ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DYNAMIC SIMULATION OF CALIBRATED ENERGY MODEL BY CONTROLING INDOOR TEMPERATURE TO MAXIMIZE THE ENERGY EFFICIENCY

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

DİNAMİK SİMÜLASYON YÖNTEMİYLE İÇ MEKAN SICAKLIKLARINA GÖRE ENERJİ MODELİNİN ENERJİ VERİMLİLİĞİNİ MAKSİMİZE ETMEK İÇİN KALİBRE EDİLMESİ

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HAZİRAN 2023

Burak Fil, a M.Sc./a Ph.D. student of İTU Graduate School student ID 301201011 successfully defended the thesis/dissertation entitled "DYNAMIC SIMULATION OF CALIBRATED ENERGY MODEL BY CONTROLING INDOOR TEMPERATURE TO MAXIMIZE THE ENERGY EFFICIENCY", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my dear spouse and family,

FOREWORD

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(Mechanical Engineer)

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ABREVIATIONS

ABC-ANN : Artificial Bee Colony Artificial Neural Network
ANNs : Artifical Neural Networks
ASHRAE : American Society of Heating Refrigerating and Air Conditioning Engineers
CAD : Computer Aided Design
CDD : Cooling Degree Day
CVRMSE : Cumulative Variation of Root Mean Squared Error
FDD : Fault Detection and Diagnosis
FEMP : Federal Energy Management Program
GA-ANN : Genetic Algorithm-Artificial Neural Network
HDD : Heating Degree Day
HVAC : Heating, Ventilation and Air Conditioning
ICAANN : Imperialist Competitive Algorithm-Artificial Neural Network
ICT : Information and Communication Technology
IPMVP : International Performance Measurement and Verification Protocol
MBE : Mean Bias Error
NMBE : Normalized Mean Bias Error
PSO-ANN : Particle Swarm Optimization-Artificial Neural Network
RF : Radio Frequency
RMSE : Root Mean Squared Error
SMAPE : Symmetric Mean Average Percentage Error
TS : Turkish Standart

SYMBOLS

d	**:** Structural Element Thickness
K	**:** Kelvin
kWh	**:** Kilowatt-hours
$\mathbf{m_i}$	**:** Measured Data of a Certain Variable During the Chosen Interval
$\bar{m}$	**:** Average of the Measured Data
$\mathbf{N_p}$	**:** Number of Variable at the Interval
N	: Number of the Structural Elements
$\mathbf{R_e}$	**:** Thermal Conduction Resistance of the Exterior Surface
$\mathbf{R_i}$	**:** Thermal Conduction Resistance of the Inner Surface
$\mathbf{s_i}$	**:** Simulated Data of a Certain Variable During the Chosen Interval
U	**:** Overall Thermal Conductivity Coefficient
W	**:** Watt
λ_h	**:** Thermal Conductivity Calculation Value
°C	**:** Degree Celcius
%	**:** Percentage

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DYNAMIC SIMULATION OF CALIBRATED ENERGY MODEL BY CONTROLING INDOOR TEMPERATURE TO MAXIMIZE THE ENERGY EFFICIENCY

SUMMARY

The residential sector is responsible for a large part of energy consumption. With the world's growing population, the need for buildings is increasing day by day. As a result, the amount of energy demanded by the building sector is also increasing. For these reasons, energy efficiency studies in the building sector, which has a large share in total energy consumption, are of great importance. Therefore, there is a need extensive research that identify the energy consumption profile of building in terms of heating, cooling, lighting, and their sources.

The aim of the study is dynamically simulating a building energy model to maximise the energy efficiency. This can be achieved through a calibrated energy model with fifteen-minute measured data by eliminating over-heated and over-cooled periods. It is also to provide additional energy savings by managing the energy consumption of the different functional zones of the building in terms of occupational scheduling, building systems scheduling and sensible temperature comfort conditions.

The case study building was selected as Energy Institute building located in Ayazağa Campus of Istanbul Technical University. The Energy Institute building was built in 1963 with 3 floors. It has a total area of 4272 m^2. The building is heated with a central radiator system using natural gas as fuel. As an educational building, it consists of classrooms, offices, and laboratories.

A systematic methodology consisting of five main parts as is proposed in the thesis. The proposed steps are followed in order and their applications are realized on the building selected as a case study. These steps are the creation of a three-dimensional model of the building, the creation of the energy model of the building, the collection of measured data from the building, the calibration of the building energy model and the improvements on the existing energy profile of the building.

In the first chapter defined in the methodology of the thesis, the three-dimensional model of the building was created using Autodesk Revit software using the floor plans of the building obtained from the university administration. Since the information in the floor plans was not sufficient, observations were made in the building and visuals of the building were utilized to detail the model. Then, in order to define the areas inside the building according to their functional uses, observations were made again, and each area was transferred to the model according to its usage function. There are seven different areas in the building with different usage functions. These are offices, classrooms, laboratories, conditioned corridors, unconditioned corridors, restrooms, and storage areas. These zones were modelled separately according to heating, cooling, lighting systems, equipment, and usage profiles.

In the second part, Design Builder software was preferred to convert 3D model to building energy model because it allows easy transfer of the three-dimensional model, zone-based parameter description, easy modelling of building systems and the

opportunity to obtain simulation results in desired periods. To provide data input to the energy model, the climate data of the region where the building is located was accessed from Energy Plus software. The thermal properties of the building envelope elements (exterior walls, roof, foundation, doors, and windows) were determined from the building drawings and observations made in the building. The properties of all systems used in the building were also obtained from technical documents and observations. The heating of the building is provided by a central radiator system, and there are split air conditioners only in the offices as a cooling system. Lighting throughout the building is provided by fluorescent lamps. There are also equipment and computers in classrooms, laboratories, and offices. In addition to these, the usage profiles of all zones in the building have been determined and the time intervals and how many hours these areas are actively used are defined in the model.

In the third section, periodic measurements were made to be used both in the calibration of the energy model and in the improvement of the existing energy profile. Monthly natural gas and electricity consumption of building for the base year 2022 was measured.

In the fourth step, the calibration of the energy model, the energy model described in detail in chapter two was first simulated. This simulation is called base line scenario in the thesis. The monthly natural gas and electricity consumptions obtained from the simulation were analysed and compared with the actual consumption of the building. As a result of the comparison, it was seen that although the simulation and real results are relatively close to each other in the summer months, the consumption values obtained from the simulation are much higher than the real values, especially in periods other than summer months. While the annual energy consumption is 307 kWh/m^2 in the simulation results, the actual consumption result is 159 kWh/m^2. In order to reduce the differences between the model and the actual data, first of all, Scenario 2 energy model was created by fine-tuning the some model parameters. The parameters modified in base line scenario are the thermal properties of the roof, windows and doors, infiltration rate and power density of the equipment in the building. With the changes applied in Scenario 2, the energy consumption is reduced to 222 kWh/m^2. Since the difference between the measured and simulated consumption is still not acceptable, Scenario 3 energy model was created and usage profiles were created separately for functional zones. The planning of heating, cooling, lighting systems and equipment were taken into consideration in determining the working hours based on zones. With the changes made with Scenario 3, energy consumption was reduced to 152 kWh/m^2. Finally, MBE and CVRMSE values were calculated as a performance indicators to see how much the results of each scenario differ from the actual results. For the model to be considered calibrated, the MBE and CVRMSE values should be within certain ranges recommended by different institutions. Since the calibration process is performed monthly in the study, the MBE and CVRMSE values calculated for all months are shown. In the calculations made over total consumption, the MBE values was calculated as -92.60% in base line scenario, -39.11% in Scenario 2 and 4.67% in Scenario 3. Also, the CVRMSE values was calculated as 125.26% in base line scenario, 48.39% in Scenario 2 and 14.67% in Scenario 3. Based on these data, the energy model created in Scenario 3 is calibrated.

In the fifth section, 15-minute measured temperature and humidity data in different zones were investigated to illustrate the effect of dynamic simulation on building energy consumption. Minimum, average and maximum temperatures of each zone during the day in a month during the heating season were determined. In addition, since the desired temperature value in the zones is also known, these four different temperatures values are defined as the heating system setpoint temperatures and the energy consumption profiles of the building at different temperatures are created. Finally, these energy consumption profiles were used to identify the periods of overheating and periods when comfort conditions were not met. The potential energy savings that can be achieved by largely eliminating these periods are calculated. Thus, it has been shown that 17% energy efficiency can be achieved with an automated heating system that controls the indoor temperatures in the zones and ensures that the temperature is always kept at the desired level. In addition, by defining the maximum temperatures recorded in the zones inside the building as the heating set temperature in those zones, the maximum amount of energy that the building can potentially consume is 95126 kWh. By eliminating the overheating time periods, the maximum energy efficiency that can potentially be achieved has been determined as 23%. Then, zone-based scheduling and zone-based comfort conditions were determined in order to achieve further improvements in the current energy model. Accordingly, with reference to ASHRAE and TS825 standards, the comfort temperature was changed to 19 °C for laboratories, offices and corridors, and the comfort condition of 20 °C was kept constant for classrooms. In addition, it has been understood that the usage profiles of the zones with different functional properties in the building differ from each other. In this case, the scheduling of the lighting system, heating system and interior equipment in the classrooms, corridors, laboratories and offices of the lecturers has been updated and determined as 9:30-16:30. The working periods for the other offices, which are actively used throughout the day, have been kept constant as 08:00-17:00. The energy model simulation was repeated and the total energy consumption in March was calculated as 59525.41 kWh. As a result of the changes made, 18% energy efficiency was achieved according to the scenario where the comfort conditions of all zones were determined as 20°C. Compared to the scenario where the average temperatures measured from the zones are defined as the heating system set temperature, it is possible to achieve 32% energy efficiency. Finally, by defining the maximum temperatures recorded in the zones as the heating set temperature in those zones, it was stated that the maximum amount of energy that the building could potentially consume was 95126 kWh. Thus, it has been proven that by determining zone-based scheduling and determining zone-based comfort conditions, periods of overheating can be eliminated and potentially a maximum of 37% energy efficiency can be achieved.

ENERJİ VERİMLİLİĞİNİ MAKSİMİZE ETMEK İÇİN İÇ MEKAN SICAKLIĞINI KONTROL EDEREK KALİBRE ENERJİ MODELİNİN DİNAMİK SİMÜLASYONU

ÖZET

Bina sektörü enerji tüketiminin büyük bir bölümünden sorumludur. Dünyanın artan nüfusu ile konut ihtiyacı da gün geçtikçe artmaktadır. Bunun sonucunda bina sektörünün talep ettiği enerji miktarı da giderek artmaktadır. Bu sebeplerden ötürü toplam enerji tüketiminde büyük bir payı olan konut sektöründe yapılacak enerji verimliliği çalışmaları büyük önem arz etmektedir. Bu nedenle, binaların ısıtma, soğutma ve aydınlatma açısından enerji tüketim profillerini belirleyen kapsamlı araştırmalara ihtiyaç vardır.

Çalışmanın amacı, enerji verimliliğini en üst düzeye çıkarmak için bir bina enerji modelini dinamik olarak simüle etmektir. Bu verimlilik, fazla ısıtma ve fazla soğutmanın gerçekleştiği periyotları ortadan kaldırarak on beş dakikalık periyotlarla kaydedilen verilerle kalibre edilmiş bir enerji modeli aracılığıyla elde edilebilir. Ayrıca, binanın farklı işlevsel zonlarının enerji tüketimini kullanıcı yoğunluğu profili, bina sistemlerinin operasyonel takvimleri ve konfor koşulları açısından yöneterek ek enerji tasarrufu sağlamaktır.

Tezde vaka çalışması olarak İstanbul Teknik Üniversitesi Ayazağa Kampüsünde bulunan Enerji Enstitüsü binası seçilmiştir. Enerji Enstitüsü binası 1963 yılında 3 katlı olarak inşaa edilmiştir. Toplamda 4272 m^2 alana sahiptir. Bina yakıt olarak doğalgaz kullanan merkezi radyatör sistemi ile ısıtılmaktadır. Bir eğitim binası olarak sınıflar, ofisler ve laboratuvarlardan oluşmaktadır.

Tezde beş ana bölümden oluşan sistematik bir metodoloji önerilmiştir. Önerilen adımlar sırasıyla takip edilerek vaka çalışması olarak seçilen bina üzerindeki uygulamaları gerçekleştirilmiştir. Bu adımlar; binanın üç boyutlu modelinin oluşturulması, binanın enerji modelinin oluşturulması, binanın enerji tüketim verilerinin toplanması, bina enerji modelinin kalibrasyonu ve binanın mevcut enerji profili üzerindeki iyileştirmelerdir.

Tezin metodolojisinde tanımlanan ilk bölümde, öncelikle üniversite yönetiminden elde edilen binanın kat planları kullanılarak binanın üç boyutlu modeli Autodesk Revit yazılımı kullanılarak oluşturulmuştur. Bina kat planlarındaki bilgilerin yeterli olmamasından ötürü modelin detaylandırılması için binada gözlemler yapılmış ve binanın görsellerinden yararlanılmıştır. Daha sonra binanın içerisindeki alanların fonksiyonel kullanımlarına göre tanımlanması için tekrardan gözlemler yapılarak her bir alan kullanım fonksiyonlarına göre enerji modeline tanımlanmıştır. Binada kullanım fonksiyonları farklılık gösteren yedi farklı alan bulunmaktadır. Bunlar, ofisler, sınıflar, laboratuvarlar, koşullandırılan koridorlar, koşullandırılmayan koridorlar, tuvaletler ve depolama alanlarıdır. Belirlenen bu zonlar ısıtma, soğutma,

aydınlatma sistemleri, ekipmanlar ve kullanım profillerine göre ayrı ayrı modellenmiştir.

İkinci bölümde, üç boyutlu modelin kolayca transfer edilebilmesi, zon bazlı parametre tanımlanmasına izin vermesi, bina sistemlerinin kolayca modellenebilmesi ve simülasyon sonuçlarını istenen periyotlarda alma imkânı sağladığı için enerji modeli oluşturmak için Design Builder yazılımı tercih edilmiştir. Enerji modeline veri girişi sağlayabilmek için binanın konumlandığı bölgenin iklim verileri Energy Plus yazılımından temin edilmiştir. Bina kabuğu elemanlarının (dış duvarlar, çatı, temel, kapılar ve pencereler) termal özellikleri binanın çizimlerinden ve binada yapılan gözlemlerden belirlenmiştir. Binada kullanılan tüm sistemlerin özellikleri de teknik dökümanlardan ve gözlemlerden elde edilmiştir. Binanın ısıtılması merkezi radyatör sistemiyle sağlanmakta, soğutma sistemi olarak sadece ofislerde split klimalar bulunmaktadır. Binanın her yerinde aydınlatma floresan lambalarla sağlanmaktadır. Ayrıca sınıflarda, ofislerde ve laboratuvarlarda ofis ekipmanları ve bilgisayarlar bulunmaktadır. Bunların yanı sıra, binadaki tüm zonların kullanım profilleri belirlenmiş ve bu alanların hangi zaman aralıklarında kaç saat boyunca aktif olarak kullanıldığı modelde tanımlanmıştır.

Üçüncü bölümde hem enerji modelinin kalibrasyonunda hem de mevcut enerji profilinin iyileştirilmesinde kullanılmak üzere düzenli periyotlarla ölçümler yapılmıştır. Binanın aylık olarak 2022 baz yılındaki doğalgaz ve elektrik tüketimleri ölçülmüştür.

Dördüncü bölüm olan enerji modelinin kalibrasyonu adımında ilk olarak ikinci bölümde detaylı bir şekilde anlatılan enerji modeli simüle edilmiştir. Bu simülasyon tezde temel senaryo olarak adlandırılmıştır. Simülasyondan alınan aylık doğalgaz ve elektrik tüketimleri incelenmiş ve binanın gerçek tüketimleri ile karşılaştırılmıştır. Yapılan karşılaştırma sonucunda simülasyon ve gerçek sonuçlar yaz aylarında nispeten birbirine yaklaşsa da özellikle yaz ayları dışındaki dönemlerde simülasyondan alınan tüketim değerlerinin gerçek değerlerden çok daha yüksek olduğu görülmüştür. Simülasyondan alınan sonuçlarda yıllık enerji tüketimi 307 kWh/m^2 iken gerçek tüketim sonuçları ise 159 kWh/m^2'dir. Model ile gerçek veriler arasındaki farkların azaltılması için öncelikle bazı model parametrelerinde ince ayarlamalar yapılarak senaryo 2 enerji modeli oluşturulmuştur. Temel senaryoda değişiklik yapılan parametreler çatı, pencere ve kapıların termal özellikleri, infiltrasyon oranı ve binadaki ekipmanların güç yoğunluğudur. Senaryo 2'de uygulanan değişiklikler ile binanın enerji tüketimi 222 kWh/m^2 değerine düşürülmüştür. Ölçülen ve simülasyondan elde edilen tüketimler arasındaki farkın hala kabul edilebilir aralıkta olmamasından dolayı senaryo 3 enerji modeli oluşturularak fonksiyonel zonlar için ayrı ayrı kullanım profilleri tanımlanmıştır. Zon bazlı çalışma saatlerinin belirlenmesinde ısıtma, soğutma, aydınlatma sistemlerinin ve ekipmanların kullanım planlamaları göz önüne alınmıştır. Senaryo 3 ile yapılan değişiklikler ile enerji tüketimi 152 kWh/m^2 değerine düşürülmüştür. Bu bölümde son olarak her bir senaryonun sonuçlarının gerçek sonuçlardan ne kadar farklılık gösterdiğini görmek için performans göstergeleri olarak ortalama yanlılık hatası (MBE) ve kök ortalama kare hatası (CVRMSE) değerleri hesaplanmıştır. Modelin kalibre edilmiş olarak kabul edilebilmesi için MBE ve CVRMSE değerlerinin farklı standartlar tarafından önerilen belirli aralıklarda olması gerekmektedir. Çalışmada kalibrasyon işlemi aylık bazda yapıldığı için tüm aylar için hesaplanan MBE ve CVRMSE değerleri gösterilmiştir. Toplam tüketimler üzerinden yapılan hesaplamalarda temel senaryoda MBE değeri % -92.60, senaryo 2'de %-39.11 ve senaryo 3'te %4.67 olarak hesaplanmıştır. Ayrıca

CVRMSE değerleri ise temel senaryoda % 125.26, senaryo 2'de %48.39 ve senaryo 3'te %14.67 olarak hesaplanmıştır. Bu veriler ışığında senaryo 3'te oluşturulan enerji modeli kalibre edilmiş olarak değerlendirilmiştir.

Beşinci bölümde ise dinamik simülasyonun bina enerji tüketimi üzerindeki etkisini göstermek için bina içerisindeki farklı zonlarda 15 dakikalık periyotlarla ölçülen sıcaklık ve nem değerleri incelenmiştir. Her bir zonun bir aylık ısıtma periyodunda gün içerisindeki minimum, ortalama ve maksimum sıcaklıkları belirlenmiştir. Ayrıca zonlarda istenen sıcaklık değeri de bilindiğinden bu dört farklı sıcaklık değerleri ısıtma sistemi ayar noktası sıcaklığı olarak tanımlanarak binanın farklı sıcaklıklardaki enerji tüketim profilleri oluşturulmuştur. Son olarak bu enerji tüketim profilleri fazla ısıtma yapılan ve konfor koşullarının sağlanmadığı periyotları belirlemek için kullanılmıştır. Bu periyotların büyük ölçüde ortadan kaldırılmasıyla elde edilebilecek potansiyel enerji tasarrufları hesaplanmıştır. Böylece otomatize edilmiş ve zonlardaki iç ortam sıcaklıklarını kontrol ederek sıcaklığın her zaman istenen seviyede tutulmasını sağlayan bir ısıtma sistemi ile %17 enerji verimliliği sağlanabileceği gösterilmiştir. Ayrıca bina içerisindeki zonlarda kaydedilen maksimum sıcaklıkların o zonlardaki ısıtma ayar noktası sıcaklığı olarak tanımlanmasıyla binanın potansiyel olarak tüketebileceği maksimum enerji miktarı 95126 kWh'dir. Fazla ısıtma yapılan zaman dilimlerinin elimine edilmesiyle de potansiyel olarak ulaşılabilecek maksimum enerji enerji verimliliği %23 olarak belirlenmiştir. Daha sonra mevcut enerji modelinde yapılabilecek iyileştirmeyi bir adım daha ileriye taşıyabilmek için zon bazlı çalışma saatleri ve zon bazlı konfor koşulları belirlenmiştir. Buna göre ASHRAE ve TS825 standartları referans alınarak laboratuvarlar, ofisler ve koridorlar için konfor sıcaklığı 19 °C olarak değiştirilmiş sınıflar için 20 °C konfor koşulu sabit tutulmuştur. Ayrıca bina içerisinde farklı işlevsel özelliklere sahip olan zonların kullanım profillerinin de birbirinden farklılık gösterdiği anlaşılmıştır. Bu durumda sınıflarda, koridorlarda, laboratuvarlarda ve öğretim elemanlarının ofislerinde aydınlatma sistemi , ısıtma sistemi ve iç ekipmanların çalışma periyodu güncellenerek 09:30-16:30 olarak belirlenmiştir. Tüm gün boyunca aktif olarak kullanılan diğer memurların ofisleri için çalışma periyotları 08:00-17:00 olarak sabit tutulmuştur. Enerji modeli simülasyonu tekrarlanmış ve mart ayı toplam enerji tüketimi 59525.41 kWh olarak hesaplanmıştır. Yapılan değişiklikler sonucunda tüm zonların konfor koşullarının 20°C olarak belirlendiği senaryoya göre %18 enerji verimliliği sağlanmıştır. Zonlardan ölçülen ortalama sıcaklıkların ısıtma sistemi ayar noktası sıcaklığı olarak tanımlandığı senaryo ile karşılaştırıldığında %32 enerji verimliliği elde etmek mümkündür. Son olarak zonlarda kaydedilen maksimum sıcaklıkların o zonlardaki ısıtma ayar noktası sıcaklığı olarak tanımlanmasıyla binanın potansiyel olarak tüketebileceği maksimum enerji miktarı 95126 kWh olduğu belirtilmişti böylece zon bazlı çalışma koşullarının belirlenmesi ve zon bazlı konfor şartlarının belirlenmesi ile fazla ısıtma yapılan periyotlar elimine edilebilecek ve potansiyel olarak maksimum %37 enerji verimliliği sağlanabileceği kanıtlanmıştır.

1. INTRODUCTION

The energy crisis in our country and all over the world has made it difficult for us to reach energy. The building sector has a large share among the energy consuming sectors. In parallel with the rapid increase in the world population, the need for housing is also increasing and the energy demand of the building sector is increasing exponentially. If we consider the issue within the scope of environmental effects, the heating systems used to provide comfort conditions in most of the existing buildings use fossil fuels such as coal and natural gas. These fuels, which are in danger of extinction, also cause gas emissions that pollute the environment. Due to the reasons listed above, energy efficiency studies gain importance in the building sector, which has a large share in energy consumption.

Buildings consume 40% of total energy consumption in the European Union. The sector is growing, which means that its energy consumption will rise [1]. When Turkey's energy consumption is analysed, fossil resources are used at a high rate in energy production in our country. According to the 2020 data of Türkiye National Energy Plan, final energy consumption of Türkiye is 105.5 Mtoe in 2020 and share of the residential sector in this total final energy consumption is 24% [2]. According to the Plan, electricity consumption of Türkiye is 306.1 TWh in 2020 and share of the residential sector is almost 20%. According to the 2019 data of the Republic of Türkiye Ministry of Energy and Natural Resources, approximately 45.3 billion m^3 of natural gas was consumed in Türkiye in 2019 and residential sector is responsible for 32% of this consumption [3].

In addition to residential buildings, the number of public buildings in our country is quite high. The systems used in public buildings and responsible for energy consumption are generally controlled from a single centre. The energy potentials that can be provided by the methods to be applied in these buildings have high rates. The reasons for choosing a public building as a case study can be listed as follows:

- Public buildings account for high percentage of the total building area in the country.
- They contain many areas with different functions and the zones have different energy profiles.
- They follow certain rules during the operation of building systems thus, modeling and programming of building systems becomes easier.
- They are suitable for accessing technical documents and building systems specifications.
- They have low awareness of energy efficiency despite having high energy efficiency potential

Due to the existence of legislation that needs to be implemented in today's structures, certain energy efficiency strategies are applied. These are covering building envelopes with insulation material, using heating and cooling systems above certain efficiency values, using energy efficient lighting technologies, and obtaining hot water from renewable sources. However, these standards have not been met in many of the buildings constructed in the past, which have a high share in our country and in the world. Studies for the implementation of energy efficient strategies for buildings constructed in the past are also important. Previously, these strategies had to be applied to buildings to see their impact on energy efficiency. However, because of the widespread use of software today, it is possible to create energy models that can be called digital energy model that reflect the energy use of the building. Thus, the effects on energy consumption can be observed with the revisions, improvements, and different techniques to be applied on the energy model created. The most important point to be considered while creating the energy model is to determine how much the results to be obtained from the model match the actual energy consumption of the building.

In addition to the strategies that can be applied in the buildings, the measurements to be made inside the building and the periods when the comfort conditions cannot be met and the periods with over-heating or over-cooling are determined. Unnecessary use of lighting can be avoided by performing linear control of lighting systems with daylight. Thus, optimization in energy consumption can be achieved easily.

With today's technology, it is quite easy to calculate the energy consumption values of buildings in specified periods. By using different software, energy models of buildings can be created in a virtual environment and thus the effect of any method considered to be applied on building energy consumption can be easily determined in advance.

In the first part of the study, general information about topic of thesis is given. In addition, the necessity of the selected subject was explained by supporting it with up-to-date information. Finally, in this section, the aim of the thesis is mentioned.

In the second part of the study, a comprehensive literature review is shown. In the literature review, studies on the subject were compiled and summarized.

In the third part of the study, the proposed methodology is explained. The methodology of the study consists of five parts. These sections are preparation of 3D building model, creating energy model, collecting measured data, calibrating the energy model and improvements at the existing energy profile. Also, the steps defined in the methodology are detailed.

In the fourth part of the study, the application of the procedures defined in the methodology for the selected case study is shown. First, the selected sample building was modelled in 3D and an energy model was created using this model. Then, monthly, and 15-minute data measured on the building were collected. Afterwards, the calibration of the energy model was carried out using these data. Finally, improvements in the current energy profile of the building were revealed.

In the fifth part of the study, the results obtained from the study were examined and interpreted.

1.1 Purpose Of Thesis

The study's main objective is real - time simulating a building energy model in order to achieve maximum energy efficiency. It can be accomplished by removing over-heated and over-cooled periods using a validated energy model with fifteen-minute measured data. It will also save energy by controlling the energy usage of the building's distinct functional zones with regard to occupational scheduling, building system timetabling, and sensible temperature comfort requirements. The education building chosen as an example in the thesis has been preferred because it has many zones with different functions, has high energy efficiency potential in terms of physical condition, energy management skills and building systems, no energy efficiency studies have been done before and energy efficiency awareness is low.

2. LITERATURE REVIEW

Chong et al. [4] have prepared a detailed review on calibrating energy simulations of buildings. It has been stated that the lack of a guide to prioritize studies on this subject constitutes the motivation of the study. The study mainly covers topics such as simulation inputs, data types and resolutions, important calibration methods and determination of calibration performance. In the study, 107 papers were evaluated according to the simulation engine used and the location of the selected case study building. It has been stated that Energy Plus, TRNSYS and DOE-2 are the most preferred simulation software. It has been shown that most of the studies were carried out in regions where arid, temperate, or continental climatic conditions are observed. The methods and code libraries used in important calibration approaches such as sensitivity analysis, optimization-based calibration and Bayesian calibration have been identified. The methods and code languages used in important calibration approaches such as sensitivity analysis, optimization-based calibration and Bayesian calibration have been identified. In the studies in the literature, it was understood that the rates of using one, two and three outputs during calibration were 62%, 29% and 8%, respectively. It was concluded that many of the inputs examined during the calibration process were weather inputs, followed by the building envelope, HVAC, and internal gains. It has been seen that the most used methods to measure the performance of the calibration are the cumulative cariation of the root mean squared error, normalized mean mias mrror, and root mean squared error methods. Error rates are given by considering the use of hourly or monthly data according to different standards and protocols to consider the model calibrated.

Tüysüz & Sözer [5] calibrated the energy model for the large-scale residential building in Istanbul using the mean bias error (MBE) and cumulative variation of root-mean-squared error (CVRMSE) methods. In addition, new strategies have been developed to provide accurate data for the times when climate data is not available, considering heating and cooling degree days, and to estimate using short-term measurement data to ensure the accuracy of the collected data. While calculating the number of heating and cooling days in the study, the base temperatures were set to 15 ℃ and 21 ℃

respectively. A model was created in the TRNSYS 16 program considering the physical characteristics of the sample building and the number and capacities of the mechanical systems used in the building. While determining the operation scheme of 3 different heating and cooling systems used in the building, the on-off control method was used considering the outdoor temperature and the temperature of the water in the collector. In the study, the calibration criteria specified in the ASHRAE standard were taken into account and the desired criteria were reached as a result of 4 iterations by changing the inputs within the specified range. In the first version, the external wall U value was increased from 0.326 W/m^2K to 0.340 W/m^2K, and in the second version, ground floor U value was increased from 0.478 W/m^2K to 0.502 W/m^2K. In the third version, the infiltration rate value was increased from 1.1 ac/h to 1.2 ac/h, and in the fourth version, the window u value was increased from 1.600 W/m^2K to 1.750 W/m^2K. In addition, Spyder software was used to determine the optimum parameters to minimize energy consumption. As a result, MBE and CVRMSE values, which were 15.12% and 17.19%, respectively in the first model, were calculated as -2.76% and 8.40% in line with the strategies applied. Thus, the energy model of the building is calibrated. It is emphasized that thanks to the calibrated model, the energy consumption values of the building will be obtained more accurately.

Sözer & Tüysüz [6] while calculating the heating and cooling energy loads of a selected building, they investigated the effect of the automation system added to the system on the energy consumption. Operation programs of equipment such as heat pump, boiler and solar collector used in the building are adjusted by the developed automation system. In order to see the effects of different situations on energy performance, 3 different scenarios were prepared. In the study, these different scenarios are named as base line, ICT and fuzzy scenarios. In the base line scenario, two modes, winter and summer, were determined and the on/off control system determined which mechanical systems would be activated according to whether the water temperature in the collectors was less than or higher than 45 °C. In the ICT scenario, in addition to the previous scenario, different mechanical systems are put into use when the outdoor temperature is higher or lower than 12 °C in winter mode. In addition, different systems were operated in summer mode, depending on whether the water temperature in the collector was higher or lower than 18 °C. In the fuzzy scenario, intervals are determined for heating and cooling modes instead of fixed temperatures (22-25 °C for heating and 23-26 °C for cooling). In addition, indoor temperature has been used as an input and comfort conditions in the indoor environment have been tried to be met with dynamically changing setpoint values. According to the Base scenario, energy consumed for heating was saved by 6.19% with the ICT scenario and 10.37% with the fuzzy scenario. Likewise, cooling loads were reduced by 6.06% with the ICT scenario and 14.88% with the fuzzy scenario. In addition, considering the best scenario, the fuzzy scenario, it was concluded that 9.14 kWh less heating energy and 3.14 kWh less cooling energy per m^2 are needed.

Roberti et al. [7] introduced the steps to be followed in the calibration process in order to ensure the reliability of the energy model of a historical building and to give results close to the real values and applied this process to a sample building. First, the model created was calibrated using hourly indoor air temperature data using root mean squared error method. A second calibration was carried out by changing the parameters used for the model according to the sensitivity analysis results. Specific heat and conductivity properties of exterior walls, roof, and partition wall, as well as air leakage from the building envelope and thermal properties of windows are the parameters determined as a result of sensitivity analysis. In the second calibration, the parameters selected in the first calibration were applied to other parts of the building, except for a reference room. Finally, the calibrated model was validated using the indoor air and surface temperatures of the building in winter and by analysing the error rates. In the first calibration, the parameters of the building elements were changed for all rooms in line with the specified intervals. Thus, the root mean squared error rate was reduced from 0.96K to 0.66K. In the second calibration, only the parameters applied for a selected room have been changed, and the other rooms are the same as in the first calibration. Thus, the RMSE was reduced to 0.62K. Finally, when the indoor surface temperatures were added to the model as an input in the validation process, the RMSE value was obtained as 0.4K.

Raftery et al. [8] aimed to calibrate the energy model for the entire Intel office building in Ireland. In the study, the calibration process was carried out using hourly energy consumption data. In addition, as mentioned in the methodology of the study, version control software (TortoiseSVN) was used to store the changes and data made during the calibration process. During the study, the building was divided into zones in detail, lighting and plug loads were examined, and the amount of energy consumed by the

HVAC system was measured hourly. Mean bias error (MBE) and cumulative variation of root mean squared error (CVRMSE) methods were used for error analysis in the study. Each floor plan of the building is divided into two as east and west and the number of zones has been increased. Different air conditioning systems are used in different zones. In addition, since different internal loads may occur in each zone, some rooms are zoned separately. The building is divided into 196 thermal zones in total. Apart from interior lighting and plug loads, exterior lighting consumptions in some parts of the building were also added to the model thanks to the measurements taken. Features such as pump characterizations, air distribution unit features, fan types and loads, maximum air flow, pressure, efficiency, coil type, water flow rates related to HVAC systems have been included in the calibrated model by conducting on-site investigations or obtaining from documents. With the model revisions made, the error rates calculated for the building's electricity consumption have been reached as MBE 0% and CVRMSE 0.01% as a result of 21 revisions. When evaluated only for HVAC systems, as a result of the last revision, the MBE value was reduced from -342.49% to -4.16%, and the CVRMSE value from 349.1% to 7.8%.

Pernetti et al. [9] examined the effects and importance of climatic conditions, infiltration rates and building envelope characteristics on the calibration of energy models of buildings. In the study, the energy model was calibrated with the help of actual internal air temperatures and internal wall surface temperatures. These temperature data were obtained from a control room in the building at 10-minute intervals. Mean bias error (MBE), root mean squared error (RMSE) and Pearson’s index r methods were chosen as calibration indices in the study. In the calibration process, climate data (temperature, solar radiation, relative humidity, and wind speed), air-change rate and building envelope thermal properties were used as inputs. When different scenarios prepared using the determined inputs are analysed, optimum scenarios are revealed for each error index. Despite the optimum results found, it was noticed that there were still inconsistencies between the real and simulated data and sensitivity analysis was performed to understand which parameters had more effect on the calibration. Sensitivity analysis was performed using differential sensitivity analysis and factorial method approaches. In the analysis, minimum and maximum temperature and zone heating and cooling degree hour indexes were investigated. While it was determined that the most important parameter for the cooling degree hour was the thermal transmittance of the roof, a comparison could not be made with the heating degree hour. In addition, it was concluded that the thermal capacity of the building envelope significantly affects the minimum and maximum temperatures. Wall and floor thermal capacity and g value for glazing surface parameters have been evaluated for factorial analysis and it has been proven that perturbation rates vary between -5% and 5%.

Salimi & Hammad [10] based on the occupancy rates of the buildings used as offices, they examined the change in building energy consumption by using different control mechanisms developed based on ventilation, heating, and air conditioning systems. First, the methods used to observe the occupancy rates in this study were compared, and the control systems that could be applied on HVAC and lighting systems were examined by using building occupancy models. Studies in the literature on motion sensors, vision-based localization technologies, RF-based localization technologies, multi-sensor networks, virtual occupancy sensors and survey methods used in occupancy monitoring are summarized. Statistical, stochastic and machine learning methods used in creating an occupancy model in the literature have been examined in detail. In addition, the energy efficiency potentials of different control mechanisms used in HVAC and lighting systems, which have been revealed in different studies, are shown.

Zekic-Susac et al. [11] explored how to incorporate big data platform and machine learning concepts into intelligent technologies used to achieve energy efficiency in public buildings. In the study, structural, energetic and attribute information, energy consumption and occupancy rates, as well as environmental conditions information of each public building were collected to create a big data platform. Artificial neural networks (ANNs) and recursive partitioning methods such as CART decision trees, and random forest (RF) methods have been used to generate energy consumption and energy efficiency prediction models of buildings. The optimum method is shown by using 2 different error indicators from the machine learning methods created by using different parameters and methods selected from the collected data. In the study, it has been proven that the most accurate model of machine learning methods used in energy efficiency predictions in public sector buildings produces 13% symmetric mean average percentage error (SMAPE).

Hernandez et al. [12] did a literature review including building energy management systems used to increase the energy efficiency potential in buildings. In addition, these strategies were compared according to the building type, the systems used in the building and the building usage purposes. In the study, active building energy management methods were examined in 4 main groups as model predictive control, demand-side management, optimization and fault detection and diagnosis.

Ciulla and D'Amico [13] used the multiple regression method that defines and develops certain simple relationships to determine the energy needs of a generic building. In order to demonstrate the reliability of the method and to select the appropriate variables, sensitivity analysis was performed using the Pearson coefficient. To ensure the reliability of the proposed method in the study, the authors used a carefully calibrated TRNSYS model as a database, which allows for 195 different scenarios. In the study, the energy model was calibrated according to the Normalized mean bias error (NMBE) and cumulative variation of the root mean squared error (CV-RMSE) indices. In addition, a total of 1560 scenarios were obtained by using 13 different geometrical configurations, 5 different climate zones and 8 different orientations for parametric dynamic simulation, and a database was created by collecting the results. As a result of the sensitivity analysis performed in the study, HDD, T, S/V and S_w parameters for heating energy need and CDD, T and S_{op} parameters for cooling energy need were determined as the parameters that most affected the results. In this study, in the multiple linear regression method, which was later applied to evaluate the heating energy need, cooling energy need and comprehensive energy demands, equations were created using different parameters for each analysis and R^2 values were calculated. It was understood from the study that more complicated correlations for determining heating, cooling and comprehensive energy demand values showed more reliable results by showing higher R^2 and lower MAE and RMSE values.

Le at al. [14] compared 4 different methods based on artificial neural networks used to estimate the heating loads of buildings. In the study, 837 buildings were analysed using different parameters. In addition, the potentials of the methods analysed using 3 different statistical criteria were evaluated. The working principles and structures of 4 different methods to be compared in the study are explained and evaluation performance indices are introduced. The correlation coefficient between predicted and measured heating loads were calculated 0.980 in the genetic algorithm-artificial neural network (GA-ANN) method, 0.972 in the partical swarm optimization-artificial neural network (PSO-ANN) method, 0.97 in the imperialist competitive algorithm-artificial neural network (ICAANN) and 0.973 in the artificial bee colony artificial neural network (ABC-ANN) method. In the study, the genetic algorithm-artificial neural network (GA-ANN) method has proven to be the method with the best results. In addition, it was determined that the surface area and glazing area variables were the variables with the highest effect on the results with the sensitivity analysis.

Zhao et al. [15] conducted a literature review that includes the application of artificial intelligence-based fault detection and diagnosis (FDD) methods in building energy systems. These methods were basically examined under two main headings; data driven-based and knowledge-driven based methods.

In their work Yang et al. [16] proposed a machine learning-based model predictive control system that optimizes both energy efficiency and indoor thermal comfort, as well as regularly updating the model with data from the building automation database.

Martin-Escudero et al. [17] performed the calibration of an in-use office building energy model. They examined the available detailed building drawings, structural details, building operating data, and data sets gathered on a minute basis in this study. The model calibration is conducted on an hourly basis, and then the simulation's whole-year performance was compared to the monitored data. Temperature, humidity, and CO_2 concentration measurements in a selected block were recorded on a minute basis. The building's varied functioning periods throughout the year have been defined, and the year has been separated into two seasons: winter and summer. In this study, Design Builder software, which uses the Energy Plus simulation engine, was preferred to determine the energy performance of the building. mean bias error (MBE) was chosen as the statistical index to verify the calibration of the energy model. The MBE values determined for hourly analysis by the ASHRAE guideline during the weeks determined in the winter and summer periods did not exceed 10%. At the same time, MBE values did not exceed the 5% value determined in the analyses made for the whole year and the recommended calibration procedure was carried out.

Pachano & Bandera [18] utilized Jeplus software to alter the HVAC parameters and data acquired at 3-month intervals of 10 minutes to perform a multi-step calibration process. The calibration procedure was carried out over the indoor temperature, heat production and electricity consumption values of the heat pumps. Results were calibrated hourly according to the statistical indices of NMBE, CVRMSE and R^2 determined in ASHRAE and IPMVP standards. The heating energy production and electric energy consumption values in a week determined in March were compared between the base model results, the measured values, and the calibrated model. It is understood from this that the results of the model calibrated for heating energy production deviated only 7% from the real results, and the results of the model calibrated for electricity consumption match the measurement data by 99%. In addition, it has been proven that the NMBE, CVRMSE and R^2 values calculated for heating energy production and electric energy consumption with hourly calibration performed over a 2600-hour period meet the values required by the standards. Finally, the indoor temperature for the sections determined inside the building was calibrated at the same time interval using the hourly calibration method, and the results show that the model was calibrated according to the requirements of the standards.

In this study, unlike other studies in the literature, the amount of waste heat in the building was determined by automating the existing heating system operating in the building in such a way as to keep the temperature in all zones at the desired comfort conditions by controlling the indoor temperatures in the zones. In addition, the current and potential maximum consumptions of the building were calculated with the maximum and average temperatures recorded in the building, and the energy savings that could be achieved by eliminating the overheated periods were determined. With the energy management carried out in the study, the improvements on the existing energy profile were revealed by determining the zone-based comfort temperature and zone-based scheduling.

3. METHODOLOGY

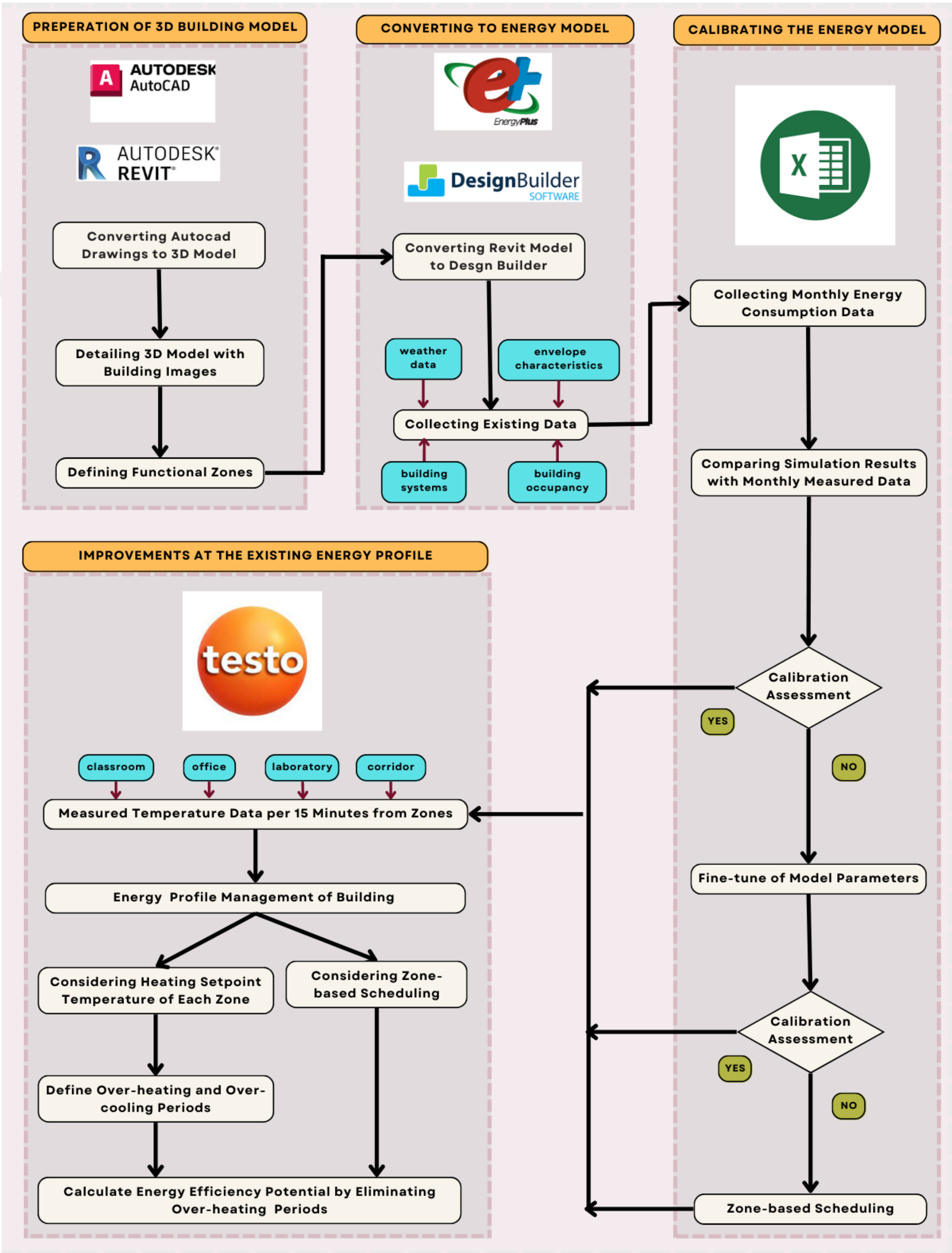

Figure 3.1: Methodology of thesis.

Within the scope of this thesis, a comprehensive methodology has been proposed and followed. All the steps followed throughout the thesis are explained in detail in this section. As can be seen in Figure 3.1 above, the methodology consists of 5 main titles. These include preparation of 3D building model, creating energy model, collecting measured data, calibrating the energy model and improvements at the existing energy profile. Intermediate steps given under each heading were applied sequentially.

3.1 Preparation of 3D Building Model

The first step of the proposed methodology is to create a 3D model of the building selected as a case study. There is already a lot of software for creating a 3D model of the building. While choosing the software to create the model, criteria such as being successful in creating complex building forms, easy transfer of 2D CAD files, easy editing of the parameters determined while modelling the building, and being compatible with the software to be energy analysis were taken into consideration. As a result of the evaluations, Autodesk Revit program was chosen to create 3D model because it complies with the criteria mentioned above. Two-dimensional AutoCAD drawings of the building were obtained from the university rectorate. First, necessary arrangements were made on these drawings. Furnishings in the drawings have been removed. In addition, the block where the nuclear reactor is located has been removed from the drawings because of its complex structure and that the necessary observations cannot be made. Then the floor plans were transferred from AutoCAD software to Revit software and used as a reference. When it was realized that all the details about the building were not understood from the AutoCAD drawings, the images of the building were used, and observations were made to eliminate the uncertainties in the building geometry and building envelope components. It is important to determine the functional zones correctly, as the correct transfer of the functions of the areas inside the building to the model significantly affects the energy consumption. For this reason, the function of each area was determined by the observation made inside the building and transferred to the model.

3.2 Converting 3D Building Model to Energy Model

After creating the 3D model of the building, the next step is converting 3D model to create energy model of the building. To create the energy model, the Design Builder software, which uses the Energy Plus simulation engine and can be integrated into the Revit software as a plug-in, was preferred. Functional zones determined in Revit software are preserved when exporting to Design Builder software. In order to detail the energy model, the climate data of the location of the building, the thermal characteristics of the building envelope elements, the characteristics of the HVAC and lighting systems in the building, and the occupancy profile and schedule of the building were needed. Climate data was obtained from the nearest measurement station to the building by using the Energy plus software. While determining the occupancy profile of the building, considering that it is an education building, holidays, and periods when the building is not used were determined. In addition to this, the usage habits of the building were investigated by conducting interviews with the residents.

3.3 Collecting Monthly Energy Consumption Data

Data measured on the building is required for the calibration of the building energy model and the improvement of the existing energy profile. It is important to reach the actual energy consumption of the building to be able to compare the energy consumption values obtained from the building energy model simulation and to be sure of the reliability of the model. Since the energy simulation results give the annual energy consumption values, bills showing the electricity and natural gas consumed by the building throughout 2022 were obtained from the rectorate monthly.

3.4 Calibration of Energy Model

In order to ensure that the results of the energy model correspond with the actual consumption values, the calibration of the energy model has been started. When the monthly energy consumptions obtained from the simulation are compared with the measured values, differences that cannot be neglected are observed. To eliminate these differences, some parameters defined in the model were fine-tuned. The building envelope elements were re-examined in detail and their thermal performances were re-evaluated. In addition, since each zone defined in the building has different functions and is used for different purposes, zone-based scheduling has been made. With the fine-tuning of the parameters and zone-based scheduling, the model has been revised multiple times to achieve the closest results to the actual energy consumption. When the studies in the literature are examined, it is understood that the mean bias error

(MBE) value and cumulative variation of root-mean-squared error (CVRMSE) value are frequently used as a performance indicator in the energy model calibration. After each revision in the model, MBE and CVRMSE values were checked, and revisions were continued until they were below the limit values determined in the guidelines.

3.5 Improvements of the Existing Energy Profile

After verifying that the energy model has been calibrated with the methods specified in the guidelines, improvements that can be made in the existing energy profile of the building have been determined.

3.5.1 15-minute indoor temperature data

Temperature measurements were made in four different zones (laboratory, office, classroom, and corridor) within the building to check whether the desired comfort conditions are provided in the determined zones and to determine the heating and cooling setpoint temperatures. Temperature measuring devices were placed in appropriate locations in each zone by following the methods determined in the measurement standards. Temperature measurements were made in 15-minute periods and data were collected.

3.5.2 Energy profile management of building

First, the data in each zone where temperature measurement was made was collected and abnormal data was removed. The minimum, maximum and average values of the indoor temperatures recorded within the specified time interval were determined. The energy consumption profiles of the zones and the building were created by changing the heating setpoint temperature value determined to provide the desired comfort conditions in the building with the minimum, average and maximum indoor temperatures measured in each zone. The energy consumption profiles created by defining the minimum, average, standard and maximum indoor temperatures in each zone as heating setpoint temperature to the model were compared. By interpreting these energy consumption results, over-heating, desirable heating, undesirable heating, and standard heating periods were determined. In addition, the amount of excess energy consumed in the over-heating period and the amount of energy required in the periods when comfort conditions are not provided were determined. Then, for further improvements, not only by changing the heating setpoint temperature, but also by zone-based scheduling, the energy saving potential was determined. For further improvements, the desired indoor temperatures were reduced in some zones by taking ASHRAE and TS 825 standards as reference. In addition, different scheduling has been made considering the usage characteristics of the zones in the building. The potential energy savings obtained as a result of these changes were determined.

4. CASE STUDY

In this section, the selection of a sample building in which the methodology proposed in the study will be applied and the applications of the proposed methods on this sample building will be explained. In addition, the results from each step will be given.

4.1 Preparation Of 3D Building Model

In this section, the sample building selected for the application of the calibration process proposed in the study will be introduce. The building chosen for the case study shown in Figure 4.1 is Energy Institute building, located on the Istanbul Technical University Ayazağa campus in the province of Istanbul. It was established in 2003 with the restructuring of the Nuclear Energy Institute, which was established in 1961, to continue its education, training, and research activities in a way to cover other fields of energy. As can be seen from the figure, the rectangular building on the right is a separate building from the institute and is used as an office by many companies. This structure was not considered when creating the energy model. In addition, the square structure in the lower left, which is seen as a unit with the energy institute building, is the part where the nuclear reactor is located, and this part was not included in the evaluation while creating the energy model.

Figure 4.1: ITU energy institute.

4.1.1 Converting AutoCAD drawings to 3D model

The building has a rectangular shape when viewed from the top, but the geometric shape of each floor differs. The energy institute building was constructed as 3 floors with a total area of 4272 m^2. Building area is divided into 7 groups according to their functions: classrooms, laboratories, offices, conditioned corridors, unconditioned corridors, storage areas and restrooms. The corridors on the 1st and 3rd floors, storage areas and restrooms are unconditioned areas, and the total conditioned area is 3523 m^2. The floor plans of the building are shown in Figure 4.2 Some areas of the first floor of the building remain under the ground. Also, it has a courtyard in the middle of the building.

Figure 4.2: Floor plans of building.

After the floor plans were transferred to Revit software, they were used as a reference for 3D modelling. The number of zones in the model is reduced by removing the interior walls between the adjacent areas on each floor that have the same function.

This reduction of the number of zones reduces the complexity of the model and significantly shortens the energy simulation time.

In Figure 4.3, views of the 3D model of the building created in Revit software from different directions are given. While creating the 3D model, attention was paid to the surfaces under the ground. The topographic structure of the ground where the building is located has also been modelled in a way that is closest to reality. While creating the model, each floor was modelled separately and integrated with each other with structural elements such as columns and floors. The entire building area consists of a flat roof and the courtyard located in the middle is not covered.

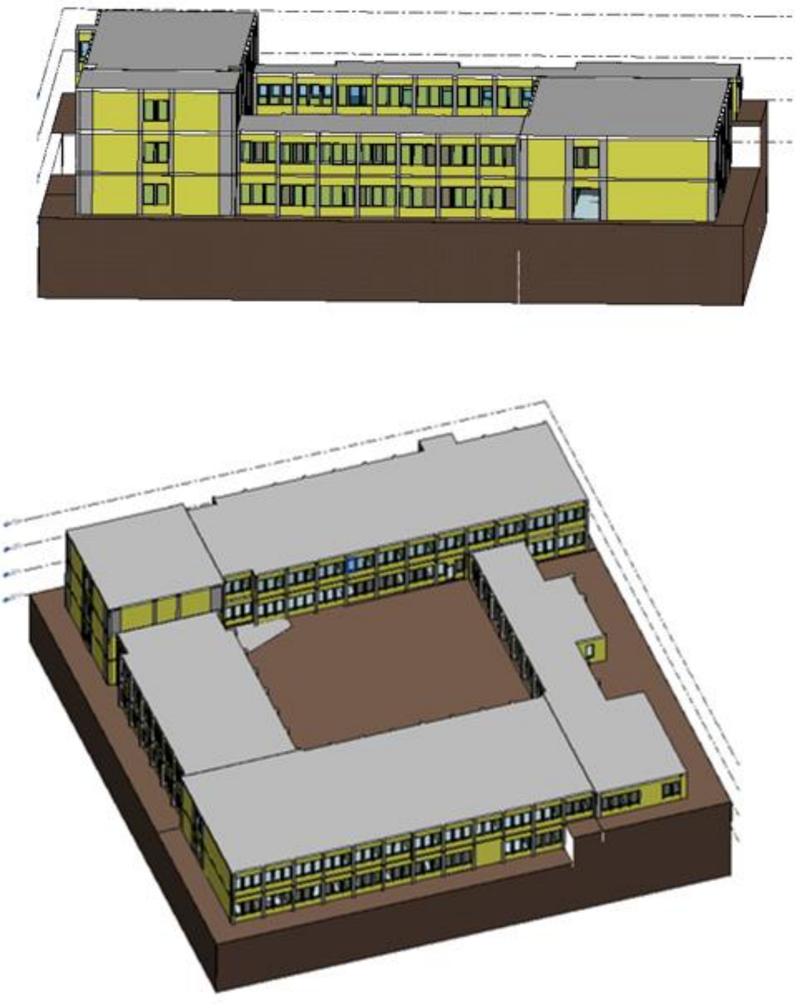

Figure 4.3: 3D revit model of building.

4.1.2 Detailing of 3D model with building images

When it was realized that all the details about the building were not understood from the AutoCAD drawings, the images of the building were used, and observations were made to eliminate the uncertainties in the building geometry and building envelope components. The locations and dimensions of openings such as windows and doors are not fully specified in the building drawings. In addition, no information about floor heights could be obtained. While creating the model, the pictures of the building and the observations made in the building were used to determine these necessary parameters. The dimensions of the windows and doors as well as the floor heights were determined by the measurements made on the building. The building images used in the detailing of the building model are shown in Figure 4.4.

Figure 4.4: Images of building**.**

4.1.3 Defining functional zones

It is important to determine the functional zones correctly, as the correct transfer of the functions of the areas inside the building to the model significantly affects the energy consumption. For this reason, the function of each area was determined by the observation made inside the building and transferred to the model. The building is divided into 7 different functional zones in total. These zones are classrooms, offices, laboratories, conditioned corridors, unconditioned corridors, restrooms, and storage areas. Each functional zone differs from each other in terms of building systems (HVAC and lightning), interior equipment and occupancy. The functions and features of each identified zone are described in Table 4.1.

Table 4.1: Functional properties of zone.

	Heating System	Cooling System	Lightning System	Interior Equipment	Occupancy
Office	Radiator	Split Air Conditioner	Fluorescent (300 lux)	Office Equipment and Computers	Occupied
Laboratory	Radiator	-	Fluorescent (500 lux)	Office Equipment and Computers	Occupied
Classroom	Radiator	-	Fluorescent (300 lux)	Office Equipment and Computers	Occupied
Conditioned corridor	Radiator	-	Fluorescent (100 lux)	-	Occupied
Unconditioned Corridor	-	-	Fluorescent (100 lux)	-	Occupied
Restroom	-	-	Fluorescent (100 lux)	-	Unoccupied
Storage Area	-	-	-	-	Unoccupied

Office and classroom zones are similar in terms of features when the cooling system is not considered. There is common central radiator heating system, fluorescent lighting system, office equipment and computers in both zones. They are occupied according to the schedules determined in the two zones. In addition to the heating system in the offices, there are split air conditioners as a cooling system. The desired illuminance level in both classrooms and offices is 300 lux. The characteristics of the laboratory zone are like the classes, the only difference is that the desired illumination level in the laboratories is 500 lux. The corridors in the building were examined in two different groups. While some corridors do not have any heating system, other corridors are heated by radiator heating system. Fluorescents are used as the lighting system in both corridor zones and the desired illuminance level is 100 lux. In addition, there is no interior equipment in the corridors, and they are occupied. When the restroom and storage areas are evaluated, there is no heating, cooling system and interior equipment in both zones. These zones are defined as unoccupied. Fluorescent lamps are used as the lighting system in the restrooms and the desired illumination level is 100 lux. Minimum illuminance levels that must be provided in different workplaces according to the TS EN 12464-1 standard are shown in Table 4.2.

Table 4.2: Minimum illuminance values of different places [19].

Place to be illuminated	Minimum illuminance level (lux)
Laboratory	500
Classroom	300
Office	300
Corridor	100

Determining the functional zones and transferring their properties to the model were made separately for each floor. Orange colours in the building floor plans represent laboratories, purple colours indicate corridors, green colours represent offices, blue colours represent restrooms and yellow colours indicate storage areas.

Functional zoning of the first floor is shown in Figure 4.5. The first floor contains almost all the zones determined in the whole model. The zones not located on the first floor are the classroom and the conditioned corridor. Since there is no heating system in the corridor on this floor, it is modelled as an unconditioned corridor. As can be seen from the figure, the first floor is dominated by laboratories and storage areas. There are 5 offices, and these offices are used by the staff of the institute. The boiler room, which has the largest area on this floor, was also taken under the category of unconditioned space and modelled as a storage area. As mentioned before, adjacent areas with the same function were combined into a single area.

Figure 4.5: Functional zoning of first floor.

Functional zoning of the second floor is shown in Figure 4.6. When the second floor of the building is examined, it is easily understood that there is no storage area. Unlike the first floor, classrooms are located on this floor. The corridor on this floor, which circulates throughout the floor, is heated using the central radiator heating system in the same way as the other heated zones. There is a balanced distribution between laboratories, offices, and classrooms in the floor layout. Classrooms, offices, and laboratories with common functions were combined into a single larger zone. As can be seen from the figure, no zone assignment has been made for the courtyard that can be reached from this floor. All zones of the building facing the courtyard have windows and the courtyard has a significant impact on the energy consumption of the building.

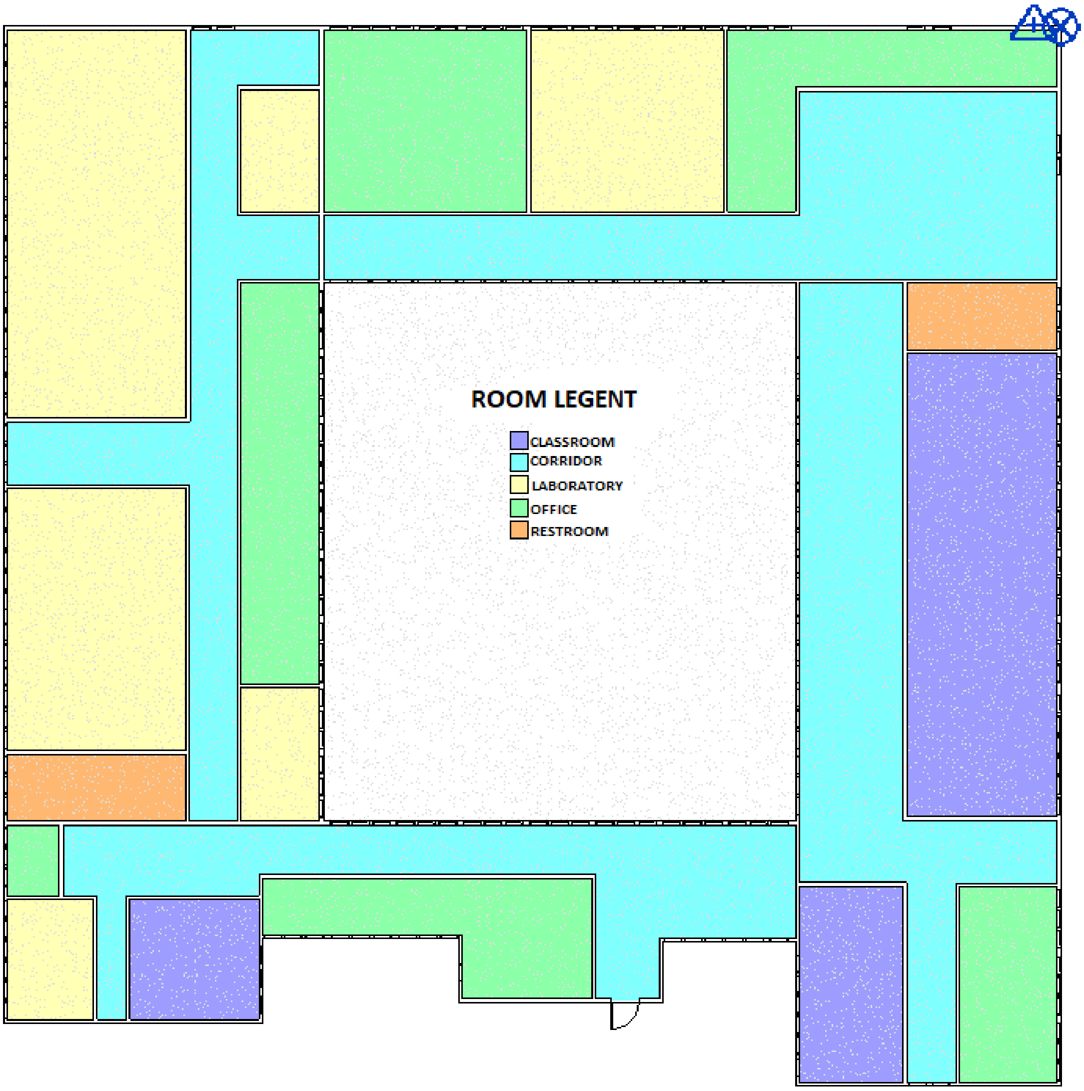

Figure 4.6: Functional zoning of second floor.

The 3rd floor of the building is the simplest compared to the other floor plans. It is built as just a single block and has the smallest total area. The floor plan and functional zoning are shown in Figure 4.7. This floor consists only of offices, unconditioned corridors, and restrooms. There are many offices on both sides of the floor, but since they have the same functions and features, these offices were combined and modelled as 3 large offices in total.

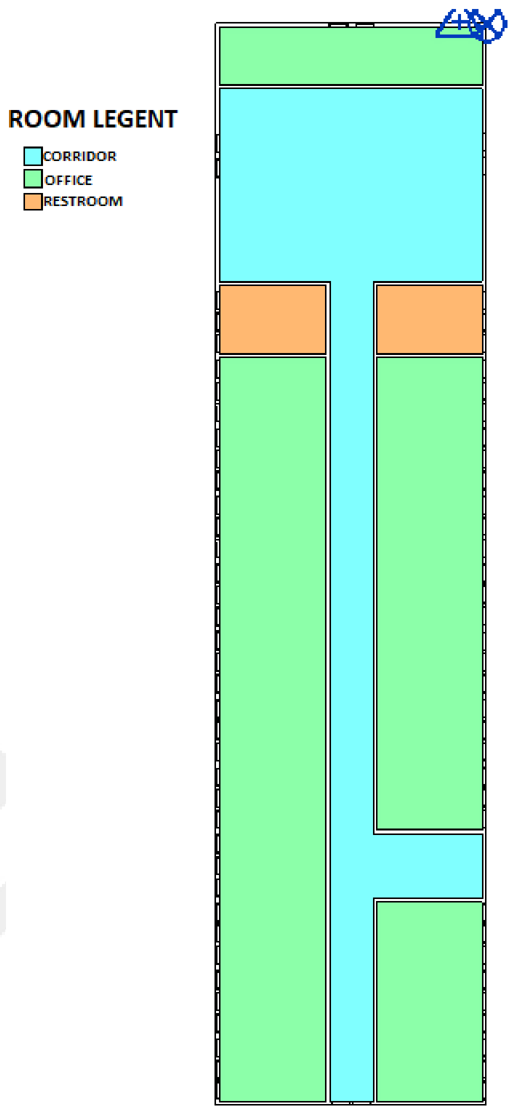

Figure 4.7: Functional zoning of third floor.

There is no mechanical ventilation system in all designated zones, and ventilation is provided naturally by opening the windows.

4.2 Creating Energy Model

Just after designing the 3-dimensional building model, further step is creating the building's energy model. The Design Builder software, which uses the Energy Plus simulation engine and can be merged into the Revit software as a plug-in, was chosen to produce the energy model. The reasons for choosing the Design Builder software to create an energy model can be listed as follows:

- It allows 3D model to be transferred with high accuracy.
- It is suitable for zone-based parameter determination.

- Easy integration of building systems (HVAC and lightning).
- It provides annual, monthly, and daily energy simulation.

4.2.1 Converting Revit model to Design Builder

Some settings set during the transfer of the model to the Design Builder software are shown in Figure 4.8. When extracting model to Design Builder software, functional zones characterized in Revit software are protected. It is ensured that the defined thermal properties of the building elements are included. Other building elements such as HVAC and lighting were required to be defined in the Design Builder software.

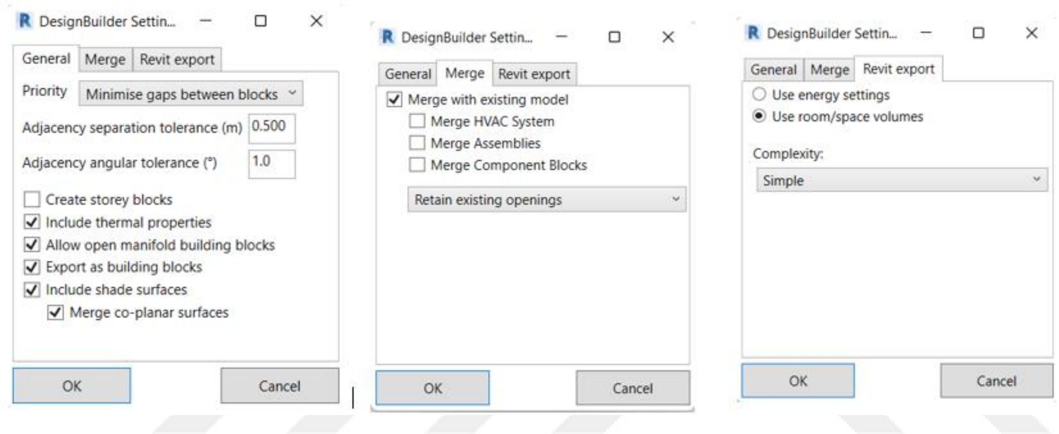

Figure 4.8: Design Builder importing settings.

Energy model of the building is shown in Figure 4.9. It can be seen from Figure 4.9 that the model imported into the Design Builder software does not differ at all from the geometrically created Revit model. Not only geometric accuracy, but also defined building envelope elements such as flat roof, floors, doors and windows were obtained with high accuracy.

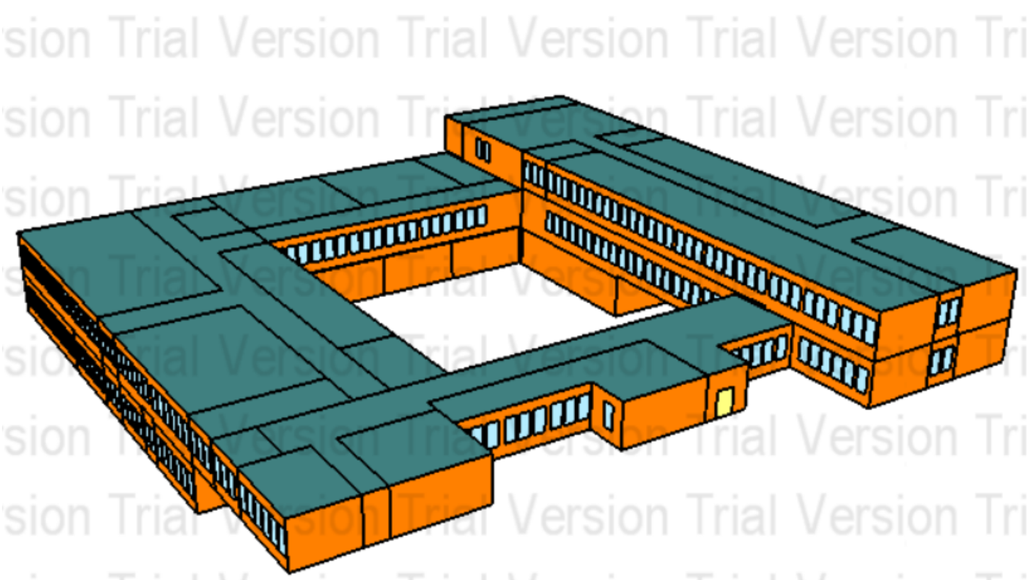

Figure 4.9: Energy model of building.

4.2.2 Collecting existing data

Climate data of the building's location, the thermophysical properties of the building elements, the features of the HVAC and lighting systems in the building, and the occupancy characteristics and timetables of the building were all considered necessary to detail the energy model. Many methods have been used to collect the data that the building has in its current condition. These methods can be classified as using different software, making real-time observations, reviewing technical documents, and interviews with building occupants. These methods and which data they are used to reach are summarized in Table 4.3.

Table 4.3: Data collection methods.

	Weather Data	Thermal Characteristics of Building Envelope	Properties of Building Systems	Occupancy Profiles
Energy Plus	√	X	X	X
Real-time Observations	X	√	√	√
Technical Documents	X	√	√	X
Interviews	X	X	X	√

4.2.2.1 Climate condition of site and weather data

The climatic characteristics of Istanbul are determined according to both the Turkish TS825 standard and the international Koppen-Geiger climate classification system. In TS825, the climate zones are classified according to degree-days and Istanbul is in the 2nd climate zone [20].

The climatic regions of Türkiye are shown in Figure 4.10. In addition, Table 4.4 shows the zone in which Istanbul is in the TS825 standard and the Köppen-Geiger climate classification system, and the heating degree day and cooling degree day values.

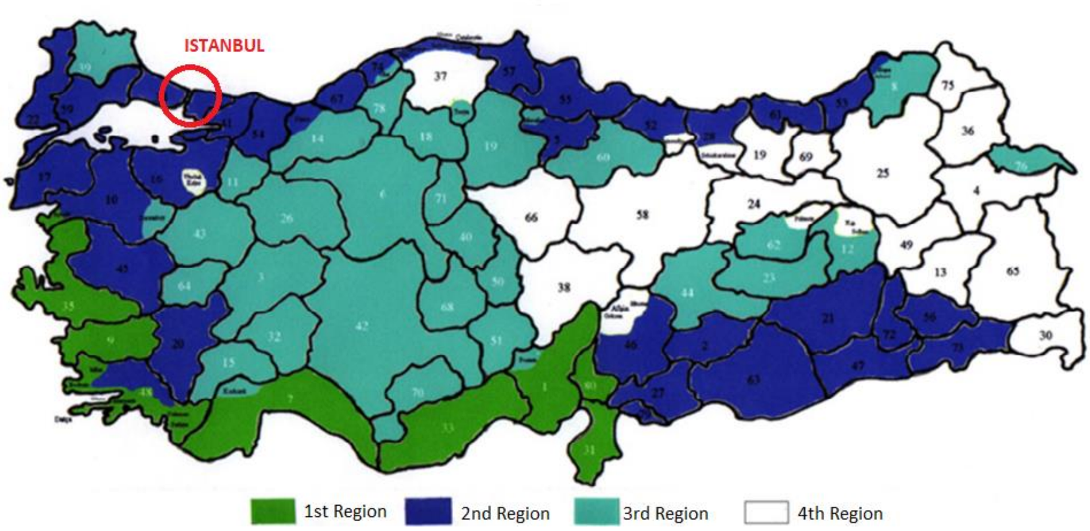

Figure 4.10: TS825 climate regions [20].

Table 4.4: Climate data [20,21].

Province	Climate Zone		HDD	CDD
	Köppen-Geiger	TS825		
Istanbul	Csa	2	1776	661

According to Köppen-Geiger Climate Classification, Istanbul has the climate code Csa. This means that the main climate is warm temperate precipitation is summer dry and temperature is hot summer. The World Map of Köppen-Geiger Climate Classification System and the position and class of Türkiye on the map are shown in Figure 4.11 and Figure 4.12 respectively.

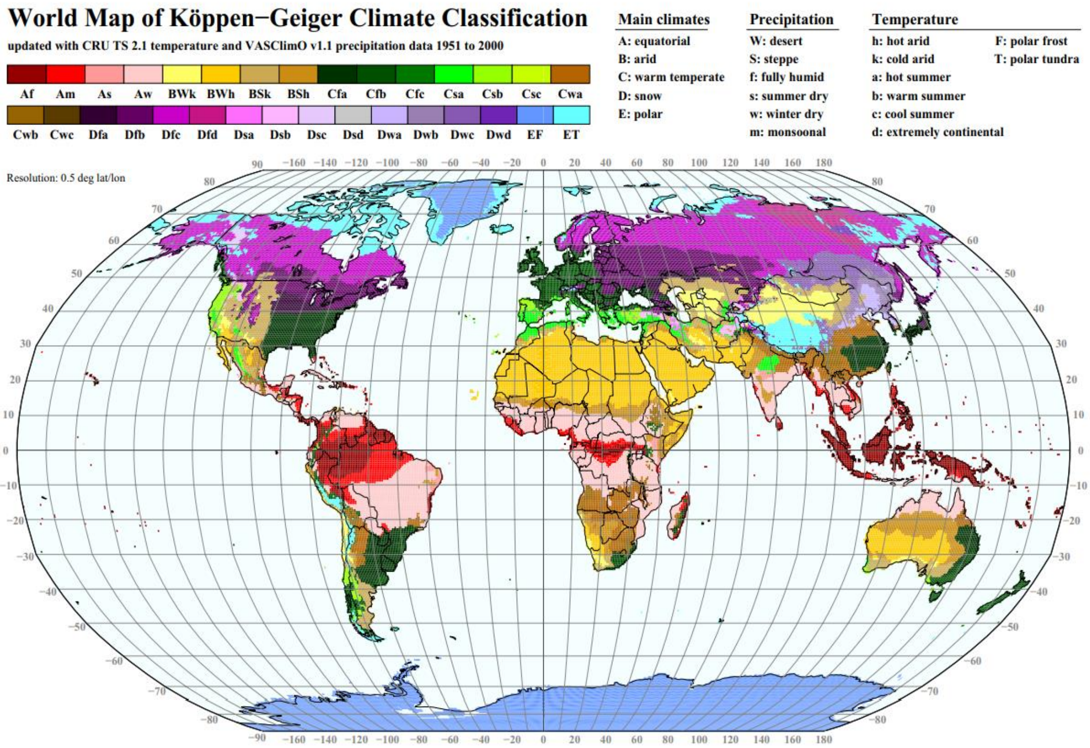

Figure 4.11: World map of Köppen-Geiger climate classification [21].

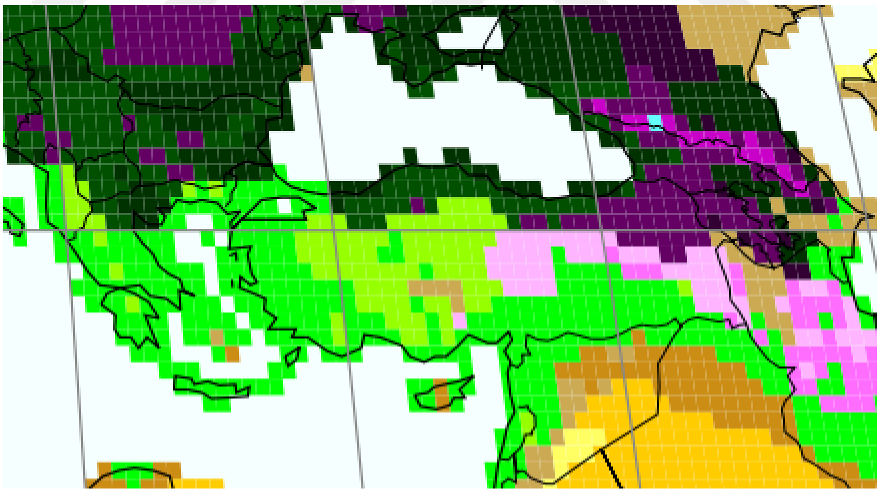

Figure 4.12: World map of Köppen-Geiger climate classification of Türkiye [21].

Figure 4.13 describes the average temperature values, the number of cloudy and sunny days, wind speed and wind rose in Istanbul.

The average temperature for the year in Istanbul is 14.4°C. The warmest month, on average, is July with an average temperature of 23.3°C. The coolest month on average is January, with an average temperature of 5.6°C. The highest recorded temperature in Istanbul is 37.8°C, which was recorded in July. The lowest recorded temperature in Istanbul is -8.9°C, which was recorded in January. The average amount of precipitation for the year in Istanbul is 640.1 mm. The month with the most precipitation on average is December with 101.6 mm of precipitation. The month with the least precipitation on average is August with an average of 15.2 mm. There is an average of 120.0 days of precipitation, with the most precipitation occurring in December with 17.0 days and the least precipitation occurring in July with 3.0 days [22].

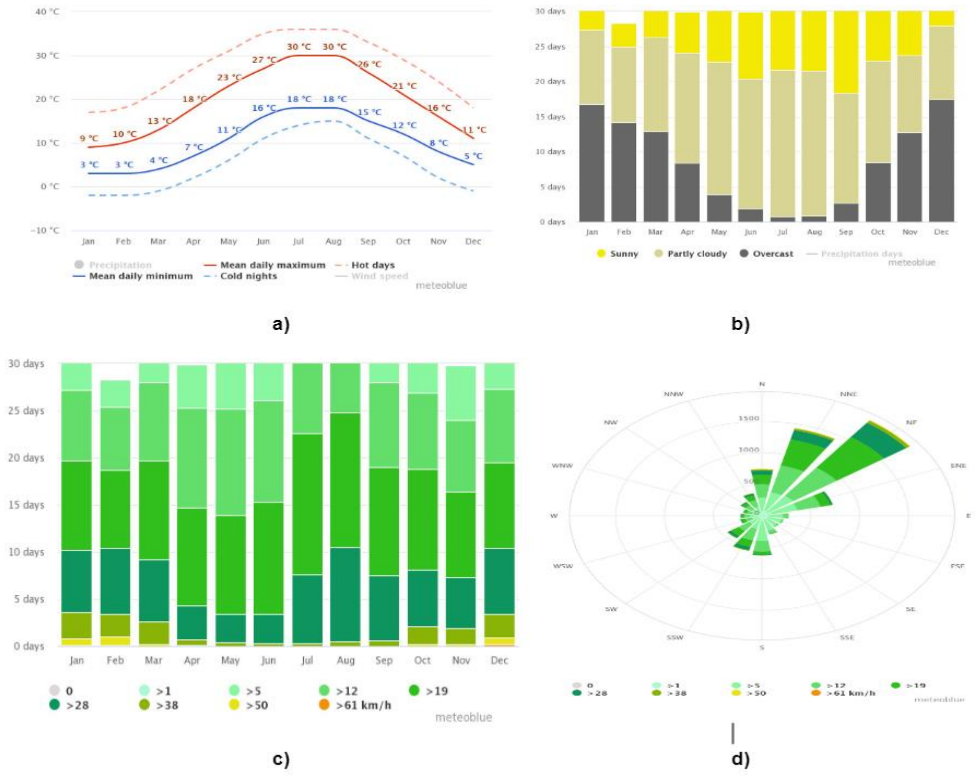

Figure 4.13: a) Average temperatures of Istanbul, b) Cloudy and sunny days in Istanbul, c) Wind speeds in Istanbul, d) Wind rose of Istanbul [22].

In addition, climate data was obtained from the nearest measurement station to the building by using the Energy plus software, since climate data definition must be made in the Design Builder software.

4.2.2.2 Building envelope thermal characteristics

Determining the thermal performance of the building envelope elements (external walls, foundation, roof, doors, and windows) is one of the biggest factors that can affect the results of the energy simulation. It is of great importance that these parameters are fully compatible with the current state of the building. While determining the thermal properties of the building envelope elements and the properties of the building systems, floor plans and observations were used. In addition, the technical documents of the building systems elements were examined. The equation used to calculate the overall thermal conductivity coefficient of the building envelope elements is explained in equation 1.

$$U\left(\frac{W}{m^2K}\right) = \frac{1}{R_i + R_e + \sum_{i=1}^{N} \frac{d}{\lambda_h}} \tag{4.1}$$

Where U is the overall thermal conductivity coefficient (W/m^2K), R_i is the surface thermal conduction resistance of the inner surface (m^2K/W), R_e is the surface thermal conduction resistance of the exterior surface (m^2K/W), d is the structural element thickness (m), λ_h is the thermal conductivity calculation value (W/mK) and N is the number of the structural elements.

No insulation material was used on the outer walls and foundation. The overall thermal conductivity coefficient value of the building envelope elements was calculated using the structural element thickness and thermal conductivity calculation value.

The overall thermal conductivity coefficient of the outer walls, roof and foundation is 2.4, 2.28 and 3.13 W/m^2K, respectively. The original windows are double glazing with aluminium frames and U value of windows is 2.1 W/m^2K and U value of doors is 2.8 W/m^2K. Thermal properties of the building envelope are listed in Table 4.5.

The exterior walls of the building consist of 2 cm exterior plaster, 20 cm brick and 1 cm interior plaster, respectively, from the outside to the inside. The flat roof of the building consists of 3 cm gravel, 5 cm levelling screed, 20 cm concrete and 1.6 cm acoustic material, respectively, from the outside to the inside. The foundation of the building consists of 2 cm laminate, 50 cm concrete and 1.5 cm plaster, respectively, from the outside to the inside.

Also, average estimated infiltration rates have also been introduced in the simulation as 1.5 ac/h (air changes per hour).

Table 4.5: Thermal properties of building envelope.

Structural Elements in the Building		Structural element thickness d(m)	Thermal Conductivity Calculation Value (λ_h) (W/mK)	Thermal Conductivity Resistance (R) (m^2K/W)	Overall Thermal Conductivity Coefficient U (W/m^2K)
Exterior Wall	R_i	-	-	0.13	
	Outer Plaster	0.02	0.65	0.030769231	
	Brick	0.2	0.54	0.37037037	
	Inner Plaster	0.01	0.65	0.015384615	
	R_e	-	-	0.04	
	Total	-	-	**0.4165**	**2.401**
Roof	R_i	-	-	0.13	
	Gravel	0.03	0.7	0.042857143	
	Levelling Screed	0.05	1.4	0.035714286	
	Concrete	0.2	2.5	0.08	
	Acoustic Material	0.0159	0.057	0.278947368	
	R_e	-	-	0.08	
	Total	-	-	**0.4375**	**2.285**
Floor	R_i	-	-	0.17	
	Laminate	0.02	0.209	0.09569378	
	Concrete	0.5	2.5	0.2	
	Plaster	0.015	0.65	0.023076923	
	R_e	-	-	0	
	Total	-	-	**0.3188**	**3.137**
Window	-	-	-	-	**2.1**
Door	-	-	-	-	**2.8**

4.2.2.3 Building systems (hvac, lightning, interior equipment)

The technical documentation of the heating and cooling systems and the lighting system were examined to determine the parameters to be used when defining the building systems in energy model. In addition, missing information was completed by making real-time observations. The heating system of the building is centralized district heating with radiators. The HVAC system of the building is simple since there is no hot water demand, no mechanical ventilation supply, or any refrigeration system. While no centralized cooling system is provided, offices have autonomous air conditioning equipment. Besides, the building is naturally ventilated through operable windows. After analysing the monitored data in the heating and cooling period months, the working set point temperature of heating and cooled has been adjusted to 20°C and 26°C respectively. The simple diagram of the central heating system is shown in Figure 4.14. The boiler in the system uses natural gas as fuel and its seasonal coefficient of performance value is 0.85.

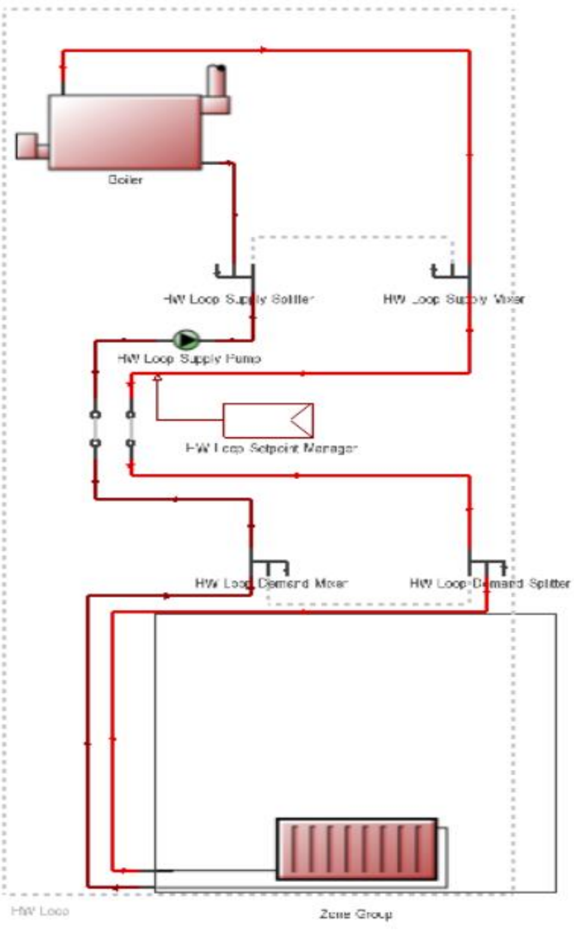

Figure 4.14: Simple diagram of the central heating system.

Predominantly, fluorescents provide the internal lighting, and most of them are constantly turned on while the building is occupied, both in summer and in winter. That is why no significant differences were found between the consumption of these seasons. Normalised power density of lightning system is 5 W/m^2-100 lux. The minimum illuminance value is defined in the model as 500 lux for laboratories, 300 lux for offices and classrooms, and 100 lux for corridors.

Interior equipment in each zone defined in the building differs. In order to transfer the effect of these equipment on the electricity consumption in the zones to the model in the best way, it is necessary to make correct definitions in each zone. However, it is not possible to define equipment specifically for each zone and to transfer the power density values of these equipment to the model in the energy simulation software used. The assumptions made regarding the internal equipment in each zone are listed below, while making these assumptions, the power density values determined for the internal equipment of the default zones defined in the Design Builder software used were considered.

- Both office equipment and computer loads are defined in laboratories and offices. Power density value for both is determined as 5 W/m^2. In addition, the working hours of the two equipment groups were determined to be the same as the occupancy schedule in the laboratories and offices.
- In classrooms, only office equipment loads are defined in the model. Similar to laboratories and offices, the power density value of office equipment is determined as 5 W/m^2.
- For the corridors, the load that will be produced from office equipment or computer use has not been defined.

4.2.2.4 Building occupancy (profile and schedule)

While determining the occupancy profile of the building, considering that it is an education building, holidays, and periods when the building is not used were determined. In addition to this, the usage habits of the building were investigated by conducting interviews with the residents. While creating the occupancy profile of the building, it has been assumed that all zones are occupied every day except weekends throughout the year and between 07:00 -18:00 during the day.

In parallel with the occupancy profile, the schedule of the systems (cooling, heating, lightning) used in the building was made with the same assumption in all zones. The schedule determined for all zones is shown in Figure 4.15. While creating this schedule, the days, and hours when the educational buildings are generally active were selected.

Profiles

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Feb	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Mar	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Apr	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
May	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Jun	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Jul	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Aug	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Sep	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Oct	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Nov	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off
Dec	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	7:00 to 18:00	Off	Off

Figure 4.15: Hvac, lightning and occupancy schedules in all zones.

Although the schedule of the heating, cooling, and lighting systems is set as above, since each zone has been defined according to its own characteristics before, the schedule specified here is valid for the zones where the specified systems are placed. In other words, the specified heating system scheduling is not valid for unconditioned zones where there is no heating system, such as restrooms and storage areas. Similarly, the defined cooling system schedule is not valid in zones such as class, lab, corridor where there are no split air conditioners.

4.3 Collecting Monthly Energy Consumption Data

It is critical to determine the actual energy consumption of the building in analysing the energy consumption result calculated from the building energy model simulation and ensure the model's reliability. Because the energy simulation results provide yearly basis energy consumption values, monthly bills for electricity and natural gas consumed by the building during 2022 were received from the rectorate. The monthly natural gas and electricity consumption of the building throughout 2022 was provided from the invoices of electricity and natural gas distribution companies. The monthly electricity and natural gas consumption data of the building will be used as a reference for the calibration of the created energy model. Monthly energy consumption values are shown in Table 4.6.

Table 4.6: Monthly real energy consumption of building in 2022.

Measured consumptions	Electricity (kWh)	Natural gas (kWh)	Total (kWh)
Januray	18700.5	83766.27	102466.77
February	17602.5	88894.79	106497.29
March	19800.75	61815.28	81616.03
April	17662.2	21216.38	38878.58
May	16594.95	0	16594.95
June	11531.25	0	11531.25
July	10354.35	0	10354.35
August	15543.45	0	15543.45
September	11501.55	0	11501.55
October	14285.1	28233.7	42518.8
November	15791.85	36884.28	52676.13
December	17575.5	54471.01	72046.51
Total	186943.95	375281.71	562225.66

As it can be understood from the table above, although there are decreases in electricity consumption in summer months, no great differences were observed during the year. The month with the lowest electricity consumption is July and the consumption is 10354.35 kWh. The month with the highest electricity consumption is March and the consumption is 19800.75 kWh. When the average of the consumptions during the year is taken, an average of 15578.6625 kWh electrical energy was consumed every month. The total electricity consumption value in 2022 was measured as 186943.95 kWh. The reason for the relatively low electricity consumption during the summer months can be explained by the fact that some zones (classroom, laboratory) in the building are not used during the summer months and the personnel generally prefer the summer months for annual leave. The reason why the consumption in August is 50% higher than the previous month during the summer months can be attributed to the use of split air conditioners in the offices because of the increase in temperatures in August. Similarly, the relatively high electricity consumption in March compared to the previous month can be explained by the fact that split air conditioners were used for heating purposes when the central heating system of the building was insufficient due to the decreasing temperatures in March.

When the real natural gas consumption of the building is examined, differences are observed considering seasonal conditions throughout the year. Natural gas consumption is zero in May, June, July, August, and September. Natural gas consumption is quite high in winter, and the highest consumption was recorded in February as 88894.79 kWh. When the average of the consumptions during the year is taken, an average of 31273.47583 kWh electrical energy was consumed every month. The total natural gas consumption value in 2022 was measured as 375281.71 kWh.

4.4 Calibrating the Energy Model

In the literature, energy models have been created for buildings with very different physical and operational differences, such as residential, public, and traditional, and energy efficiency studies have been carried out using these models from different perspectives. By creating energy models of buildings, digital twins are created, which allows us to easily determine and evaluate the results of any new application, improvement, and technology integration. In addition to the creation of the energy model of the building, the extent to which the results obtained from the simulation of this model match the actual energy consumption of the building is as important as the creation of the model. Determining how much the results obtained from the energy model differ from the actual consumption values by considering different criteria, and studies based on the values recommended in different guidelines for these differences are called the calibration of the energy model. The calibration process of the building energy model, as understood from many studies in the literature, can be carried out by evaluating only the heating energy consumption, only the electricity consumption of the building or the total energy consumption regardless of the source. In fact, there are studies in which the energy model is calibrated using the measured indoor temperature values of the zones inside the building and the ambient temperature values simulated from the energy model. While performing the energy model calibration process, comparing the results, and determining the differences between the real values and the simulated values, the periods in which this is done also differ. In the literature, there are many studies in which the calibration process is performed using hourly, daily, monthly, and annual periods. The methods used during the calibration process also differ. One of the most used methods is the fine tuning of parameters. Fine-tuned parameters can be thermal properties of building envelope elements, characteristics of heating or cooling systems, scheduling, and control mechanisms of energy-consuming equipment within the building, or setpoint temperatures. There are studies in which revisions are made in these parameters as a priority by determining which parameters have the greatest effects on the energy model and simulation results by sensitivity analysis. In addition, many performance indicators have been used in studies in the literature to determine the differences between real data and simulated data. The most well-known of these indicators are mean bias error (MBE), normalized mean bias error (NMBE), root mean squared error (RMSE), cumulative variation of the root mean squared error (CVRMSE), R^2.

4.4.1 Comparing simulation result with monthly measured data

First, the energy model described in detail in sections 4.1 and 4.2 was simulated. The first energy model created will be called the base line scenario in the next parts of the study. While the base line scenario energy model is being simulated, the thermal properties of the building envelope elements, building systems (hvac, lighting, interior equipment) properties and the parameters that have a direct effect on the energy consumption of these systems, the occupancy schedule of each zone group in the building, and the heating system, cooling system, lighting system and interior equipment operation schedules which are explained in detail in section 4.2 have been preserved. The monthly energy consumptions obtained from the base line scenario energy model simulation are shown in Table 4.7. While creating the table, energy consumptions are shown as electricity and natural gas as two main groups. In addition, the total energy consumption for each month is also shown.

Table 4.7: Energy consumption results of base line scenario energy simulation.

Base line scenario consumptions	Electricity (kWh)	Natural gas (kWh)	Total (kWh)
Januray	18796.65	214108.08	232904.73
February	16525.61	174441.45	190967.06
March	17595.45	124226.41	141821.86
April	17977.36	64222.32	82199.68
May	19807.54	22258.21	42065.75
June	21089.09	182	21271.09
July	27795.01	3.39	27798.4
August	27939.65	3.94	27943.59
September	20413.5	1204.78	21618.28
October	18787.93	19973.63	38761.56
November	17400.81	70567.85	87968.66
December	18185.57	149349.55	167535.12
Total	242314.17	840541.61	1082855.78

As can be seen in Table 4.7, according to the simulation results, monthly electricity consumption throughout the year does not differ much, except for the summer period. Electricity consumption, which exceeded 20000 kWh in summer months, exceeded 27000 kWh especially in July and August. In these months, the effect of the electrical loads coming from the split air conditioners used in the offices is seen directly. On the other hand, natural gas consumption shows a regular distribution when seasonal climatic conditions are considered. Natural gas consumption in May and September is relatively low compared to other months. They can be neglected with consumption in June, July, and August. When the total consumptions are analysed, it is understood that the highest consumption was in January with 232904.73 kWh, and the lowest consumption was in June with 21271.09 kWh. According to the results of the base line scenario energy simulation, the total energy consumption in 2022 is calculated as 1082855.78 kWh.

In order to understand the accuracy of the simulation results, these results should be compared with the measured energy consumption values explained in detail in section 4.3. The comparison of the base line scenario total energy consumptions with the measured total energy consumptions is shown in Figure 4.16. When the graph is examined, it is seen that the measured and simulated consumptions overlap with each other only in October. In the summer period (June, July, August and September) consumption values are close to each other. In these months, no natural gas consumption has occurred in real measurements, whereas natural gas consumption is negligible in simulated data. Thus, the difference between the two cases is only the difference in electricity consumption. When the heating period is examined, the gap between the measured and simulated consumptions from October to February widens. From February until June, the gap between consumptions tend to close.

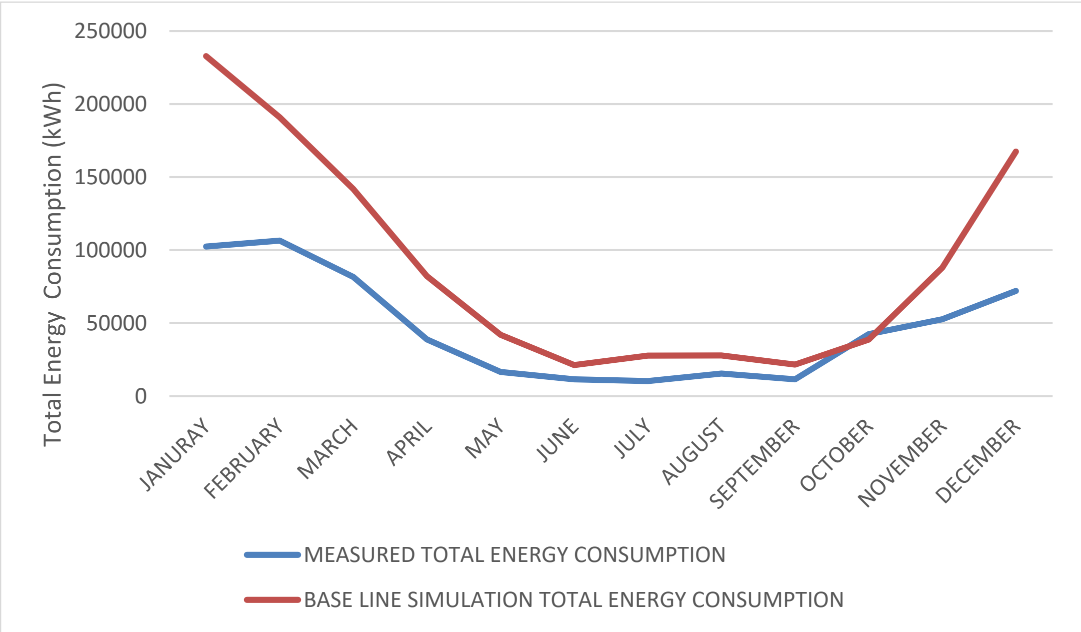

Figure 4.16: Total energy consumption comparison between base line scenario simulation and measured.

When Figure 4.16 is examined, it is clearly seen that the consumption data from the base line scenario energy simulation does not overlap to a large extent with the measured consumption data. It has been understood that it is necessary to make revisions in the parameters defined in the model in order to eliminate the differences in energy consumption on a monthly basis.

4.4.2 Fine-tune of the model parameters

When comparing the results of the base line scenario simulation with the measured energy consumption values, large differences were observed. To eliminate these differences, some parameters defined in the model were fine-tuned. The new energy model created as a result of the fine-tunes made in the determined parameters is called the scenario 2 energy model. The parameters to be fine-tuned and the changes made are as follows:

- **U value of roof:** When the results from the base line scenario simulation are analysed zone-based basis, it has been observed that the heat losses from the zones with the roof on the 2nd and 3rd floors of the building are much higher than the heat losses from the zones on the 1st floor. Although the higher heat losses in the zones with the roof on the 2nd and 3rd floors can be explained by the greater surface area exposed to the outdoor conditions, the thermal properties of the roof have been re-examined. After investigations and discussions with the university technical staff, it was learned that a renovation was made to the roof of the building recently and insulation material was placed during the renovation process. As a result, the overall thermal conductivity coefficient of the roof was recalculated. The roof U value, which was defined as 2.28 W/m^{2}K in the base line scenario energy model, has been changed to 1.5 W/m^{2}K in the scenario 2 energy model.
- **U value of windows and doors:** It was learned that the doors and windows, which are elements of the building envelope, were also renewed during the renovation to the roof in order to increase the thermal performance of the building. Assuming that TS825 standards are complied with in the selection of doors and windows placed after the renovation, the U values for windows and doors, which were 2.1 W/m^{2}K and 2.8 W/m^{2}K in base line scenario energy model, were changed to 1.8 W/m^{2}K in scenario 2.
- **Infiltration rate:** Comparing the simulated and measured consumption values, it was seen that the simulated consumption was always higher. While determining the infiltration rate in base line scenario, no experimental study was done, and 1.5 ac/h value was assumed and defined to the model. In order to reduce the natural gas consumption of the model, the infiltration rate has been revised as 0.5 ac/h in scenario 2.
- **Power density of interior equipment:** In the base line scenario energy model, the default values of the energy simulation software were used to determine the consumption profiles and power densities of energy-consuming equipment such as office equipment, computers, and experimental equipment in laboratories. With the changes made in scenario 2, computer loads have been

added to the zones defined as classes and the power density value of both office equipment and computers has been increased from 5 W/m^2 to 9 W/m^2.

By making the revisions mentioned above, the scenario 2 energy model was created and simulated to obtain energy consumption values. The simulation results are shown in Table 4.8. Also, comparison of the base line scenario and scenario 2 total energy consumptions with the measured total energy consumptions is shown in Figure 4.17

Table 4.8: Energy consumption results of scenario 2 energy simulation.

Scenario 2 consumptions	Electricity (kWh)	Natural gas (kWh)	Total (kWh)
Januray	22475.5	110028.21	132503.71
February	21385.41	111730.95	133116.36
March	24609.19	96580.81	121190
April	23276.01	30766.42	54042.43
May	25217.94	8293.15	33511.09
June	25955.03	31.83	25986.86
July	25209.22	0	25209.22
August	27641.27	0	27641.27
September	25658.54	370.8	26029.34
October	20566.95	5427.45	25994.4
November	21552.9	51962.46	73515.36
December	21405.48	81986.64	103392.12
Total	284953.44	497178.72	782132.16

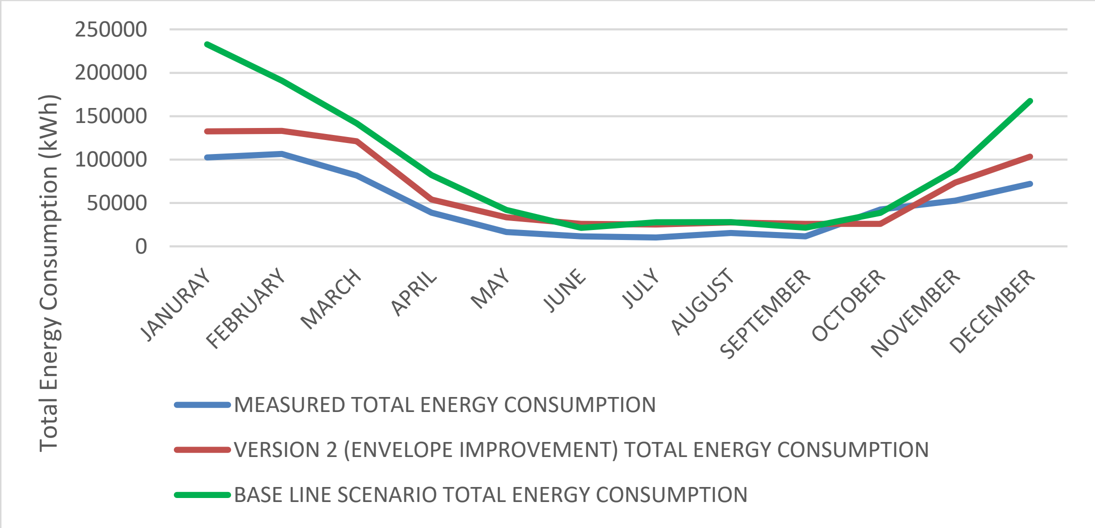

Figure 4.17: Total energy consumption comparison between base line scenario and scenario 2 simulation with measured consumption.

When Table 4.8 is examined, the electricity consumption values of the interior equipment have increased with the change made in the power density parameter and are evenly distributed between the months. In addition, with the changes made in the U value parameters of the building envelope elements, the natural gas consumption, which exceeded 200000 kWh in some months in base line scenario, was reduced to a maximum of 111000 kWh and started to approach the real value. It can be seen from Figure 4.17 that compared to base line scenario, the newly created model gave results closer to the measured data. Since there is no natural gas consumption in the summer months or it is negligible, the results are close to each other in three models in these months. However, the improvement in total energy consumption, especially between November and March, is remarkable. Although the fine-tuning method made in the determined parameters have brought the simulated energy consumption values closer to the measured real values, the reliability of the model has still not been confirmed. The model should be revised again to ensure that the differences between the simulated results and the measured results remain below the limit values recommended by different guidelines.

4.4.3 Defining zone-based scheduling

As a result of the fine-tuning in the parameters, it was decided to perform zone-based scheduling since the simulated consumptions did not fully match the actual consumption data. The main reason for zone-based scheduling is that the usage functions, usage frequency and operational hours of each zone differ. While performing zone-based scheduling, interviews were made with the users in each zone and occupancy schedules of the zones were created with the feedback received from them. Scenario 3 energy model was created by revising the occupancy schedules and operational profiles of the heating and cooling systems specific to each zone. The renovated occupancy schedule of laboratories and classrooms are shown in Figure 4.18.

Profiles

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Feb	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Mar	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Apr	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
May	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	9:00 - 16:00	9:00 - 16:00	Off	Off	Off	Off	Off
Sep	9:00 - 16:00	9:00 - 16:00	Off	Off	Off	Off	Off
Oct	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	Off	Off
Nov	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	9:00 - 16:00	Off	Off
Dec	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off

Figure 4.18: Occupancy schedule of laboratories and classrooms.

In base line scenario and scenario 2 energy models, the occupancy scheduling of all zones was defined to be active from Monday to Friday throughout the year and to be active between 07:00 and 18:00 during the day. As a result of observations and interviews made in laboratories and classrooms, it was understood that the occupancy schedules defined in this way should be revised. First, it was learned that the laboratories and classrooms were started to be used at 08:00 at the earliest, not at 7:00 in the morning, and were unoccupied at the latest at 17:00 instead of 18:00 in the evening, and this change was added to the model. Since the months of May, October and November are the beginning and the end of the education period, it has been observed that there is a slight decrease in the usage hours of the classrooms and laboratories. In these months, the occupied hours during the day have been revised as 09:00-16:00. When June, July, August, and September are evaluated, it is thought that students are not in the building and these zones are unoccupied. But later, it was understood that these zones were used by the staff in the building, even if there were no students in August and September. In order to transfer this situation to the model correctly, it is assumed that the laboratories and classrooms are occupied for 2 days each in August and September. In June and July, classrooms and laboratories are modelled as unoccupied because both students and staff do not use these zones.

The revised occupancy schedule of offices and corridors are shown in Figure 4.19.

Profiles

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Feb	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Mar	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Apr	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
May	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Jun	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Jul	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Aug	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Sep	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Oct	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Nov	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Dec	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off

Figure 4.19: Occupancy schedule of offices and conditioned corridors.

While scheduling offices and corridors in base line scenario and scenario 2, these zones were assumed to be occupied on weekdays throughout the year and between 7:00-18:00 during the day. It has been understood that the occupancy of the offices and corridors does not change on a monthly basis, but they are occupied between 8:00 and 17:00 during the day. With the revised occupancy profile, it has been transferred to the model where offices and corridors are in use between 8:00 and 17:00 on weekdays.

The operating profiles of the lighting systems, office equipment and computers in the four zones (laboratories, classrooms, offices, and corridors) are modelled to be the same as the occupancy profiles of these zones.

The results obtained from the base line scenario and scenario 2 energy models showed that there is a small amount of natural gas consumption even in the summer months. However, the central radiator heating system used in the building is turned off during the summer season. In this case, the need for revisions has emerged in the operational profiles of the heating and cooling systems. The operational profile of the heating system is shown in Figure 4.20.

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Feb	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Mar	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Apr	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Nov	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Dec	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off

Figure 4.20: Operational profile of heating system.

In base line scenario and scenario 2 energy models, the operational profile of the heating system was modelled as 07:00-18:00 on weekdays. However, by examining the measured monthly consumption values, it was seen that natural gas consumption was 0 in the summer period (May, June, July, August, and September). As a result, it was transferred to the new model that the heating system was not in operation during these months. In addition, it was learned that the heating system of the building was activated as of 08:00 since working hours started at 08:30 and it was deactivated half an hour before 17:30, which is the end of the working hours. The operational profile of the heating system was revised using this information. No changes were made on the weekends. The heating system does not operate on weekends. Similarly, the operational profile of the cooling system is given in Figure 4.21.

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Off	Off	Off	Off	Off	Off	Off
Feb	Off	Off	Off	Off	Off	Off	Off
Mar	Off	Off	Off	Off	Off	Off	Off
Apr	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Jul	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Aug	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	8:00 to 17:00	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	Off	Off	Off	Off	Off	Off	Off
Dec	Off	Off	Off	Off	Off	Off	Off

Figure 4.21: Operational profile of cooling system.

It was previously mentioned that the selected example building does not have a central cooling system. Split air conditioners are used as cooling system only in offices. While creating the operational profile of these cooling systems, which are defined only for office zones, it was modelled to be between 07:00-18:00 on weekdays in base line scenario and scenario 2. Even though the operation of the cooling systems is determined by the cooling setpoint temperature, it was decided that the split air conditioners in the offices are only active in June, July, and August in the revised model. In the mentioned months, it has been stated that the cooling systems operate between 08:00 and 17:00, when the offices are occupied during the day. Changes made in the operational profiles of the heating and cooling systems have been applied to each zone in the building that has these systems.

By making the revisions mentioned above, the scenario 3 energy model was created and simulated to obtain energy consumption values. The simulation results are shown in Table 4.9.

Table 4.9: Energy consumption results of scenario 3 energy simulation.

Scenario 3 consumptions	Electricity (kWh)	Natural gas (kWh)	Total (kWh)
Januray	18564.37	82811.28	101375.65
February	17648.18	85927.06	103575.24
March	20242.75	64903.48	85146.23
April	18526.85	22229.21	40756.06
May	15824.99	0	15824.99
June	11283.91	0	11283.91
July	9965.84	0	9965.84
August	14795.71	0	14795.71
September	11149.46	0	11149.46
October	13951.81	3845.85	17797.66
November	15260.27	35101.59	50361.86
December	17700.72	56187.09	73887.81
Total	184914.86	351005.56	535920.42

As seen in Table 4.9, as a result of zone-based occupancy, lightning and interior equipment schedules, electricity consumption is reduced in summer months when laboratories and classrooms are not used. In addition, with the changes made in the operational profile of the heating system, natural gas consumption was reduced to 0, as in the data measured in May, June, July, August, and September. As a result of the revision, the month with the highest consumption in the scenario 3 energy model is February with 103575.25 kWh, and the month with the least consumption is June with 9965 kWh. According to the results obtained from the simulation, a total of 184914.86 kWh of electricity, 351005.56 kWh of natural gas and a total of 535920.42 kWh of energy were consumed in 2022.

Also, comparison of the base line scenario, scenario 2 and scenario 3 total energy consumptions with the measured total energy consumptions is shown in Figure 4.22.

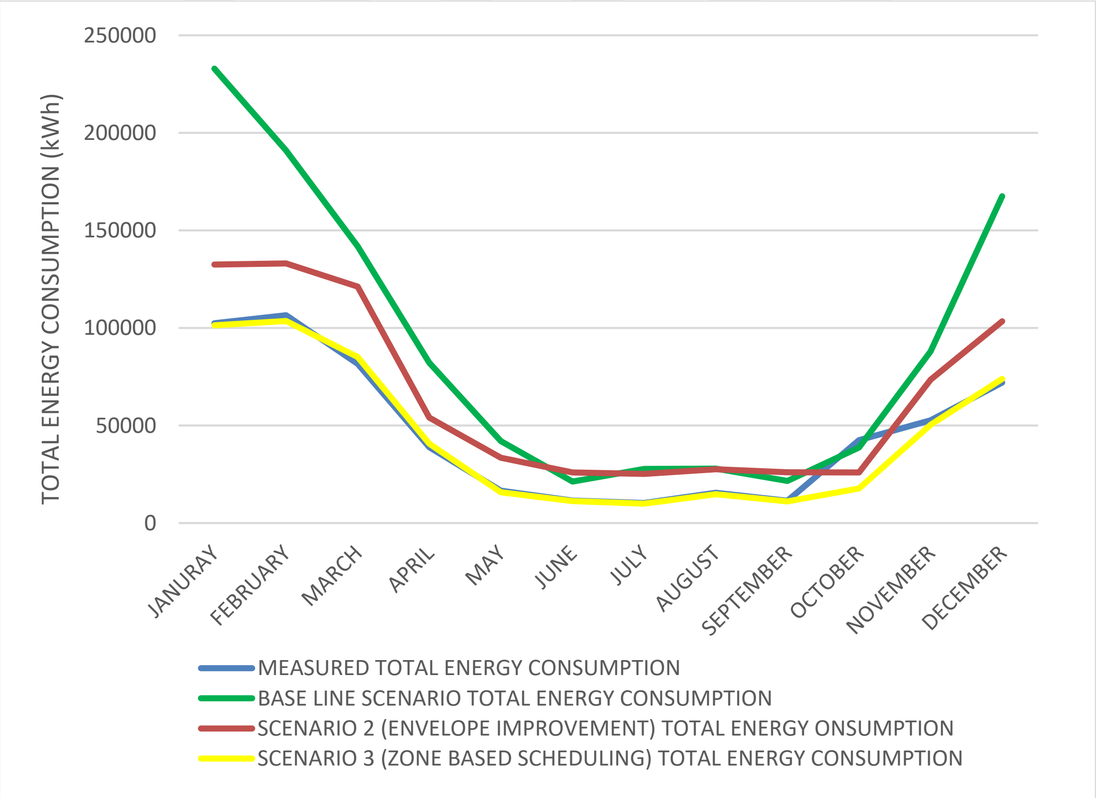

Figure 4.22: Total energy consumption comparison between base line scenario, scenario 2 and scenario 3 with measured consumption.

When Figure 4.22 is examined, it is understood that the monthly total energy consumption values obtained from the scenario 3 energy simulation are largely matched with the measured total energy consumption values. When the yellow and blue lines in the graph are followed, there is a remarkable difference between the model and the actual results only in October. It has been understood that there is no need to make further revisions on the energy model since the simulation and measured values are very close to each other. How the simulated monthly electricity and natural gas consumption differs from the measured values will be investigated in detail in the next section.

4.4.4 Calibration assessment

Furthermore, many performance indicators were used in the research studies to find the differences between real and simulated data. mean bias error (MBE), normalized mean bias error (NMBE), root mean squared error (RMSE), cumulative variation of the root mean squared error (CVRMSE), and R^2 methods are a very well of these indicators. In this study, the mean bias error method and cumulative variation of root mean squared error were used as a performance indicators to assess the calibration of the energy model. The formula used to calculate MBE and CVRMSE are given in equation 4.2 and equation 4.3.

$$MBE\ (\%) = \frac{\sum_{i=1}^{N} (m_i - s_i)}{\sum_{i=1}^{N} m_i} \times 100 \tag{4.2}$$

$$CVRMSE\ (\%) = \frac{\sqrt{\sum_{i=1}^{N} \frac{(m_i - s_i)^2}{N_p}}}{\bar{m}} \times 100 \tag{4.3}$$

Where m_i is measured data of a certain variable during the chosen time interval, s_i is simulated data of a certain variable during the chosen time interval, N is number of data points of the interval, N_p is number of variable at the interval, $\bar{m}$ is average of the mesured data.

Limit values for the determined performance indicator are defined in many guidelines. Some of these guidelines are the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the International Performance Measurement & Verification Protocol (IPMVP) and the Federal Energy Management Program (FEMP). The limit values defined in these guidelines are shown in Table 4.10.

Table 4.10: Acceptance criteria for the calibration process [23-25].

	MBE (Hourly criteria)	MBE (Monthly criteria)	CVRMSE (Hourly criteria)	CVRMSE (Monthly criteria)
ASHRAE	10%	5%	30%	15%
FEMP	10%	5%	30%	15%
IPMVP	5%	20%	20%	-

In the study, both simulated monthly electricity consumption and simulated monthly natural gas consumption were calibrated with measured values. For the model to be considered calibrated, the monthly MBE criteria must not be more than 5% and the monthly CVRMSE criteria must not be more than 15%. MBE and CVRMSE values were calculated for the results obtained from the base line scenario, scenario 2 and scenario 3 energy models, respectively, and it was examined whether the models were calibrated or not. The graphs showing the differences between the simulated monthly electricity and natural gas consumptions and the measured values for the base line scenario energy model are shown in Figures 4.23 and 4.24, respectively.

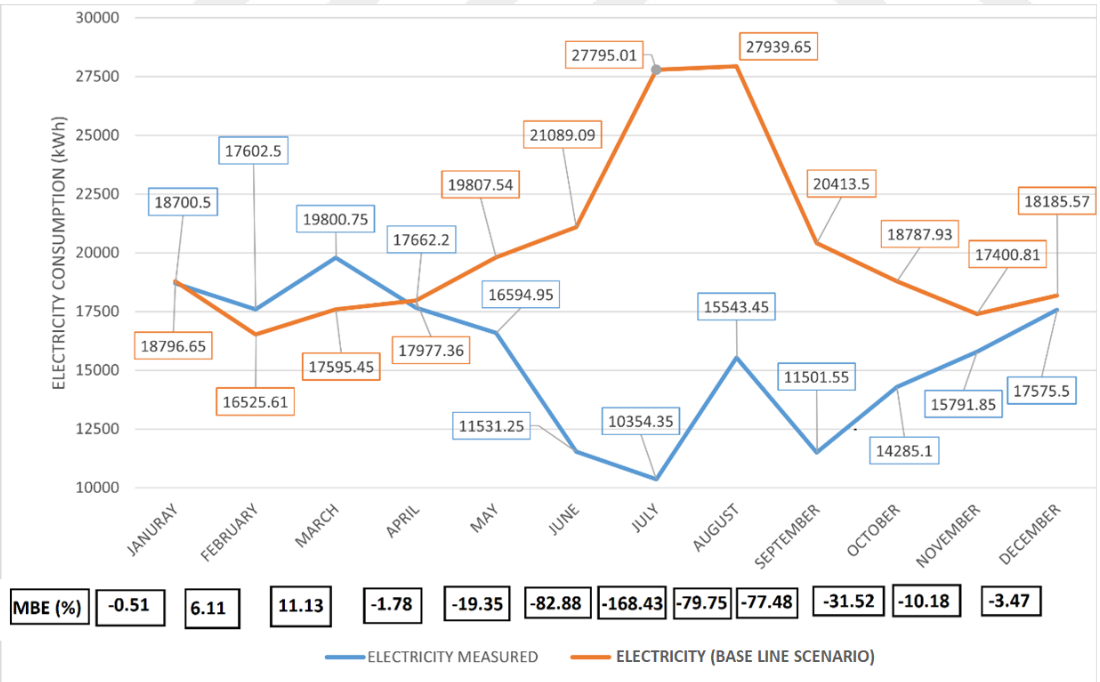

Figure 4.23: MBE check of electricity consumption of base line scenario simulation.

When Figure 4.23 is examined, it is seen that the MBE values calculated from the measured monthly electricity consumptions and simulated monthly electricity consumptions are higher than the minimum values recommended by the guidelines in nine months. Although the MBE values calculated in January, April and December were lower than 5%, this condition could not be met in all months. Especially in the summer months (June, July, August, and September) MBE values were calculated very high. It is observed that simulated electricity consumption is very high in these months.

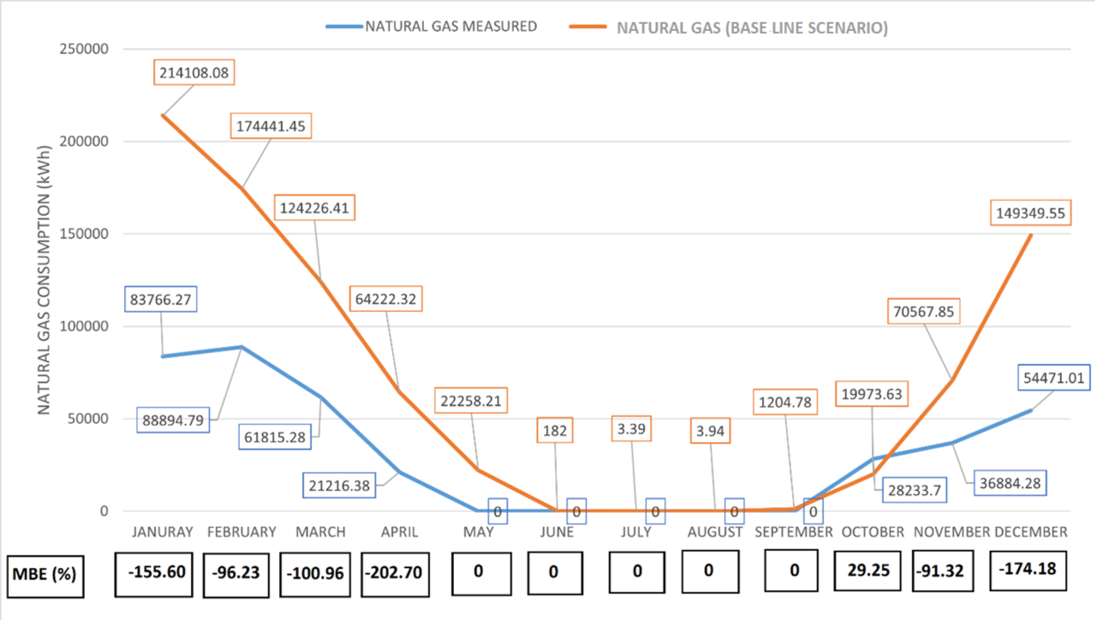

Figure 4.24: MBE check of natural gas consumption of base line scenario simulation.

When Figure 4.24 is examined, it is seen that the MBE values calculated from the measured monthly natural gas consumptions and simulated monthly natural gas consumptions are higher than the minimum values recommended by the guidelines in eight months. Although the MBE values calculated in the summer months (June, July, August, and September) were within the acceptable range, the MBE values in the other eight months increased up to -200%. As can be seen from the two graphs, the model is far from being calibrated according to the MBE values calculated based on the base line scenario energy model results.

The CVRMSE values calculated for the base line scenario are shown in Table 4.11.

Table 4.11: CVRMSE check of base line scenario simulation.

	CVRMSE
Electricity consumpton	47.90%
Natural gas consumption	186.34%

It was seen that the CVRMSE value calculated using the measured and simulated electricity consumptions was 47.90%, and the CVRMSE value calculated using the measured and simulated natural gas consumption was 186.34%. They are well above the limit value of 15% specified in different guidelines.As can be seen from the table, the model is far from being calibrated according to the CVRMSE values calculated based on the base line scenario energy model results.

Differences between the simulated monthly electricity and natural gas consumptions and the measured values for the scenario 2 energy model are shown in Figures 4.25 and 4.26, respectively. The MBE values calculated for electricity consumption are not within the range of MBE values recommended by the guidelines in any month. Because when creating scenario 2, the power density value of the interior equipment in base line scenario was increased and this caused the simulated electricity consumption to increase further and MBE values to increase. However, with fine-tuning, the electricity consumption, which showed great differences between months in base line scenario, was more balanced in scenario 2.

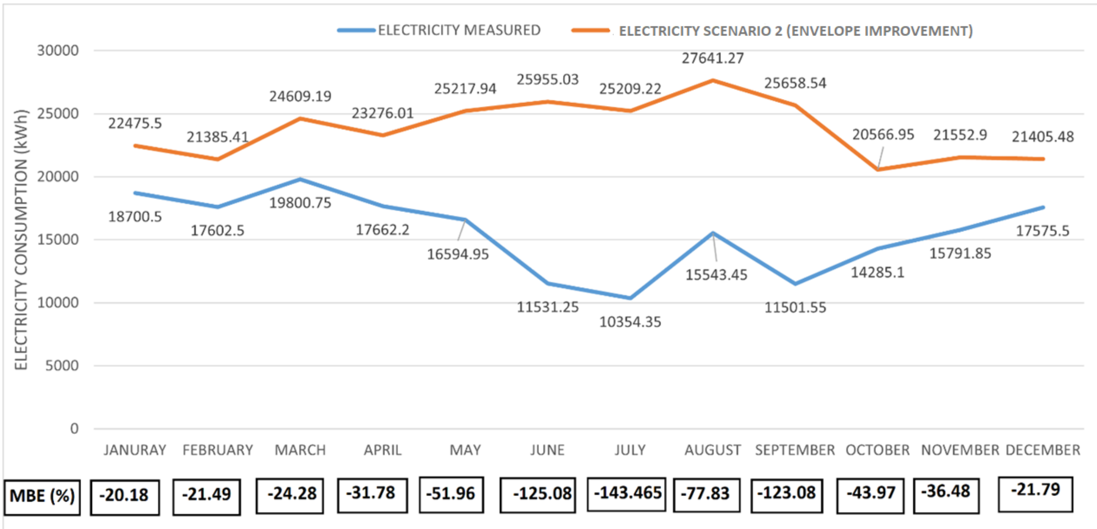

Figure 4.25: MBE check of electricity consumption of scenario 2 simulation.

When the MBE values calculated for the simulated and measured natural gas consumptions are examined, it is seen that the calculated values do not meet the calibration criteria. In common with base line scenario, the differences in consumption in June, July, August, and September are negligible. However, in other months, the MBE value increased to a maximum of 80.77%. However, in base line scenario, most of the MBE values calculated in the months outside the summer period were above 100% and reached a maximum of 200%. Considering the calculated MBE values of the months other than the summer period in scenario 2, it is clearly seen that a correct method is followed for the calibration process. As a result, it has been proven that the MBE values calculated according to the scenario 2 simulated electricity and natural gas results are still much higher than the values determined in the guidelines and the scenario 2 model cannot be considered as a calibrated model.

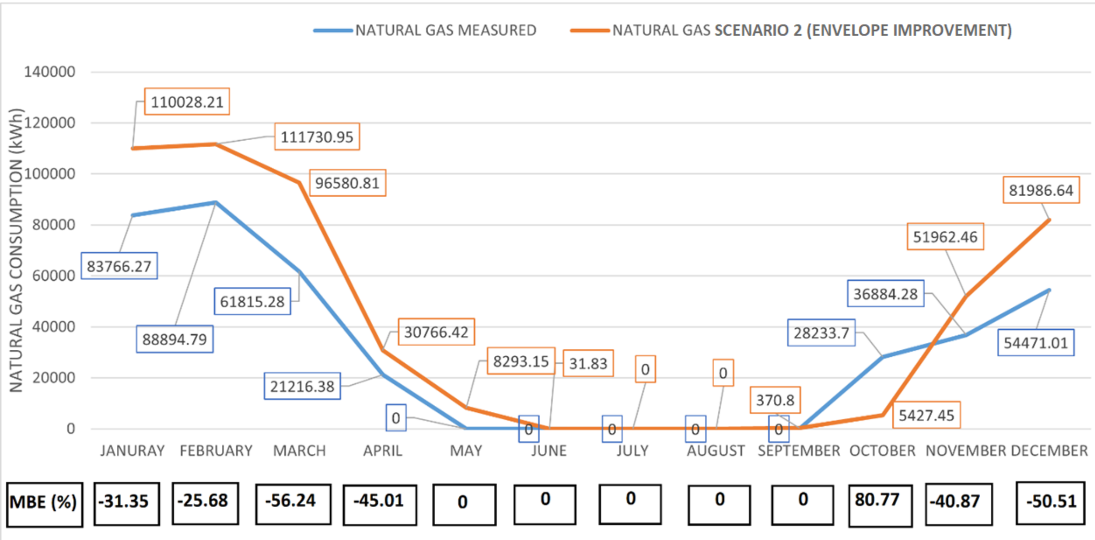

Figure 4.26: MBE check of natural gas consumption of scenario 2 simulation.

The CVRMSE values calculated for the scenario 2 are shown in Table 4.12.

Table 4.12: CVRMSE check of scenario 2 simulation.

	CVRMSE
Electricity consumption	59.19%
Natural gas consumption	58.99%

When the CVRMSE values calculated for the simulated and measured natural gas consumptions are examined, it was seen that the CVRMSE value calculated using the measured and simulated electricity consumptions was 59.19%, and the CVRMSE value calculated using the measured and simulated natural gas consumption was 58.99%. Compared to the base line scenario, a significant decrease was observed in the CVRMSE value calculated for natural gas consumption. The reason for this is the reduction of natural gas consumption with the improvements made in the thermal properties of the building envelope elements and approaching the real consumption values. Compared to the base line scenario, a slight increase was observed in the CVRMSE value calculated for electricity consumption. This is because in scenario 2 the power densities of the internal equipment have been increased and thus the difference between the measured and simulated consumptions has increased. As a result, it has been proven that the CVRMSE values calculated according to the scenario 2 simulated electricity and natural gas results are still much higher than the values determined in the guidelines and the scenario 2 model cannot be considered as a calibrated model.

Differences between the simulated monthly electricity and natural gas consumptions and the measured values for the scenario 3 energy model are shown in Figures 4.27 and 4.28, respectively. It seems that the MBE values calculated for the electricity consumption values for scenario 3 are within the range specified by the guidelines in all months. The calculated maximum MBE value is in April with -4.89%, and the minimum MBE value is in February with -0.25%. It seems that the MBE values calculated for the natural gas consumption values for scenario 3 are within the range specified by the guidelines in all months except October. Although the MBE values calculated in all other months are below 5%, the MBE calculated in October is 86%. Although the difference between the consumption values obtained from the energy model and the actual consumption values in all other months is within an acceptable range, such a large difference in October indicates a specific uncontrollable consumption in this month that did not occur in other months. The reason for the measured natural gas consumption, which is very high compared to the consumption taken from the model in October, can be explained as follows. Heating season is determined according to TS825 standard for public buildings with central heating system in Turkey. According to this determined heating season, central heating systems should be active between 15 November and 15 April. Because when the climatic conditions in Turkey are evaluated, there is usually no need for heating in buildings in October. The result from the energy model supports this fact. According to the result obtained from the energy model, the total natural gas consumption in October is only 3845.85 kWh. However, when the measured natural gas consumption is analysed, 28233.7 kWh consumption is seen in October. As a result, although the heating season has not yet started in Turkey, the heating system was activated in the sample building in October. It is quite natural that this uncontrolled and unnecessary consumption in the sample building affects the energy calibration process. Due to this unusual consumption in October, only the value calculated in October exceeds the limit values recommended by the guidelines in the MBE values calculated in the scenario 3 energy model. Since it is not possible to transfer this uncontrolled energy use in October to the model, October will be excluded from the model calibration calculations. When October is not taken into account in the calculations, the 5% MBE recommended for monthly calibration by both ASHRAE and FEMP is provided for scenario 3 electricity and natural gas consumption. scenario 3 energy model can be described as a calibrated model.

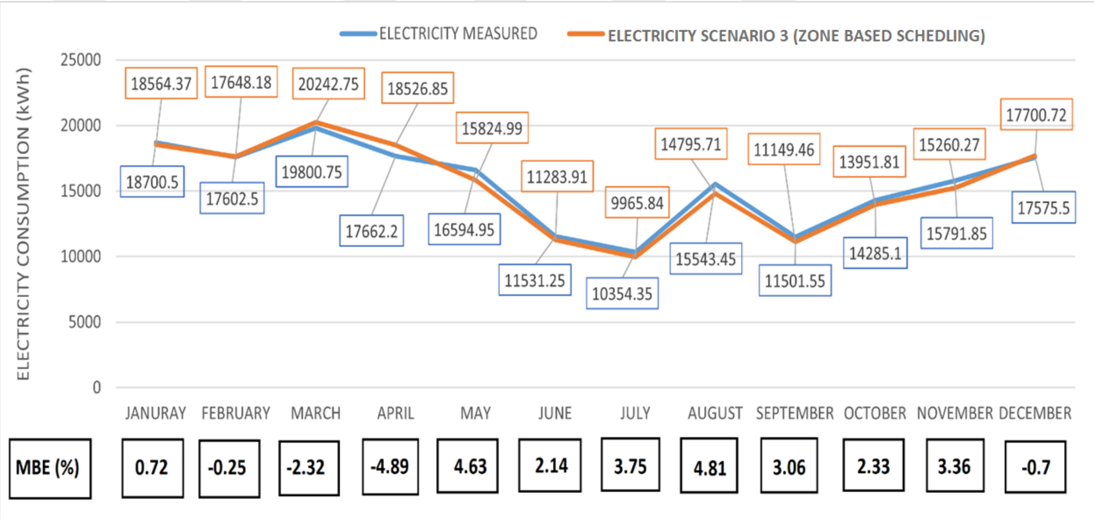

Figure 4.27: MBE check of electricity consumption of scenario 3 simulation.

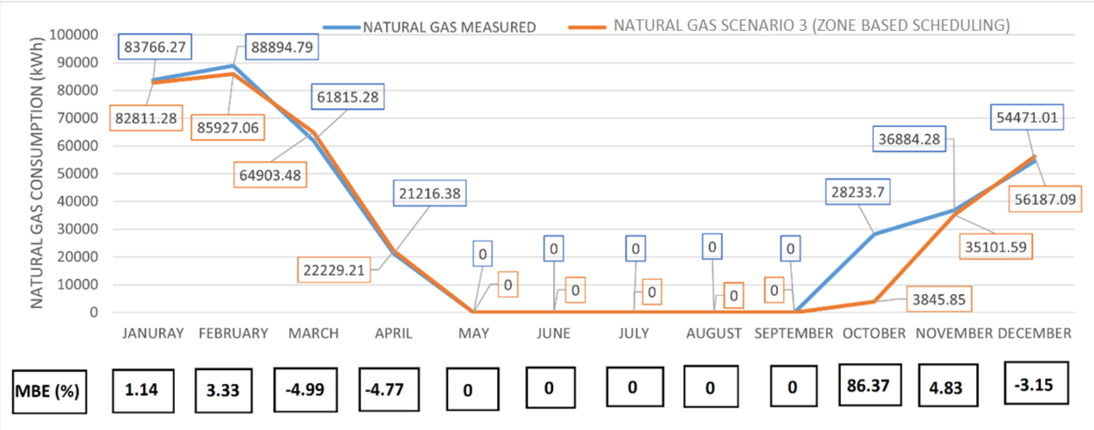

Figure 4.28: MBE check of natural gas consumption of scenario 3 simulation.

The CVRMSE values calculated for the scenario 2 are shown in Table 4.13.

Table 4.13: CVRMSE check of scenario 3 simulation.

	CVRMSE
Electricity consumpton	3.13%
Natural Gas consumption	23.00%
Natural Gas consumption (without october)	4.91 %

When the CVRMSE values calculated for the simulated and measured natural gas consumptions are examined, it was seen that the CVRMSE value calculated using the measured and simulated electricity consumptions was 3.13%, and the CVRMSE value calculated using the measured and simulated natural gas consumption was 23%. With the changes made in scenario 3, the simulated and real electricity consumptions are very close to each other. The CVRMSE value of 3.13% is below the limit value recommended by different guidelines. However, the CVRMSE value for natural gas consumption was calculated as 23%. While calculating the MBE values, it was noticed that the calibration assessment could not be provided only in October. Uncontrolled and unnecessary natural gas consumption in October caused the CVRMSE value to be higher than the value determined by the standards in the calibration assessment process. Thus, October was excluded from the CVRMSE calculations. As a result, the CVRMSE value was calculated as 4.91%. When October is not taken into account in the calculations, the 15% CVRMSE recommended for monthly calibration by both ASHRAE and FEMP is provided for scenario 3 electricity and natural gas consumption. scenario 3 energy model can be described as a calibrated model.

4.5 Improvements at the Existing Energy Profile

After calibrating the building energy model and making sure that the results obtained from the model show the real energy consumption of the building, the step of improving the existing energy profile of the building and identifying energy saving opportunities was started. First, indoor temperature measurements were carried out at 15-minute intervals over a one-month period in different functional zones in the building. Then, the minimum, maximum and average temperatures seen in four different zones for each day were determined from the one-month measurement results. These determined temperature values were defined as the heating setpoint temperatures in the energy model and the daily energy consumptions of the building were determined. Thus, four different energy consumption values were obtained for each day in the determined period. These; energy consumption at maximum temperature, energy consumption at minimum temperature, energy consumption at average temperature and energy consumption values at 20°C determined as standard. As a result, the periods in which the overheated and comfort conditions could not be met within the specified one-month period were determined. The energy savings to be obtained by eliminating the over-heating periods have been determined for each day throughout specified period. As a further improvement, the standard desired indoor temperatures for each zone were revised with reference to the ASHRAE and TS825 standards. In addition, the operating schedules of different functional zones have been revised. As a result of these changes, the energy consumption values of the building within the specified period were recalculated and the energy efficiency potential that could be obtained was revealed.

4.5.1 Measured temperature and humidity data per 15 minutes from zones

In order to improve the existing energy profile of the building, temperature and humidity measurements were made in the heated zones (office, classroom, laboratory, and corridor) within the building. Measurements were carried out for 15-minute periods during March 2023. For measurements, sample rooms from each zone group were selected and temperature measuring devices were placed in these rooms. The sample rooms where the measurements were recorded are shown on the floor plans in Figure 4.29. These rooms were chosen as measurement points, as they were thought to best reflect the characteristics and usage functions of the zones. In addition, the locations where the temperature and humidity sensors are placed within the zones are shown in Figure 4.30.

Temperature and humidity measurements in the specified zones were carried out in 15-minute periods during a 1-month period. To show the daily temperature distribution in each zone, measured data for the first day of March are shown in Figure 4.31 and Table 4.14, as it is not possible to show all the measurement data collected. The measurement data is displayed hourly from 12:00 am to 11:00 pm in the graph and table, although recorded in 15-minute periods. Because the 15-minute measurement results will greatly increase the size of tables and graphs. While generating hourly measurement results, the averages of 4 measurements taken at 15-minute intervals were calculated.

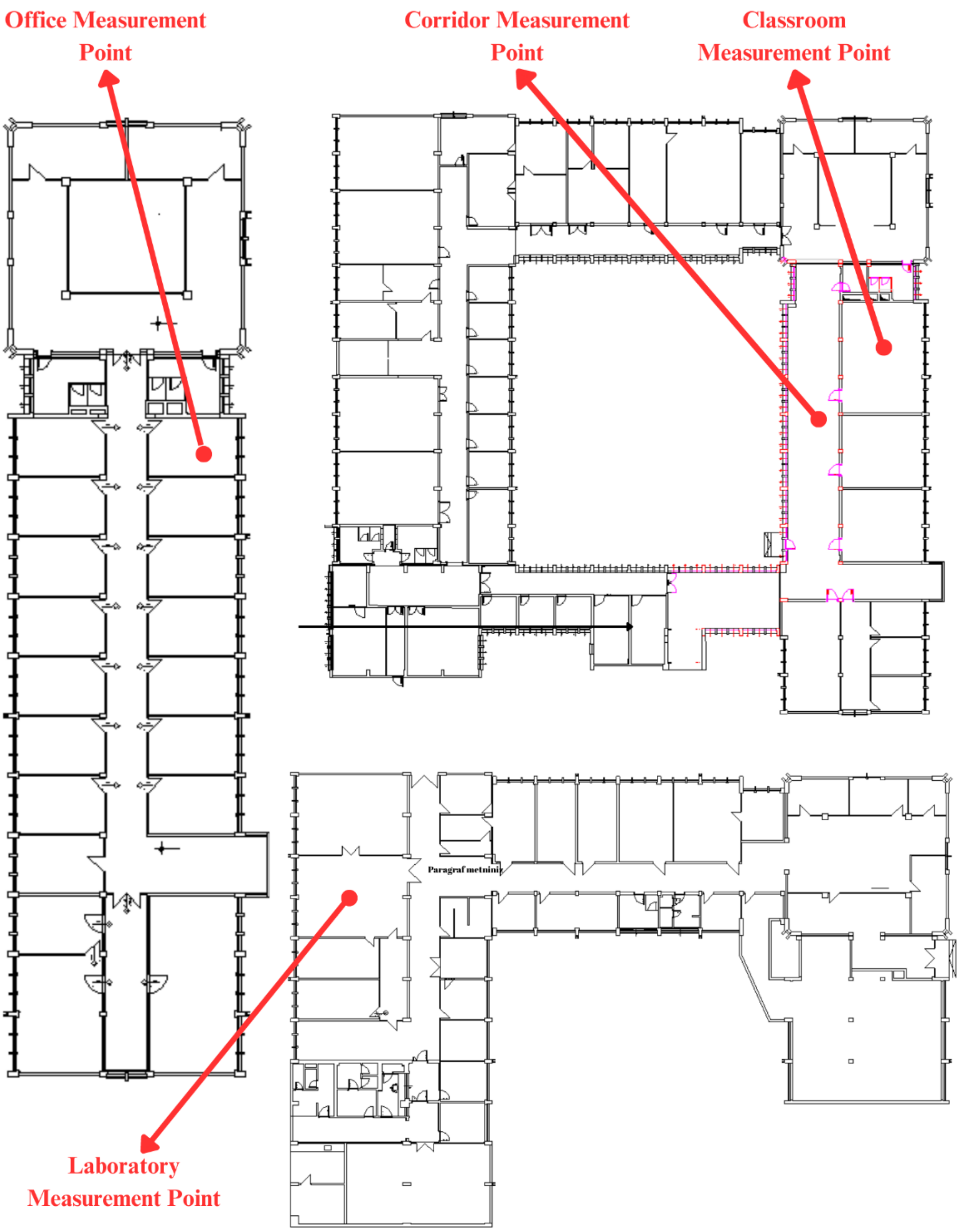

Figure 4.29: Temperature and humidity measurement points.

Figure 4.30: Locations of temperature and humidity sensors.

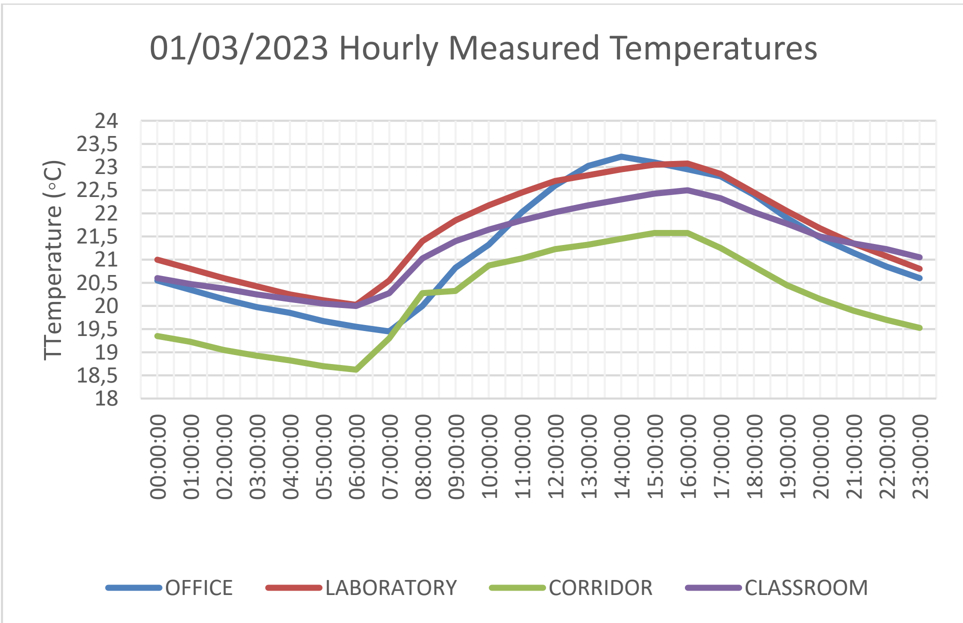

Figure 4.31: 01/03/2023 hourly mesured indoor temperatures.

Table 4.14: 01/03/2023 hourly measured indoor temperatures.

01.03.2023	Office (°C)	Laboratory (°C)	Corrıdor (°C)	Classroom (°C)
12:00 am	20.55	21	19.35	20.6
1:00 am	20.35	20.8	19.225	20.475
2:00 am	20.15	20.6	19.05	20.375
3:00 am	19.975	20.425	18.925	20.25
4:00 am	19.85	20.25	18.825	20.15
5:00 am	19.675	20.125	18.7	20.05
6:00 am	19.55	20.025	18.625	20
7:00 am	19.45	20.55	19.3	20.275
8:00 am	20	21.4	20.275	21.025
9:00 am	20.825	21.85	20.325	21.4
10:00 am	21.325	22.175	20.875	21.65
11:00 am	22.025	22.45	21.025	21.85
12:00 pm	22.6	22.7	21.225	22.025
1:00 pm	23.025	22.825	21.325	22.175
2:00 pm	23.225	22.95	21.45	22.3
3:00 pm	23.1	23.05	21.575	22.425
4:00 pm	22.95	23.075	21.575	22.5
5:00 pm	22.8	22.85	21.25	22.325
6:00 pm	22.4	22.45	20.85	22.025
7:00 pm	21.9	22.05	20.45	21.775
8:00 pm	21.475	21.675	20.15	21.5
9:00 pm	21.15	21.35	19.9	21.35
10:00 pm	20.85	21.075	19.7	21.225
11:00 pm	20.6	20.8	19.525	21.05

As can be seen from both the table and the graph, the indoor temperatures in each zone drop by about 1°C between 12 pm and 7 am. Indoor temperatures gradually rise from 7:00 am to 4:00 pm. This time range represents the working hours of all zones. All zones are occupied during this time interval. After working hours, a downward trend is observed in temperature values again until 12 am. Compared to 4 different zones, it seems that the zone with the lowest temperatures is the corridor. We can explain the reason for this as follows: corridors have more openings than other zones. The window to wall ratio on the walls of the corridors facing the inner courtyard is much higher than the other walls. Therefore, it is expected that there will be more heat loss from the corridors and thus the ambient temperatures are lower. The highest temperatures recorded in the office, laboratory, corridor, and classroom were 23.225°C, 23.075°C, 21,575°C and 22.5°C, respectively. The minimum temperatures recorded in the office, laboratory, corridor, and classroom were 19.45°C, 20.025°C, 18,625°C and 20°C, respectively.

In addition, Figure 4.32 was created to show the daily temperature distribution of each zone during the month of March when the measurement was made. In order to show the daily temperature distribution, the temperature values at 12:00 pm were selected for each day and its variation throughout March was examined.

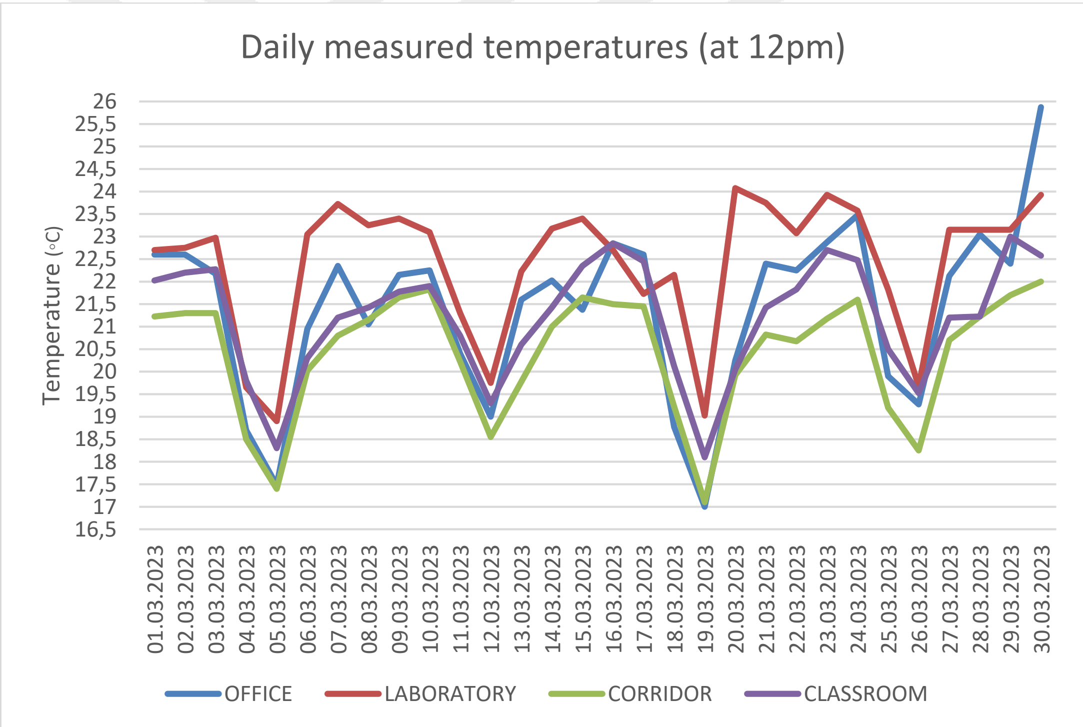

Figure 4.32: Daily measured temperatures in March (at 12pm).

Examining Figure 4.32, the monthly temperature distribution for the classroom and corridors shows a similar correlation. However, unexpected decreases and increases were observed in laboratories and offices. This situation can be explained by the usage habits of the people in the laboratories and offices. Depending on the user, the windows may be opened, and the temperature inside may be affected. It can be clearly seen in the graph that a significant decrease was observed in temperatures in all zones in eight days in May. These days are weekends. It is normal to see these drops during the weekends as the setpoint temperatures of the heating system are different during the weekends. On the last day of March, at 12:00 pm, the temperature in the office, which differs greatly from other days, rises to almost 26 °C, indicating that in addition to the central heating system of the building, the split air conditioner is used for heating purposes in this zone. These indoor temperatures collected from the building were used to create the existing energy profile of the building and then to determine the possible improvements in the existing energy profile.

To show the daily humidity distribution in each zone, measured data for the first day of March are shown in Figure 4.33 and Table 4.15.

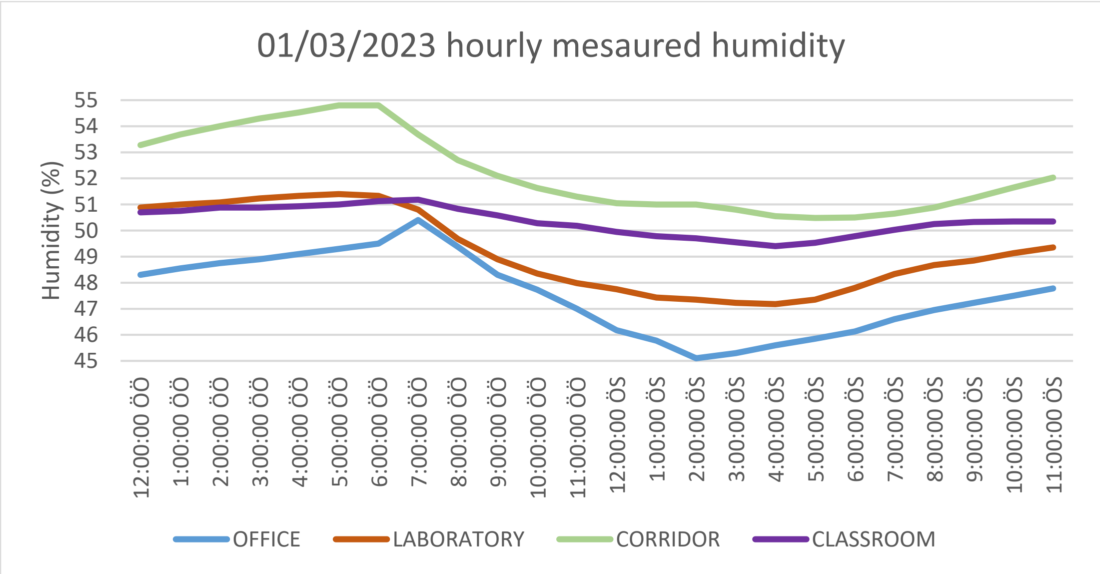

Figure 4.33: 01/03/2023 hourly measured humidity.

Table 4.15: 01/03/2023 hourly measured indoor humidity.

01.03.2023	Office (%)	Laboratory (%)	Corridor (%)	Classroom (%)
12:00 am	48.30	50.88	53.28	50.70
1:00 am	48.55	51	53.68	50.75
2:00 am	48.75	51.08	54	50.88
3:00 am	48.90	51.23	54.30	50.88
4:00 am	49.10	51.33	54.53	50.93
5:00 am	49.30	51.40	54.80	51
6:00 am	49.50	51.33	54.80	51.13
7:00 am	50.40	50.80	53.68	51.18
8:00 am	49.38	49.68	52.70	50.83
9:00 am	48.30	48.90	52.10	50.58
10:00 am	47.73	48.35	51.63	50.28
11:00 am	47	47.98	51.30	50.18
12:00 am	46.18	47.75	51.05	49.95
1:00 pm	45.78	47.43	51	49.78
2:00 pm	45.10	47.35	51	49.70
3:00 pm	45.30	47.23	50.80	49.55
4:00 pm	45.60	47.18	50.55	49.40
5:00 pm	45.85	47.35	50.48	49.53
6:00 pm	46.13	47.80	50.50	49.78
7:00 pm	46.60	48.33	50.65	50.03
8:00 pm	46.95	48.68	50.88	50.25
9:00 pm	47.23	48.85	51.25	50.33
10:00 pm	47.50	49.13	51.65	50.35
11:00 pm	47.78	49.35	52.03	50.35

As can be seen from both the table and the graph, the indoor humidities in each zone varies between 45% and 55%. The maximum humidity value was recorded in the corridor with 54.80%, and the minimum humidity value was recorded in the office with 45.10%. Similarly, the humidity value decreases between 12 am and 7 am in all zones. Afterwards, a decrease in the humidity value is observed during the working hours. After 5 pm, a slight increase in humidity values was noted again.

In addition, Figure 4.34 was created to show the daily humidity distribution of each zone during the month of March when the measurement was made. In order to show the daily humidity distribution, the humidity values at 12:00 pm were selected for each day and its variation throughout March was examined.

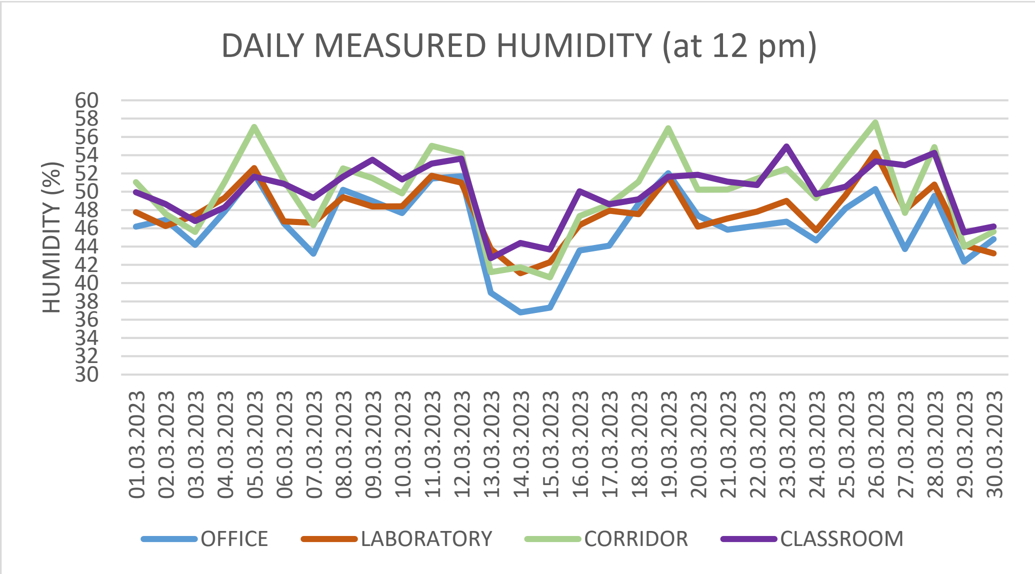

Figure 4.34: Daily measured humidity in March (at 12pm).

When Figure 4.34 is examined, it is seen that the humidity varies between 36% and 58% in all zones throughout March. Humidity was generally highest in corridors and lowest in offices. As a result of the humidity measurements, the humidity rates recorded in March in all zones provide the comfort conditions.

4.5.2 Energy profile management of building

The current energy profile of the building was obtained after the calibration process. In order to analyze the effect of the improvements to be made on the current energy profile, March, which is in the heating season, was chosen. In the central radiator system operating in the building, the desired indoor temperature is set to 20°C. However, it is understood from the measurements made in different zones that the indoor temperatures differ. It has been observed that there are periods when indoor temperatures are above or below the comfort conditions determined as 20°C. Indoor temperatures were examined to determine the periods when comfort conditions could not be achieved and the zones were overheated, and to determine the amount of waste heat caused by overheating. From the measurements made in 4 different zones (laboratory, classroom, office and corridor) from the first day of March to the last day of March, the maximum, minimum and average indoor temperature values of the zones were determined between the working hours of the building (8 am to 5 pm). The temperatures determined for the 15th day of March are given in Table 4.16 as an example.

Table 4.16: 15/03/2023 temperature mesaurement of zones.

15.03.2023	Minimum temperature (°C)	Standart temperature (°C)	Average temperature (°C)	Maximum temperature (°C)
Laboratory	20.6	20	22.82	23.4
Classroom	20.7	20	22.3	23.8
Conditioned corridor	19.7	20	21.37	21.7
Ofiice	19.4	20	21.5	23.9

As seen in Table 4.16, the temperature values in the zones decreased below 20°C in some periods of the day and the maximum measured temperature values exceeded 23°C. The average temperatures during the working hours of the building were measured as 22.82°C, 22.3°C, 21.7°C and 23.9°C for the laboratory, classroom, corridor and offices, respectively. The standard temperature value in the table represents the heating setpoint temperature that is desired in the building and defined in the energy model. The minimum, average and maximum temperatures recorded in the laboratory, classroom, corridor and office during the month of March when the building is actively used and the heating system is in operation (Monday to Friday) are given in Figures 4.35, 4.36, 4.37 and 4.38, respectively.

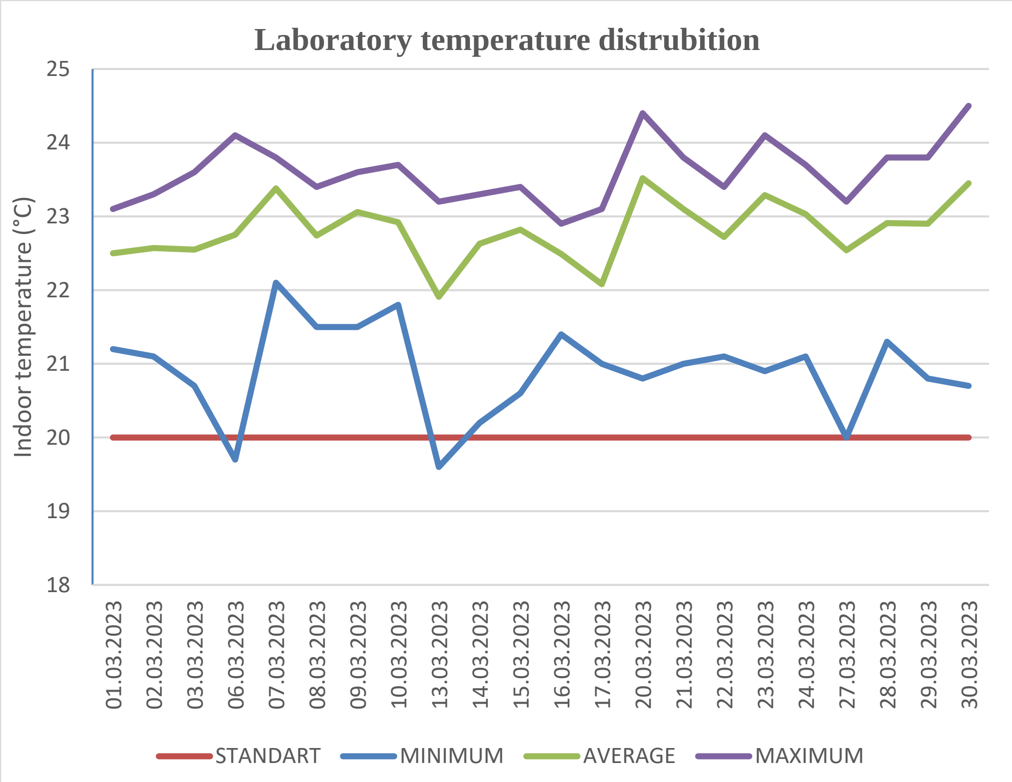

Figure 4.35: Laboratory temperature distribution.

As seen in Figure 4.35, the minimum temperature values measured in two days in March dropped below 20°C. These days are Mondays and the minimum temperature values were recorded in the morning when the heating system was newly active. This is normal considering that the heating system is out of use on weekends and it takes time for the zones to reach the desired temperature level after the heating system starts operating on Mondays. It is understood that the minimum temperatures are higher than 21°C, the average temperatures are higher than 22°C and the maximum temperatures are higher than 24°C on weekdays. Although the periods in which comfort conditions cannot be met are very few, overheated periods appear every day.

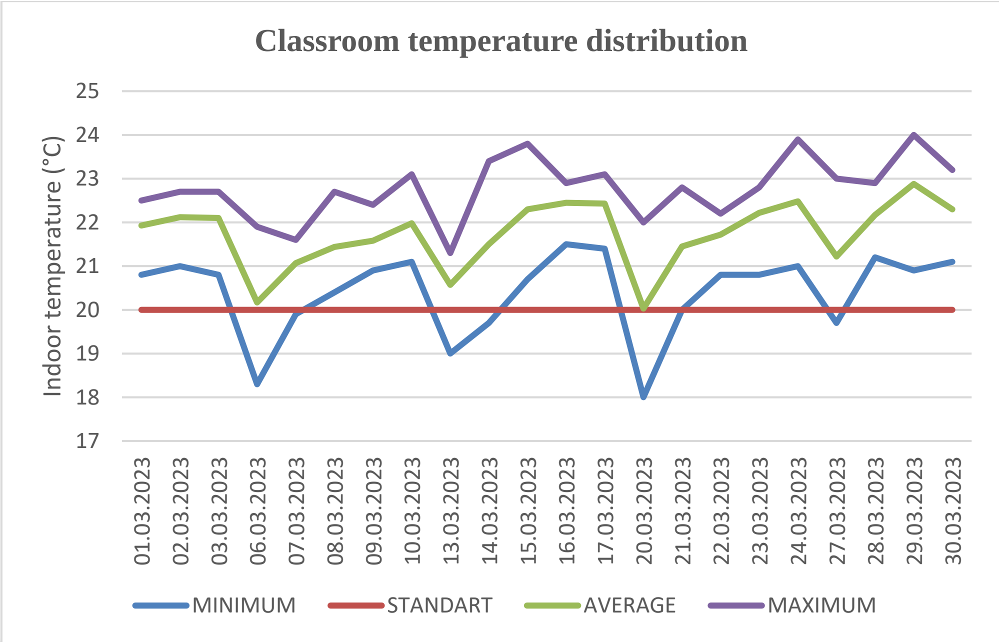

Figure 4.36: Classroom temperature distribution.

As seen in Figure 4.36, similar to the temperature distribution in the laboratory, the four days where the temperature drops below 20°C in the classroom are Mondays. The fact that indoor temperatures have reached 24°C indicates that there are overhating periods in the classrooms.

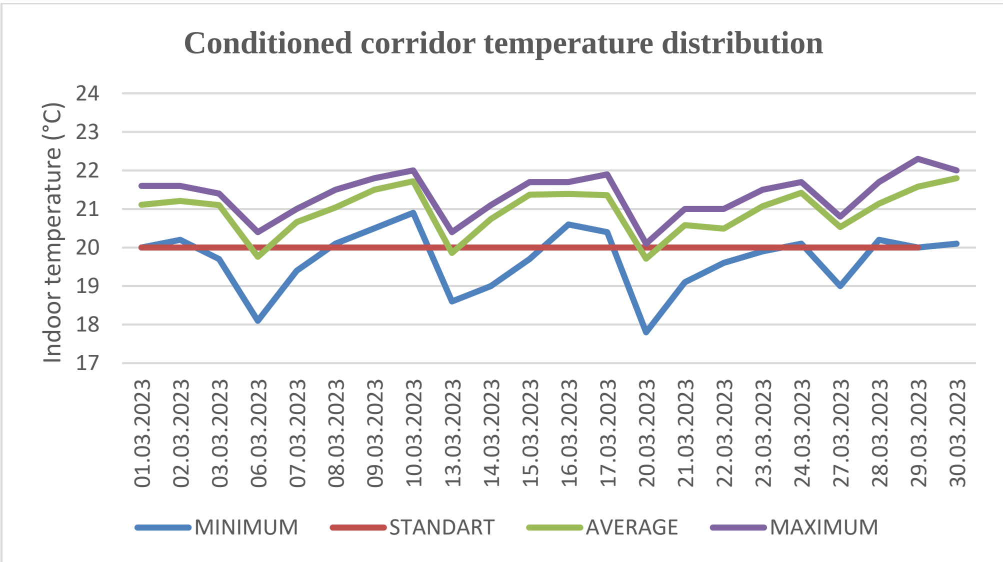

Figure 4.37: Conditioned corridor temperature distribution.

As seen in Figure 4.37, the temperature distribution in the corridor is also similar to other zones. The fact that the maximum temperatures recorded in the corridor are below 22 °C except for one day can be explained by the fact that there are too many windows and doors in the corridors and the heat losses from these areas are higher than the other zones. It has been understood that the overheated periods are less in the corridors and the energy savings that can be obtained from these zones are less compared to other zones.

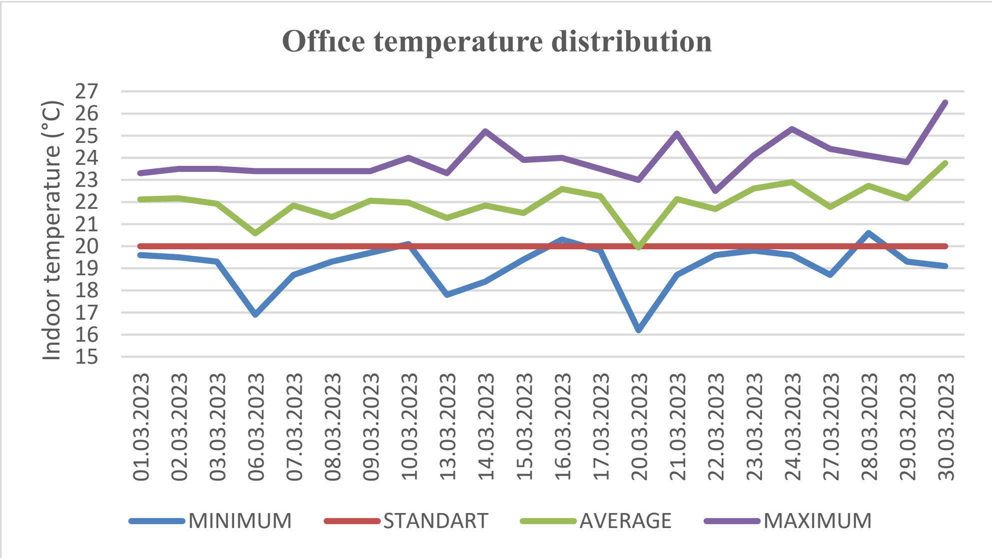

Figure 4.38: Office temperature distribution.

As seen in Figure 4.38, The minimum temperature measured almost every day has fallen below 20°C. The fact that the users prefer to open the windows for natural ventilation in the offices ensures that the ambient temperatures sometimes fall below the comfort conditions. In addition, the fact that the maximum temperatures are higher than the other zones shows that the split . It is clear that there are more overheated periods in offices and more energy efficiency can be achieved by controlling the temperature in these zones.

4.5.2.1 Energy efficiency potential of building by controling heating setpoint temperature of each zone

The minimum, average and maximum temperatures given for each zone in section 4.5.2 are set as the heating setpoint temperature for those zones. The energy model was simulated again for each day with these heating setpoint temperatures. As a result, the daily energy consumption values of the building during the month of March were calculated for four different cases. These four different cases are as follows:

- The heating setpoint temperatures of the zones are equal to the minimum recorded temperature in that zone.

- The heating setpoint temperatures of the zones are equal to the average of the temperature recorded in that zone during the operating hours.
- The heating setpoint temperatures of the zones are equal to the maximum recorded temperature in that zone.
- The heating setpoint temperatures of the zones are equal to 20°C, which is the desired comfort condition.

When the minimum temperatures recorded in the zones are set as the heating setpoint temperatures, the energy consumption values will not change much because the minimum temperatures are just below and just above the 20°C which is desired comfort temperature. Setting the average temperatures recorded in the zones as the heating setpoint temperature will give the closest results to the actual energy consumption values of the building. When the results obtained from here are compared with the scenario where the heating setpoint temperature is 20°C in all zones, the amount of energy savings that can be achieved will be determined. When the maximum temperatures recorded in the zones are set as the heating setpoint temperatures, the daily energy consumption of the building will increase as the maximum recorded temperatures are fairly above 20 °C. The results from this scenario will reveal the maximum waste heat potential that may occur in these zones, since the determined zones are not at these maximum temperatures during all operational hours. Indoor temperatures in all zones are required to be 20°C during operation hours. In order to achieve this, the heating system should be automated and should operate integrated with the indoor temperatures in the zones. Thus, not only the periods in which comfort conditions are not met during the operation hours will be eliminated, but also the periods in which overheating will be eliminated. The daily energy consumption values obtained from the simulations when the above-determined temperatures are set as the heating setpoint temperature are shown in Figure 4.39.

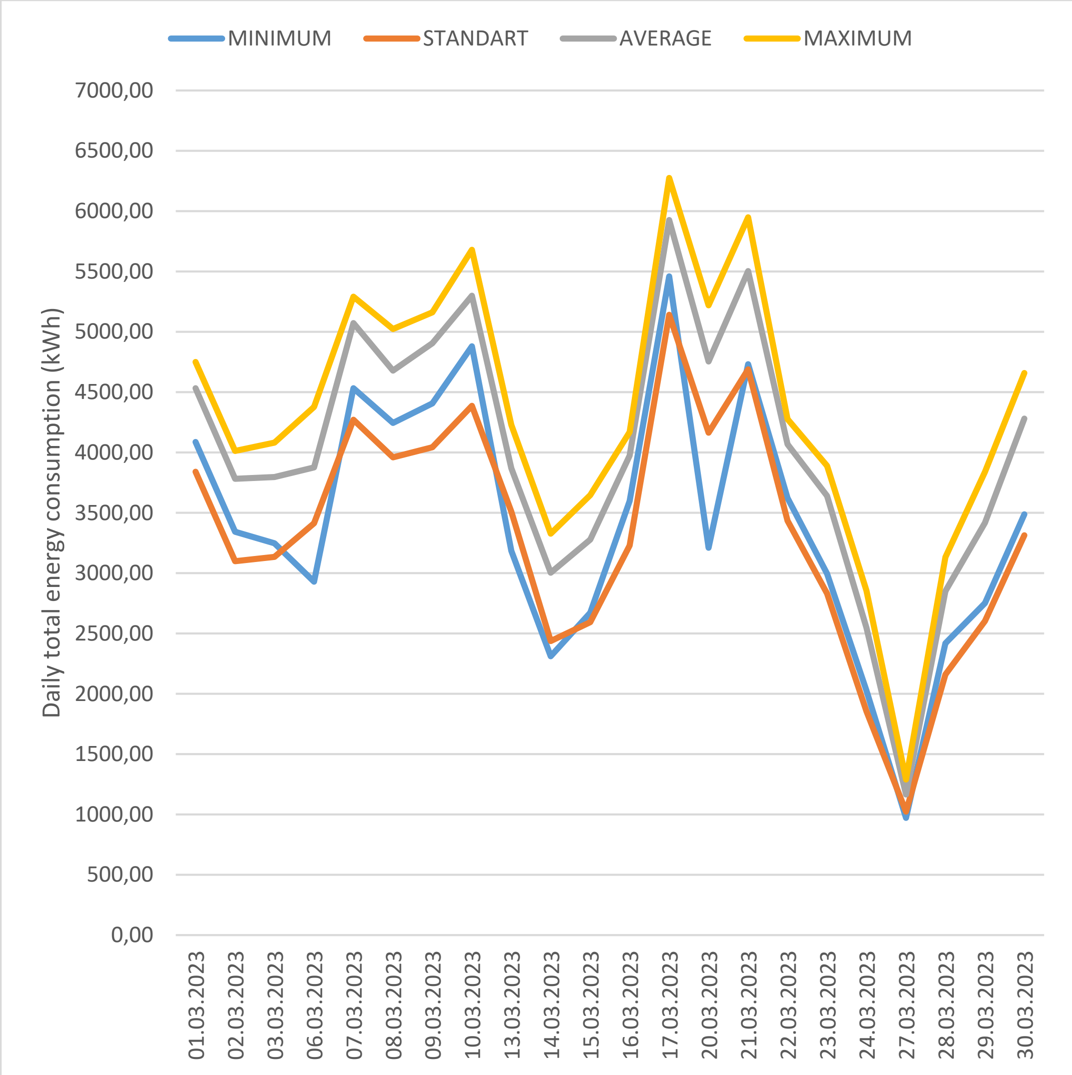

Figure 4.39: Daily energy consumption of building with different heating setpoint temperatures.

As seen in Figure 4.39, there is no big difference in energy consumption between the scenario where the minimum temperatures determined in the zones are set as heating setpoint temperature and the scenario where all zones are kept constant at 20°C. However, when the heating setpoint temperatures are adjusted by considering the average and maximum temperatures, it is seen that the energy consumption increases gradually. It is understood from the fluctuations in the graph that there have been increases and decreases in outdoor temperatures on different days during March, and parallel to this, the energy consumption of the building has also changed.

Comparison of energy consumption of building in March with different heating setpoint temperatures is given in Table 4.17.

Table 4.17: Comparison of energy consumption of building in March with different heating setpoint temperatures.

Heating setpoint temperatures	Monthly energy consumption (kwh)	Energy saving (%)
Standart	73122.89	-
Minimum	75105.97	2.64
Average	88213.56	17.10
Maximum	95126.91	23.13

As can be seen from Table 4.17, when the heating setpoint temperature is set to 20°C in all zones, the total consumption in March is 73122.89 kWh. When the standard heating setpoint temperature of 20°C is replaced with the minimum temperatures measured in the zones, the total energy consumption becomes 75105.97 kWh. When the heating setpoint temperatures are replaced by the average and maximum temperatures measured in the zones, respectively, the total energy consumption is 88213.56 kWh and 95126.91 kWh. It was previously stated that the scenario that best reflects the actual consumption of the building is the scenario where the average temperatures are set as the heating setpoint temperature. As a result, it has been proven that 17% energy efficiency can be achieved with the automation system that will ensure that the building heating system keeps the temperature at the desired level by controlling the indoor temperatures in the zones. When the maximum indoor temperatures in the zones are set as the heating setpoint, the energy consumption of 95126.91 kWh obtained from the simulation shows the maximum energy level that the sample building can potentially consume. It has been shown that potentially 23% energy efficiency can be achieved by eliminating overheating periods.

4.5.2.2 Energy efficiency potential of building by considering zone-based scheduling

While creating the current energy profile of the building, the heating setpoint temperatures of all functional zones were the same and set to 20°C. In addition, occupancy, lightning, interior equipment and heating system schedules in all zones were defined to be active between 8 am and 5 pm on weekdays. It has been understood that the desired indoor temperatures in different zones in the building and the operational time tables of different zones may differ. Firstly, in order to see the effect of zone-based scheduling of occupancy, interior equipment, lighting and heating systems on energy consumption, the zones are grouped according to their operating profiles. It is known that the laboratories, classrooms, corridors and some offices in the building are in active use between 9:30 and 16:30 on weekdays. Since the selected sample building is the education building, the lessons are held between the specified hours. Thus, outside of these hours, not conditioning and lighting the laboratories, classrooms, corridors and lecturers' offices and not operating energy-consuming equipment will have a great impact on energy consumption. Occupancy, ligthning, heating system and interior equipment schedule of specified zones is shown in Figure 4.40.

Profiles

M...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Off	Off	Off	Off	Off	Off	Off
Feb	Off	Off	Off	Off	Off	Off	Off
Mar	9:30 - 16:30	9:30 - 16:30	9:30 - 16:30	9:30 - 16:30	9:30 - 16:30	Off	Off
Apr	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	Off	Off	Off	Off	Off	Off	Off
Dec	Off	Off	Off	Off	Off	Off	Off

Figure 4.40: Occupancy, lightning, heating system and interior equipment schedule of zones.

Except for the zones mentioned above, the scheduling of the offices, which are actively used all day on weekdays, has not been changed and has been left as 8 am to 5 pm.

Secondly, considering that the desired comfort conditions may differ in different zones, national and international guidelines were taken as reference for the changes to be made. The graph created to determine the comfort conditions according to the ASHRAE standard is given in Figure 4.41.

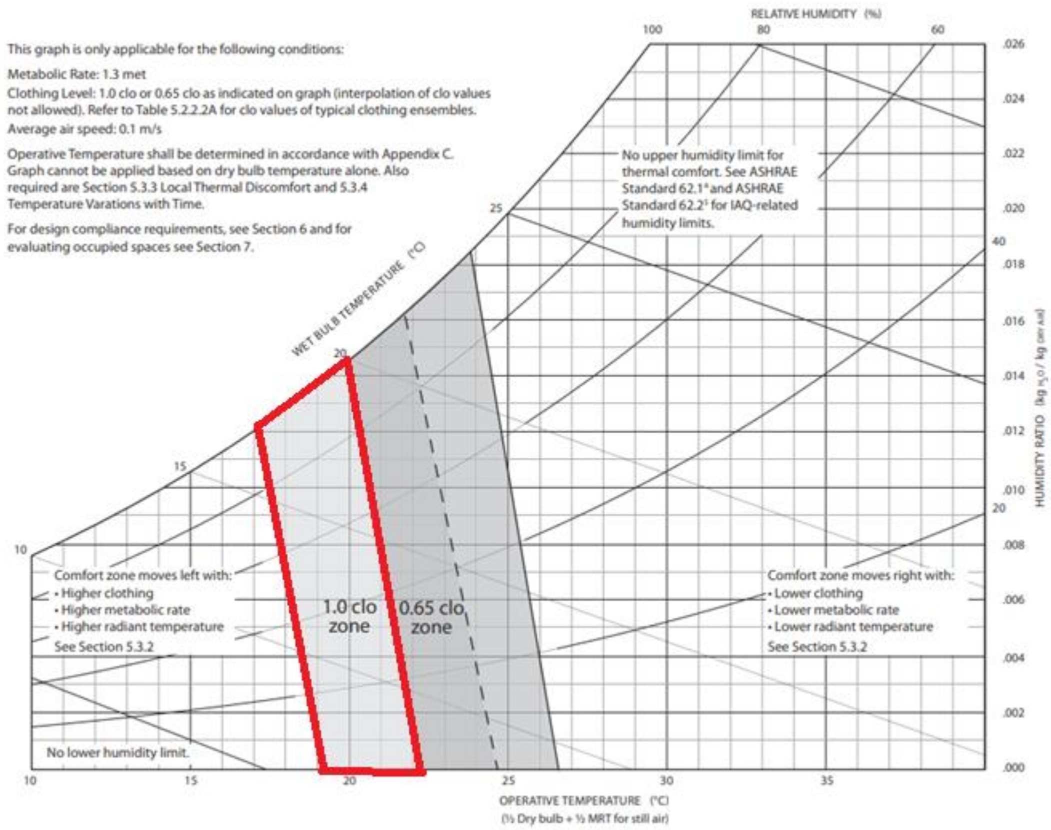

Figure 4.41: Analytical comfort zone method diagram [26].

As can be seen from Figure 4.41, according to ASHRAE 55 guideline, heating setpoint temperature could be depend on the methabolic rates, clothing factor, humidity and air velocity. Metabolic rate was accepted as 1.3 met, clothing factor 1.0 clo and average air speed 0.1 m/s in the selected training building to determine the comfort conditions by using the graph. On top of that, acceptable heating setpoint temperature is between 19°C and 22°C. Since the sample building is located in Türkiye, the indoor temperatures of the buildings used for different purposes recommended in the national standard TS825 are given in Table 4.18.

Table 4.18: Average temperature values to be used in calculations for buildings used for different purposes [20].

Building to be Heated	Temperature (°C)
Administration Buildings	19
Service Buildings	19
Educational Buildings	20

According to TSE 825, 19°C can be tolerated for laboratories and offices in Türkiye conditions. Therefore, by examining both national and international standards, the heating setpoint temperature was kept constant at 20 °C in the classrooms, but it was reduced to 19 °C in offices, laboratories and corridors.

In order to see the effects of zone-based scheduling and zone-based comfort conditions on energy consumption, the changes described above were transferred to the energy model and daily energy consumption values were recalculated in March. The daily energy consumption values obtained from the energy simulation in which zone-based scheduling and zone-based comfort conditions are adjusted are given in Figure 4.42. The zone based curve shown with the green line represents the energy consumption when zone-based scheduling and zone-based comfort conditions are set.

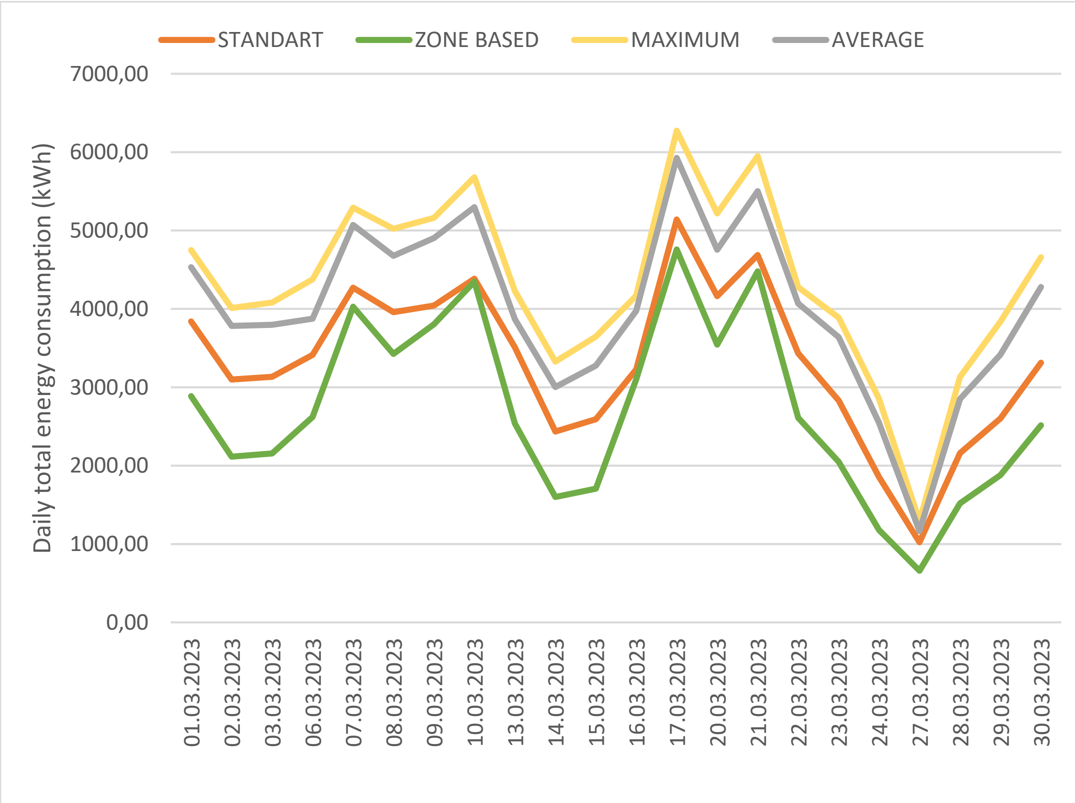

Figure 4.42: Daily energy consumption of building with zone-based scheduling and zone-based comfort conditions.

The curves shown in orange, gray and yellow represent the cases where the heating set temperature for all zones is 20°C, the case where the average temperatures recorded from the zones are defined as the heating set temperature, and the case where maximum temperatures recorded from the zones are defined as the heating set points resectively. It is clearly seen that by defining zone-based scheduling and zone-based comfort conditions, the daily energy consumption of the building has been reduced. With the re-schedulings made in different zones, the working hours of lighting, heating, and interior equipment in some zones were reduced, and the desired temperature value in some zones was reduced with the comfort conditions determined on a zone basis. The monthly total energy consumption in four different case is given in Table 4.19.

Table 4.19: Comparison of energy consumptions of building in different cases.

Heating setpoint temperatures (°C)	Monthly energy consumption (kwh)	Energy saving (%)
Zone based	59525.41	-
Standart	73122.89	18. 59
Average	88213.56	32.52
Maximum	95126.91	37.42

As can be seen from Table 4.19, when the zone based scheduling and zone based heating setpoint temperature are adjusted , the total consumption in March is 59525.41 kWh. When the heating setpoint temperature is set to 20°C in all zones, the total consumption in March is 73122.89 kWh. When the heating setpoint temperatures are replaced by the average and maximum temperatures measured in the zones, respectively, the total energy consumption is 88213.56 kWh and 95126.91 kWh. In the model created by determining zone-based scheduling and zone-based comfort conditions, 18.59% energy efficiency was achieved when compared to the scenario where the heating setpoint temperature is 20°C in all zones. When it was compared to the scenario where the indoor average temperatures are set as the heating setpoint temperature, which is the scenario that best reflects the current energy profile of the building, 32.52% energy efficiency has been achieved. When the maximum indoor temperatures in the zones are set as the heating setpoint, the energy consumption of 95126.91 kWh obtained from the simulation shows the maximum energy level that the sample building can potentially consume. It has been shown that potentially 37.42% energy efficiency can be achieved by eliminating overheating periods.

5. CONCLUSION AND DISCUSSION

In this thesis, the energy efficiency that can be obtained by dynamic simulation of a calibrated energy model has been determined. Systematic energy management strategies have been determined for the zones in the building for the improvements to be made in the existing energy profile of the building. The common goal in the determined strategies is to eliminate the overheated periods and to ensure that the indoor temperatures are not higher than the specified comfort conditions. For this purpose, it has been focused on determining zone-based comfort conditions and zone-based scheduling of building systems. In order to achieve energy efficiency by eliminating overheated periods, the necessity of an integrated operation of the building's heating system by controlling the indoor temperatures in the zones is explained. The effect of keeping the temperature at the desired comfort conditions on the energy consumption by controlling the indoor temperatures at certain periods with an automated heating system has been demonstrated.

First of all, an energy model was created in the computer environment of the education building selected as a sample building. In order to prove that the results obtained from the created energy model are reliable, the energy model has been calibrated using the monthly energy consumption values of the building. According to the results from the first energy model created before the calibration process, the annual energy consumption of the building was 1082855.78 kWh. However, it was known that the real annual energy consumption of the building was 562225.66 kWh. In order to ensure that the results obtained from the energy model match the actual results, the energy model was first fine-tuned. The U values of the roof and windows, infiltration rate and power density of interior equipment values were redefined and the model was simulated again. The annual energy consumption value taken from this simulation, called scenario 2, is 782132.16 kWh. Since the results still do not agreeably match the actual values, the scenario 3 energy model was created. The occupancy, ligthning system, heating system and interior equipment schedulings, which were previously defined in the same way in all zones, were defined on a zone basis. With zone-based scheduling, the simulated energy consumption value in scenario 3 is very close to the real energy consumption with 535920.42 kWh. Mean bias error (MBE) and cumulative variation of root mean squared error (CVRMSE) values as a performance indicator were calculated on a monthly basis in order to understand whether the model has been calibrated with the revisions and changes made in the energy model. In base line scenario, it has been shown that the monthly calculated MBE and CVRMSE values for both electricity and natural gas consumption are much higher than the limit values recommended by the guidelines. Even with improvements in MBE and CVRMSE values in scenario 2, the energy model is still far from being calibrated. Finally in scenario 3 energy model, MBE values calculated for electricity consumption are below 5% in all months and CVRMSE value is below 15%. In the MBE values calculated for natural gas consumptions, all values remained below 5% except for October and CVRMSE value is slightly more than %15. Although it was suggested that central heating systems should not be active yet according to TS825 standards in Türkiye conditions in October, the heating system was actively used in the building in October. The energy consumption due to the activation of the heating system before the heating need arises explains the MBE value, which is much higher than expected in October. Assuming that October is not taken into account in the calculations, the scenario 3 energy model has been proven to be the calibrated model.

After making sure that the energy model was calibrated, possible improvements to the existing energy profile were evaluated. In order to improve the energy model, two main factors were taken into account. These are zone-based heating setpoint temperature and zone-based scheduling. In the calibrated energy model, the desired comfort temperature for all zones was determined as 20°C. In order to understand whether the temperatures in the zones are really 20°C or not, temperature measurements were made in 15-minute periods from four zones with different functions in the building throughout the month of March. It has been seen from the measurement results that the temperature in the zones varies during the day. The minimum, average and maximum temperature values in each zone were determined for each day of the measurements. Minimum, average and maximum temperature values were used to determine the amount of waste heat caused by overheating and the periods when comfort conditions could not be met.

First, a series of simulations were performed by setting the minimum, average and maximum temperature values recorded during the day in each zone as the heating setpoint temperature for that day. It should be said that the scenario where the heating setpoint temperature values are defined as the average indoor temperature values best reflects the real energy profile of the building. Because the zones have not always remained constant at minimum and temperature values during the day. The energy consumption values obtained as a result of setting the recorded maximum temperatures as heating setpoint temperature also helped us to predict the maximum amount of energy that the building could potentially consume.

Secondly, considering that the desired comfort conditions in all zones may differ from each other, the ASHRAE standard was examined first. While determining the comfort conditions according to the ASHRAE standard, 19°C -23°C are given as limit values. In addition, considering the conditions in Türkiye, it was stated that 19 °C can be accepted as a comfort condition in offices, laboratories and corridors according to the TS825 standard. Thus, the heating setpoint temperature was revised to 19 °C for offices, laboratories and corridors and 20°C for classrooms. In addition, it is known that classrooms, laboratories, corridors and some offices are not actively used throughout the day during the specified period. Considering that these zones do not need to be heated and illuminated during periods when they are not actively used, the operating periods of the building systems in these zones have been changed from 8:00-17:00 to 9:30-16:30.

The energy efficiencies achieved during the creation of the calibrated energy model are listed below.

- In the energy model created as scenario 2, unlike base line scenario, the U values of the roof and windows, which are the building envelope elements, were improved. Also, the infiltration rate and power density of interior equipment have been improved. As a result, the total energy consumption has been reduced from 1082855.78 kWh to 782132.16 kWh and it has been proven that 27% energy efficiency can be achieved.
- In the energy model created as scenario 3, the scheduling of the occupancy, lighting system, heating system, cooling system and interior equipment are determined on a zone basis. With zone-based scheduling, the total energy consumption was reduced from 782132.16 kWh to 535920.42 kWh and 31% energy efficiency was achieved.

The energy efficiencies obtained in the current energy profile of the building with zone-based energy management in the building are listed below.

- Although the heating setpoint temperature was determined as 20 °C in the heating system used in the building, it was understood that the temperatures were higher in the measurement zones. The total energy consumption during March was calculated as 88213.56 kWh from the energy model created by adjusting the daily average temperatures recorded in the zones as the heating setpoint temperature of that day. This scenario most closely represents the current energy profile of the building. When an automatized heating system is used to keep the comfort conditions in the zones at the desired level (20°C), the energy consumption of the building becomes 73122.89 kWh. Thus, it has been proven that 17% energy efficiency can be achieved.
- The monthly total consumption is 95126.91 kWh, according to the energy model created by adjusting the heating setpoint temperature for that day with the maximum temperature values recorded during the day in the zones. Even if this scenario does not show the actual energy consumption profile of the building, it gives the maximum energy value that the building can potentially consume. It has been proven that 23% energy efficiency can be achieved with the use of an automated heating system.
- In the scenario created by determining zone-based scheduling and zone-based comfort conditions, the total energy consumption value is 59525.41 kWh. It is possible to achieve 18% energy efficiency according to the energy consumption value when the comfort conditions in all zones are 20 °C and the working periods of all zones are the same.
- When the scenario in which zone-based scheduling and comfort conditions are determined, the total energy consumption has been reduced from 88213.56 kWh to 59525.41 kWh and it has been proven that 32% energy efficiency can be achieved, when compared to the scenario where the average temperatures measured in the zones are set as heating setpoint temperature.
- The monthly total consumption is 95126.91 kWh, according to the energy model created by adjusting the heating setpoint temperature for that day with the maximum temperature values recorded during the day in the zones. Even if this scenario does not show the actual energy consumption profile of the

building, it gives the maximum energy value that the building can potentially consume. It has been proven that 37% energy efficiency can be achieved with the integration of an automated heating system and zone-based scheduling and comfort condition.

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