likewise, unglazed solar collectors prevent optical discomfort caused by the light reflection from the glass, they provide new possibilities to their integration within façades and roofs. Moreover, the study examined the integration of hybrid RES, such as the integration of photovoltaic system with Trombe wall, providing electricity along with the chimney effect. Another option was the integration of PV panels with small wind turbines, taking advantage from the natural environmental resources specific to the site.

The efficiency of each technology depends on the seasonal variances and site conditions in which it is installed, and thus the amount of produced energy. Consequently, there are minor shortcomings regarding the use of RES, such as a low COP (coefficient of performance) related to seasonal changes, which could be overcome by maintaining a connection to the main grid system. By this way, when there is shortage in energy production, the building can still depend on the main grid provided by the local municipality. On the other hand, if the energy generated exceeds the building's demands, it can return back to the grid, and thus contributes to the country's energy production. According to Dabaieh et al. (2016), the use of RES provides a solution for the energy crisis globally and especially in developing countries, while reducing the rate of destruction of historical vernacular villages due to their deficiency of modern facilities.

2.4 EXEMPLARY APPLICATIONS

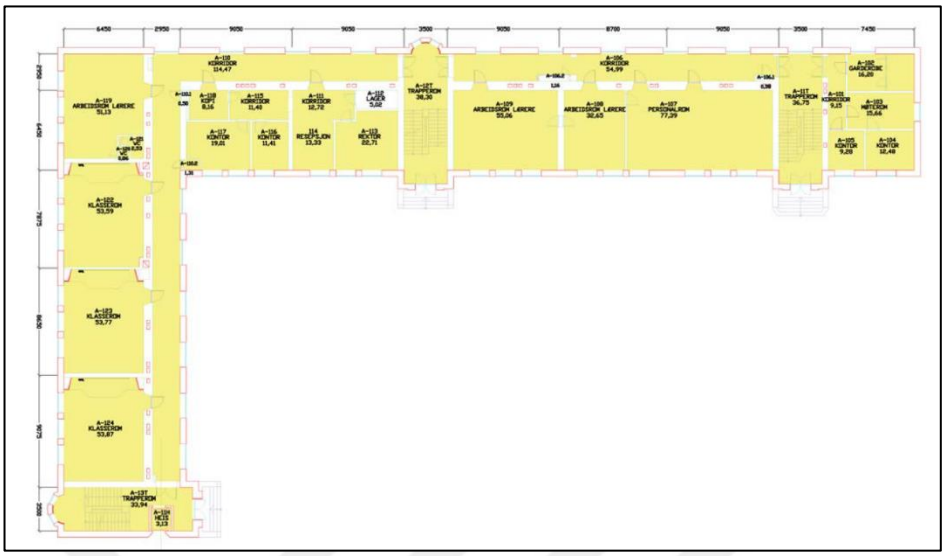
2.4.1 Case Study 1 - Norway School Building

This case investigates the retrofitting of a historical school building in Norway (Figure 2.1). The authors (Buvik et al., 2015) explain that Brandengen Primary School in Drammen complies with the EU 7FP project 2011-2016 in the aim of reducing energy consumption and providing better indoor environmental quality. The school complex was built in 1914 by a famous Norwegian designer. It consists of three buildings (main building, activity building, and a small building for leisure) all made of bricks and connected together with arcades (Figure 2.2). Its total floor area is 7079 m². Due to its significant historic value, Drammen municipality planned a refurbishment project with an emphasis on restoring the facades' aesthetic to appear as close to the original historic appearance. The retrofitting strategies included the insertion of supplementary insulation, the replacement of windows and the use of renewable energy systems.

Figure 2.1: The school complex. Photo showing the three buildings. (a): aerial view (b): top view

Source: (Andersen 2010).

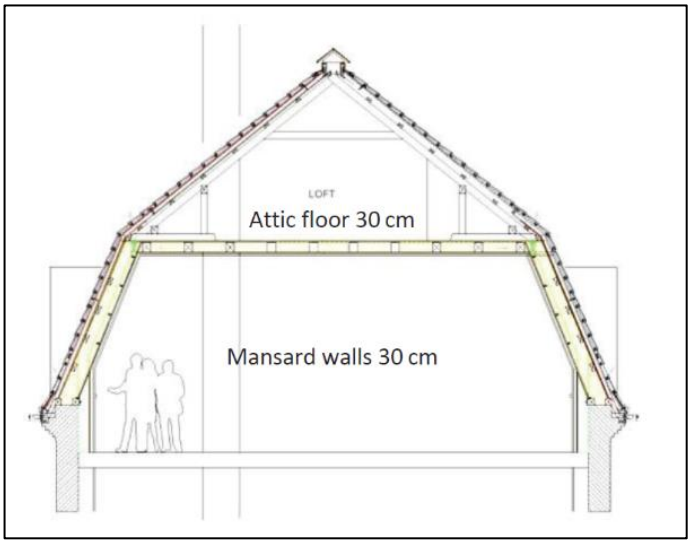
Figure 2.2: Main building's ground floor plan



Source: (Andersen 2010).

Firstly, an extra insulation layer of 30 cm mineral wool was inserted inside the mansard wall along with in the floor of the attic (Figure 2.3). Moreover, a 10 cm layer of added insulation was wrapped around the ducts placed in the attic (Figure 2.4). In addition, new drainage ditches were added in the east and south basement walls in order to lower the moisture level, provide better basement's insulation and support collector pipes for the heat pump.

Figure 2.3: Section of the extra insulation layer of mineral wool in the attic.



Source: (Buvik et al. 2015)

Figure 2.4: ventilation ducts of the attic (a): pre-insulation (b): post-insulation

Source: (Seehusen 2012).

Subsequently, the windows were replaced with high-performance windows (Figure 2.5c) that comply with the original historic aesthetic of the building. Solar control glass windows with low solar energy transmittance provided better indoor thermal comfort along with a reduction in energy demands. This refurbishment allowed the elimination of exterior sunscreen devices of the 60's and 70's (Figure 2.5b) with the aim of reestablishing the original facades' look (Figure 2.5a). In order to examine thermal comfort, the indoor climate was assessed using building energy management system (BEMS) in conjunction with occupants' feedbacks. The results of this assessment conducted during two days in winter were positive, exhibiting an improvement in the indoor thermal comfort.

Figure 2.5: Main building's Southern elevation. (a): Old photograph from 1914. (b): Photograph before retrofitting (c): Photograph after retrofitting

Source: (b): (Andersen 2011), (c): (Buvik 2013).

Lastly, oil-based heating systems were replaced with heat pumps linked to energy wells from the ground source. Hence, 19 wells, 250 m deep each, were newly drilled in the schoolyard. However, with the aim of achieving a better COP (coefficient of performance) of the heat pumps, a new model was developed by the building owner in cooperation with Thermoconsult, a consulting company for heat pumps and refrigeration). The designed heat pump prototype is based on liquid subcooling the refrigerants, placing the condensers in series and using high-performance piston compressors. This model has an enhanced energy efficiency and therefore an improved COP value. The heat pumps provided heat to the entire complex using newly installed pipelines. As a result, this new type of heat pump became a "standard" model and it is now being produced by several manufacturers in Norway. Replacing the burning fossil fuel with geothermal heat have achieved the energy performance goal.

In conclusion, all retrofitting targets were accomplished by this refurbishment project including the diminution of consumed energy by 67 % along with the improvement of indoor thermal comfort and the restoration of the original facades' aesthetics.

2.4.2 Case Study 2 – Dutch Embassy in Amman

This case study is about the real retrofitting and adaptive reuse project of a historic villa-type building into the current embassy of the Kingdom of the Netherlands in Amman, Jordan. The project was awarded the LEED silver certification from the USGBC in 2010, with a score of 34/69 (USGBC). This project was distinguished because it is the first building in Jordan and the first Dutch embassy to receive such green certification. It is considered a pioneering example for the country in terms of green retrofitting and adaptive reuse, in the framework of energy and water efficiency, which are significant national concerns.

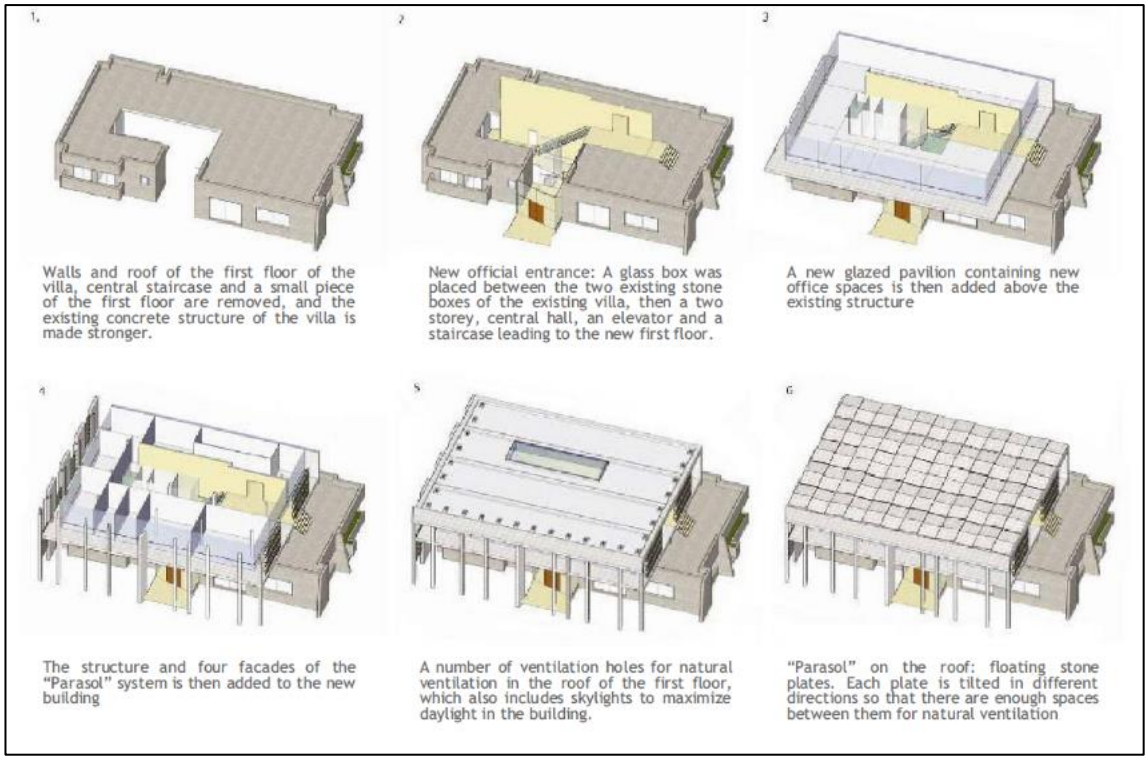
The project consists of the adaptive reuse of an old stand-alone villa by adding a floating floor on the existing structure to serve as the office facility for the new building's function. It was designed by the Dutch architect Rudy Uytenhaak in cooperation with the local firm Consolidated Consultants Engineering and Environment. The total project area,

comprising the existing and added areas, is 1253 m^2 (Consolidated Consultants Group, n.d.).

Pursuing a gold ranking, the design included several sustainable interventions targeting energy efficiency, water saving, material reuse and indoor environmental control. The Dutch architect Visser (2010), involved in the site supervision during construction, describes these interventions in details as clarified subsequently.

Known as the great act of sustainability, the reuse of the existing villa was the first green step towards the certification. Such reuse allows the salvation of existing materials while lowering the consumption of raw materials. Besides, in order to provide more space for offices, meeting rooms, and storage area, the villa was topped with an additional floor which is larger in area, thus providing shading for the ground floor on the southern façade while reducing direct solar heat gain (Figure 2.6). Such addition takes into consideration the cold winter weather, allowing the low sun rays to enter the building and reducing energy demand for heating and cooling needs.

Figure 2.6: Preliminary design concept showing the additional floor implementation

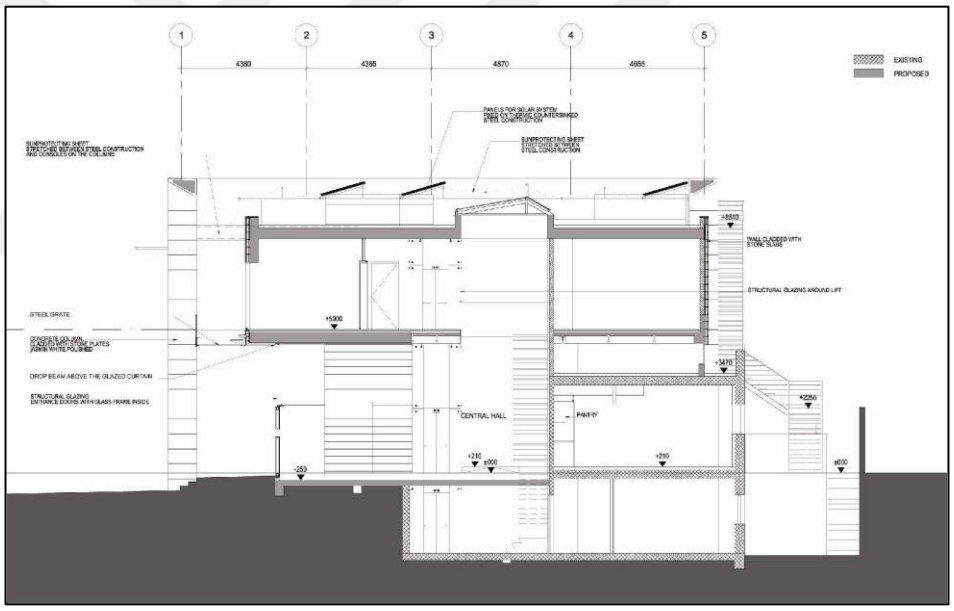


Source: (Al Nasa'a 2009).

In resistance to earthquakes, the upper structure was strengthened with supporting columns, resulting in a unique front façade, merging modernity with a historic character. The colonnade reflects the architectural history along with the hospitality of Jordanian society.

Concerning the daylight illumination, the core of the existing structure was hollowed out, creating a wide central atrium illuminated by skylights. This atrium acts also as an internal courtyard in summer days, when the skylights are opened, releasing excess heat and allowing natural ventilation in the building's core (Figure 2.7). This intervention refers to the concept of traditional courtyard used in Islamic architecture.

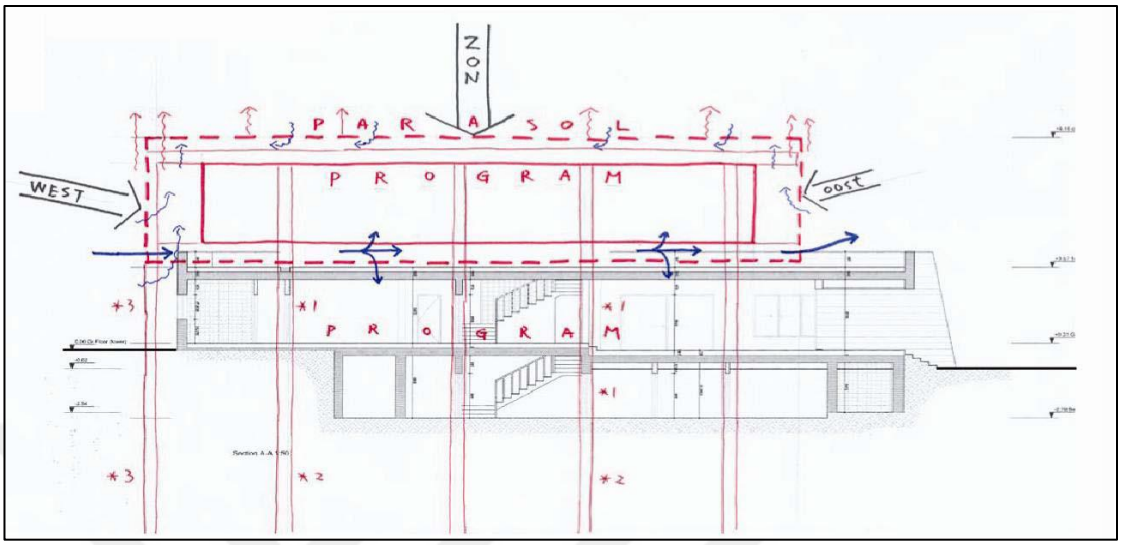
Figure 2.7: Section showing the internal atrium topped with skylight



Source: (Al Nasa'a 2009).

Natural ventilation is also emphasized by the space created between existing and new floors. This horizontal space is designed to accommodate the mechanical equipment, such as ductwork and fan coils of the HVAC system. This transitional space is completed with grills which provide passage for cool night breeze, generating night ventilation (Figure 2.8).

Figure 2.8: Section showing the air flow in the transitional space



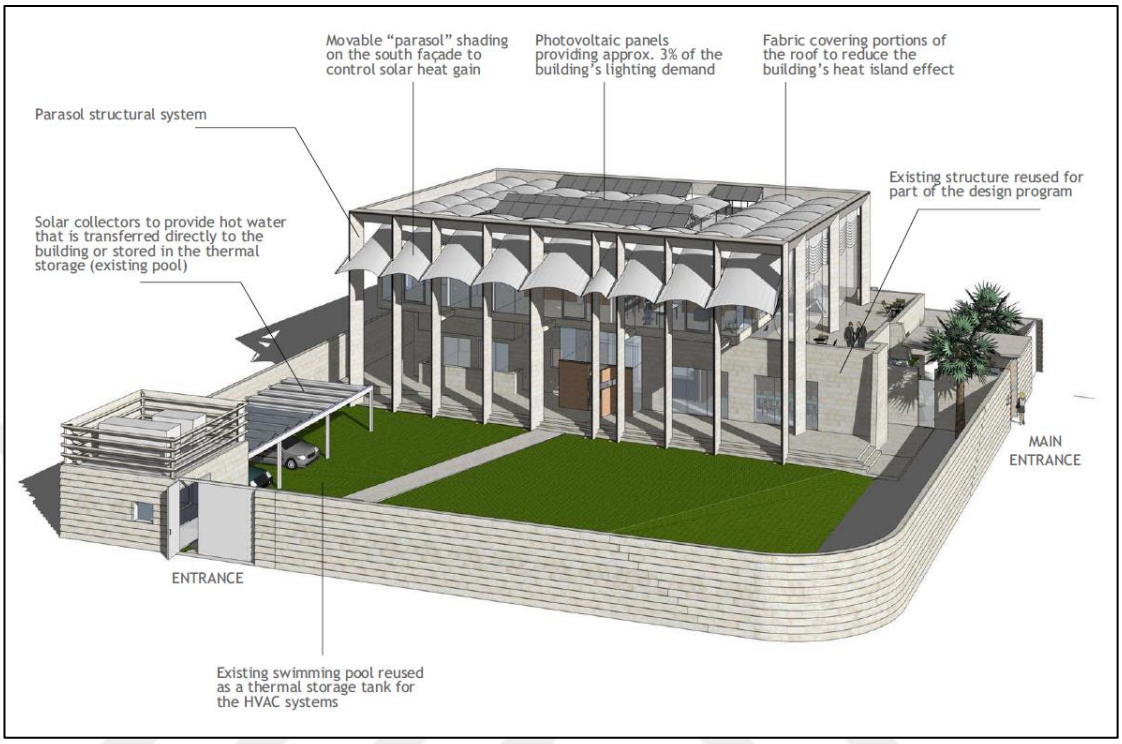
Source: (Al Nasa'a 2009).

Apropos the HVAC system, solar thermal panels were introduced to deliver the building's hot water. The existing swimming pool was covered and reused as an underground thermal tank to store heat/cold for the solar collectors.

Regarding the Energy & Atmosphere (EA) category, the project introduced renewable energy with the installation of photovoltaic panels on the roof, generating 12% of the electricity needs while providing shade for the roof from direct solar heat gain.

In conclusion, the retrofitting project succeeded to increase energy performance levels and to gain a green certificate (Figure 2.9) while merging the traditional concept along with contemporary design additions.

Figure 2.9: Sustainable interventions



Source: (Al Nasa'a 2009).

In the aim to provide a holistic comparison of the two previously mentioned case studies, Table 2.1 highlights the main differences between the retrofitting projects. Even though the cases are located in different climatic regions, it is noticeable that both of them are targeting the building envelope performance along with the solar radiation from windows and shading devices, for different purposes of heating or cooling. Additionally the introduction of renewable systems is manifested in the aim to provide on-site energy. Lastly, both projects dealt carefully with the historic character of their building, either by restoring the original aesthetic or by emphasizing the local identity.

Table 2.1: Comparison of the case studies

	Case Study 1 - Norway School Building	**Case Study 2 – Dutch Embassy in Amman**
Location	Drammen, Norway	Amman, Jordan
Climate	Cold & temperate	Semi-arid climate
Main structural material	Brick	Stone
Retrofitting aims	1. Comply with the EU 7FP project 2011-2016 2. Restore the facades' original aesthetics	1. Pursue a LEED gold ranking 2. Reflect the architectural history & hospitality of Jordanian society
Retrofitting strategies	1. Mineral wool insulation (in the mansard wall, floor of the attic, and around the ducts), 2. Replacement with high-performance windows, 3. Elimination of exterior sunscreen devices, 4. Introduction of oil-based heating systems with heat pumps linked to energy wells.	1. Addition of floating floor that provides shading for ground floor, and natural ventilation thru the space in-between, 2. Parasol shading system, 3. Creation of a wide central atrium illuminated by skylights, providing daylight & ventilation. Refers to traditional courtyard concept, 4. Introduction of solar thermal panels & photovoltaic panels.
Retrofitting results	67 % energy savings	LEED silver certification

3. ENERGY EFFICIENCY ASSESSMENT OF RETROFITTING THROUGH LIFE CYCLE COST

3.1 ENERGY EFFICIENCY ASSESSMENT

Energy assessment, or energy audit, is a tool to evaluate the amount of energy consumed by a building. It allows the evaluation of possible measures to lower the energy consumption and thus allowing the building to be more energy efficient. The main target of this assessment is to provide the annual energy usage along with CO_2 emissions. Such assessment delineates the setbacks of the building's components, and hence they can be targeted to save resources and capital. An energy assessment is usually conducted on already erected buildings, however, energy simulation could be performed earlier in the design and during the construction phases in order to achieve higher results. Each country defines its minimum energy efficiency criterion depending on the local legislation and the building's type. Moreover, several indicators can be employed to evaluate energy efficiency in numerical format. These indicators include Life-Cycle-cost calculation to assess alternatives impact on future cost, indoor thermal comfort, indoor air quality, and daylight level to measure the satisfaction of human body with physical environment.

3.1.1 Energy Modeling

According to Fishwick (1995), a simulation model is a numerical model which imitates the operation of a real-life system over a designated period of time. Using such modeling technique allows the analysis of the current system's behavior as well as the examination of its performance with certain changeable inputs. Energy model offers the users several building performance indicators, for instance, energy consumptions and needs, temperature, humidity, and budgets (Crawley et al., 2008). It includes all active and passive systems of the building, such as thermal, electric, and ventilation systems.

In the case of existing buildings, data about building's components are gathered, special details are examined (for historic buildings), and energy consumptions are measured. The collected data should be clear and reliable before inserting it in Building Performance Simulation (BPS) programs to evaluate current energy performance and to check its compatibility with the local required values. Subsequently, with the results of the

simulation, interventions on the building are targeted to optimize the consumption to be compatible with the energy requirements. In the field of energy simulation it exist a broad variation of modeling tools. The mostly used simulation tools are: DesignBuilder, EnergyPlus, TRNSYS, TRACE, eQUEST, and Simergy. Each software is distinctive with its input parameters and its accuracy. These software are used for new buildings or deep retrofitting projects in order to provide accurate decisions concerning energy savings. The process involve creating an initial simulation and then re-simulate the model with changing parameters. In the next segment, the three widely used energy simulation tools are described in detail.

DesignBuilder software is used to measure and calibrate energy, carbon, lighting and comfort rate (Altensis, 2015). It allows the comparison of building design alternatives with the use of function and performance-based methods. The software combines three-dimensional structure modeling along with dynamic energy simulations. Its flexible modules allow its usage in any stage of the design process or after erection, as well as the simulation of complex buildings' shapes. Besides its utilization for energy efficiency assessment, it can be used to evaluate the façade's performance, indoor thermal comfort levels, and daylight penetration. DesignBuilder is an EnergyPlus based software, therefore, it creates a graphical interface for the latter to perform a thermal simulation.

Likewise, EnergyPlus is another building energy simulation program developed by the US DoP. It permits the modeling of building's systems, such as heating, cooling, lighting, and ventilation in the aim to pursue effective interventions. It contains several innovative features, for instance, heat transfer balance-based zone simulation, multi-zone air conditioning system, indoor comfort, and renewable energy integration (Altensis, 2015). Both programs can be used simultaneously via the common graphical interface.

TRNSYS is also a building simulation program that can equally well be used to assess the performance of renewable energies. It comprises an extensive library of components, each belonging to a specific part of a system. The standard library includes 150 model of components (TRNSYS, 2018), allowing a faster building modeling process.

3.1.2 Calibration of Energy Model

Calibrating the energy model is a crucial step in the simulation process because a wide difference in energy performance between simulated and actual building is frequently noticed. In this manner, calibration minimizes these differences between the model and the reality by means of plotting the deviation and related uncertainty and hence allowing the modification of the model correspondingly (ASHRAE, 2002).

The energy model of the building should be calibrated. Such calibration is made with the measurements of energy data along with weather data of the designated city, obtained from the national meteorological service. The methodology is described in the ASHRAE Guideline 14 as the "whole building calibrated simulation". It consists of two indices employed to assess the level of precision of the calibration, which are the mean bias error (MBE) and the coefficient of variation of the root mean square error (CV [RMSE]), provided below. According to ASHRAE Guideline 14, the threshold for an acceptable calibration should not surpass 5% for MBE and 15% for CV (RMSE), for monthly measured energy data.

$$MBE = \frac{\sum_{i=1}^{Np}(M_i - S_i)}{\sum_{i=1}^{Np} M_i} \qquad (3.1)$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{Np} \frac{(M_i - S_i)^2}{Np}}}{M_p} \qquad (3.2)$$

In order to have an appropriate calibration of the energy model, input parameters with uncertain values have to be outlined along with their ranges, according to energy consumption data obtained on a monthly basis (ASHRAE, 2002). These input parameters with uncertain values can be designated based on a detailed field study of the case building, using observations, questionnaires, and interviews with the construction authorities or producer companies. Some parameters, due to their unstable schedule, are assumed through detailed this field inspection. For instance, if the building does not include sensors to determine the heating and cooling set points, or if the ventilation occurs based on a manual behavior of the occupants (Yılmaz, 2018), in such cases a field investigation of these parameters is required to obtain accurate results of calibration.

The calibration of the building variants is displayed in a graph, where the MBE and CV (RMSE) variants are plotted. The less scattered indices are included in the acceptable zone defined by the guideline, they represent the best building's alternatives, where the differences between measured and simulated data are minor. In contrary, the most scattered indices reveal a major variation on results related to unsuccessful variants.

Moreover, the EN 15603 (2007) suggests an approach to assess existing building's modeled along with actual measured results. The technique consists of firstly measuring the energy consumption of the building along with collecting data related to the climate, envelope performance, ventilation rate, and HVAC system efficiency. Then it involves the simulation of the building with the insertion of the previously collected data. Later, the real measured results and the simulated results are compared. If the variation between the two outcomes surpasses the intervals of confidence, then the outcomes are not accurate and further inspections should be performed.

In historic buildings particularly, calibration is a hard process due to the material layers' complexity besides the unavailability of some data. However, the process of calibration can overcome this shortage of data related to materials' thermal properties using on-site temperature measurements (Cornaro et al., 2016). Thus, such approach requires an extensive and accurate field survey of the building construction history along with regular manual monitoring of the designated variants. Roberti et al. (2015) suggest a methodology to calibrate historic buildings' energy models using hourly indoor air and surface temperatures, instead of the monthly measurement.

For these motives, calibrated building's simulation is considered an effective approach for buildings refurbishment in general and historic buildings in specific. Precise calibration of the simulated model rebuilds the case building as accurately as possible in order to be reliable for sustainable interventions.

3.1.3 Energy Performance Calculation

Energy Performance Calculation is centered on the calculated or annually measured building's energy. It allows an evaluation of building's energy performance in order to improve their compliance with minimum energy standards. It requires the conversion of the total amount of energy needs into primary energy. The total primary energy is the sum

of different types of energy produced from renewable and non-renewable sources, it includes the total delivered energy along with the exported energy. The calculation involves the annual primary energy use and CO_2 emissions by the building's systems, such as heating, cooling, ventilation, electricity, hot water and renewable energy systems. It takes into consideration all energy losses by these different systems, which include losses by heat sources and mechanical systems, losses by the process of transmission and distribution of energy from one type to another, losses by building envelope due to conduction and infiltration effects. To conduct such calculations, primary energy factors are required, comprising all the phases of delivery, from production, transportation, to extraction. For the calculation, the inserted data can be yearly based or divided into time steps, where an individual calculation is made for each step. Both approaches are valid, allowing the conversion of building's total energy into primary energy, which is defined as the raw energy found in nature unexposed to human interventions. Such calculation allows the estimation of natural resources depletion. Prior to calculation, the systems' boundaries must be well defined, because in some cases a group of buildings shares the same systems and thus their energy bills are common. Hence the need to define the boundaries of the systems in the framework of the assessment.

The EN ISO 13790 (2008) defines a procedure to calculate energy demands for heating and cooling according to three different levels of details. It includes "monthly quasi-steady-state", "simple hourly dynamic", and "detailed dynamic" calculation methods. Each method differs in the time steps used of the calculation, ranging from a month/ season, an hour, or even shorter intervals. With the aim of calculating the annual energy demand of the systems, separate calculations are performed for each time step. Each methods reflect the building's thermal behavior, depending on the time interval, in a more realistic manner. They also allow the determination of indoor comfort conditions according to the operative temperature.

The EN 15603 (2007) delineates a procedure to assess the total buildings' energy usage. It suggests two approaches to assess building's energy. Firstly, the "Calculated energy rating" is employed in new buildings. It calculates the energy requirements in terms of electric and thermal needs of a designated building, thus concluding the amount of primary energy. Secondly, the "Measured energy rating" does likewise calculate the total

amount of energy of a building but in a distinct period of time. The application of any of the two methods is decided by each of the member states of the EU.

The ECEEE (2011) document also defines a method for energy performance calculation consisting of three steps. Firstly, the total energy demand is calculated for different systems such as cooling, heating, ventilation, electricity and hot water. Secondly, the annual delivered energy for these systems is determined. As a final step, the delivered energy is converted into primary energy.

In summary, all previously described standards have the intention to calculate the energy performance of building's systems by converting the delivered energy into annual primary energy ($kWh/m^2/year$) and CO_2 emissions, utilizing conversion factors which differ according to the national standards.

With the aim of achieving energy conservation in historic buildings, several retrofitting scenarios are proposed, energy efficiency calculations are made for each, and a comparison is made to reach the optimum solution with the highest energy savings amount.

3.2 LIFE CYCLE COST CALCULATION METHODS

Life Cycle Cost Analysis (LCCA) is an approach to evaluate the total cost of an entity thru its entire lifespan (Fuller, 2016). It considers different costs from initial, operation, maintenance, repair, and discarding of building's components. It also takes into account financial rates, such as market interest, inflation, and price escalation rates. This method of analysis consists of the summation of all these different costs occurring in different times, with variations, during the whole lifespan of the building. The objective of the analysis is to compare the cost of different project scenarios that have the same performance requirements but with different corresponding costs, with the aim of achieving the best net savings. Whether in new construction or in interventions on existing buildings, LCCA is preferably performed earlier in the design process to achieve the lowest project costs.

3.2.1 Calculation Methods

There exists a broad variety of economic evaluation of the Life Cycle Cost analysis. Each method presents several advantages and disadvantages, and each was formed for different purposes (Levander et al, 2018). The EN 15459:2007 proposes life cycle cost calculations based on two different methods: "Global Cost" or "Net Present Value" in which each cost during a time period is converted to the present value of starting year of the project, and "Equivalent Annual Annuity" in which each cost during a time period is converted to annual cost by annuity factor (European Standard, 2007). Both calculation methods are defined in detail in the EN 15459:2007 standard.

3.2.1.1 Global cost or Net Present Value (NPV)

In the Regulation 244/2012 (European Commission, 2012), "Net Present Value" method is accepted as "Global Cost" calculation. It is based on the conversion of different costs, both incomes, and outcomes, into present value. This calculation is founded on basic parameters such as energy-related investments, periodic replacement costs of these investments, maintenance and operation costs, energy costs, as declared in ECEEE document (European Council for an Energy Efficient Economy, 2011). One of the benefits of this methodology is the consideration of time value of money, which delivers a return equal to the present market interest rate, hence its wide usage in LCC calculations (Flanagan et al., 1989). However, it is not suitable in the comparison of alternatives with different lifespans (Kishk et al., 2003).

The following equation 3.3, is the formula for global cost (Cg) calculation according to EN 15459:2007.

$$C_g(\tau) = C_I + \sum_{i=1}^{T}(C_{a(i)} \times f_{pv}(i)) - \sum_{j=1} V_{T-f}(j) \qquad (3.3)$$

Where:

a. τ: period of calculation;
b. $C_g(\tau)$: global cost (referred to the starting year) over the calculation period;
c. C_I: initial investment costs for the energy efficiency measure or set of measures j;
d. $C_{a,i}(i)$: annual cost during the year I;
e. $f_{pv}(i)$: present value factor;

f. $V_{f,\tau}(j)$: residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year);

Global cost in the starting year ($Cg(\tau)$) is equal to the sum of initial investment costs (C_I) and long term (τ years) energy costs, operational costs, replacement costs, periodic maintenance costs related to investment j ($Ca,i(i)$) multiplied by present value factor for year i ($f_{pv}(i)$) and subtraction of residual value of component j ($Vf,\tau(j)$). Present value factor depends on the real interest rate R_R on the year I, as given in equation 3.4.

$$f_{pv}(n) = \frac{1-(1+R_R)^{-n}}{R_R} \qquad (3.4)$$

$$R_R = \frac{R-R_i}{1+R_i} \qquad (3.5)$$

Real interest rate (R_R) varies according to the market rate (R) and on the inflation rate (R_i) on the year i, as given in equation 3.5.

As proclaimed by the Regulation 244/2012 (European Commission, 2012), the economic life cycle is estimated as 30 years for residential buildings, and 20 years for non-residential ones. With regards to this calculation method, the cost optimum solution can be defined as the package with the lowest global cost, as for the nZEB solution is defined as the one with minimal energy consumption.

3.2.1.2 Equivalent Annual Annuity (EAA)

As for the Equivalent Annual Annuity calculation, it is based on a definite period of time which corresponds to the planned payback time of the building. The total cost calculated for a year rate corresponds to the sum of each annualized cost of different systems and components (investment and replacements costs), the energy costs, and the annual costs of operation, maintenance, and additional costs. Investment and replacement costs are converted to annualized costs by applying the equivalent annuity factor. This methodology allows the comparison of several alternatives with different lifespans (ISO, 2004). The following equation 3.6 is used to calculate LCC in terms of equivalent annuity according to EN 15459:2007.

$$C = \frac{r \times NPV}{1-(1+r)^{-n}} \qquad (3.6)$$

Where:

a. C = equivalent annuity cash flow
b. NPV = net present value
c. r = interest rate per period
d. n = number of periods

3.2.2 Parameters Affecting Life Cycle Cost

Life Cycle Cost calculation is as effective as the availability of the data. Thus the employed data must be obtainable and accurate to the current conditions. Subsequently, the parameters affecting the "global cost" calculation will be examined. They involve the building lifespan, initial investment costs, energy costs, maintenance and repair costs, and numerous economic parameters.

3.2.2.1 Building lifespan

With regards to the global cost calculation, which is based on a net present value method that converts all expenses and returns into present value equivalent taking into consideration the time value of money, hence the building lifespan is a trigger component in that calculation. Calculation period is thus defined by the economic life cycle of the building, according to its type. Residential buildings have an estimated lifespan of 30 years, as for non-residential buildings they have 20 years of lifespan (European Commission, 2012).

With reference to historic buildings, which lasted for quite a long time and some for several centuries, the determination of lifespan is indefinite. According to ECEEE (2011), usually retrofit activities are performed on buildings erected from the 70's or earlier, thus these buildings have a lifespan more than 30 years and require great interventions regarding energy efficiency and materials replacement. Even though deterioration might cause a shortfall in performance, but regular maintenance and replacement can delay this

shortfall. Some authors (Ashworth, 1996) argues that if a building has a proper design and structure, it will have an endless lifespan with suitable maintenance.

Therefore the designation of building's lifespan is directly related to individual components' lifespans. Even if building's components might have a long lifespan but they have different life expectancies from one another, depending on several factors such as physical, economic, functional, technological and social characteristics. In the framework of calculating the building LCC, useful data about the components involved in the calculation is needed. However with the absence of the complete data, especially in historic buildings, one or more identified information can be utilized. Such information about building's components is described in the Life Expectancies of Building Components published by RICS/BRE (1992). It provides the estimated life expectancies in years of numerous components.

3.2.2.2 Initial investment costs

The initial investment includes the products' costs along with their installation costs. The products' costs depend highly on the type and the location of the purchased items, in addition to their quantity in the building. Thus it is difficult to convert them to the present market values. For this reason, discount rates approach is employed in the aim of converting the value of building's components in any time into present time value (Kalaycioğlu, 2017). Construction investments not related to energy can also be added to the global cost calculations but should be fixed for all different packages of measures (Kalaycioğlu, 2017).

3.2.2.3 Energy costs

The operational expenses include the annual expenses related to energy and water and other utilities' consumption in the building, with or without energy conservation measures. They include but not limited to heating and cooling, domestic hot water, ventilation, etc. The current energy prices are provided from local suppliers, and they depend on the rate type, rate structure, seasonal differences, block rates, and demand charges (Fuller, 2016). The dynamic calculation should be employed taking into

consideration the current rates and the yearly variations of energy prices. The energy price escalation is independent of the general inflation rate. According to Fuller (2016), energy price predictions can be acquired from local suppliers or from the energy price escalation published by the Department of Energy on an annual basis.

3.2.2.4 Maintenance and Repair Costs

Annual maintenance costs of the building components are added to the calculation as well, after converting their future values into present values using the discount rates approach. Moreover, some mechanical equipment has a shorter lifespan than the defined building lifespan, thus they need replacement several times throughout the calculation period, and hence each replacement should be calculated. On the other hand, building's materials have a longer lifetime, which is identified by the manufacturers. In such case, the residual value of the material, which is the remaining value at the termination of the calculation period, is calculated, converted to present value, and extracted from the total sum of the global cost. Lifetime periods along with maintenance costs including operation, repair and servicing cost, are stated in the EN 15459:2007.

3.2.2.5 Economical parameters

Economic indicators of the Turkish financial market must be as well investigated, including inflation, market interest, and price escalation rates. Inflation rate is the rate at which prices increase over time, which means the increase of the total cost of living in a country. Market interest rate is the rate the national central bank charges on the borrowed money. Price escalation rate is considered the rate at which the price of certain goods or services changes over a period of time. These indicators are expressed in annual percentage and are obtained or estimated from available economical institute data. The inflation rate is the mean value throughout the calculation period, while the market interest rate is the mean expected value of the interest throughout the calculation period, according to the EN 15459:2007.

Global cost calculation requires these economic indicators to predict the future costs necessary for the calculation period of the estimated building’s lifespan. A year is

designated as the representative year in the case study, based on which future predictions will be conducted. These rates are mainly affected by the market conditions, and hence the instability of the market in a country might cause deceptive results regarding the real value of the discount rate. In this regard, some parametric calculations can be performed to expose the effect of the discount rate on the final results.

3.3 COST OPTIMAL ENERGY RETROFITTING

According to the EPBD recast, published by the European Commission (2010), cost optimality of a building is described as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle". The report emphasizes the need to correlate minimum energy requirements along with achieving cost optimal balance between different costs involved during the expected lifecycle of the building, in the framework of a comparative methodology for calculation.

The methodology for calculation is made available by the European Commission, but the analysis of the input parameters and the calculation of the results is performed differently depending on each Member State. This methodology allows the identification of the cost optimal solution for energy performance requirements, either in new or existing buildings, and thus comparing the results of that optimal solution with the lower required level of energy performance defined by each of the Member States.

3.3.1 Cost Optimal Approach

The Regulation 244/2012 (European Commission, 2012) sets the guidelines for cost optimal calculation.

a. Firstly, it involves of the identification of the different building categories and their different energy requirements stated by the regulation, along with the selection of the reference building which should be representative of its category in terms of functionality and climatic conditions. Concerning historic buildings, the designation of a reference building might be difficult, due to the wide range of historic architectural styles and categories.

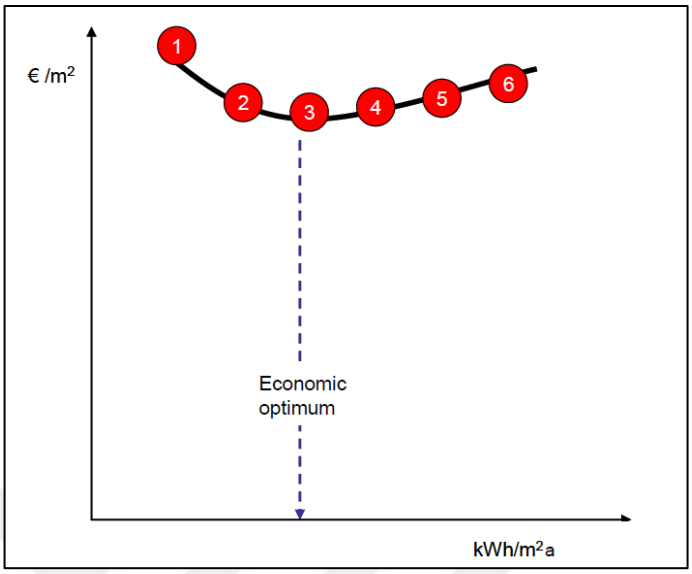
b. Then, it includes the determination of the energy-related scenarios for retrofitting.
c. Next, it involves the calculation of primary energy consumption for each scenario in terms of “current practices”, “best practices” and “state of art solutions”.
d. Later, it engages the assessment of energy-related costs of each scenario in the framework of global cost calculation during the expected economic life cycle of the building.
e. Finally, a sensitivity analysis for cost input data is performed with the aim of determining the cost optimal solutions for the reference building.

Sensitivity analysis allows the determination of the impact of the value of a specific variable if the latter is different from the expected one. Thus the strength of the cost input data can be evaluated according to the escalation of energy prices and the discount rates (Ascione et al., 2015). Such analysis contributes to the decision making and elaboration of recommendations regarding the changeable economic variables. It allows the designation of the cost optimal solution which is consistent under the changing circumstances.

3.3.2 Cost Optimal Point

Cost optimal methodology consists of a comparison between global costs, expressed as cost per area (€/m^2), with the annual primary energy consumptions, expressed as energy per area (kWh/m^2a). The projection of both measures is displayed in a graph (Figure 3.1). The data sets will establish a sort of a cloud which its average will most probably be in the shape of a concave up parabola. The vertex of this parabola denotes the cost optimal point among the different suggested scenarios. The comparison of several alternatives is necessary in order to obtain accurate cost optimal values. The EPBD (2016) requires the calculation of minimum 10 variants per reference building, but an average of 20 to 40 variants is considered ideal.

Figure 3.1: Defining a cost optimum



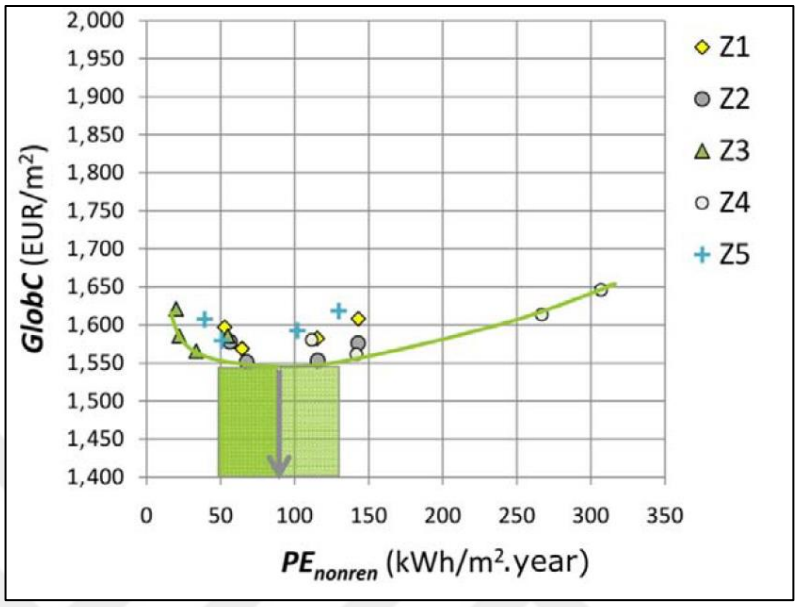
Source: (ECEEE, 2011)

Based on the results from the illustrative graph, the cost optimal point creates a strong fall in terms of both global cost and primary energy consumption levels when compared to the reference case. It displays an economic optimum that has the lowest global cost among the different suggested energy efficiency retrofitting scenarios. Moreover, if several scenarios have the same cost, then the one with minimum energy consumption is to be nominated.

3.3.3 Cost Optimal Range

From the numerous suggested scenarios, the one which has the lowermost cost will deliver the minimum level of energy requirements along with an economical cost. However in some cases, the curve is quite flat, displaying a small difference in energy performance between the different scenarios, thus the optimal point cannot be marked. In such cases a cost optimal range of measures is identified, combining building envelope and technical systems instead of a single optimal point EPBD (2016). A cost optimal point is defined at the lower end of the curve, in order to mark the lowest energy consumption within the cost optimal range (Figure 3.2).

Figure 3.2: An example of cost optimal range



Source: (EPBD 2016)

With the introduction of nZEB target by EPBD recast, the economic optimum might not be sufficient to reach such high energy performance levels. Some authors (Becchio et al., 2015) argues the impossibility to match nZEB with cost optimal results. However, the ECEEE (2011) affirmed that the cost optimal methodology should be "robust" enough to improve the current conditions to reach environmental and societal targets defined by the member states. Several parameters were mentioned in the report, they aim at achieving the switch from private economic requirements of cost-optimum to nZEB target for buildings after 2020.

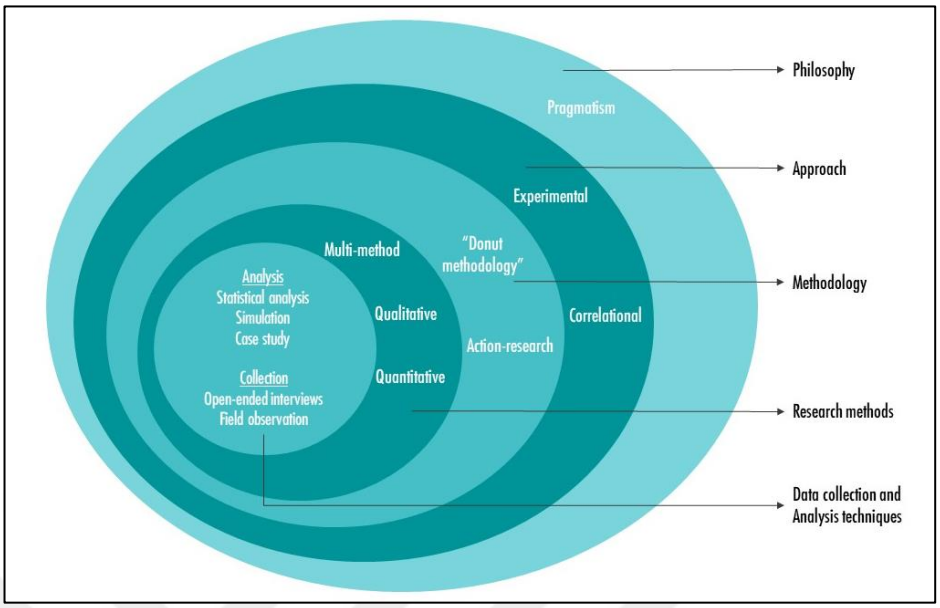
In brief, the cost optimal scenario is the solution that highly decreases the primary energy consumption while slightly increasing the investment costs compared to the reference building.

4. METHODOLOGY

This chapter presents the methodology and the pursued methods of this research. The study is based on a pragmatist paradigm as its philosophy, where reality is constantly renegotiated and the researcher finds the best method to solve the problem. Within this paradigm, the research design and interpretation of the results follow one of the design thinking methodology. The research adopts a “donut methodology” that is circular and iterative. The aim of this methodology is to solve the problem in a strategic way. Starting from the search of a problem by observing the state-of-the-art, then designating the issues to tackle by outlining the points of intervention, later proposing different solutions, and finally choosing the most suitable solution according to the analysis of results. Additionally, in the framework of an action-research methodology, the study is implementing experimental and correlational approaches, relying on isolating the object of study and manipulating its relevant conditions, while statistical tests serve as a mean of comparison between these different conditions.

To answer the research questions, quantitative methods were primarily adopted as its methodological framework, supplemented by qualitative data collection. The quantitative research methods include a statistical analysis of the simulated model of a case building in terms of energy and cost efficiency, before and after retrofitting. A comparative analysis is conducted between the different retrofit scenarios and their relation to the baseline. As for the qualitative methods, they aim at facilitating the acquisition of data related to the case building through open-ended interviews with the users and personnel in authority, supported by field observation to determine the types of building systems. The relationship between these different concepts is clarified in Figure 4.1.

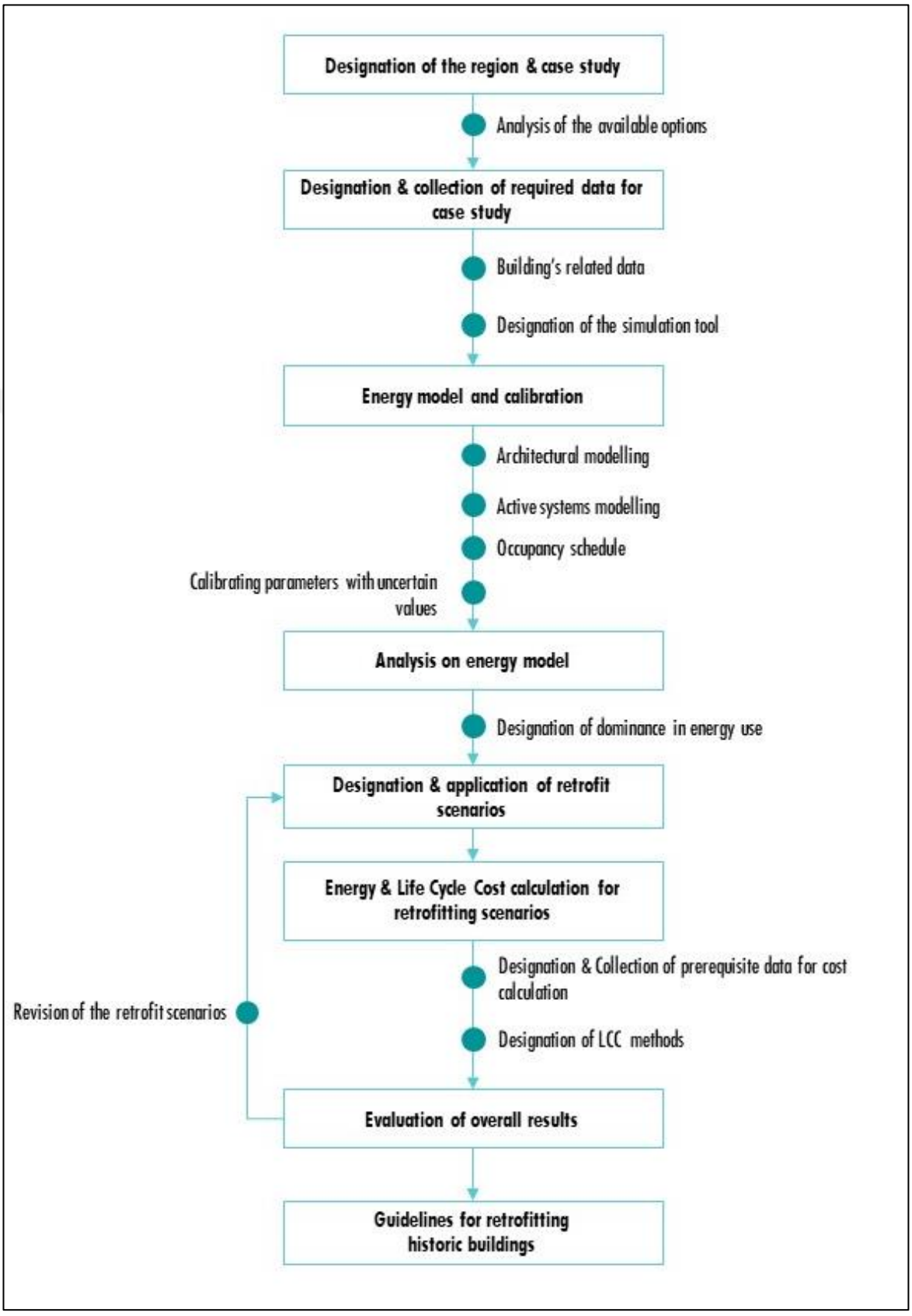
Figure 4.1: Research philosophy, methodology and methods



After conducting an extensive literature review and compiling the necessary information about the topic, the researcher sculpted this methodology, described in the conceptual framework (Figure 4.2), in the aim to solve the discussed problem.

The methodology includes firstly the designation of a pilot region / city. The climatic data of the specific region is collected from a national meteorological service. From this region a building type is selected, then a case building is designated based on the availability, accessibility, durability of its related data. Next, the building is analyzed in terms of end-use energy consumption, and the need for retrofit intervention is assessed. Later an energy model of the baseline is simulated using a suitable modeling software. After which the model is calibrated using the energy bills. According to the energy simulation results and the local preservation guidelines, retrofit strategies are delineated and different alternatives are simulated. Subsequently, calculation regarding energy performance and Life Cycle Cost are carried out. Finally, cost optimal point or range is designated, representing the optimum retrofit scenario. This methodology will be examined throughout the next chapter, and its barriers to the research will be delineated in the conclusion chapter.

Figure 4.2: Methodology of the research.



4.1 DESIGNATION OF THE REGION AND CASE STUDY

At the outset, the designation of a region for the study is one of the essential phases in the projected methodology, as it defines the climate as well as the topography and the urban fabric where the analysis would be performed. The designated region or pilot city should be a representative case on the level of the country of study. It should represent a conventional case in comparison with different regions, and thus different weather conditions in the country. The establishment of a representative region defines the type of energy efficient interventions for the designated climate. In this regard, the set of climatic data is then collected from a national meteorological service. Such specification allows an effective performance of the methodology, alongside providing a suitable foundation for the choice of the baseline reference building.

From the selected region, a case building or reference building is designated in the aim to implement energy retrofit strategies and to judge the energy performance results of each intervention, as well as to distinguish a cost optimum. Reference building is thus the manifestation of the building's existing energy status, the baseline. In the aim to make the analysis statistically viable and accurate, the case building should be representative of a category of buildings in the designated region and climate. Being illustrative of a category provides a thorough study regarding the entire building stock under this category. Therefore, the case building should be conventional in terms of the overall geometry, envelope layers, building systems' characteristics and period of construction. For a proper selection of the case building, several benchmarks must be taken into consideration, as for example the involved user's schedule, occupancy number and different energy usage. Each one of these benchmarks influences the energy performance of the building. Thus they are important to consider in the selection process in order to attain a more conventional choice in terms of energy consumption.

4.2 DESIGNATION & COLLECTION OF REQUIRED DATA FOR CASE STUDY

Thenceforth, a set of required data related to the building within the scope of study is collected. Primarily the type of required information is identified, succeeded by the elaboration of a set of methods to extract these data.

There exist various approaches to designating data. Every scope of study is different in terms of building type, location, climate, and duration of study. An appropriate identification of the required data is based on the research design, which takes into consideration the involved inputs and the anticipated outputs of the study. The research consists of several consequent actions, each one of them includes a set of requirement and results needed to proceed to the next step.

Then in order to extract these data, several research tools or instruments can be employed, according to the available options to the researcher from qualitative and quantitative measures. Some examples include but not limited to: interviews, questionnaires, observations, surveys, field assessment, etc. After constructing the proper research tool, it is then utilized to extract data from the concerned authorities. In many cases, the best way to collect accurate data is from the source itself, i.e. responsible authorities for the building's operation and maintenance.

Due to the numerous barriers that might be present in collecting these data, the case building should also be chosen based on the availability, accessibility, durability of its related data. A shortage in the obtained documents will lead to a repetition of the building designation process.

4.3 ENERGY MODEL AND CALIBRATION

After selecting the reference case building for the analysis and collecting the required data, an energy model is simulated using a suitable Building Performance Simulation tool (BPS). As it exists a broad variation of BPS tools, the selection of an appropriate one is based on the capabilities of the tool and the required specifications for the modeling phase. According to Attia et al. (2012), there are 5 main criteria with the aim of evaluating the relevance of the energy modeling tool. The first criteria includes the "usability and

information management of the interface", which deals with the functional operation, media and presentation techniques of the interface to support users in their tasks. The second criteria known as "integration of intelligent design knowledge-base" provides advices related to decision making as well as answers to design questions. This criterion is important to consider for the optimization of design solutions and Life Cycle Cost calculations. The "accuracy and ability to simulate detailed and complex building components" criterion deals with the required level of details and quality assurance of the simulated model. Then the "interoperability of building modeling" is employed when the model is being managed by several operators with multidisciplinary backgrounds. It is related to the possibility of sharing and communicating building data between the different collaborating individuals. Finally the "integration of tools in building design process" is a criterion that verifies if the tool can be adaptable for different purposes at different design stages. It emphasizes the 'whole building design' strategy which integrates all element of the design process. After selecting the most suitable modeling software according to the above mentioned criteria, the model is then erected.

The simulation process depends on inserting the collected data about the building's characteristics and its active systems. The process is divided into three phases, architectural modeling, active systems modeling, and occupancy schedule. In the architectural modeling stage, the geometry of the building is created using the available building's drawings. Automatically, the simulation tool divides the model into zones with different thermal properties according to their shape, size, orientation, window-to-wall ratio, and existing doors. In this phase, the layers and materials of each element composing the building envelope is defined. In the second phase, active systems including HVAC, illumination and domestic hot water are included in the model, in order to delineate the internal energy loads. In the last phase, the collected schedules related to the building's occupants serve as input data in the model. For instance, these data include the occupants' density and their timetables, the usage of heating/cooling/lighting systems, the windows operation in relation to different days (week days / weekends) and seasons. These data have diverse values according to each zone in the model.

Subsequently, with the intention of having a precise simulation, the model is calibrated to minimize the differences between reality and simulation with regards to energy performance. It consists of calibrating the energy model with the monthly energy bills for

a duration of 12-14 months, together with recent weather statistics attained from a national meteorological service. Elsewise, hourly calibration method can be as well performed by placing temperature sensors inside the building in order to obtain accurate measurements of indoor air temperature on an hourly basis. The calibration consists of determining deviation between the simulation and the real measurements by defining input parameters with uncertain values. After specifying possible values or ranges for these parameters and defining energy simulation combinations, energy calculation using the energy bills is conducted. After which calculation of the deviation indices is performed as stated by ASHRAE guideline 14. The outcomes are considered according to the permissible range by the guideline. If they fall within the range, this indicated a consistency between simulation results and acquired energy demands permitting the progression of the study. An inconsistency instigates the repetition of the process until the specified values of the parameters fall within the permissible range.

4.4 ANALYSIS ON ENERGY MODEL

After collecting all the required data and erecting the model using a suitable BPS, the building model is analyzed in terms of end-use energy consumption, using the obtained energy bills for a duration of 12-14 months. Its annual energy consumption is converted and expressed in terms of annual primary energy consumption using one of the conversion factors mentioned in international standards such as EN 15603, ECEEE or EN ISO 13790. The compatibility of the results is assessed according to the minimum levels of energy performance defined by local or international legislations. The incompatibility with the latter suggests a need for retrofit interventions.

The analysis of the simulated model is quite important in this process, it provides a performance assessment of the selected building. It provides an insight to areas with dominant energy consumption, deficiency of systems, air infiltration, in addition to indoor thermal comfort assessment. Such assessment highlights the flaws in energy consumption, showing the zones with peak energy consumptions and poor envelope performance, if available. The knowledge of these zones with dominancy in energy usage, allows the identification of the areas of potential energy savings and thus nominating the intervention points.

4.5 DESIGNATION AND APPLICATION OF RETROFITTING SCENARIOS

With the intent of improving the energy performance of the case building, a set of corrective measures are applied to the energy model. These measures can be categorized in terms of: 1) envelope performance, including floor / wall / roof insulation and replacement of fenestration; 2) control systems efficiency, containing HVAC, lighting, smart metering, and low-energy appliances; and lastly 3) energy generating systems, comprising the insertion of a wide range of renewable energy systems. Several measures can be coupled together to form different packages exhibiting advanced levels of improvement in terms of energy efficiency.

The designation of the most suitable intervention points is based on the examination of deficiencies from the energy simulation results. The application of any strategy or package must always be compatible with the local preservation codes. They shouldn't conflict with the regional regulations with the aim of preserving the integrity and historical value of the building.

4.6 ENERGY AND LIFE CYCLE COST CALCULATION OF RETROFITTING SCENARIOS

Following the delineation of the different retrofit packages, energy performance calculation is conducted for each package separately. It consists of the sum of different types of energy in the building after the application of retrofitting strategies. Then, using a conversion factor, this sum is converted into primary energy in order to have an estimation of the raw energy consumption and thus an assessment of the natural resources depletion. Conversion factors are defined in several international standards, the most relevant one is selected according to its compatibility with the local energy calculation directives.

In the aim to calculate the Life Cycle Cost, several data are collected regarding the market state. These data include the inflation rate, market interest rate, price escalation rate and unit cost of each system or appliance utilized in the framework of the retrofitting project. Such data needs to be contemporary to the year of the study and can be obtained from a

local economic institute data center in addition to the manufacturers or distributors of the different building systems.

Subsequent to the market data collection, Life Cycle Cost can be calculated according to one of the methods described in several standards, such as EN 15459 standard, ECEEE document, or NIST handbook. This calculation aims to bring future costs to their contemporary values using a discount rate. So as to proceed with the calculation, a period of analysis is defined, as the life span of the building, and a suitable calculation method is chosen. From the two methods described in chapter 3.2., Net Present Value and Equivalent Annual Annuity, the selection of the calculation method is based on the most appropriate method for the case. Each economic evaluation method has its advantages and disadvantages. Most of them employ a similar equation for calculation, but with different cost elements' breakdown. The choice of an appropriate method depends on the available indices obtained from the economic data center. These indices serve as the input parameters for LCC calculations, therefore their suitability with the local construction sector is imperative. For a more comprehensive analysis, each retrofitting scenario should be defined with its investment costs, including materials or systems, transportation, labor and tax costs.

After choosing the suitable LCC calculation method, global costs for each retrofitting scenario is determined based on the different costs involved during the expected lifecycle of the building, in the framework of a comparative methodology for calculation. These costs involve the initial investment costs, energy costs, maintenance and repair costs, and the economic parameters acquired earlier.

4.7 EVALUATION OF OVERALL RESULTS

Retrofitting projects aim to fulfill the minimum required levels of energy performance, but those requirements should also aim at achieving cost-optimal balance between investments costs and the savings from energy costs during the life span of a building. Thus the intervention aims at attaining several target points, which are energy performance requirements, energy savings, and cost savings. In the aim of defining the cost optimal point, a comparison is conducted between the calculated LCC and the annual

primary energy consumption, as explained in the EPBD recast. The two measures are projected into a graph forming a cloud of points, most probably resulting in the shape of concave up parabola. A cost optimum point is defined as the vertex of this parabola, it represents an economic optimum among the different suggested retrofitting scenarios. In case of obtaining a flat curve, a cost optimal range is then defined as the different retrofitting scenarios having the same global costs. In this case, the scenario with the lowest annual primary energy is hence preferred.

The overall results are compared with the minimum levels of energy consumption defined by local and international legislations. If the results are not satisfying in terms energy depletion or the LCC are too high, then a revision of the implemented retrofitting scenarios is mandatory. The process is repeated until obtaining the sustaining results while respecting the local preservation codes.

Finally, conclusions are drawn from numerical data and energy simulation model about energy and cost efficiency of the retrofitting project. The methodology is completed with a SWOT analysis outlining the strength, weakness, opportunities and threats facing the completion of the study. With the conceptual framework of the methodology explicated in Figure 2, such breakdown explores the practice of incorporating sustainable technologies into historic buildings. Lastly, the researcher provides a full guideline for a comprehensive intervention, integrating energy efficient measures at a cost optimum while respecting the historic character.

5. IMPLEMENTATION: A CASE STUDY

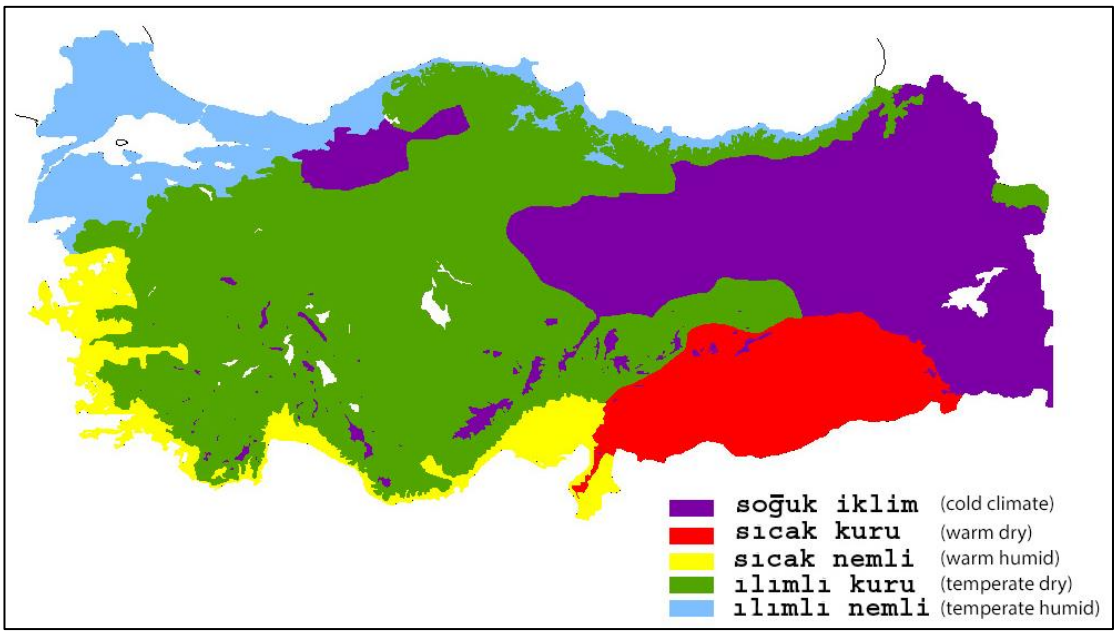
The previous chapter exposed in detail the suggested methodology of this research. In this chapter the methodology is employed on a real case study and the outcomes are analyzed in the aim of providing decision support to compare different alternatives for cost-optimum energy retrofitting. In this manner, the same subchapters of the methodology are followed latter.

5.1 DESIGNATION OF THE REGION AND CASE STUDY

5.1.1 Climatic Region

The country where the research takes place, Turkey, has a variety of climatic zones. These zones stretch between cold, warm-dry, warm-humid, temperate-dry, and temperate-humid climates. From this wide variety of climatic zones, the most illustrative climate, on the level of the country, is the temperate weather, represented by the blue and green zones of Figure 5.1. Since its wide spread in the country, in the Central-West region and in the West along the Aegean and Marmara coasts, this type of weather is assumed representative of the country.

Figure 5.1: Turkey's climatic zones map



Source: (Zeren 1959)

From the representative climate, the largest and most recognized city, Istanbul (latitude 41° 0' N and longitude 28° 58' E), is designated. It has a population density of 82,003,882 person as in 2018 (TUIK, 2019). The selected city is classified by a temperate-humid climate due to its position in a transitional zone between the Black Sea and the Marmara Sea. In summer, the city have a high temperature average of 27.2 °C and a low temperature average of 20.4 °C in August, with rare precipitation. Winters are cold and wet with high temperature average of 8.7 °C and a low temperature average of 2.9 °C in February. Spring and autumn seasons have usually mild temperatures, which is sometimes unpredictable with often precipitation and chilly winds. Humidity is medium to high in the city with a daily average of 70 %. The daily sunshine hours varies between 2.6 hours in January and 11.6 hours in July. (Turkish State Meteorological Service Official Web Sites, n.d.)

Given that the selected case building is a historic building in Istanbul, it is then located in one of the ancient districts of the historic peninsula. This area has witnessed the flourishment of Byzantine and later Ottoman Empires. The historic peninsula has seven hills, where are distributed many mosque complexes and major historic landmarks, making it a coveted area where rulers spent much of their resources for its embellishment. Due to its outstanding universal value, four sites of the historic peninsula were designated as a UNESCO World Heritage Sites in 1985. This site-specific context is therefore characterized by a high density urban fabric. This micro-climate is distinguished by a lower solar radiation, thus the inefficiency of natural lighting, and a reduced wind speed caused by the artificial dense surrounding.

In the study, the weather data including temperature, solar radiation, humidity, and wind speed is obtained from the National Meteorological Service of Istanbul. It is used later as input parameters in the simulation model, in order to obtain accurate simulation conform to the real case.

5.1.2 Case Study

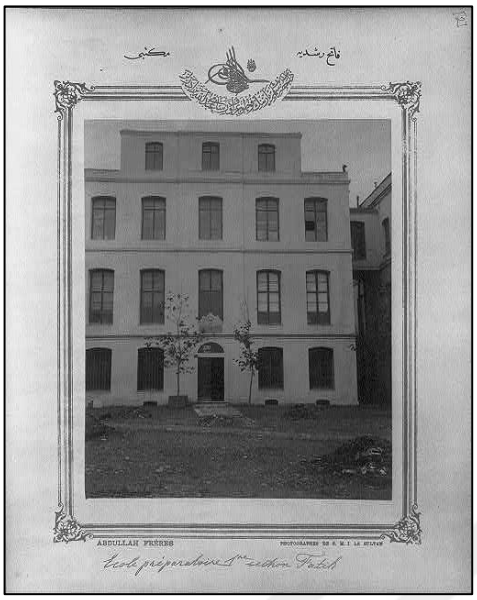
The case building serves as a baseline in terms of energy consumption, it represents a baseline for comparing different alternatives. Since the large stock of historic buildings in Istanbul are being used either for governmental or higher education purposes, they

offer an effective scope of study. The scope of study was further narrowed to historic buildings housing educational facilities. One building was chosen based on the availability and the accessibility of the researcher to its related data. The selected case building is Hasan Ali Yücel Eğitim Faculty (B-block) belonging to Istanbul University, Beyazit campus. The campus is located in Süleymaniye neighborhood of Fatih district, in the historic peninsula which is listed as a World Heritage by the UNESCO (Ahunbay, 2004). The case building occupies plot 1 and 579 building block, it is registered by Istanbul IV Cultural and Natural Heritage Preservation Board as a cultural heritage, under the preservation group I (Ministry of Culture and Tourism, 2006). The building is prototypical in terms of its common construction practices which is representative to the era of its erection, not giving much consideration to the building energy performance.

Building's history

The campus was first established in 1846 as an institution of higher education named *Darülfünun*, House of Sciences. It was designed as a western style university by the Italian architect Fossatti (İstanbul Üniversitesi, n.d.). The case building was named as Fatih Middle School in the archive photograph of Abdullah Frères published between 1880 and 1893 (Figure 5.2). By the end of the 18th century, and due to the defeats in wars, the school buildings were reformed in order to meet the military needs to train required staff members, like surgeons, physician etc. A German blue map of the area from 1911-1913 refers to the case building with the name of Beyazit Secondary School (Figure 5.3a), such map recalls the political and military cooperation with Germans during WWI. A later Pervititch Map edited in 1935 refers to the building as the Court of Sessions (Figure 5.3b). Its latest function consisted of a student dorm appropriated by the Ministry of National Defense. The building witnessed several functional changes before it was reorganized, in 1933, as what it is known today as Istanbul University, following the republican reforms.

Figure 5.2: "Fatih middle school"



Source: photograph by Abdullah Frères 1880.

Figure 5.3: building location old maps: (a) German blue map, (b) Pervititch map

Source: (Bozkurt et al. 2016)

In 2012, the case building underwent a recent restoration project with the aim to remove featureless additions, restore the building's original features and to repair and clean masonry members (Bozkurt et al., 2016). As the function of the building changed several times during its lifespan, the restitution project was based of the review and investigation of old documents, photographs and maps from archives. The restoration interventions were designated accordingly. The project was accepted and approved by the decree of

Istanbul no. I Regional Board of Preserving Cultural Heritage (2012). The restoration improved the overall structure, material, form and originality of the building. However, the project didn't tackle the issue of energy performance of the building by any means.

5.2 DESIGNATION & COLLECTION OF REQUIRED DATA FOR CASE STUDY

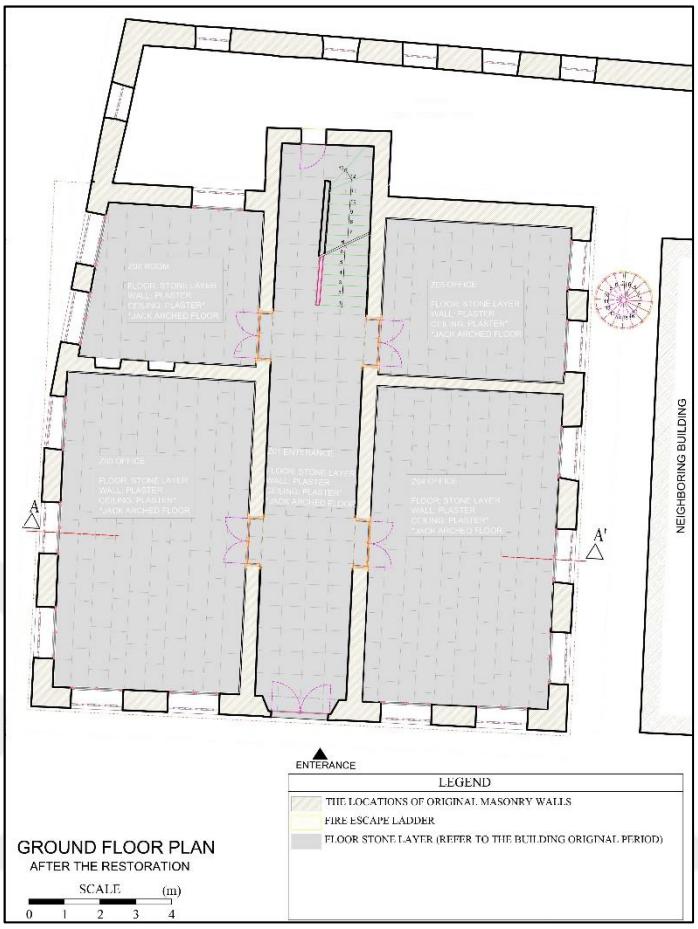
5.2.1 Simulation Related Data

With the intention of performing a complete simulation of the case building, details regarding architectural, thermal and optical properties, active systems properties, and occupancy & operation schedules are collected. All related data are obtained from the construction department (Yapı işleri) of the University, by conducting thorough interviews with civil, mechanical and electrical engineers along with frequent filed visits. As for the occupant's schedules they are attained by conducting interviews with personnel working at the building. Additionally, field observation where carried out to determine the number of lighting features as well as the envelope details. These data are demonstrated below.

Architectural, thermal and optical properties

The building consists of 1 below grade floor housing a storage, kitchen, WC and technical rooms, and 4 above grade floors housing instructors' offices and a lecture room. The building has a pitched roof which is unoccupied and unconditioned. The total floor area of the masonry building is 892.64 m^2. It has an almost square shape with principal dimensions of 15.1 m by 14.7 m, with a small rotation of 3^o towards the East. The entrance is on the South façade. The building's floor heights are 2.80 m for basement, 3.75 m for ground floor, 4.84 m for first floor, 4.48 m for second floor, and 3.10 m for the roof. The building is connected to its twin building (A-block) on the second floor of the East façade using a passage bridge with separate door. The vertical circulation is located in the middle of the Northern façade. Each floor in the building is divided into 5 conditioned zones, except for the roof floor which has 3 zones, thus there are 23 thermal zones in total. The air temperature in these conditioned zones is almost uniform. Ground floor plan is illustrated in Figure 5.4.

Figure 5.4: Ground floor plan after restoration



Similar to most historic constructions in Istanbul, the main construction material forming the walls of this building is masonry brick blocks, joined together by lime-based mortar. The structure of this building is load bearing walls, justifying the large walls' thickness which varies in each floor. For instance, the wall thickness varies between 0.44-0.58 m on the ground floor, 0.41-0.56 m on the first floor, 0.43-0.47 m on the second floor, and 0.23-0.40 m on the roof. The façades are uniformly washed with mortar render. The floors are jack arched floors made of brick and mortar. The basement and ground floor have marble finishes, while the other floors have wooden finishes. The building is topped by an unoccupied hipped roof. It has a timber framed structure and Marseilles tiles finish. Table 5.1 summarizes the building's different construction materials and their thermal transmittance. The entire building envelope do not contain any insulation materials, thus it does not comply with the recommended values specified by the national building standard TS 825 (2008).

Table 5.1: Reference building's construction elements and their thermal properties

Building elements	Materials	Thickness (m)	U-Value (W/m^2K)
Exterior walls	Lime-based mortar Masonry brick Lime-based mortar	0.03 varies according to floors 0.03	1.216 (1^{st} floor walls)
Floors	Masonry brick (jack-arched) Cement screed Finish (marble / wood)	0.2 0.07 0.03	1.692 (Ground floor)
Pitched roof	Terracotta ceramic tiles Air gap Roofing felt OSB - wood panel	0.02 0.10 0.005 0.02	1.731
Windows (external)	Clear glass Air gap Clear glass	0.003 0.01 0.003	2.816

Transparent elements include windows which are double glazed with an air gap of 1 cm, and wooden framed. They do not have any overhang nor exterior shading device, leaving unprotected. They are only shaded by interior blinds which are employed only in summer. The WWR on the North, East South, and West façades is respectively 23.42 %, 20.83 %, 28.65 %, and 27.07 %. The overall WWR is then 24.91 %. The U-value of the glazing unit is 2.816 W/m^2K which is above the advised levels of 2.4 W/m^2K by the standard (TS 825, 2008).

Active systems

Building's active systems are employed to ensure indoor thermal comfort, by adjusting the interior environment by means of heating, cooling, ventilation, and lighting. General data about active systems are obtained from the construction department of the university. Besides, specific details related to the capacity and efficiency of these active systems are assimilated from experts in the field.

Interior lighting

In this building, lighting management system is not employed. Natural lighting is not sufficient for daily activities, due to the neighboring buildings and the height ceilings. Therefore artificial lighting is turned on daily, during the occupants' presence. The installed lighting power is 2.5 W/m^2. The basement floor along with the corridor in the ground floor have fluorescent lighting. Beside these, all other rooms have LED lighting.

HVAC system

The building has different mechanical systems in terms of heating and cooling, and no mechanical ventilation system. Firstly, heating system of the building is shared with three other neighboring buildings, and the mechanical equipment are located within the largest building, the Congress Cultural Center. The system is composed of central natural gas boiler and radiators distributed in each room and in the corridors. The heating set point is fixed at 22^o. Secondly, the cooling system is composed of VRF (Variable Refrigerant Flow), where two outdoor units are placed on the roof deck of the third floor. The indoor units have centralized controller with a cooling set point of 24^o. Both systems have operation schedules uniform to the occupants' schedule, depending on the seasons. Since no mechanical ventilation system is considered, natural ventilation is employed occasionally by users during summer, but with an undefined schedule.

Given that the heating system is communal, the energy bills would not provide accurate results about the exact energy consumption of the building. In addition, this type of data wasn't accessible by the researcher, due to privacy reasons.

Occupancy & operation schedules

The building under study is an office building used by instructors from the university. It is occupied regularly by 46 people/instructors. Each floor has 14 occupants, except the third floor with 4 occupants, and the basement which is unoccupied. The occupancy density of 17.7 m^2/person is very low according to National Building Energy Performance Calculation Methodology for Turkey (BEP-TR, 2010). Each occupant has a light activity, which corresponds to a heat gain of 127 W. The operating hours follow a typical office occupancy pattern, offices are occupied each day from 8 am to 5 pm, all year long, except

for weekends and official holidays where the building is closed. The afternoon break time is from 12 am to 1 pm, where most of the occupants leave their offices.

5.2.2 Designation of Simulation Tool

With regards to the range of choices of BPS tools, the selection of a simulation software is based on the specificities and capabilities of each software along with the needs of the researcher. As there are several nuances in the literature to describe and compare different simulation tools, the researcher's selection was based on the criteria stipulated by Attia et al. (2012), as they provide an analytical review of the status of quo on the various available tools. By analyzing the existing literature, five selection criteria where mostly discussed. These criteria are:

a. "usability and information management of the interface"
b. "integration of intelligent design knowledge-base"
c. "accuracy and ability to simulate detailed and complex building components"
d. "interoperability of building modeling"
e. "integration of tools in building design process" (Attia et al., 2012)

The software used in the simulation is DesignBuilder, and the selection is based on its capability to provide detailed energy analysis. According to criterion 1, the software's interface is adaptable and flexible to different user's needs. The Graphical User Interface (GUI) allows data entry from basic to complex data inputs, which responds to the involved skill level of the user. In line with criterion 2, the software integrates "knowledge-base" support in terms of the breadth library of templates, materials, building's components, which complies with different international codes and standards. Additionally, it provides "intelligent" design decision support by performing parametric analysis, allowing the comparison of different design parameters. Concerning the 3rd criterion, DesignBuilder allows the simulation of complex detailed building components, such as HVAC systems, daylight controls, RES, green roofs, trombe walls, adaptive façade systems, etc. Furthermore, the software allows the calibration of parameters with uncertain values, which develop accurate results that are analytically verified and validated. In this way, it affords quality assurance and high level of modeling. In terms of criterion 4, the "interoperability of building modeling" is not much considered in this

study, since it is conducted by one researcher and it is not a team based project. Unlike other BPS tools, DesignBuilder does not include international information exchange involving different collaborating participants. Nevertheless, it provides interoperability regarding data exchange with BIM models, allowing the import of 3-D architectural models created in Revit, ArchiCAD, Microstation or any other software supporting gbXML. Lastly, the 'whole building design' strategy is emphasized by the software, which integrates all elements of the design process at different stages. It can be employed in different stages such as the pre-design, design, operation, restoration, retrofit, etc. thus verifying its ability for adaptive use for diverse intents.

After designating DesignBuilder as the simulation software, the model is performed by creating the entire architecture configuration within the software itself, and by specifying mechanical systems as well as occupants' schedules.

5.3 ENERGY MODELING

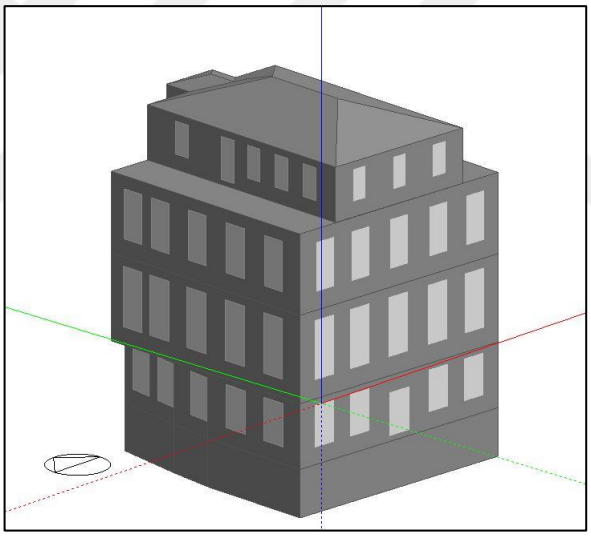
The modeling and simulation of energy consumption of the selected case building is performed in this phase. The entire set of sources responsible for energy consumption is accounted in the software. The modeling of the case study is divided into three phases, consisting of the architectural, thermal and optical properties, then the active systems properties, and lastly the occupancy & operation schedules. In DesignBuilder, a model is created according to a sequence specifying in order: Site, Building, Block, Zone, and Surface data.

5.3.1 Definition of Architectural, Thermal and Optical Properties

At first, the site of the case building is defined being Istanbul, Turkey. Then CAD plans are imported into the software and the 2D layouts are used to trace over the main walls and partitions defining the building's geometry. The created blocks outline the main geometries of the building, they represent the five floors of the building. Since the building has a basement floor, the entire building is moved down the Z-axis, placing the ground floor block on the 0 coordinate. The software later demarcates thermal zones according to the internal partitions. Each zone has different thermal properties responding to its layout, orientation, and thermal masses of walls, partitions, floors, and roof. The

thermal mass of each construction element, namely surface data, is provided by the software after entering the layers and thicknesses composing each material. Being a historic building with load-bearing walls, their thickness differs in each level, thus the need to specify a new wall type for each floor. The area of the third floor is smaller than other floors, thus the building has a pitched roof topping the third floor block as well as a flat roof topping part of the second floor block. Therefore different roof types are created for each one of them. After drawing the overall geometry, openings such as windows and doors are created, along with their materials and thermal properties. All data related to the building's configuration, mentioned in 5.2.1., are major consideration in the modeling phase. Figure 5.5 is a representation of the geometric model erected in DesignBuilder software.

Figure 5.5: 3D modeling of the case building



5.3.2 Definition of Active Systems Properties

In the second step, heating and cooling systems are designed according to a compact HVAC model option, where they are defined with moderately basic HVAC descriptions. These basic descriptions are later expanded into detailed HVAC properties, and modelled within EnergyPlus plugin. A detailed model option requires a thorough description of each system's functionality, components distribution, components size, and thermal capacity. Such in-depth investigation can be performed in another complementary study. As for the compact HVAC autosize method, it includes the specification of heating and cooling set points and set back temperatures as well as a detailed schedule of their usage.

Autosizing pre-simulations are conducted as part of the main simulation using the default built-in autosizing function. The schedule is obtained by conducting interviews with personnel working in the building. The schedule involve pattern of usage during the day, weekdays and weekends, different seasons, and during official holidays. In addition, lighting system is identified, including lighting power that is expressed as wattage /m^2, and the sort of lighting bulbs.

5.3.3 Definition of Occupancy & Operation Schedules

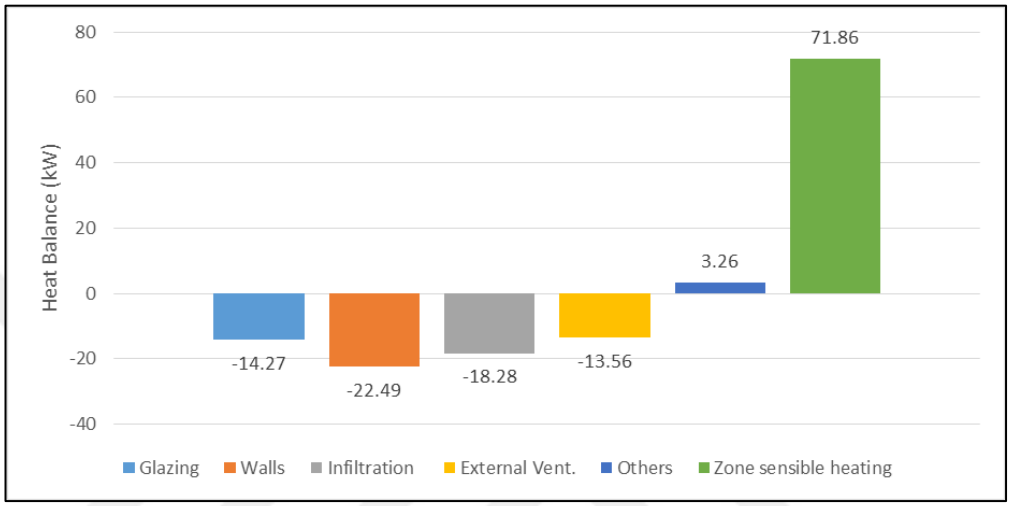
Lastly, the activity pattern is introduced, including the number of users in each floor along with their operating time, which follows a typical workday schedule. The schedule is defined by daily start time, end time, afternoon break time, working days per week, seasonal variations, and official holidays. Given that public holidays of Turkey are not in the library of the software, they were defined manually according to the national public holidays of the country.

As mentioned in the methodology, the model should be calibrated with monthly energy bills in order to obtain an accurate simulation with minimum deviations from reality. However due to the collective heating system shared between four buildings, the exact energy consumption of the case building can't be distinguished. Moreover, the data related to energy bills couldn't be obtained from the rectorate of the university (Rektörlük) due to confidentiality reasons. Regarding this matter, the researcher was unable to define parameters with uncertain values, and thus determining their deviation from the real measurements. Therefore, calibration is omitted from the implementation process. In the next phase, energy analysis is conducted based on the simulation of the baseline.

5.4 ANALYSIS ON ENERGY MODEL AND CURRENT CONDITION

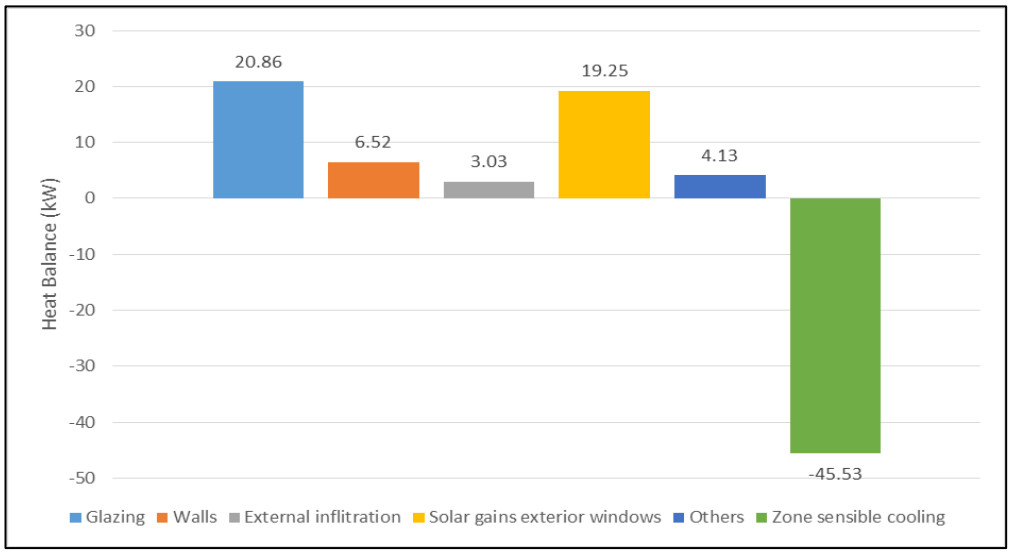
The whole building energy simulation is conducted with a simulation period of a year, based on Istanbul's weather data. It follows a daily, monthly and annual output intervals for reporting the analysis. Such simulation facilitates the study of building's performance according to seasonal variations.

Figure 5.6: Heating design simulation



Heating design simulation is performed to reveal the amount of heating needs to compensate the coldest winter weather conditions. As shown in Figure 5.6, the heat loss by glazing (-14.27 kW) and walls (-22.49 kW) is great, requiring large heating loads (71.86 kW) in order to maintain comfort indoor temperature.

Figure 5.7: Cooling design simulation



Likewise, cooling design simulation is performed to reveal the capacity of mechanical cooling equipment necessary to compensate the hottest summer weather conditions. As illustrated in Figure 5.7, the heat gain by glazing (20.86 kW) and solar gains by exterior windows (19.25 kW) are the main factors contributing to the high cooling loads (-45.53 kW).

As for the annual end-use energy consumption per total floor area, it is recorded 31.13 kWh/m^2 for heating, 16.75 kWh/m^2 for cooling and 13.11 kWh/m^2 for lighting. As a result, heating needs are much higher compared to cooling and lighting needs. This is due to the great differences between the exterior average temperatures in winter, 8^o (Dec) / 6^o (Jan) / 6^o (Feb) / 8^o (Mar), and the interior heating set point 22^o. This large difference produces high levels of energy consumption with the aim of ensuring indoor thermal comfort. It confirms the need for solutions regarding the peak consumptions for heating. These amounts are then converted into primary energy using the conversion factors employed in Turkey, which are 2.36 for electricity and 1.0 for natural gas, as recommended by Turkish National Building Energy Certification Methodology. Accordingly, the total primary energy consumption of the case building is 101.58 kWh/m^2/year.

Moreover, when analyzing the U-values of each assembly as illustrated previously in Table 5.1, it can be noticed that masonry elements have high thermal transmittance compared with the limit values given for Istanbul (climate zone 2) in TS 825 standard, these values are 0.57 W/m^2K for walls, 0.38 W/m^2K for roofs and 1.8 W/m^2K for glass (TS 825, 2008). Another factor causing heat loss is the air infiltration, which contributes to significant heating loads. Since the building envelope's opaque elements (walls, floors, and roof) represent a huge surface of thermal exchange, solutions targeting these elements can have high contribution in reducing heating consumption, due to the absence of insulation layer. It is also observed in Figure 5.7, that solar gains from exterior windows have significant impact on the heat balance. Therefore, retrofit actions targeting building envelope opaque as well as transparent elements is needed for reducing energy loads.

Deficiencies in some control systems is also detected. For example, even though lighting bulbs are mostly LED, lighting controls and sensors are totally absent, lights are just operated manually. This results in high electricity consumption and waste due continuous

lighting operation. Shading devices present as well shortages, they are only employed in summer with undefined schedule. As shown in Figure 5.7, solar gains by exterior windows are high, thus the need for solar control shading devices. With minor changes in the operation schedules of these systems, adequate energy savings can be achieved.

Simple technical solutions are sufficient for attaining energy efficient levels. Although, with the intent of reaching higher levels of energy performance, advanced technical solutions are necessary in the process of retrofitting; and with the intent of achieving nZEB, the introduction of R.E.S. is essential. According to the analysis of the baseline simulation and the comprehensive list of climate responsive strategies mentioned in the literature, the following retrofitting interventions are suggested:

a. Improvements on envelope: integrating insulation for walls and roof, and replacing glazing.
b. Improvements on internal conditions: including daylighting control, changes on shading control schedule.
c. Improvements on building systems: changes on ventilation settings.
d. Integration of R.E.S.: introducing photovoltaic panels.

5.5 DESIGNATION AND APPLICATION OF RETROFITTING SCENARIOS

Since the simulated building exists in real life, thus its reference configuration serves as a baseline for comparison with future energy retrofit alternatives. This baseline reflects the methods of construction of this era, thus all applied alternatives must be conventional with the historic character of the building.

5.5.1 Strategies Related to the Envelope

As a result of the dominant energy consumption for heating and the poor U-values of envelope elements, strategies addressing the insulation of opaque as well as transparent components are targeted for retrofitting. So as to obtain satisfactory results with regards to energy efficiency and later LCC, different variants are involved in the retrofitting. For walls and roof insulation, several insulation thicknesses are suggested based on their

thermal performance complying with the minimum requirements described in TS 825 standard. Likewise different window types are investigated.

Retrofitting of opaque elements insulation

A study assessing the impacts of applying insulation layer to the opaque envelope elements in the aim of retrofitting a school building in Istanbul, Turkey (Yılmaz, et al., 2018), presents comprehensive information for the interventions adopted in this research. The study discusses the application of rock wool insulation material on the exterior walls, roof and ground floor. It assesses the performance of the insulation material at different thicknesses for each opaque element. The different U-values are compared along with their prices in the suggested combinations.

Since the present study is located in the same climatic region and city as the previous research (Yılmaz, et al., 2018), rock wool insulation material is also employed due to its availability in the local market, its fire performance property, its water vapor diffusion resistance protecting historical structure from getting damp. Moreover it presents high ecological characteristics, for instance it presents minor embodied energy as well as a low risk of global warming, and it consists of 70% recycled materials. Additionally, rock wool has a high R-value around 3.0-3.3, which means a higher efficiency in terms of heat loss prevention. The material characteristics are obtained from a local supplier, Özpor ("Taş Yünü Fiyatları Fiyat Listesi," 2019), which explains the ease of installation of this material due to the simplicity of cutting, moving and fitting it into place.

Insulation is inserted to the innermost side of the exterior walls and roof, based on the common practice described in the literature, stating that interventions should not affect the character of the historic structures. The different thicknesses were chosen to comply with the lower level of thermal performance required by TS 825 standard, stated earlier, along with exhibiting a notable U-value difference between each thickness. Table 5.2 shows the chosen thicknesses for walls and roof with their U-values.

Table 5.2: retrofitting alternatives for building's opaque elements

Insulation type	Thickness (cm)	U-value (W/m²K)
Exterior Wall Rockwool insulation [a]	4	0.529
	6	0.414
	9	0.312
	12	0.25
Roof Rockwool insulation [b]	8	0.373
	9	0.339
	11	0.288
	14	0.235
	17	0.198

[a] U-values are calculated for 1st floor exterior walls

[b] U-values are calculated for pitched roof

Retrofitting of transparent elements

As for the windows' retrofitting, 4 alternatives were chosen according to the most common glazing types in the local market. From the wide variety of glazing products provided by the local supplier Isıcam ("K Serisi Cam Sistemleri ile Etkin Isı ve Ses Yalıtımı | Isıcam," 2019), the chosen options are based on their thermal properties satisfying the minimum thermal requirement. The detailed characteristics of each type, allowed the researcher to asses, compare and contrast the actual performances of different glazing products. Isıcam K-series was chosen due to its high quality heat and solar coating, providing maximum insulation, thus reducing heating as well as cooling loads. It prevents window's fronts from being cold in winter and hot in summer and delays condensation compared to ordinary double glazing. The data of the selected glazing units from the local market are available in Table 5.3. One glazing option includes a clear double glazed window with 16mm argon cavity. Other options include glazing with 4mm solar Low-E glass with 16 mm air or argon cavity. Triple glazing unit was also nominated due to its high thermal performance.

Table 5.3: retrofitting alternatives for glazing

Glazing type	U-value (W/m^2K)	Total Solar transmittance (SHGC)	Light transmittance (Tvis)
4 + 16 (argon) + 4	1.83	0.598	0.769
Low-E 4 + 16 (air) + 4	1.378	0.505	0.727
Low-E 4 + 16 (argon) + 4	1.202	0.51	0.727
Low-E 4+ 16 (air) +4 +16 (air) +4	0.949	0.474	0.661

5.5.2 Strategies Related to the Control Systems

Smart blind control

Windows are already protected with internal blinds that are manually operable by users depending on their preference or the technical management of the building. These blinds reduce not only solar gain but also light transmittance of glazing. Thus designating a shading control schedule ensures the protection of windows from solar radiation during user's operation in summer, based on the external temperature. Hence, the schedule is designed to open the blinds when exterior temperature in summer exceeds 22^oC. In order to set such schedule, smart blind control system was incorporated for each window. This system is locally available and can be easily be installed like any traditional blind switch.

Lighting control

Artificial lighting control system is defined by integrating daylight sensors, 1 in small rooms, 2 in large rooms and 2 in corridors. Therefore the building has a total of 31 daylight sensors (basement is not included). Artificial lights are then operated with a dimming control system based on the available natural light in order to meet the minimum lux level for users. In DesignBuilder, such system is defined by a linear/off control. It reduces the light's intensity constantly with a linear tactic from the highest to the lowest electric power, with regards to the daylight illuminance levels. The lights are turned off entirely when the minimum dimming point is reached, with further increase in the

daylight illuminance. In the building simulation, the control system operates with a value of 300 lux.

Nocturnal convective cooling

Masonry structures have a high density, therefore a high thermal mass which traps hot air inside the building making it warmer. This technique is beneficial in winter providing passive heating for the interior space. However, in summer and with the increasing climate change effects, the high thermal mass is an issue due to the resulted high cooling demands. With the intent of surmounting this shortcoming, a night ventilation schedule is designed to passively cool the building. It has an important effect in reducing cooling needs in summer. At night, windows are opened to exhaust warmer air, replacing it with exterior fresher air by means of convection. This technique releases internal gains acquired during daytime by the building envelope. Night ventilation has also an effect over ameliorating the indoor thermal comfort. This technique is employed in traditional houses located in warm-dry climatic regions of the country, such as Mardin.

These three parameters are constant in all simulations, hence they do not affect the comparison values of the different insulation thicknesses and window types.

5.5.3 Strategies Related to the Introduction of Renewable Energy

In this research, the purpose of introducing renewable energy system is to compensate the loads of energy by producing on-site energy, as well as reaching nearly zero energy values. From the wide range of renewable systems, photovoltaic technology is selected due to its availability in the local market. This system can take advantage of the relatively high number of daily sunshine hours, which varies between 2.6 hours in January and 11.6 hours in July. Moreover, the application of PV panels on the pitched roof along with the flat roof terrace wouldn't affect the historical structure, since it doesn't require major labor work, thus the integrity of the old structure will remain unaltered.

In the simulation model, a PV system is added on the total roof area with modules directed towards the South for higher efficiency having an inclination angle that is adjusted in terms of summer performance. According to the Solar Electricity Handbook (Boxwell, 2011), the inclination angle depends on the location's latitude and the season where best

performance can occur. In this case study, the photovoltaic panels are angled towards the summer months which is calculated as 18^{o} according to Istanbul's latitude. These modules are separated from each other by a suitable distance preventing their shadows from affecting their performance. The system consists of one module repeated 24 times on the flat roof, and 13 PV arrays (5 modules per array) on the total area of the pitched roof. The generation system is designed with a simple inverter and a simple storage unit. A total number of 89 modules (1.46 m^2 each) is obtained based on the vacant space for modules, one module dimensions and the minimum required distance between them.

After investigating the local market, Poly Crystalline Silicon Cells exhibit better performance. The data are acquired from the technical data sheet of Ankara Solar manufacturer (Ankara Solar AS, 2019). The selected module is AS-P60 260-290W Poly Solar Panel. The selection was based on its efficiency that is up to 17.83%, its reasonable cost compared to the other alternatives in the market, its superior performance under low light intensity, and its weather resistant reliability.

Ultimately, if we perform a complete parametric study for the selected parameters, the number of possible combinations is 80, which is the result of their multiplication. However one more alternative is added, which is a simulation based on the improvement of solely the internal control system mentioned in 5.4.2. Additionally, an alternative with renewable energy is performed merely to measure the amount of on-site produced energy and thus saved from the total energy consumption. As a result 82 alternatives are simulated, they are detailed in Appendix A.1.

5.6 ENERGY AND LIFE CYCLE COST CALCULATION OF RETROFITTING SCENARIOS

5.6.1 Calculation of Energy Performance

All 82 retrofitting scenarios, listed above, were simulated separately in DesignBuilder. Their energy performance is calculated in the software and values were extracted as annual building energy consumption. It includes the end-use electricity and natural gas consumption. Natural gas consumption is the result of the operation of heating system (boiler and radiators), as for electricity consumption it is the result of the sum of cooling

system (including AC, fans and pumps) and interior lighting. Later the annual energy consumption is converted into annual primary energy consumption. Primary energy conversion factors are 2.36 for electricity and 1.0 for natural gas, they are obtained from Turkish National Building Energy Certification Methodology. This energy performance calculation will later serve for comparing cost optimal and energy efficient scenarios with the baseline.

5.6.2 Collection of Market Related Data

In the evaluation method of Life-Cycle-Cost analysis, the discounting approach used is Net Present Value due to: its consideration of time value of money, its ability to generate returns equal to the market interest rate, its utilization of all market data, its ability to indicate the cost during each year separately, and its ability to compare different alternatives with same life span. The cost measurement basis for this calculation is Euro, with 6.6 exchange rate for € to TL, as in April 2019.

In order to perform cost analysis, the availability of its data is imperative. Therefore the data used in the calculation should be accessible, accurate and updated to present time. A comprehensive market investigation was carried out, in the aim of collecting all market and financial related data.

Market data include the current prices of building materials, i.e. rock wool insulation (for wall and roof), glazing, control system, as well as the average annual maintenance costs in percent of investment costs. These prices are collected directly from local manufacturers and suppliers in Turkey. A price list is created with the required quantity for each component in Table 5.4.

Table 5.4: unit price for retrofit components

Retrofit Type	Product Detail	Unit Price (TL)
Wall insulation [a]	Wall Rockwool insulation (4 cm)	10.14
	Wall Rockwool insulation (6 cm)	15.25
	Wall Rockwool insulation (9 cm)	22.87

	Wall Rockwool insulation (12 cm)	30.42
Roof insulation [a]	Roof Rockwool insulation (08 cm)	17.8
	Roof Rockwool insulation (09 cm)	19.89
	Roof Rockwool insulation (11 cm)	24.26
	Roof Rockwool insulation (14 cm)	30.96
	Roof Rockwool insulation (17 cm)	37.52
Glazing [b]	C serie Glazing (4+16+4 - argon)	82.4
	K serie Glazing (LowE 4+16+4 - air)	122.3
	K serie Glazing (LowE 4+16+4 - argon)	122.3
	K serie Glazing (LowE 4+16+4+16+4- air)	198
Equipment for Control Strategies [c]	Daylight sensor	41.56
	Smart blind control	93.04

[a] From Özpor ("Taş Yünü Fiyatları Fiyat Listesi," 2019)

[b] From Isıcam ("K Serisi Cam Sistemleri ile Etkin Isı ve Ses Yalıtımı | Isıcam," 2019)

[c] From Alibaba online store (https://www.alibaba.com/)

Furthermore, financial data related to the Turkish financial market are as well acquired. They include inflation rate, market interest rate, energy nominal price escalation, and the unit price for electricity and natural gas. These rates are calculated based on a 10 years average to represent more generically the market situation, except the unit prices which are conform to current values. These data are represented in Table 5.5. Inflation rate is obtained from the Turkish Statistical Institute (TUIK). The 10 years average inflation rate is estimated from 2009-2018 based on monthly Consumer Price Index. Besides, market interest rate is obtained from the Central Bank of the Republic of Turkey (TCMB), its average is also calculated from 2009 to 2018 for more accurate outcomes. Additionally, energy prices related to electricity and natural gas are published by Energy Market Regulatory Authority (EPDK) from the year of 2004 till 2018. Escalation rates are calculated based on these numbers for a 10 years average. Unit prices for electricity and natural gas are obtained from the values recorded in energy bills, issued by Turkish Electricity Distribution Company (TEDAS) and Istanbul Gas Distribution Industry and Trade Incorporated Company (IGDAS) respectively. Prices include the Value Added Tax

(VAT) and all other taxes. The month of April 2019 is selected as the representative time of the research.

Table 5.5: Economic parameters for LCC calculation

Parameter	Unit	Value
Duration of the calculation (T)	years	30
Inflation rate (R_i)	%	8.945129628
Market interest rate (R)	%	12.75833333
Nominal price escalation on electricity ($R_{E\ electricity}$)	%	10.32905296
Nominal price escalation on natural gas ($R_{E\ gas}$)	%	7.957048172
Unit price for electricity	TL/kWh	0.53490816
Unit price for natural gas	TL/kWh	0.127178618

5.6.3 Calculation of Life Cycle Cost

Life span is an important factor in the LCC calculation since buildings exhibit relatively consistent energy performance when the period of calculation is longer. Thus in this research, calculations are made for a life span of 30 years.

$$LCC\ (T) = C_I + \sum_{i=1}^{T}(C_{a(i)} \times f_{pv}(i)) - \sum_{j=1} V_{T-f}(j) \qquad (5.1)$$

$$R_R = \frac{R-R_i}{1+R_i} \qquad (5.2)$$

$$f_{pv}(n) = \frac{1-(1+R_R)^{-n}}{R_R} \qquad (5.3)$$

$$R_e = \frac{1+R_E}{1+R_i} - 1 \qquad (5.4)$$

$$f_{pvm}(n) = \left(\frac{1+R_e}{R_R-R_e}\right) \times \left[1 - \left(\frac{1+R_e}{1+R_R}\right)^n\right] \qquad (5.5)$$

The formula of global cost, based on the method provided by NIST handbook, is expressed in equation 5.1. It is the summation of initial costs (C_I) and annual costs (C_a), which include several factors such as product's maintenance cost, replacement cost (if needed), energy and water prices with a subtraction of residual cost (V_{T_f}). All these costs, occurring during the life span (T) of the building, are discounted to present time using present value factors defined by NIST (Fuller and Petersen, 1995).

Each retrofit scenario has several components (wall/roof insulation, glazing, and control systems). For each component the calculation includes initial investment costs as well as maintenance costs on a span of 30 years. These costs are brought into the present value using present value factor f_{pv}. Replacement cost is not needed in this calculation, since the components have equal or higher life time period to 30 years. Moreover, residual costs are also neglected due to the absence of material re-claiming activity in Turkey.

As for the NPV of energy it includes NPV of the end-use electricity and natural gas consumption. For this calculation a modified present factor f_{pvm} is employed due to the constantly changeable economic parameters in Turkey, i.e. inflation rate, market interest rate, and energy price escalation rates. A variation of present value factors are described in detail in the Life-Cycle-Costing Manual issued by NIST. In this manual, f_{pvm} is employed "to calculate the present value recurring annual amounts that change from year to year at a constant escalation rate" (Fuller and Petersen, 1995).

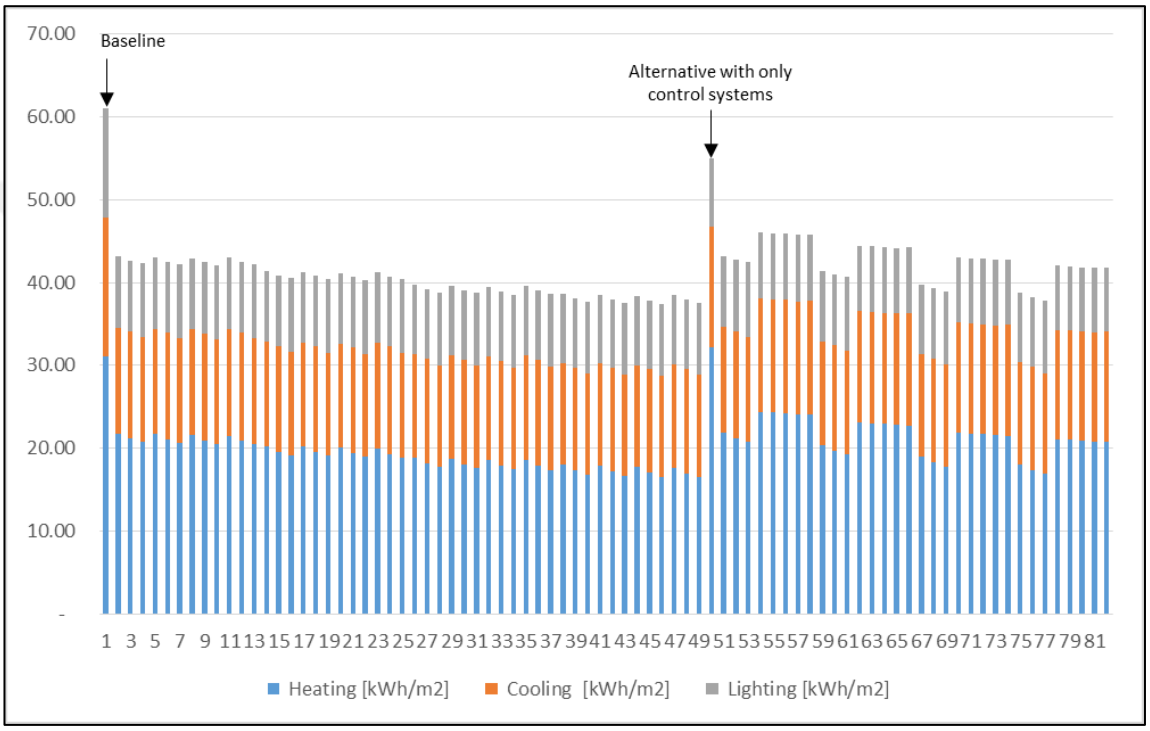
With the aim of calculating the present value factor (f_{pv}) (equation 5.3), the real interest rate (R_R) (equation 5.2) must be calculated first using the inflation rate (R_i) and market interest rate (R) acquired formerly in Table 5.5. Likewise, for calculating the modified present value factor (f_{pvm}) (equation 5.5), the real interest rate (R_R) is needed in addition to the real energy price escalation (R_e) (equation 5.4), this last one requires the nominal energy price escalation rate (R_E) for each energy type, i.e. electricity and natural gas. Finally, LCC is calculated using equation 5.1 for 30 years life span (T).

Regarding renewable system component, it was excluded from the global cost calculation as the solely purpose of its integration is in terms of energy efficiency, so as to compensate the utmost of building' energy consumption.

5.7 EVALUATION OF OVERALL RESULTS

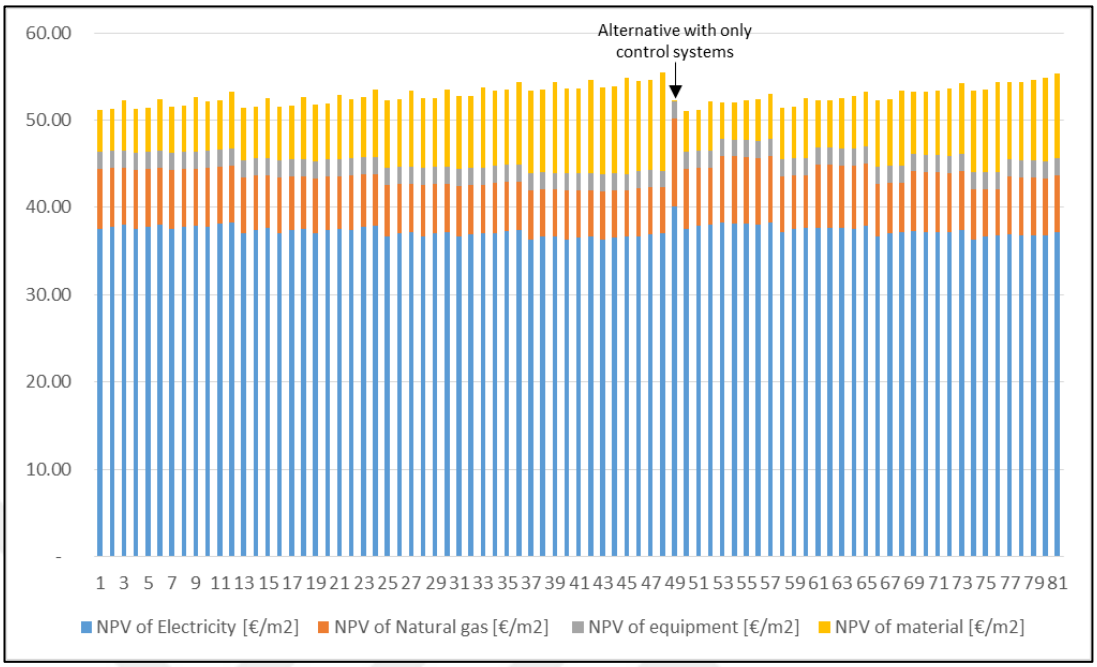
After performing energy calculations for each scenario, Figure 5.8 compares the end-use energy consumptions breakdown of all alternatives, which are mentioned in details in Appendix A.1.

Figure 5.8: Comparison of annual end-use energy consumptions breakdown of different alternatives



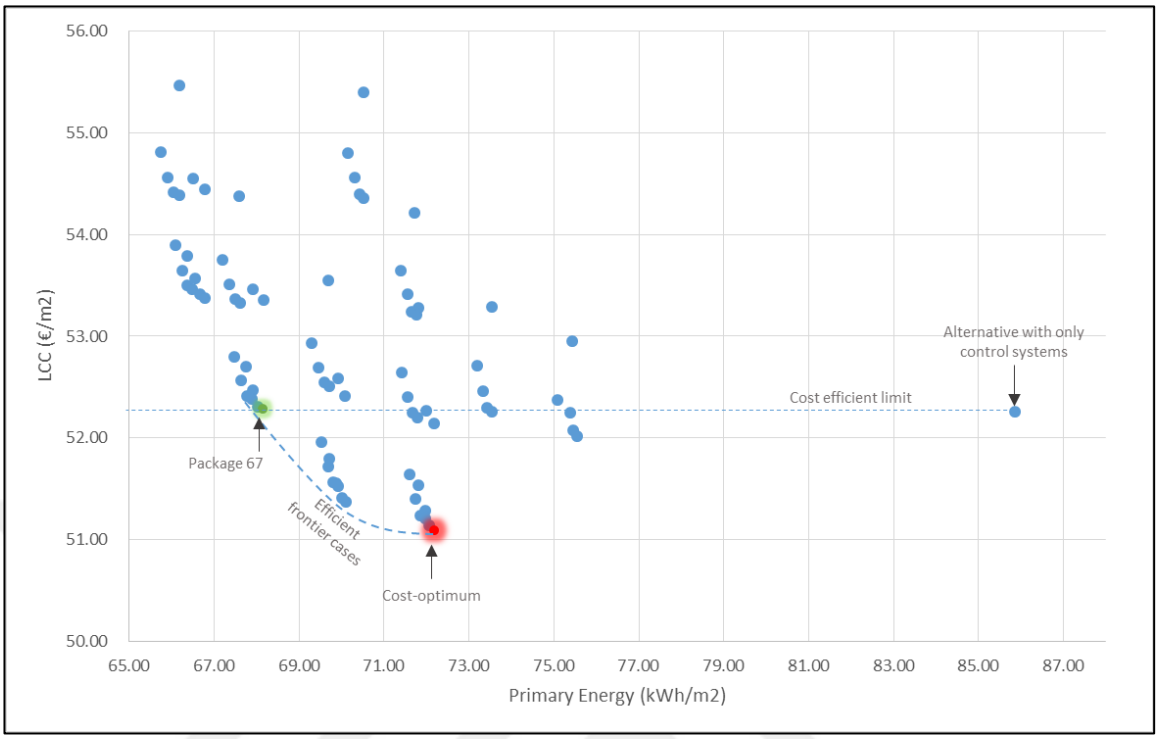
Subsequently, Life Cycle Cost calculations are conducted for each scenario. Figure 5.9 presents the graph of the breakdown of costs for each alternative as comprehensively reported in Appendix A.1. It can be noticed that even though natural gas consumption for heating is much higher compared with electricity (Figure 5.8), the NPV of electricity is the highest compared to all other cost factors. Thus including energy prices in the calculation has a considerable influence on the total cost of each scenario, and therefore affecting the cost optimum outcome.

Figure 5.9: Comparison of global cost breakdown of different alternatives



Following the calculation of primary energy and LCC for each scenario, these two measures are plotted into a graph forming a cloud of points (Figure 5.10). The values for primary energy vary between the range of 65.74 to 85.86 kWh/m^2, and between 51.09 to 55.46 €/m^2 for LCC. A cost-optimum is then defined as the alternative having the lowest value on y-axis, meaning the lowest global cost. The package 51 is the cost optimal case, it corresponds to a LCC value of 51.09 €/m^2 and a primary energy of 72.18 kWh/m^2. The optimum scenario implies the addition of 4cm thickness of rock wool insulation for wall and 8cm for roof, the glazing replacement by double Low-E glass with a 16mm air cavity (glass U-value 1.378 W/m^{2}K), and the integration of control systems, i.e. daylight sensor, smart blinds control, nocturnal ventilation. When this optimum scenario is compared with the baseline, it achieved 29.40 kWh/m^2 primary energy savings equal to 29% reduction in total energy consumption.

Figure 5.10: Cost-effective alternative solution



In general, all alternatives exhibit major energy reduction from the baseline. With regards to primary energy, the highest consuming scenario corresponds to a reduction of 15% from the baseline, and the lowest consuming scenario demonstrates a reduction of 35%. When these values are coupled with the amount of energy produced from photovoltaic panels, a 73% energy savings can be noted for the cost optimal scenario, and 79% for the most energy efficient scenario.

It can be noted that the alternative with only control system retrofit has the highest primary energy consumption from all alternatives. Nevertheless it exhibits a rather raised LCC of 52.26 €/m^2. This is due to the high cost of energy expenditure as shown in Figure 5.9. The researcher chose to nominate this point as the cost efficient limit, meaning that all alternatives below this line are considered within the cost optimal range.

Within this limit, the package 67 is the most energy efficient scenario, satisfying cost efficiency, it corresponds to a LCC value of 52.28 €/m^2 and it has a low primary energy of 68.16 kWh/m^2. This scenario includes the addition of 9cm thickness of rock wool insulation for wall and 8cm for roof, the glazing replacement by double Low-E glass with a 16mm air cavity (glass U-value 1.378 W/m^2K), and the integration of control systems,

i.e. daylight sensor, smart blinds control, nocturnal ventilation. This scenario achieved 33.42 kWh/m^2 primary energy savings from the baseline, equal to 33% reduction in total energy consumption.

Cost optimal and energy efficient scenarios are pointed in Figure 5.10. Their energy consumption breakdown are shown previously in Figure 5.8, were a major energy consumption reduction is obtained in the heating loads, due to the efficiency of the Rockwool insulation. Some scenarios exhibit better performance in terms of primary energy consumption, however they are not preferred for implementation due to their high LCC.

Efficient frontier cases which have high energy efficiency and fall within the cost-optimal limit are delineated in Figure 5.10 by a curve. These efficient frontier cases are described with their pursued parameters in Table 5.6. According to this table, the frontier cases have a common parameter, which is the glazing type. This is due to the high cost of glazing units as well as their great required quantity, constituting a dominant factor in efficient frontier packages. These packages also include nearby envelope insulation thicknesses, thus having minor effects on the LCC as well as primary energy, creating the small differences between alternatives. Package 67 is noted as the most energy efficient scenario, and 51 as the cost optimal one.

Table 5.6: Efficient frontier packages

Package no	Primary energy (kWh/m^2)	LCC (€/m^2)	Wall insulation (U-value)	Roof insulation (U-value)	Glazing type (U-value)
67	68.16	52.28	9cm (0.312)	8cm (0.373)	4+16(air)+4 (1.378)
13	70.00	51.41	6cm (0.414)	9cm (0.339)	4+16(air)+4 (1.378)
59	70.11	51.37	6cm (0.414)	8cm (0.373)	4+16(air)+4 (1.378)
52	71.97	51.21	4cm (0.529)	8cm (0.373)	4+16(argon)+4 (1.202)

22	70.08	52.41	6cm (0.414)	17cm (0.198)	4+16(air)+4 (1.378)
51	72.18	51.09	4cm (0.529)	8cm (0.373)	4+16(air)+4 (1.378)

Moreover, several clusters of points can be discerned in Figure 5.10. These points corresponds to alternatives that achieve similar performance in terms of energy consumption and have quite similar LCC. After investigating these alternatives, it can be deduced that the wall insulation is the chief factor combining different alternatives under the same cluster. It is due to the considerable wall area (1198.17 m^2) provoking a massive change in energy consumption with the change of its U-value, likewise affecting its cost.

Furthermore a deduction can be drawn from the application of renewable energy resources, which is the ability to reach nZEB or even ZEB by integrating them along with simple technical solutions that improved the building's energy consumption.

In conclusion, this chapter demonstrated the possibility of applying the suggested methodology for retrofitting a historic building with 81 different alternatives, while comparing them with regards to primary energy consumption and delineating the cost-optimum scenario. The methodology was validated with the suggestion of energy efficient and cost feasible intervention for energy rehabilitation of historic buildings, while respecting their integrity. This methodology can be applied later to similar building design problem.

6. CONCLUSION

This study documented the results of retrofitting a historic building located in the historical peninsula of Istanbul, by modeling it using a state-of-art graphical user interface and assigning different scenarios for interventions. Along these line, applying the suggested methodology to a real case study validated the possibility of identifying a set of effective technical solutions with different costs and energy consumptions and comparing between them according to the criteria in consideration. With the utilization of this approach, finding solutions satisfying special requirements or constraints was possible. Retrofitting solutions with low energy consumptions can be obtained with acceptable investment costs producing a certainly low environmental impact. The last chapter has demonstrated in which way the developed methodology of this research contributed, with the help of energy and LCC calculation, to finding the cost-optimal scenario for the retrofitting project.

Due to its historical character, retrofitting interventions were limited and constrained by several factors. According to the state-of-the-art, the integration of an insulation layer is always on the inner side of the building's envelope (exterior walls and roof). Additionally the choice of insulation material should not harm the historic structure. This explains the choice of rock wool insulation placed on the inner side of the walls and roof. Besides the insertion of PCM was avoided in this study due to the lack of research conducted about the effect of this material on historic structures. Furthermore, the replacement of windows was made with designs similar to the existing ones but with better performance, and tainted glazing was avoided. Moreover, any alteration of the exterior façade's aesthetic is completely rejected by the local preservation regulations, thus external shading devices were not employed in this study, only control system were placed for the existing interior blinds.

In the aim of evaluating the entire process for the application of the methodology of this research, a SWOT analysis was conducted to highlight the strength, weakness, opportunity, and threat.

In terms of strength, the software can be definitely recommended for comparing retrofitting design decisions, after conducting this extensive process with DesignBuilder. The analysis of state-of-art of different retrofitting parameters and technical solutions, allowed the establishment of a library of possible interventions on historic buildings. Moreover the analysis of the base case highlighted the tracks on which the reduction of energy consumption can be carried out efficiently. Targeting thermal as well as optical envelope elements in the retrofitting process, with several alternatives, provided satisfying results in terms of cost-optimum. Additionally, calculating the Life Cycle Cost for a time span of 10 years proved its advantage in a developing country like Turkey, which has an unsteady economy leading to major variation of prices for each year.

As for the weaknesses, although DesignBuilder software was learnt and operated quickly, shortcomings were frequently occurring due to the hierarchy of entering model data, and the complexity of assigning compact schedules. Disadvantageously, the simulations process had to be repeated several times alongside the LCC calculation in order to reach better results satisfying the cost-optimal concept. Moreover, due to the limited time of the research, some components in the model were simplified. For example, the HVAC system was designed under a compact system type because the software does not support having two different HVAC system, which are in this case a central heating system and a VRF system for cooling. Other components, such as internal loads schedules, were collected based on mere questionnaires with the working staff, instead of reliable real-time measurements that would otherwise require one year to collect them. Another weakness in this process was the inability to calibrate the energy model due to the absence of energy bills and the short time span of the research. This uncalibrated model might present variations from the real life building's conditions, thus a lower level of truthfulness.

Considering the opportunities, DesignBuilder software has a multifaceted interface, thus with minor changes in the settings, the simulation results can be enhanced with regards to energy as well as cost efficiency. Additionally, the amelioration of the renewable energy alternative can have a substantial impact on energy reduction, allowing the model to reach ZEB. Besides, the delineation of a set of efficient frontier cases, in the cost-optimum graph, provides several intervention options having similar LCC and primary energy consumption. It provides choices for the related stakeholders in the retrofitting

field. Moreover, the optimization of cost-optimal solution can extensively shorten the implementation process by determining certain constraints via mathematical algorithms. The addition of this step in the methodology, allows the increase of the number of alternatives in the simulations but with a reduced simulation duration.

On the other hand, with the intention of obtaining an energy model equivalent to the real case building, the complexity of the energy modeling software requires the assistance of professionals in the mechanical and electrical field, which is regarded as a threat in the process. Even though the implementation delivered satisfying results, the methodology should be employed with precaution. The collection of all data and information prior to simulation is a must, because a shortage in any information whether related to the building's configuration, the retrofit alternatives, or the cost data, can result in an obstruction to the entire process.

In summary, the main findings from the proposed methodology and case study implementation are as listed below:

a. While historic buildings are somehow exempted from minimum energy requirement, they do exhibit high values of energy consumption, thus the need for interventions to reduce their consumption, ameliorate indoor thermal comfort, and equip them with modern efficient systems.
b. A comprehensive energy analysis should be conducted prior to the selection of retrofit interventions. Alternatives should be selected based on the minimum required U-value by local standards. They should also comply with the local preservation regulations.
c. In order to reach acceptable results for cost-optimal scenario, numerous alternatives should be simulated, presenting variations with regards to primary energy and LCC.
d. In the cost-optimal graph, several scenarios fall under the cost efficient limit, therefore allowing investors to choose from a broad variation the most suitable scenario. These efficient frontier cases are acknowledged as cost as well as energy efficient, having minor differences in values.

e. In this case study, the package with the lowest cost is assigned s cost-optimal scenario, and the one with lowest primary energy, within cost efficient limit, as the most energy efficient scenario.
f. It is also noted that the wall thickness is the dominant factor affecting both values, energy and cost. Due to the large surface area that it occupies, exterior walls insulation thicknesses produce clusters in the graph.

In this case study, the research was limited to interventions targeting the building's envelope elements along with internal control systems. Nevertheless, interventions targeting building mechanical and electrical system as well as the use of other types of materials is an interesting trajectory for future studies. Phase Changing Materials, for example, can be tested in terms of their efficiency together with their effect on historical masonry structures. The application of this methodology can be extended to other building's typology and other climatic regions. Moreover in order to make historic building reach nearly zero energy building, an advanced system of renewable energy should be developed according to the natural resource assets and the allowed interventions by local regulations. This methodology can also be used in the framework of environmental certification of buildings, such as LEED, BREAM, etc.

To conclude, the approach followed in this research provides a comprehensive guideline for energy rehabilitation intervention on historic buildings with a broad variety of alternatives, where the choice of alternative is based on the design objective. This methodology can be a very effective decision support tool for designers and decision-makers in the field of building construction and renovation.

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APPENDICES

Appendix A.1 Implemented packages of energy efficient measures

Alternatives	Rock wool wall insulation				Rock wool roof insulation					Glazing replacement				Shading control	Lighting control	Ventilation
	4 cm	6 cm	9 cm	12 cm	8 cm	9 cm	11 cm	14 cm	17 cm	Double Clear 16mm argon	Double Low-E 16 mm air	Double Low-E 16 mm argon	Triple Low-E 16 mm air	control by T° schedule	Linear/off	night schedule
U-value	0.529	0.414	0.312	0.25	0.373	0.339	0.288	0.235	0.198	1.83	1.378	1.202	0.949	--	--	--
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