ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

CALIBRATING THE BUILDING ENERGY MODEL BY INVESTIGATING DIFFERENT CONTROL STRATEGIES TO IMPROVE THE EFFECT OF AUTOMATION SYSTEM

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

OTOMASYON SİSTEMİNİN ETKİSİNİ İYİLEŞTİRMEK İÇİN FARKLI KONTROL STRATEJİLERİNİN İNCELENMESİ İLE BİNA ENERJİ MODELİNİN KALİBRASYONU

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Fatih TÜYSÜZ, a M.Sc. student of ITU Institute of Energy student ID 301171015, successfully defended the thesis entitled "CALIBRATING THE BUILDING ENERGY MODEL BY INVESTIGATING DIFFERENT CONTROL STRATEGIES TO IMPROVE THE EFFECT OF AUTOMATION SYSTEM", 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 family and friends,

FOREWORD

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ABBREVIATIONS

ASHP	**:** Air Source Heat Pump
ASHRAE	**:** American Society of Heating Refrigerating and Air Conditioning Engineers
CDD	**:** Cooling Degree Days
COP	**:** Coefficient of Performance
CVRMSE	**:** Cumulative Variation of Root Maean Squarred Error
DSHP	**:** Dual Source Heat Pump
ECM	**:** Energy Conservation Measures
EER	**:** Energy Efficiency Ratio
EF	**:** Energy Factor
FEMP	**:** Federal Energy Management Program
GOF	**:** Goodnes of Fit
HAGHE	**:** Horizontal Air-Ground Heat Exchanger
HDD	**:** Heating Degree Days
HVAC	**:** Heating Ventilating and Air Conditioning
ICT	**:** Information and Communication Technology
IPMVP	**:** International Performance Measurement and Verification Protocol
MBE	**:** Mean Bias Error
MPC	**:** Model Predictive Control
PI	**:** Proportional Integral
RBC	**:** Rule-based Control
ROV	**:** Range of Variation
SPF	**:** Seasonal Performance Factor
TRNSYS	**:** Transient System Simulation Tool
WSHP	**:** Water Source Heat Pump

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CALIBRATING THE BUILDING ENERGY MODEL BY INVESTIGATING DIFFERENT CONTROL STRATEGIES TO IMPROVE THE EFFECT OF AUTOMATION SYSTEM

SUMMARY

In this thesis, the energy performance of a case study building, including the heating and cooling systems, was investigated by integrating different automation control strategies. At the same time, calibration of the generated energy model of the case study building, by using real measurements from the actual building, was also performed. The case study building was a large-scale residential building located in Kartal, Istanbul. It was designed for serving to elderly people and completed in 2005. After 7 years of use, the building was considered to be inefficient in terms of energy performance and decided to be retrofitted to make it more efficient. Therefore, several Energy Conservation Measures (ECMs), including insulation, efficient mechanical systems, automation system were applied to the building, and with the aim of seeing the effects of each ECM individually, the energy model of the building was created. Thus, by using this model, information about the energy performance of the retrofitted building was obtained, and the effects have been observed by applying different scenarios.

The aim of this study was to propose a methodology that would enable, both obtaining the energy savings by applying different control strategies to the automation systems, and the calibration of the generated energy model by using the energy consumptions measured from the building. For this purpose, a comprehensive methodology consisting of three main sections has been developed, and the case study building was investigated by following this methodology.

In the first case of the study, three different control strategy scenarios which were called base-case, Information and Communication Technology (ICT) and fuzzy, to enable to control the ASHP, WSHP and boiler which provide heating and cooling energy for the building, were examined. The base-case scenario is a simple scenario that controls when the mechanical systems of the building will be activated or deactivated, depending on the outlet water temperature of the solar collectors. The second scenario, ICT, is similar to the first one, but, unlike, the number of inputs has been increased to two. The additional input was outside air temperature. With the increased number of inputs, the provision of control of the system has become more customizable. It was aimed to improve the energy performance with the use of this customization capability. In the fuzzy scenario, the control strategy was taken a little further, and was intended to provide a dynamic control. To perform this, a fuzzy logic system that operates depending on the outlet water temperature of the solar collector and inside air temperature and controls the set-point temperature in hourly basis, has been developed. Besides, a second fuzzy strategy was applied. In the second case, the input variables were outside and indoor temperature. Finally, the heating and cooling energy consumptions of each scenario were compared and achieved energy savings were represented. But it should be noted that these results were obtained from the non-calibrated model.

Second case of the study was performed with the aim of dealing with the calibration of the case study building' energy model, in terms of heating and cooling energy consumptions. The heating and cooling energy consumptions required to perform this process was measured hourly. The measurements started in early 2018 and lasted until early December. But, due to renovation works until end of the May, there was no one in the building until beginning of June. Therefore, the measurements covering this period were not useful. As a result, the data from June to early December was used for calibration. Two different error indicators, Mean Bias Serror (MBE) and Cumulative Variation of Root Maean Squarred Error (CVRMSE) were used while performing calibration. These indicators provide link between the simulation results and the measurements to decide whether the model is calibrated or not. While making this decision, calibration criteria defined by institutions such as American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) was taken into consideration. If the calculated indicators are within the specified criteria range, the model may be considered as calibrated. In this study, it was decided that the model was calibrated after the 4th revision.

The third case of the study covers the comparison of the calibrated and uncalibrated results obtained in the first and second case. In fact, it might be considered as the evaluation of the study.

The results for the first case demonstrated that the energy performance of the case study building was considerably improved. In the base-case scenario, the annual heating and cooling energy performances were 88.16 kWh/m2 and 21.57 kWh/m2 respectively. With the implementation of the ICT scenario, savings of 6.19% for heating and 6.06% for cooling were accomplished, and the consumptions of heating and cooling were dropped to 82.71 kWh/m2 and 20.26 kWh/m2 respectively. Furthermore, the energy consumptions were decreased slightly with the first fuzzy scenario. When it was compared with the ICT scenario, the obtained savings were 4.46% for heating and 9.39% for cooling. On the other hand, overall savings of first fuzzy scenario, which was reached 8.35% for heating and 10.54% for cooling, was considerably high. In the second fuzzy case, the heating saving and cooling saving were 10.37% and 14.88% respectively. It should be noted that higher or lower savings may be obtained by applying different control scenarios which contains different input variables and outputs.

In the calibration case, as mentioned above, the MBE and CVRMSE indicators were compared to evaluate the model. The existing ICT model had error of 15.12% for MBE and 17.19% for CVRMSE. These values were not in the range of calibration criteria, but they were close. After the external wall U-value, ground floor U-value, infiltration rate and windows U-value were changed, the 4th version of the model was obtained. The MBE and CVRMSE values were improved to -2.76% and 8.40% respectively, in the last model. These results met the calibration criteria; therefore, this model was considered to be calibrated.

Consequently, the results of this study demonstrated that the energy performances of the buildings might be considerably improved with the utilization of the automation systems, especially on the large-scale buildings due to the high degree of energy consumptions. Also, it may be provided that the building models may behave similar to the actual buildings thanks to calibration process. This gives us the opportunity to understand the effects of the adjustments on the building before applying it to actual building. Once and for all, considering how important energy is today, increasing the number of such useful applications is important and should be encouraged.

OTOMASYON SİSTEMİNİN ETKİSİNİ İYİLEŞTİRMEK İÇİN FARKLI KONTROL STRATEJİLERİNİN İNCELENMESİ İLE BİNA ENERJİ MODELİNİN KALİBRASYONU

ÖZET

Dünyada, hızla artan nüfus, sanayileşme ve teknolojinin gelişmesiyle birlikte enerji tüketimi de bu etkenlere paralel olarak artmaktadır. Tüketilen bu enerjinin büyük çoğunluğu, doğaya karşı birçok zararı olan fosil yakıtlardan üretilmektedir. Bu nedenle son zamanlarda, yenilenebilir enerji kaynaklarına yönelimler artmakta ve teşvikler yapılmaktadır. Ancak hızla artan enerji tüketimini ve doğaya verilen tahribatı azaltmak için bunlar yeterli değildir. Bu da üretimi sürekli arttırmaktansa elimizde olan üretilmiş olan enerjiyi verimli kullanarak tüketimi azaltma fikrini ön plana çıkartmaktadır. Dünyanın büyük kısmında olduğu gibi Türkiye'de de bu amaçla; enerji tüketimin büyük çoğunluğu oluşturan binalarda, sanayide ve ulaşımda, enerji verimliliği çalışmaları yapılmaktadır.

Bu tezde yapılan çalışmanın amacı, vaka çalışması olarak seçilen bir binanın enerji modelinin oluşturulması, bu model yardımıyla, mekanik sistemlerin kontrolünü sağlayan otomasyon sistemine farklı kontrol stratejileri uygulayarak elde edilebilecek enerji tasarruflarının görülmesi ve bu modelin, sensörler yardımıyla binadan alınan gerçek enerji tüketimleri kullanılarak kalibrasyonun yapılmasıdır. Bu amaçla, vaka çalışması olarak İstanbul'un Kartal ilçesinde bulunan bir yaşlı bakımevi ele alınmıştır. Bakımevi 2005 yılında hizmete başlamış, ancak daha sonra enerji performansı açısından verimsiz bulunmuş ve yukarıda belirtildiği gibi enerji verimliliği çalışmaları kapsamında 2012 yılında binada renovasyon çalışmalarına başlanmıştır. İzolasyon yapılması, cam ve pencerelerin değiştirilmesi, aydınlatma sistemlerinin iyileştirilmesi, sıcak su üretimi için güneş panellerinin eklenmesi ve otomasyon sistemlerinin dahil edilmesi gibi uygulamalar 2018 yılının Mayıs ayı sonuna kadar sürmüştür ve bina, Haziran 2018 itibariyle tekrar tam kapasite hizmete başlamıştır. Bu tezde, yapılan renovasyon çalışmalarından biri olan otomasyon sistemlerinin enerji performansına etkisi incelenmek istenmiştir.

Bu tezde, üç ana adımdan oluşan kapsamlı bir metodoloji geliştirilmiştir ve bu metodoloji takip edilerek vaka çalışması irdelenmiştir. Bu adımlar otomasyon sistemlerinin enerji performansına etkisi, enerji modelinin kalibrasyonu ve sonuçların karşılaştırılmasıdır.

Tezin birinci uygulamasında, metodolojinin birinci adımı izlenerek otomasyon sisteminin bina enerji performansına etkisi incelenmek istenmiştir. Bu nedenle ilk olarak yaşlı bakımevinin enerji performans modeli oluşturulmuştur. Binanın mekanik sistemleri de detaylı bir şekilde modellenmiş ve oluşturulan modele entegre edilmiştir. Ardından, mekanik sistemleri kontrol etmek amacıyla, otomasyon sistemini temsilen bir kontrol mekanizması modele eklenmiştir. Eklenen bu kontrol mekanizması yardımıyla, base-case, ICT ve fuzzy adında üç farklı kontrol stratejisi, binanın mekanik sistemlerini kontrol etmek için modele uygulanmıştır. Daha sonra uygulanan bu

stratejilerin enerji performansları elde edilmiştir ve birbirleriyle karşılaştırılarak erişilen enerji tasarrufları vurgulanmıştır. Ancak, bu sonuçların kalibre edilmemiş modelden elde edilen sonuçlar olduğu unutulmamalıdır.

İkinci uygulamada ise, metodolojinin ikinci adımı izlenerek bina enerji modelinin kalibrasyonunun yapılması hedeflenmiştir. Bu kısımda, bir önceki uygulamada oluşturulan ve ICT kontrol stratejisine göre çalışan model kalibrasyon işlemine tâbi tutulmuştur. Çünkü yaşlı bakımevinin mekanik sistemleri bu stratejiye göre çalışmaktadır. Kalibrasyon işlemine başlarken, ilk olarak binadan, sensörler yardımıyla enerji tüketimleri ölçülmüştür ve depolanmıştır. Ölçümler, 2018 yılı Ocak-Kasım ayları arasında yapılmıştır. Ancak, Mayıs ayının sonuna kadar bina kullanımda olmadığı için, bu dönemi kapsayan ölçümler kalibrasyon işleminde kullanılamamıştır. Bu nedenle Haziran-Kasım aralığındaki veriler faydalanılmıştır. Öte yandan, modelin kalibre edilip edilmediğini anlamak için MBE ve CVRMSE olmak üzere iki farklı hata indikatörü hesaplanmış ve değerlendirilmiştir. Bu indikatörler, simülasyondan gelen enerji tüketimleri ile binadan ölçülen tüketimler arasında bir bağlantı kurarak modelin doğruluğu hakkında fikir vermektedir. Bu doğruluk değerlendirmesi de ASHRAE tarafından belirlenen, kalibrasyon kriterleri göz önünde bulundurularak yapılmaktadır. Modelde yapılan 4 değişiklikten sonra, hesaplanan MBE ve CVRMSE değerleri belirlenen kalibrasyon kriterlerini sağladığı için, model kalibre edilmiş olarak değerlendirilmiştir. Ardından ilk bölümde uygulanan fuzzy kontrol stratejisi bu kez kalibre edilen modele uygulanmıştır ve sonuçlar değerlendirilmiştir.

Üçüncü adımda ise kalibre edilmiş ve kalibre edilmemiş modelin sonuçları karşılaştırılarak değerlendirilmiştir.

İlk adım için sonuçlar, yapılan çalışmanın bina enerji performansının önemli ölçüde arttığını göstermiştir. Base-case kontrol stratejisinde, yıllık ısıtma ve soğutma değerleri sırasıyla 88,16 kWh/m^2 ve 21,57 kWh/m^2 olarak elde edilmiştir. Bu değerler yüksek sayılabilecek değerlerdir. Bu tüketimi zaltmak için farklı kontrol stratejileri uyuglanmıştır. ICT stratejisinin uygulanmasıyla birlikte bu değerler 82,71 kWh/m^2 ve 20,26 kWh/m^2 olarak elde edilmiştir. Sonuç olarak ısıtma ve soğutma enerji tüketiminde sırasıyla %6,19 ve %6,06 tasarruf sağlanmıştır. Elde edilen bu tasarruflar yüzdesel olarak küçük gözükse dahi büyük çaplı binalarda gözardı edilemeyecek tasarruflardır. Daha sonra uygulanan fuzzy stratejileriyle tüketimler bir miktar daha azaltılmıştır. Birinci fuzzy senaryosu base-case stratejisi ile karşılaştırıldığında bu değerler ısıtma için %8,35’ e ve soğutma için %10,54’ e ulaşmıştır. İkinci fuzzy senaryosunda ise tasarruflar birinci fuzzy senaryosuna göre daha daiyileştirilmiştir. Bundaki en önemli etken ilk fuzzy senaryosundaki kollektör suyu çıkış sıcaklığının yerine iç sıcaklığın giriş değişkenil olarak atanması olmuştur. Bu değişim ile beraber ısıtma için %10,37, soğutma için %14,88 tasarruf elde edilmiştir. Unutulmamalıdır ki farklı girdi değişkenleri ve farklı senaryolar ile bu tasarrfulardan daha az ya da daha çok tasarruflar elde edilebilir. Bu tassarruflar sadece bu çalışma dahilinde modellenen bina ve oluşturulan senaryolara özgüdür.

Kalibrasyon uygulamasında ise, daha önce bahsedildiği gibi, modeli değerlendirmek için MBE ve CVRMSE değerleri kullanılmıştır. Modelin kalibre edildiğini söyleyebilmek için bu değerlerin farklı kurumlar tarafından belirlenen belirli aralıklarda olması gerekmektedir. Bu çalışmada aylık bazda bir kalibrasyon işlemi yapılmıştır. İlk modelde MBE %15,12 ve CVRMSE %17,19 olarak hesaplanmıştır. Bu değerler belirlenen kalibrasyon kriterlerine yakın olmasına rağmen istenen aralıkta değildir. Model üzerinde yapılan değişiklikler sonrasında, 4. revizyon itibari ile MBE değeri %-2,76 ve CVRMSE değeri %8,40 olarak hesaplanmıştır. Kalibrasyon kriterlerini sağlayan bu değerler, modelin kalibre edilmiş olarak değerlendirilmesini sağlamıştır. Her ne kadar model kalibre edilmiş sayılsa da bu değerler daha iyi seviyelere gelebilir ancak bu çalışmadaki simülasyonlarda gerçek hava durumu yerine tarihsel hava durumu verileri kullanıldığı için bu hata değerleri kabul edilebilir olarak değerlendirilmiştir. Daha sonra eld"e edilen bu kalibre modele birinci fuzzy senaryosu uygulanarak gerçekte nasıl bir enerji tüketimi olacağı gözlemlenmiştir.

Sonuç olarak, bu çalışma, otomasyon sistemlerinin binalarda, özellikle büyük ölçekli binalarda kullanılmasıyla enerji tüketimlerinin büyük ölçüde azaltılabileceğini göstermiştir. Ayrıca, bina modellerinin kalibrasyonun yapılmasıyla birlikte, modellerin gerçek binalara benzer şekilde davranıp gerçeğe yakın sonuçlar verebileceğini gözlememize yardımcı olmuştur. Bu işlem bize, renovasyonları gerçek binaya uygulanmadan bina üzerindeki etkilerini görme fırsatı verir. Son olarak, günümüzde enerjinin ne kadar önemli olduğu göz önünde bulundurulduğunda, bu tür faydalı uygulamaların sayısının arttırılmasının önemli olduğu ve teşvik edilmesi gerektiği aşikârdır.

1. INTRODUCTION

The energy consumption in the world is rising rapidly with the increasing population, industrialization and technology development; due to the limited resources available, the energy need problem arises. Increasing the need for energy, one of the most fundamental needs of today, highlights the issue of energy efficiency.

When energy use of Turkey is evaluated, a large part of our country's energy needs is provided by fossil fuels. According to the 2017 data of the Republic of Turkey Ministry of Energy and Natural Resources, 30.44% of the primary energy used in our country is petroleum, 30.47% is natural gas, 27.20% is coal, 3.44% is hydraulic, 1.74% is bioenergy, 4.90% is geothermal, 0.75% is solar and 1.06% is wind power sources [1]. In addition, Turkey is largely dependent on foreign energy terms. When this situation into consideration, efficient use of energy is becoming more and more important in Turkey.

The inefficient use of energy in Turkey, there is a significant share of the energy consumed in buildings. Due to the lack of adequate inspections and sanctions, many of the constructed buildings in the past have not taken measures for energy efficiency, and this problem has survived to the present day. It is very important to make, these buildings constructed in the past, energy-efficient and to take measures on this issue in the buildings to be constructed after today.

There are many ways to make buildings energy efficient. Some of these are; insulation, utilization of efficient systems, utilization of waste heat and integration of automation systems etc. These applications have a large positive effect on the energy consumption in the building. In the past, it was almost impossible to see these effects without applying them to the building, but nowadays, the effects of these applications may be seen easily without applying to the actual building with the possibility of modeling the buildings in computer environment that are widely used in many countries in Europe but it has gradually started to find a place in the sector of our country.

In the first chapter of this thesis, a general information was given about the subject of the thesis, the aim of the thesis was mentioned and the studies, which were used while writing the thesis, were mentioned.

In the second chapter, the methodology we proposed, which consists of 3 sections in total, was mentioned. These sections were; improving the building energy performance, calibration of the model and comparative results. Later, each of these sections of the methodology was explained step by step in detail, and important points were highlighted.

In the third chapter, the case study was explained by following the first section of the methodology. Firstly, the properties of the case study building were explained, and then, different control strategies were applied to the mechanical systems of the building. Later, the energy performances of each strategy were compared to each other and obtained savings were pointed out. However, it should be noted that the results were obtained from the non-calibrated model.

In the fourth chapter, the building model was tried to be calibrated by taking advantage of the second step of the methodology and the measurements made in the building. The purpose of this process was to make the building model as similar as possible with the actual building. After the calibration was done, the same control strategies with the previous chapter was applied to the model and the energy performances were obtained.

In the fifth chapter, both non-calibrated and calibrated energy performances were compared to each other and evaluations were made based on the comparisons.

In the sixth and also the last chapter, the obtained results throughout the entire study were interpreted and recommendations were made.

1.1 Purpose of Thesis

The aim of this thesis is to model the saving that can be achieved by application of automation systems that applied for mechanical systems of a big scale building. Therefore, energy performance model is developed and calibrated to represent the savings that can be achieved by applying different automation scenarios of the building’s mechanical systems.

1.2 Literature Review

The literature was examined based on two main topics; the effect of mechanical system's automation on building energy performance, and calibration of building energy models. There were various studies on these subjects in the literature. A number of studies only provide theoretical information while others have produced results with case studies. The articles published in this field, which were also used in this thesis, were given in the sections below with brief summaries.

1.2.1 Integration of mechanical and automation sytems to the buildings

Mohanraj et al. [2, 3] have made a comprehensive research on solar assisted heat pump systems in terms of system configurations, modeling, performance and modifications in the first paper [2]. In second paper, these systems were classified in terms of their usage into five groups; drying, room space heating, agricultural green house space heating, water heating and desalination applications. Then these applications were explained in detail.

Genkinger et al. [4] investigated the air-to-water heat pumps combined with solar thermal collectors and photovoltaics for domestic hot water production in Switzerland to evaluate these two systems from different perspectives; ecological and financial aspects. The results of that study showed that both combined systems have similar economic and environmental affect.

Fraga et al. [5] monitored an existing heat pump and solar collector system used to produce both heating and hot water of a large-scale complex (about 10,000 m2) to see the behavior of the system and calculate the Coefficient of Performance (COP) of the system. Monitoring was implemented in only one of the 10 buildings in the winter of 2011-2012. As a result, demand for heating (about 20kWh / m2 / year) was lower than Swiss standards, while domestic hot water demand (about 35 kWh / m2 / year) was higher than Swiss standards. Furthermore, the system was in COP 1.7-5.6.

Eicher et al. [6] studied on using solar energy on the HP evaporator side to maximize the performance level of the system. In order to see the performance of the system, both for test bench measurements and dynamic simulations (TRNSYS 16) were used.

Lerch et al. [7] investigated different combinations of solar thermal and heat pump systems by using dynamic system simulations in TRNSYS. In total, six different solar thermal heat pump systems were examined and compared. Three different building types were selected as boundary conditions, and behaviors of these heating systems were shown on one of the selected buildings. As a result, the seasonal performance factor of the system was increased from 2.55 to 3.65 by adding solar thermal system to heat pump. By preheating the ambient air at the outdoor unit of the Heat Pump (HP) were raised Seasonal Performance Factor (SPF) from 3.65 to 3.68. In addition, the results showed that, an additional ice storage could increase SPF. Carbonell et al. [8] numerically analyzed the solar thermal systems with heat pumps for different climates in Europe by using Polysun-6. According to results of this study, the performance of the ground source heat pumps increased when a solar system was added, on the other hand, the performance of the air source heat pumps decreases when a solar system was added. Therefore, potential electricity savings of ground source heat pumps were higher than air source heat pumps. Furthermore, in another study, TRNSYS and PolySun-6 were compared in detail by Carbonell et al. [9]. In general, differences between these two simulation tools, the seasonal system factors for the heat pump and the system, were up to 4% for ASHP and up to 14% for GSHP systems.

Zhu et al. [10] studied about solar water source heat pumps used in the buildings in three different cities to see the load characteristics in dissimilar climate regions by using eQuest and TRNSYS software. As a conclusion of this study, the three different climate regions were evaluated under four headings; feasibility, energy saving property, economy and environmental protection property. Severe cold regions were the most appropriate one for feasibility and energy saving headings, while hot summer and cold winter regions was the 1st in economy heading. Buker et al. [11] made a research about solar assisted heat pump systems for low temperature heating applications in detail. They gave information about direct and indirect series systems, system components and efficiencies and COP.

Baglivo et al. [12] investigated air cooled heat pumps coupled with Horizontal Air-Ground Heat Exchanger (HAGHE) to see the performances of the systems with and without HAGHE by using TRNSYS 17 software. According to this study, in winter period, the combined system (with HAGHE) showed good COP values until February, in March it lost its effect, so the use of HAGHE had to be by-passed in March. On the other hand, in summer period, combined system had always higher Energy Efficiency Ratio (EER) values than the system without HAGHE.

Yin et al. [13] worked on an air-source heat pump combined with solar heating and thermal storage. The purpose of this study was maximizing the overall efficiency of the system. The results of this study showed that; overall energy efficiency of the system decreased when the solar radiation and ambient temperature were decreased. Also, electricity consumption could be reduced up to 31%, the optimal operation type was: during daytime, solar heating system was activated, and hot water was stored in the tank; during nighttime, water tank releases the heat and air-source heat pump works.

Emmi et al. [14] compared ground-based heat pumps in two different buildings in Italy with air-source heat pumps and a common plant system using a gas boiler for heating and air-to-air cooler for cooling. According to this study, the (Gorund Source Heat Pump) GSHP system has always been the best solution from the primary energy point of view.

Jonas et al. [15] conducted a study of solar thermal system ground (SGSHP-P) and air heat pumps (SAShP-P) and used TRNSYS to obtain simulation results of these different combined systems. This study showed that SPF increases with the increasing ratio of ST collector area, and it was higher for SGSHP-P systems than SASHP-P systems. For Strasbourg climate, SPF of SGSHP-P was between 0.5-1.1 higher than SPF of SASHP-P. For Helsinki climate, SPF of SGSHP-P was between 1.0-2.0.

Wang et al. [16] designed a solar photovoltaic/thermal (PV/T) heat pump system which had heating mode in winter, cooling mode in summer, domestic hot water heating and generating electricity for the building. Besides, 7 different modes for heating, cooling, power generation and water heating were identified, analyzed and compared.

Li et al. [17] created three different solar thermal heat pump models in TRNSYS to see which system offers better energy consumption, energy utilization and COP in winter season. Additionally, a practical operation of the solar thermal heat pump systemin a office building in winter was monitored for one day and the COP factor was evaluated.

Qian [18] has constructed a solar powered GSHP by using GSHP, solar PV panels, batteries, converter, charge controller and additional stuffs. Monitoring and data acquisition system were used to receive instant data from different sensors that placed different locations on the system. Monitoring was performed for four weeks. Moreover, a model was created with Modelica software and simulation results were compared with the on-site measurements. The results demonstrated that actual measured produced energy from solar panels was 242 MJ and theoretical was about 297 MJ. According to simulation results, COP of the system was around 2.9 when the system was in steady state.

Lotz [19] investigated the performance of the heat pump assisted solar thermal system. For this purpose, a dashboard was created that shows the collected data from sensors and calculated system performance metrics. These calculated metrics were overall energy factor, solar energy factor, heat pump energy factor, total energy consumption/collection/delivered loads and heat delivery efficiency. Monitoring period of the system was between February 29th and March 28th, 2016 but testing period of the system was lasted last two weeks of the given period. Consequently, solar Energy Factor (EF), heat pump EF and overall EF calculated by dashboard were compared with the manual calculated results to evaluate the accuracy of the energy dashboard algorithm. The errors of the solar EF, heat pump EF and overall EF were 1.7%, 0.8% and 0.8% respectively. According to dashboard, energy factors of solar, heat pump and overall were 26.95, 1.25 and 2.29 respectively.

Grossi et al. [20] have investigated the operation of a dual-source heat pump in different modes such as; air source, ground source and dual source. A PI control strategy was used in order to select when the heat pump treat like a ground or air source heat pump. It was based on supply water temperature. The set-point value of the supply water temperature was set to 45 ˚C in heating mode and 7 ˚C in cooling mode. The on-off logic worked based on a dead band of 5K centered on the set-point value. When the external air temperature was lower than defined temperature, then the Dual Source Heat Pump (DSHP) changed its operating mode from air to ground-source mode.

Potočnik et al. [21] studied on analysis and optimization of a weather-controlled air-to-water heat pump by using TRNSYS and MATLAB. Six different cases were defined, and results of these cases were compared. According to this study, it was observed that addition of solar radiation input as an additional factor to the temperature improved the results.

Péan et al. [22] prepared a study about control strategies of the heat pump systems for improving the energy flexibility. Rule-Based Controls (RBC) and Model Predictive controls (MPC) were the two main control strategies classified and explained in the study. The principle of the most of the rule-based control strategies was that a parameter was monitored and according to monitoring process, heat pump was start or stop. Even though rule-based controls could serve important improvements, MPC strategy served better results.

Weeratunge et al. [23] have examined two different types of solar assisted ground source heat pump and three different modes. In first type, it was used the ground as a thermal storage and in the second one there was an additional insulated hot water tank to store the water. The three control modes were that; set point (baseline), minConsumption and minCost. According to results, system 2 had the lowest electricity consumption for the coldest month.

Li et al. [24] have used Taguchi optimization to compare performance of single tank and dual tank solar thermal heat pumps in five different climatic conditions. Three control factors were determined for single tank system and four control factors were determined for dual tank system. As a result, it was observed that each factor had different effects on different climatic conditions. However, for all climatic conditions, the flow rate of the heat pump was the most influential factor for single tank system, on the other hand, the flow rate of the solar collector was the most influential factor for dual tank system.

Degrove [25] have analyzed the operation of a solar thermal heat pump supported by a hydronic system. The control system of the heat pump system had a total of 28 inputs and 13 outputs. It also had seven different modes including solar pre-heat mode, heat pump mode, hybrid mode, solar mode, solar dissipation mode, solar storage mode and system off mode. The system was monitored between 25 February and 13 March. According to results, the system generated about 205,000 Wh of thermal energy from heat pump and solar collectors, and 35.2% of the total heat gained was contributed from the solar thermal collectors. In addition, the results demonstrated that the system ranged from 58% in off mode, 16% in solar storage mode, 10% in heat pump mode and 3% to 7% of remaining modes.

1.2.2 Calibration of the building energy models

Coakley et al. [26] have made a comprehensive review about the calibration techniques and divided it into two main headings as manual and automated. After, each heading was explained in detail by presenting the previous studies about calibration.

Fabrizio et al. [27] have had a research about the calibration techniques similar to Coakley et al. [26]. They have separated the calibration into five levels based on the available information of the building. Level 1 comprised utility bills and as-build data, Level 2 had site visit or inspection in addition the Level 1. Detailed audit was the difference between Level 2 and 3. Level 4 consisted short-term monitoring, and Level 5 had long-term monitoring. Level 4 and 5 were the most detailed levels of the calibration.

Raftery et al. [28-30] have modelled 30,000m2 Intel office building in Ireland. Firstly, an initial model was created, and the model was checked that if it provided the calibration criteria. After that, the model was updated by zone-typing, fixing internal loads and HVAC respectively. Following these applications, the calibration criteria was checked again and again in each update. The revision 15 model met the calibration criteria, but it still could be improved. The revision 23 model was the last model. Total electricity CV(RMSE)monthly changed from 79.26% to 1.35%, MBEmonthly changed from -78.98% to -1.00% and CV(RMSE)hourly changed from 94.02 to 1.87%.

Similar to Raftery et al. [28], Parker et al. [31] updated the model iteratively but versions of the model were different. Iterative calibration was based on constructions, zone typing, heating ventilation and air conditioning systems, infiltration, set point adjustments, passenger occupancy, lighting energy, equipment energy, air flow and boiler efficiency respectively. Finally, total energy consumption CV(RMSE)monthly was 5.82% and MBEmonthly was 1.37% which met the ASHRAE calibration criteria.

Hong et al. [32] have followed a five-step methodology. These were collecting the information about the facility, creating the BES model, calibration of the BES model in according to CV(RMSE), setting the design variables and objective functions and improving the calibration by using optimization algorithm. As a result of this study, while the manual NMBE value was 11.57%, the optimization NMBE was 6.24%. Furthermore, CV(RMSE)was observed to fall from 18.10% to 12.62%.

Ruiz et al. [33, 34] have tried to calibrate the envelope parameters of the building. For this purpose, they have focused on the free-floating periods of the building which gives them the advantage of the not dealing with the other parameters such as internal loads, HVAC system and operation schedules to reduce the calibration complexity. It was used seven different free-floating periods, six of them was short (about 2 days) while one was long (about 10 days). Totally, almost 20 full days were used to calibration process. Genetic algorithm was used while performing calibration. As a consequence, best solutions were listed, the CV(RMSE) and NMBE values were quite good.

Sun et al. [35] have calibrated a single-story building (929 m2) located in San Fransisco, California by using an automatic model calibration technique. As a result, the model had reached the calibration criteria after 4 steps which were decreasing lighting power density, increasing occupancy density, increasing average outdoor air flow per person and increasing cooling COP. The CV(RMSE) for electricity and gas was 8.5% and 14.1% respectively, while the NMBE was 4.7% for electricity and -0.2% for gas.

Paliouras et al. [36] have focused on operative temperature, relative humidity and concentration of carbon dioxide for calibration instead of the calibration of energy consumption of the building. 30 days of continuous monitoring with the interval of 10 minutes' data was available. After 10 iterations, the CV(RMSE) was reached the lowest value. It was 3% for operative temperature, 11.3% for carbon dioxide and 5.2% for relative humidity.

Monetti et al. [37] have followed a four-step methodology which were creating the model, pre-processing, optimization and post-processing, and validation. While performing the calibration, instead of performing sensitivity and uncertainty analyses, the parameters, that effects the building energy consumption the most, were chosen based on the literature. As a result, in the last run, the MBE varied within the range of -0.01%-0.83% for four different zones, while the range for CV(RMSE) was 20.40%-0.19% for the same zones.

Mustafaraj et al. [38] have focused on calibrating a three-storey 4500 m2 building in Ireland. First level and second level of calibration were performed. The CV(RMSE) and MBE values were represented for both first and second level of calibration. The range of hourly MBE was -9.1%-18.7% for the first level, while it was -6.5%-11.4%

for the second level. Similarly, hourly CV(RMSE) varied between 15.3% and 36.2% for the first level, while it varied between 12.3%-33.5% for the second level. Besides, the monthly values which have better results were mentioned in the study.

Bertagnolio et al. [39] have performed fourth level of calibration on a 10,100 m2 building. After they have been sure that the model behaved like the real one, the simulation was run and the whole-building electricity consumption was obtained. The relative uncertainty of the envisaged energy use was between 2.5% and 17.0%.

Coakley et al. [40] have proposed an analytical optimization approach for the calibration and followed an evidence-based structure. The methodology follows data gathering, model development, defining ranges of variation (ROV) and computing Goodness-Of-Fit (GOF) stages. The GOF was calculated for electrical consumption, heat energy consumption and zone temperatures separately. GOF was 4.499 for hourly average zone temperature in the 71st simulation, while it was 22.146 for hourly whole building electricity consumption in the 77th simulation.

Yoon et al. [41] have tried to calibrate a 26-stories commercial building located in Seoul through the methodology they have developed. The proposed methodology consisted of seven steps as base-case modelling, base load consumption analysis, swing-season calibration, site interview and measurements, heating and cooling season calibration and validation of calibrated base model. The calibration was performed based on the electricity and gas consumption. As a result of this study, after 13 revision, the MBE and CVRMSE values for electricity were improved from 24.9% and 24.9% to 2.3% and 3.6% respectively. On the other hand, a great progress has been made on the errors of gas consumption. While the MBE and CVRMSE were -115.6% and 120.0% in the first model, they were -15.8% and 22.7% in the last version.

Johnson [42] made a calibration on a six story multi-use university building upon electricity consumption and heating energy use by using the 2003-2006 measured data. Before starting for calibration, they have determined the most important inputs as a result of sensitivity analysis. According to sensitivity analysis, there were 8 important inputs as outside air flow rate, fan power, pump power, thermal bridge, monthly schedule, plug load power density, lighting/ plug load schedule and internal temp H, for their model.

Cooke [43] has investigated two case studies to implement calibration procedure. The major difference between the case studies was the available data. While the data was monthly bills for first case, it was hourly data for second case. In the first case, the MBE and CVRMSE indicators were in the calibration criteria. In addition, two regression models were generated based on Cooling Degree Days (CDD) and Heating Degree Days (HDD) with occupancy schedules. It was seen that the calibrated model had 66% better results than regression model 1, and 19% better results than regression model 2. Also, regression 2 model was performed 58% better than regression model 1.

Up to now, in the first section of the literature, research relating with the solar thermal heat pumps and automation systems were summarized. Most of the literature are focused on the efficiency, selection and integration process of the systems. In this thesis, a methodology was developed to integrate diverse building systems such as heat pumps, boiler and solar collectors with their operational arrangements through an automation system. Additionally, during this process, a dynamic hourly simulation method was proposed which performed by changing the set-point temperature values within a certain range instead of using fixed seasonal set-points. The aim was to improve the building energy efficiency while providing comfort conditions in the building. Also, developed method provides a sequence of procedures for stipulating simulation of the dynamic set-points to get more accurate results.

In addition, in the second section of the literature, the studies dealing with the calibration of the building models were mentioned. It was seen that most of the studies used real weather data for the simulation models. The utilization of real weather data obviously improves the calibration results and gives chance to compare the simulation results and the measurements directly. On the other hand, in our study, the historical weather data was used instead of real weather data. Therefore, when it comes to compare the simulation results with the measurements, a problem is occurred because of the weather data. Because the obtained results from the simulation was based on the historical weather data, and the real measurements were based on the real weather data. The method was that the HDD and CDD of the historical and real weather data were calculated for each month. This application gives us chance to make realistic evaluations while comparing the results. And the results showed that the HDD and CDD values confirmed our results.

2. METHODOLOGY

In this thesis, a comprehensive methodology has been developed to see the effect of the automation systems on the building energy performance, and calibration of a building simulation model. The methodology consists of two steps; improving the energy performance of the building by the automation system application and calibrating the model by real-time measured data. It will be explained in the following sections in detail, but in general; the actual building is modeled on the computer environment as a first stage. While modelling the building, several information were obtained from the actual building. Because modelling the building has a significant importance. Afterwards, different control strategies for mechanical systems of the building are defined and applied on the model. These control strategies were classified into three headings as Basecase, ICT and Fuzzy. Fuzzy control strategy was divided into two case in itself. It means that, totally 4 different energy performances were evaluated in this study. After the application of the control strategies, the simulation model was run to get energy performances of the scenarios. When the results are obtained, they compared with each other to see the achieved energy savings. However, it is important to remember that this model is not calibrated, and the results are not related with the actual energy performance of the actual building.

Later, the generated model was calibrated by using the measured data from the actual building. These data were heating and cooling energy consumptions. The building was tracked nearly 1 year, but the usuable data were only for 6 months. While calibrating the building model, this 6 months data were used. To calibrate the building, firstly, several input variables were selected and these variables were changed in a specified range. After 4 revisions the model was evaluated as calibrated. When the calibrated model was obtained, the same Fuzzy control strategy was applied to the calibrated model, and the results are compared, and evaluated. The followed methodology in this thesis was represented step by step in the Figure 2.1.

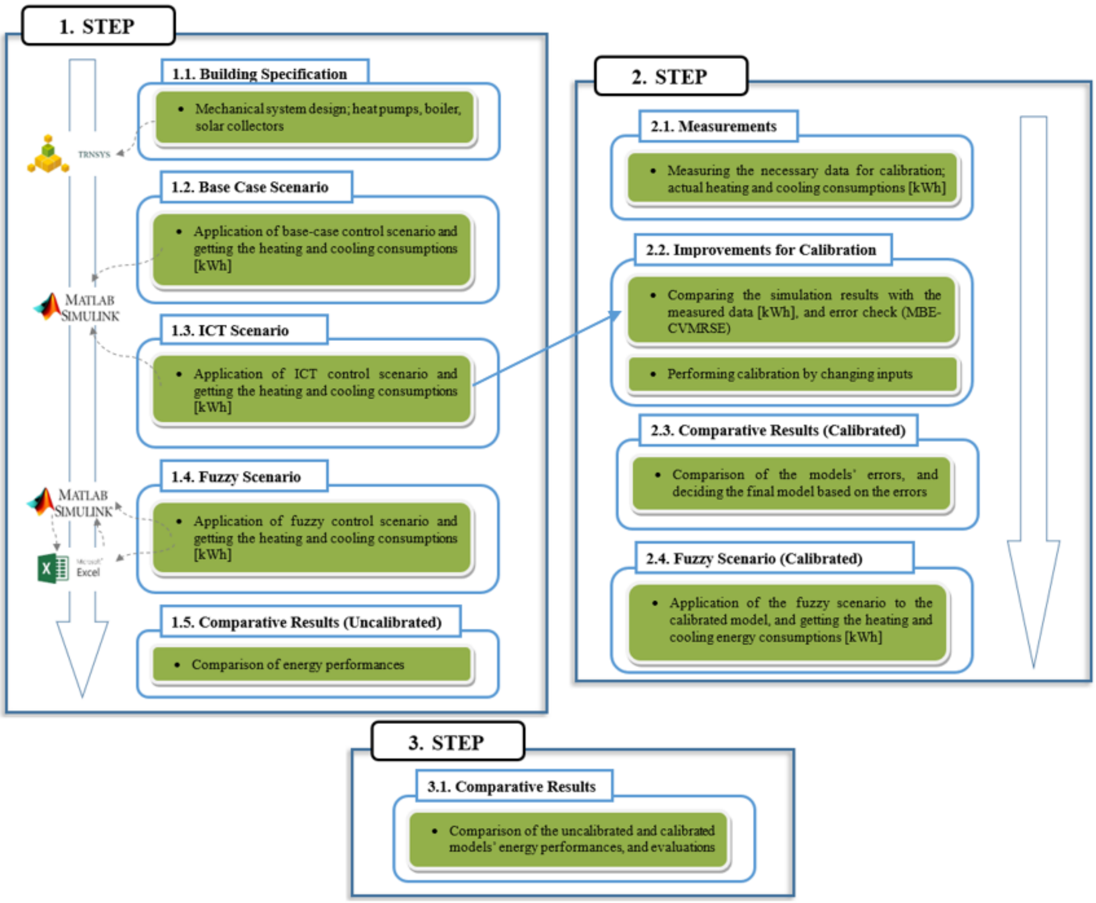


Figure 2.1: Proposed methodology.

2.1 Step 1 – Improving the Building Energy Performance

As mentioned before, the aim of the methodology' first step is to propose a path for improving the building energy performance through using different automation working layouts. As it will be described in the next headings, it consists of 5 sub-steps; building specification, base-case scenario, ICT scenario, Fuzzy scenario and comparative results. The bulding specification covers the getting information about the building and the modellimg it. The next three steps which were base case, ICT and Fuzzy scenairo deal with the creating the control strategies for the mechanical system. Later, the created control stragtegies were applied to the mechanical system of the building and the energy performances of each scenario were obtained. Afterwards, these heating and cooling energy performances were compared with each other to evaluate which scenario provides the best energy performance. The first step of the methodology is represented in the Figure 2.2.

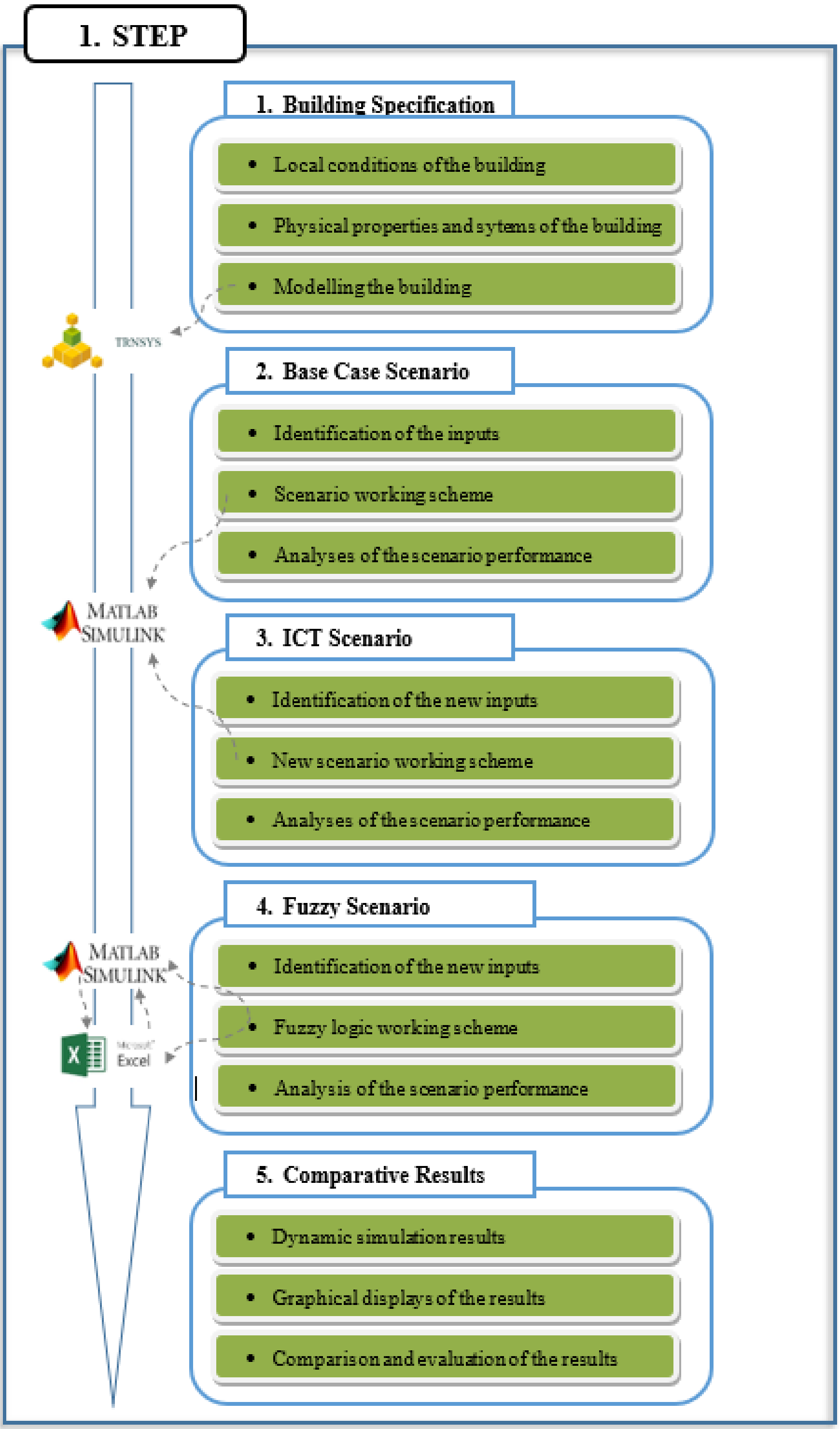


Figure 2.2: Step 1 overview.

2.1.1 Building specification

The starting point of the proposed methodology' 1.Step is the building specification. This section might be divided into three steps; identifying local conditions, defining the building features and modelling the building.

As mentioned above, firstly, the local conditions of the selected building should be identified. Location and orientation of the building might be two of the local conditions and have a significant effect on the energy performance of the building. Whether the building is in the northern hemisphere or in the southern hemisphere, it is near the sea or is far away, these information are really important. Site visits might be done to check the accuracy of the information. While these information are entered to the simulation software, should be careful. Also, the other and one of the most substantial factor, weather data, is intensely related with the location. It has a high degree of importance because it contains information such as, the maximum and minimum temperatures, the heating and cooling degree days of that area, and these factors strongly affect the building heating and cooling demand. That is why extra attention should be given for this process.

After the definition of the local conditions, as a second step, the physical properties and the mechanical systems of the building should be specified. The building area, building type, number of floors, applied materials and their u-values, occupancy rate, infiltration rate, applied equipment in the building could be considered as basic properties of the physical characteristics. Furthermore, specification of mechanical systems with their components for the heating and cooling operations should be described. These components could be boilers, heat pumps, solar thermals, furnaces, pumps, fans, etc. It is not enough to determine the system components, the number of the components and the capacities should be also defined. On the other hand, the way how these system work; controlling by human or automation system, should be well explained.

Final step for this section is the modelling. The mentioned data above will be used to model the building. Therefore, all the information should be collected carefully as they will be used as an input for the building model. There are several programs about establishing and simulating the building model to evaluate their energy performance such as e-Quest, Design Builder, TRNSYS [27, 28, 29]. Also, in the literature, there are two studies which contain information about comparing these simulation programs according to their functionality, accuracy, flexibility, clarity, usability, integration, adaptability and support, are founded [30, 31]. In our study, TRNSYS is utilized.

2.1.2 Base-case Scenario

The application of the scenarios to the model is the scope of the second stage, and it explains the working scheme of the building' mechanical systems. It consists of three steps; identification of the input parameters, definition of the systems' working scheme and analyses of the system performance.

As a first step, the input parameters for the base-case scenario should be assigned. These inputs may differ case by case. However, the important point is the same for all cases; description of the inputs. The ways of how to obtain required data for inputs should be specified and explained.

Second, the definition of the work plan of the baseline control system should be clarified. The entries of the scenario are described in the previous step and now the variables affected by the entries must be explained. These variables can be called the outputs of the system and control the related equipment of the mechanical systems to operate the on / off scenarios. These scenarios may be created using MATLAB and may be easily integrated into TRNSYS using a specific component called Type155. The key point in this process is to change the Type155 in accordance with the MATLAB code. After writing the required code for the baseline scenario to MATLAB, an .m file, it must be enclosed. The number of inputs and outputs must also be specified and associated with the relevant parameters in the TRNSYS model. As a result, this step can be said to be the most important step, because it explains how all systems are operated and controlled. The integration way of the .m file to the TRNSYS is represented in the Figure 2.3.

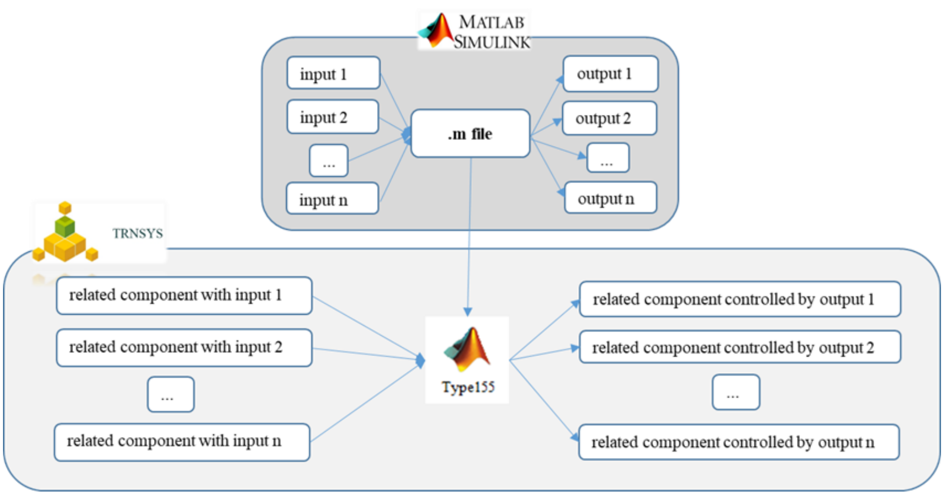


Figure 2.3: How to import the .m file into TRNSYS.

The final step of this phase is to run the created model to obtain the system performance data. However, various problems may be encountered when the model is run. The problems may be due to incompatibility of programs, meaningless simulation results or design inaccuracies. When these problems occur, the entire process must be repeated until being confident that the program is working correctly and that the results are logical.

2.1.3 ICT scenario

This part of the methodology follows a similar path with the previous step by adding extra information. The ICT scenarios are usually more complicated than the base case-scenarios. The reason of this complexity is to improve the building's energy performance by controlling the building systems in more detail with more inputs and outputs to accomplish reliable results. Therefore, in addition to the previous step, there are some additional works at this stage, including identification of new inputs and outputs and explanations on how to integrate them into the system. It should be noted that these changing conditions need to be updated in MATLAB codes and in Type155 to run the program properly.

After all updates, the model should be run to see if the program is running, if it does not work, the applied updates should be checked and adjusted until the program runs. It should then be examined whether the results are reasonable. If the simulation outputs are realistic, the obtained results can be regarded as the performance of the ICT system.

2.1.4 Fuzzy scenario

The last scenario of this section is the implementation of fuzzy logic. The main purpose is to perform a dynamic simulation according to working principle of the fuzzy logic.

As in the previous sections, input variables must be selected and explained. Here, unlike the previous parts, after the selection of inputs, these inputs should be classified as good, bad, average according to their values. However, there is no definite value determined for good, bad or average range. Some points have uncertainty due to the human feeling, taking into account different comfort conditions depending on the age and sex. Therefore, there should be an intersection area between each identified group.

The next step is to explain how the fuzzy logic system works. The Figure 2.4 represents the working scheme of the fuzzy logic system.

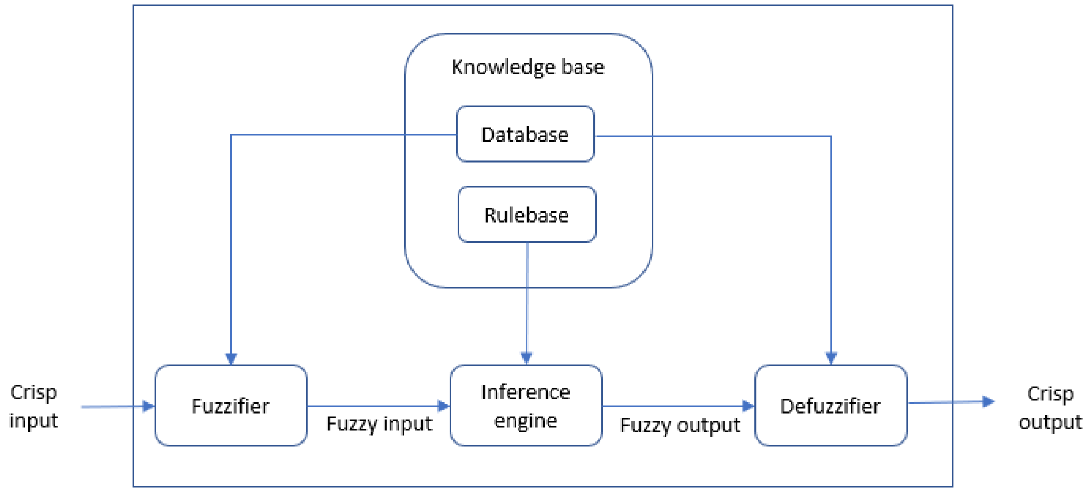


Figure 2.4: Fuzzy logic working scheme.

Totally, the fuzzy controller has four main components; fuzzifier, inference engine, defuzzifier and knowledge base. The knowledge base consists of the rule-base and database. The knowledge, in the form of a set of IF-THEN rules, and the information about antecedent-consequent membership functions are stored in the rule-base and database, respectively. In the fuzzifier, crisp input values are converted to fuzzy values so that they can be evaluated in the inference engine. In the inference engine, a conclusion is generated by using the knowledge stored in the knowledge base. The fuzzy outputs are translated into crisp values in the defuzzifier.

After an explanation about how the fuzzy logic works was done, the fuzzy logic system is ready to be transferred to TRNSYS. Finally, the simulation can be run to obtain results.

2.1.5 Comparative results (Uncalibrated)

The last step in the methodology' first step is to compare and evaluate the results obtained from the ICT systems and the fuzzy logic to see developments in the energy performance of the building. All the above-mentioned steps should be considered in order to achieve rigorous results. Savings can be calculated after receiving the results of all scenarios. With the help of TRNSYS the results can be taken at 1-hour intervals. Although the comparison may be done on hourly basis, it is enough to perform it on a monthly or annual basis. Because, the purpose of the study is to see the achieved savings, therefore evaluation of the monthly or annual energy savings is sufficient.

2.2 Step 2 – Calibration

Until now, a model is created, and different control strategies are applied on the model. Then the results are compared to each other and, an evaluation is made by means of the energy savings. However, it should be noted that the performed operations so far were made on the uncalibrated model. It means that the energy performance of the building model may not reflect the energy performance of the actual building. The second step of the methodology tries to solve this problem by proposing a calibration strategy. It consists of three steps; real time measurements, improvements for calibration and calibrated results. The modelling phase is not involved in this step again, because it was already performed in the first step. The followed steps are representeed in Figure 2.5.

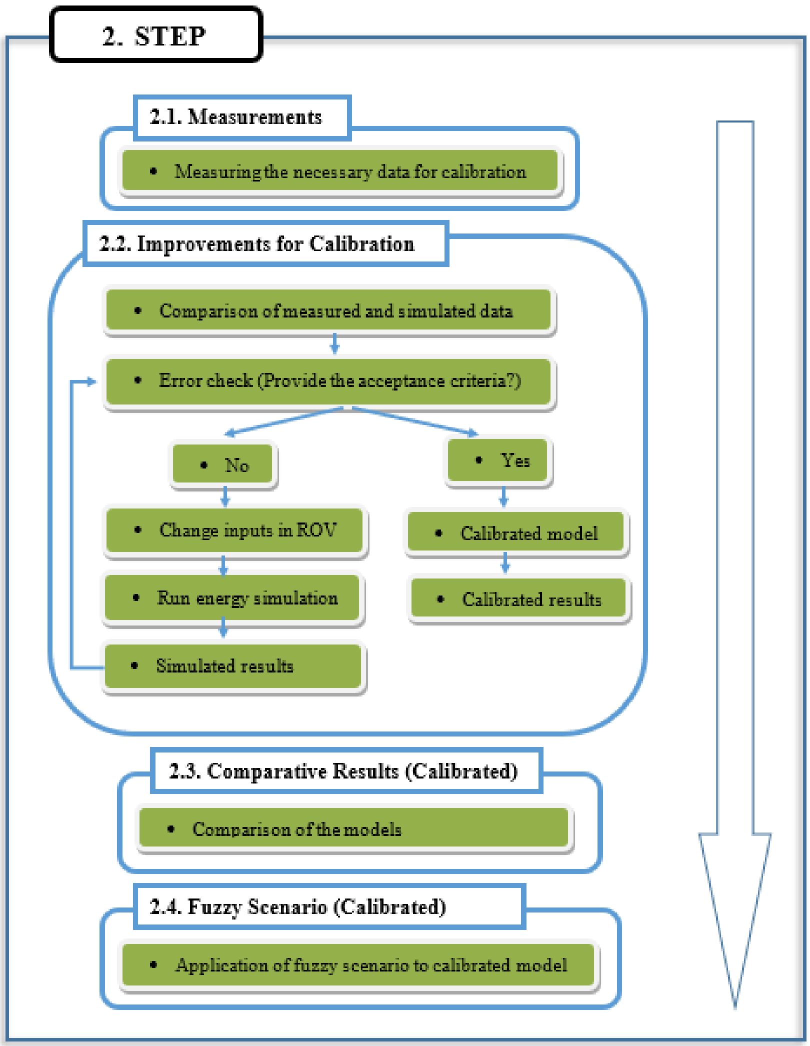


Figure 2.5: Step 2 overview.

2.2.1 Measurements

Measurements from the building have a significant importance on the calibration process. These measurements reflect the building' dynamic behavior moment by moment. Many different items can be measured for the calibration process. It differs based on what the model will be calibrated. Some of the measurable items for the calibration process are these;

- The total energy consumption of the building (kWh),
- Heating and cooling energy consumptions (kWh),
- Electricity consumption (kWh),
- Zone temperatures (˚C),
- Relative humidity (%) etc.

It is important to collect them in accordance with the calibration process to ensure better quality in the process. If the calibration is to be performed on an hourly basis, the sensors must provide data with the same frequency and precision. If the sensors measure energy consumption data at 1000 kWh intervals, they may not be suitable for hourly calibration. On the other hand, if it is to be done monthly, there is no need for sensitive sensors. Again, depending on the quality of the calibration, the duration of the measurements may vary. Both short- and long-term measurements can be used, but they affect calibration accuracy.

2.2.2 Improvements for calibration

So far, the model has been created and real-time measurements have been made. These operations can be considered as preparation for calibration. Due to the presence of the simulated and measured data required for the calibration, the calibration can now be performed. The steps of this process will be described below.

2.2.2.1 Iterative model improvement

On this stage, the created model will be tried to make similar as much as possible to the actual building. To do this, the values of the related input variables of the model need to be changed. However, it should first be decided which inputs are going to be changed. Sensitivity analysis can be done to find the answer of this question. The aim of sensitivity analysis is to find the most effective inputs. These inputs may vary in each model. On the other hand, it is possible to comment on the most effective inputs without doing sensitivity analysis by looking at the studies in the literature. Once the most effective inputs are found, one more problem remains; change these input values. Yet, these inputs cannot be changed randomly. According to the research done in the literature, it is based on certain rules that these inputs may be changed. First, the data source of each input must be determined, and then the Range of Variation (ROV) must be assigned to the inputs, depending on this data source [47]. After these preliminary operations, the inputs are ready to be modified to make the model similar to actual building. The ROV percentages according to source of data are represented in Figure 2.6.

Source of Data	ROV (%)
Sensor Data	2
Spot Measured Data	5
As-Built Drawings	10
Design Documents	15
Guides & Standarts	30
Reference Manual / Default Values	40
No Information	50

Figure 2.6: Defined acceptable ROV based on the source of the information [47].

After each change to the inputs, the model must be run, and the results should be compared with the measured values to evaluate the model. In addition, a revision number must be assigned to each model and recorded. Recording these changes is important to see the achieved improvements in the calibration process. This should be done continuously until the model is calibrated.

2.2.2.2 Error check

Mean Bias Error (MBE) and Cumulative Variation of Root Mean Squared Error (CVRMSE) are the statistical indicators for evaluating the calibration process according the published guidelines [49-51]. The plus and minus errors in the MBE index eliminate each other, while in the CVRMSE index, these errors do not eliminate each other and give healthier results because the squares and square root of these errors are taken in. The formulas used to calculate these statistical indices are seen in the following equations. (2.1 – 2.2)

$$MBE\ (\%) = \frac{\sum_{i=1}^{N_i}(m_i - s_i)}{\sum_{i=1}^{N_i} m_i} \qquad (2.1)$$

$$CVRMSE\ (\%) = \frac{\sqrt{\sum_{i=1}^{N_i}(m_i - s_i)^2 / N_p}}{\bar{m}} \qquad (2.2)$$

Where m_i and s_i are measured and simulated data at instance I, p is the interval (hourly, daily, monthly), N_p is the number of values at interval p (N_{month}= 12, N_{daily}= 365, N_{hourly}= 8760), and m the average of the measured data.

Calibration process can be done based on hourly or monthly data according to U.S. Department of Energy guideline [51]. However, it is not limited with these intervals, it can also be done based on weekly and daily basis. CVRMSE values for weekly and daily basis should be between hourly and monthly CVRMSE values. The hierarchy of CVRMSE values are given below:

$CVRMSE_{monthly} \leq CVRMSE_{weekly} \leq CVRMSE_{daily} \leq CVRMSE_{hourly}$ [30].

The acceptable criteria defined by ASHRAE, International Performance Measurement and Verification Protocol (IPMVP) and Federal Energy Management Program (FEMP) are represented on the Table 2.1. If the calculated statistical indices are below these values, then the model can be assumed as calibrated.

Table 2.1: Defined calibration criteria [49-51].

	Hourly Criteria		Monthly Criteria	
Guideline	MBE	CVRMSE	MBE	CVRMSE
ASHRAE	10%	30%	5%	15%
IPMVP	5%	20%	20%	-
FEMP	10%	30%	5%	15%

2.2.3 Comparative results

The calibrated model is obtained as a result of total process including each above-mentioned step by progressing until the performance achieved to the equivalent behavior of the actual building with some acceptable tolerances. The acceptable range of tolerances which were specified by ASHRAE, IPMVP and FEMP were defined in the Table 2.1. In this thesis, while calibrating the model, the ASHRAE standards were used. With the acquisition of the calibrated model, the energy performance of the building can be easily obtained by running the simulation. Also, one of the most significant benefit of the calibrated model, it can be utilized to estimate the energy consumption of the building by implementation of Energy Conservation Measures (ECM) to the model before applying them to the actual building.

2.2.4 Fuzzy scenario

In this section, the same procedure in the section 2.1.4. STEP 1 – Fuzzy scenario, may be followed. The only difference between these two cases is that the model is calibrated now, so the simulation may represent more accurate results.

2.3 Step3 - Comparison of Calibrated and Uncalibrated Results

In the Step 3, the obtained results from both Case 1 and Case 2 will be compared. The aim at this stage is to show what the energy performance difference between the uncalibrated model and the calibrated model is. Also, it may give us a chance to see how the model results are improved. The Figure 2.7 represents the overview of Step 3.

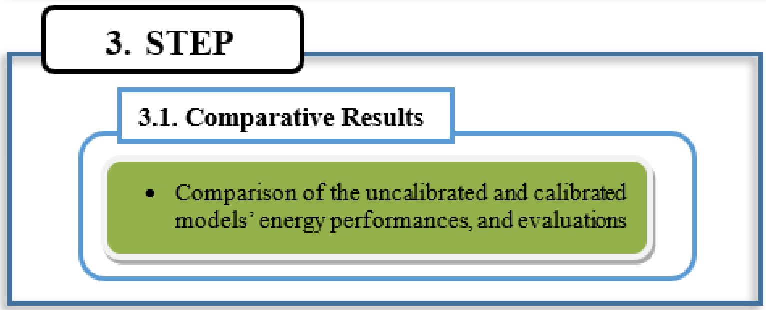


Figure 2.7: Step 3 overview.

The important point is here that the models working according to the same control strategy should be compared to each other. While comparing, the heating and cooling energy consumption for each month may be used to be allowed to evaluate the model in detail. So, it may be seen which months are affected from the processes the most and the least.

3. CASE 1- IMPROVING THE BUILDING ENERGY PERFORMANCE

As described earlier, at this stage, firstly, a building will be selected as a case study. Later, this building will be modeled as real as possible. Also, the mechanical systems of the building will be modeled in detail. Here, modeling of mechanical systems is of great importance because most of the energy performance of the building depends on it. Then, by applying 3 different control strategies to control the mechanical systems, the energy performance of these strategies will be achieved. Finally, by comparing this energy performance, the savings will be calculated and evaluated.

3.1 Building Specification

The case study of this thesis is an elderly house in Kartal. The building is located in Kartal where is in the southern part of the city of Istanbul where is represented on the Figure 3.1.

Figure 3.1: Location of the case study building.

The building has a total conditioned floor area of nearly 18.108 m^2, distributed over 8 floors. It was designed as a building for elderly people and completed in 2005. After 7 years of use, the building was restored from 2012 to 2018 in order to increase energy efficiency. It had been under restoration for a long time, and there was no occupancy in the building for a long time due to renovation works. The renovation works was completed in late May 2018, then the elderly people were moved to the building at the beginning of June 2018, and it is started to be operated 7/24. The building's aerial and front views are shown in the Figure 3.2.

Figure 3.2: Views of building.

The region has a mild climate, and in the summer the weather is warm and slightly rainy. On the other hand, winters can be cold and rainy with little snow. The rest of the year can be called moderate. In 2018, according to Turkey's State Meteorological Service HDD and CDD 1448 and 340, respectively [52]. The number of days when the average temperature of the day was equal to or below 15 °C was 166, which means the demand for heating. Also, the number of days when the average temperature of the day is higher than 22 °C is 106, which means cooling demand. The Table 3.1 summarizes the weather conditions.

Table 3.1: HDD and CDD of İstanbul.

	İstanbul
HDD	1448
T ≤ 15˚C	166
CDD	340
T > 22˚C	106

The foremost physical characteristics of the building are summarized as, the U-values of the external walls, below grade walls, flat roof, ground floor and windows are 0.330, 0.950, 0.620, 0.482 and 1.6 W/m^2-K respectively. Window to wall ratio is nearly 30%. The other features such as occupancy rate, infiltration rate, power density of the office equipment and normalized power density of lighting have 0.07 people/m^2, 1.1 ac/h, 6.0 W/m^2 and 2.35 W/m^2-100lux values respectively. These properties are represented in the Table 3.2 and the TRNSYS model is represented in the Figure 3.3.

Table 3.2: Physical properties of the building.

Property	Value
External wall U-value	0.330 W/m^2K
Below grade wall U-value	0.950 W/m^2K
Flat roof U-value	0.620 W/m^2K
Ground floor U-value	0.482 W/m^2K
Windows U-value	1.600 W/m^2K
Occupancy rate	0.07 people/m^2
Infiltration rate	1.1 ac/h
Power density of office equipment	6.0 W/m^2
Power density of lighting	2.35 W/m^2-100lux
Windows to wall ratio	30%

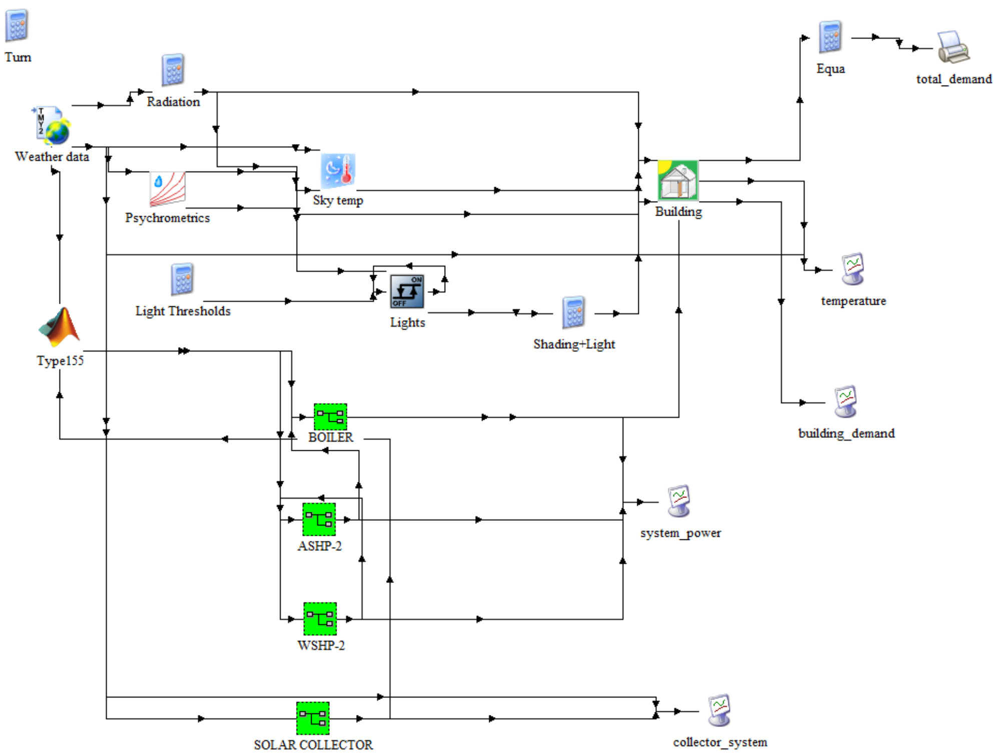


Figure 3.3: TRNSYS model.

The most important aspect of this step was to define the mechanical systems properly because main purpose of this study was to evaluate the heating and cooling demands. 3 boilers, 3 WSHP and 4 ASHP were used in the mechanical system of the Kartal building. Boilers were used for only heating, while air source and water source heat pumps were used both for heating and cooling. The capacity of each boiler, WSHP and ASHP were 100 kW, 200 kW and 130 kW respectively. Also, 150 solar panels were used to produce hot water. The mechanical systems of the building are represented in the Table 3.3.

Table 3.3: Mechanical systems.

Mechanical System	Number	Purpose
Boiler	3	Heating
Air Source Heat Pump	4	Heating and Cooling
Water Source Heat Pump	3	Heating and Cooling
Solar Collectors	150	Water Heating

The modelling step can be started in the light of this information. The building model must include well-defined mechanical systems and all the physical characteristics. Modelling the building should be as basic as possible to simplify the simulation, that's why the whole building divided into three zones called A-block, B-block and atrium. A-block and B-block had the same volume as 25,125 m^3, while atrium had 5,625 m^3. The Figure 3.4 represents how the buildng was seperated into zones.

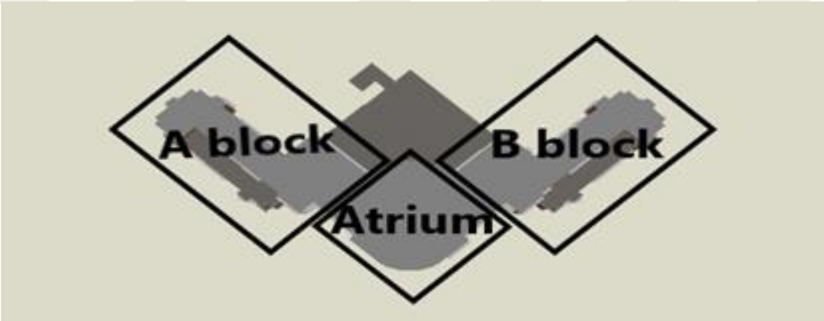


Figure 3.4: Zones of the building model.

3.2 Base-case Scenario

The mechanical system of the building can operate according to the communication capabilities. One system can be controlled depending on the output of another system. The working principles of such systems should be well understood. Because they can have a complicated way of working, and the slightest information that is overlooked can prevent the system from working properly. Therefore, as much attention should be paid to modeling as possible.

The mechanical system works with a basic control system in the base case scenario. The control mechanism works according to only an input variable, and it is the outlet water temperature of the solar collectors. It determines when the mechanical systems are activated and when they are deactivated. The working scheme of the base case scenario is represented in the Table 3.4.

Table 3.4: Base-case scenario working scheme.

Seasonal Mode	Input	ASHP	WSHP	Boiler
Winter Mode	$T_{collector} \geq 45^{\circ}C$	On	On	Off
	$T_{collector} < 45^{\circ}C$	On	On	On
Summer Mode	-	On	On	Off

As it can be seen from the table, the base case scenario was a very basic control scenario, and it was divided into 2 seasonal modes, as winter mode and summer mode, to control the mechanical system under different conditions. The mechanical equipment affected by the input were ASHP, WSHP and boiler. In winter mode, there were two conditions as $T_{collector} \geq 45^{\circ}C$ and $T_{collector} < 45^{\circ}C$, while there was no condition in the summer mode. In summer mode, boiler is off while the heat pumps are always activated. On the other hand, ASHP and WSHP always works, and boiler becomes on or off situation according the status of the input in winter mode.

After these conditions were written on the MATLAB, the .m file was imported into Type155 component in the model created in advance. The process of importing the .m file into the TRNSYS should be taken careful consideration since it could be encountered several problems such as difficulty of creating a proper integration between MATLAB and TRSYS as well as suitability of the format of the code.

The results obtained from the first scenario is represented in the Table 3.5. The results are shown for per month as individual heating, cooling and total energy consumption.

Table 3.5: Base-case scenario results.

	Heating Consumption [kWh]	Cooling Consumption [kWh]	Total Consumption [kWh]
January	303,202.70	0.00	303,302.70
February	249,616.19	0.00	249,616.19
March	221,334.72	0.00	221,334.72
April	154,243.38	0.00	154,243.38
May	77,368.80	24,327.35	101,696.15
June	0.00	64,894.98	64,894.98
July	0.00	124,370.08	124,370.08
August	0.00	115,054.80	115,054.80
September	0.00	49,650.32	49,650.32
October	105,454.31	12,215.09	117,669.40
November	204,229.37	0.00	204,229.37
December	280,873.49	0.00	280,873.49
Total	1,596,422.97	390,512.63	1,986,935.60
Total [kWh/m^2]	88.16	21.57	109.73

3.3 ICT Scenario

The second control strategy applied to case analysis is a further improvement of the previous strategy. For this purpose, the number of the inputs has been increased to two. The added input is the outside air temperature. So, in this strategy, the system will be controlled according to the temperature of the outside air and the outlet water temperature of the collector. The conditions of the control mechanism are shown in the Table 3.6.

Table 3.6: ICT scenario working scheme.

Seasonal Mode	Input 1	Input 2	ASHP	WSHP	Boiler
Winter Mode	$T_{collector} \geq 45^\circ C$	$T_{out} < 12^\circ C$	Off	On	Off
	$40^\circ C < T_{collector} < 45^\circ C$	$T_{out} < 12^\circ C$	Off	On	On
	$T_{collector} \leq 40^\circ C$	$T_{out} < 12^\circ C$	On	On	On
	$T_{collector} \geq 45^\circ C$	$T_{out} \geq 12^\circ C$	On	Off	Off
	$T_{collector} < 45^\circ C$	$T_{out} \geq 12^\circ C$	On	On	On
Summer Mode	$T_{collector} \geq 18^\circ C$		On	On	Off
	$T_{collector} < 18^\circ C$		Off	On	Off

As can be seen from the table, this system is divided into two modes, summer and winter. In summer mode, the boiler is always switched off because the boiler is only used for heating. the air and water source heat pumps only operate depending on the collector temperature, where the critical temperature is 18 ˚C. If the temperature is greater than 18 ˚C, while the two pumps are running, if the temperature falls below 18 ˚C, the air source heat pump is switched off and only the water source heat pump operates. On the other hand, in winter mode, there is more operating status than summer mode. Here, the system works depending on two inputs, and it is more complex. The critical point for the outside temperature is 12 ˚C. For the outlet water temperature of the collectors, 40 ˚C and 45 ˚C are critical points. Depending on the state of the inputs, it is decided whether the mechanical systems will work or not. For instance, when the $T_{collector}$ is less than 45 ˚C and the T_{out} is greater than 12 ˚C, all systems are operational. However, if the $T_{collector}$ rises above 45 ˚C when the T_{out} is greater than 12 ˚C, the water source heat pump and the boiler are shut off, only the air source heat pump operates. The working structure of the ICT system is represented in Figure 3.5.

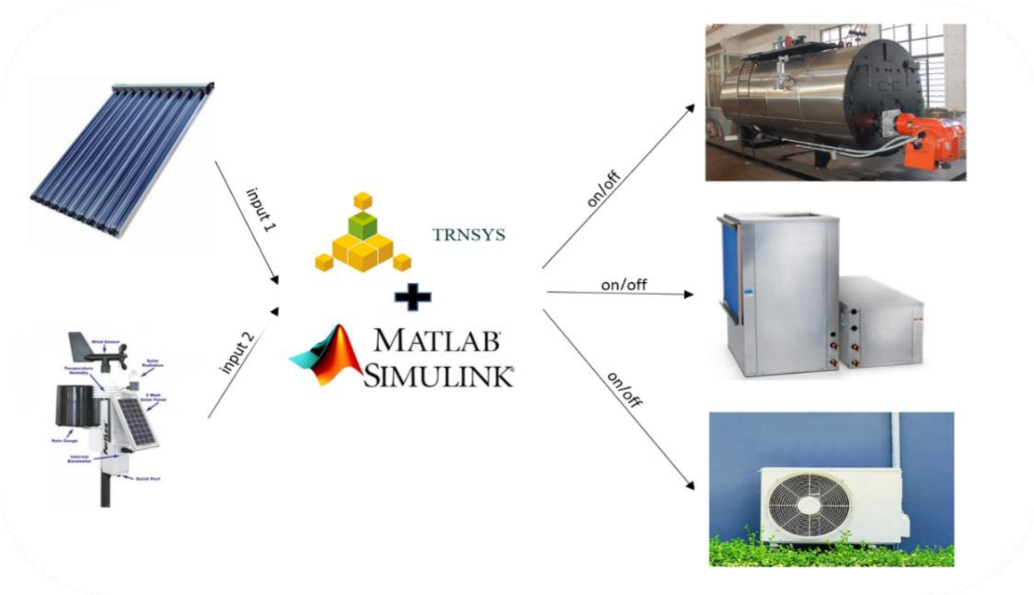


Figure 3.5: ICT scenario system components.

Finally, after the necessary arrangements have been made in the TRNSYS, these operating conditions are coded in the MATLAB and transferred to the TRNSYS to control the mechanical systems. This process is followed by simulation, and the results are obtained.

The obtained results from the ICT scenario represented in the Table 3.7. As in the previous scenario, the results were shown for per month as individual heating, cooling and total energy consumption.

Table 3.7: ICT scenario results.

	Heating Consumption [kWh]	Cooling Consumption [kWh]	Total Consumption [kWh]
January	289,531.50	0.00	289,531.51
February	237,292.17	0.00	237,292.17
March	207,787.07	0.00	207,787.07
April	141,950.94	0.00	141,950.94
May	68,191.45	24,619.04	92,810.49
June	0.00	61,793.51	61,793.51
July	0.00	115,051.30	115,051.30
August	0.00	106,119.52	106,119.52
September	0.00	46,743.49	46,743.49
October	94,566.60	12,537.09	107,103.69
November	191,403.48	0.00	191,403.48
December	266,931.92	0.00	266,931.92
Total	**1,497,655.14**	**366,863.95**	**1,864,519.09**
Total [kWh/m^2]	**82.71**	**20.26**	**102.97**

3.4 Fuzzy Scenario

With the Fuzzy application, a dynamic hourly simulation was performed by changing the set-point values within a certain range instead of using fixed seasonal set-points. The aim was to provide comfort conditions in the building with the dynamic set-points and get more accurate results. To perform this, two different fuzzy control strategies were specifed as it was described in the next chapters.

3.4.1 First fuzzy case

In the first fuzzy case, the input variables were outlet water temperature of the solar collectors ($T_{collector}$) and outside temperature (T_{out}). The sub-groups of the outside temperature were defined as very cold, cold, comfort, hot and very hot. The ranges were very cold below 8°C, cold between 5-21°C, comfort 17-27°C, hot 25-33°C and very hot upper than 30°C. The other variable has 3 sub-groups as below 40°C, 40-45°C and above 45°C.

The principle of fuzzy logic is based on uncertainties. These uncertainties arise for things that are not certain. For example, the temperature is 19 degrees, while it may be cold for some people, it is comfortable for some people. In such cases, 19 degrees may be in both the cold and the comfort zone. Fuzzy comes into play at this point. It makes a decision in his own logic and makes transactions according to it. Therefore, it has been created some intersection points in the inputs in our study. The inputs and the sub-groups are represented in the Figure 3.6.

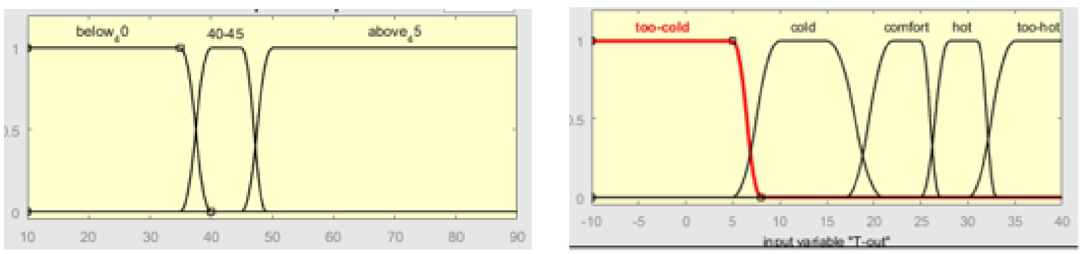


Figure 3.6: $T_{collector}$ (left) and $T_{outside}$ (right) fuzzyfication.

The next step was to define the output variables that would be affected by the entries. In our study, the output was set as the setpoint temperature. By selecting the setpoint temperature, it is aimed to provide comfort conditions inside the building dynamically. As shown in the Figure 3.7, two different setpoint ranges are assigned for the heating season: 22-25 ° C and the other for 23-26 ° C for the cooling season.

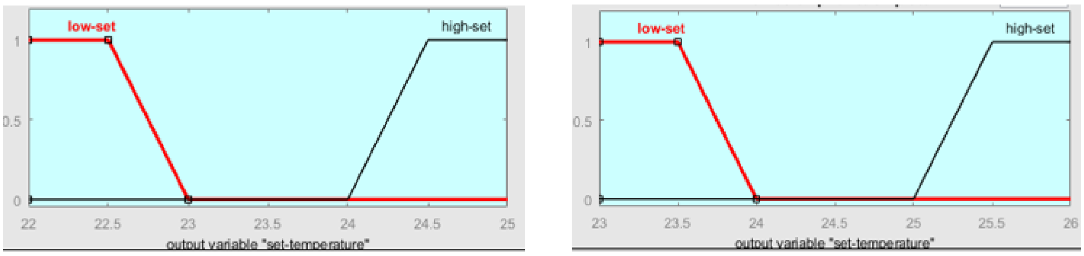


Figure 3.7: Fuzzyfication of the heating (left) and cooling (right) set-points.

After determining the inputs and outputs, there is only one problem, which is the determination of the rules, left. These rules provide the link between inputs and outputs, and it includes invoices about how fuzzy should work. Also, the structure of these rules is based on the "if/else" working principle, and the determined rules in this case are represented in Figure 3.8.

1. If (T-in is too-cold) and (T-out is too-cold) then (set-temperature is high-set) (1)
2. If (T-in is too-cold) and (T-out is cold) then (set-temperature is high-set) (1)
3. If (T-in is too-cold) and (T-out is comfort) then (set-temperature is high-set) (1)
4. If (T-in is too-cold) and (T-out is hot) then (set-temperature is high-set) (1)
5. If (T-in is too-cold) and (T-out is too-hot) then (set-temperature is low-set) (1)
6. If (T-in is cold) and (T-out is too-cold) then (set-temperature is high-set) (1)
7. If (T-in is cold) and (T-out is cold) then (set-temperature is high-set) (1)
8. If (T-in is cold) and (T-out is comfort) then (set-temperature is high-set) (1)
9. If (T-in is cold) and (T-out is hot) then (set-temperature is low-set) (1)
10. If (T-in is cold) and (T-out is too-hot) then (set-temperature is low-set) (1)

Figure 3.8: Defined rules.

According to these inputs, outputs and rules, a diagram which explains all of the working scheme of the first fuzzy case was occured. The Figure 3.9 represents the diagram of the first fuzzy case. The blue regions represent the low set points according to the inside and outside temperatures situation, while the yellow regions indicate the high set points.

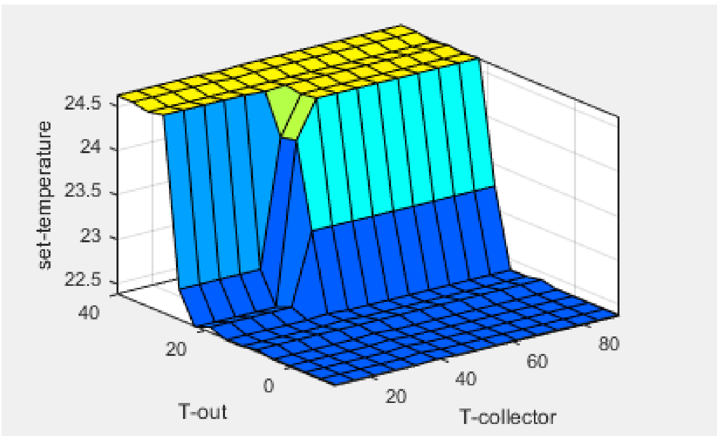


Figure 3.9: Diagram of the first fuzzy logic system.

The monthly results were obtained from the first fuzzy case were represented on the Table 3.8. As in the previous scenarios, the results were shown for per month as heating, cooling and total energy consumption.

Table 3.8: First fuzzy case results.

	Heating Consumption [kWh]	Cooling Consumption [kWh]	Total Consumption [kWh]
January	289,262.11	0.00	289,262.11
February	235,865.43	0.00	235,865.43
March	203,414.68	0.00	203,414.68
April	135,916.54	0.00	135,916.54
May	62,663.37	22,911.27	85,574.64
June	0.00	58,179.52	58,179.52
July	0.00	111,221.41	111,221.41
August	0.00	101,146.23	101,146.23
September	0.00	43,947.48	43,947.48
October	87,125.51	11,938.37	99,063.88
November	185,426.25	0.00	185,426.25
December	263,452.56	0.00	263,452.56
Total	**1,463,126.45**	**349,344.28**	**1,812,470.73**
Total [kWh/m^2]	**80.80**	**19.29**	**100.09**

3.4.2 Second fuzzy case

As in the previous case, firstly, the input variables were selected. These were outside temperature (T_{out}) and indoor temperature (T_{in}). Each input variable had 5 sub-groups as very cold, cold, comfort, hot and very hot. The very cold, cold, comfort, hot and very hot ranges of indoor temperatures were below 15°C, 12-20°C, 18-27°C, 25-32°C and upper than 29°C respectively. For the outside temperature, the ranges were very cold below 8°C, cold between 5-21°C, comfort 17-27°C, hot 25-33°C and very hot upper than 30°C. Figure 3.10 represents the input variables.

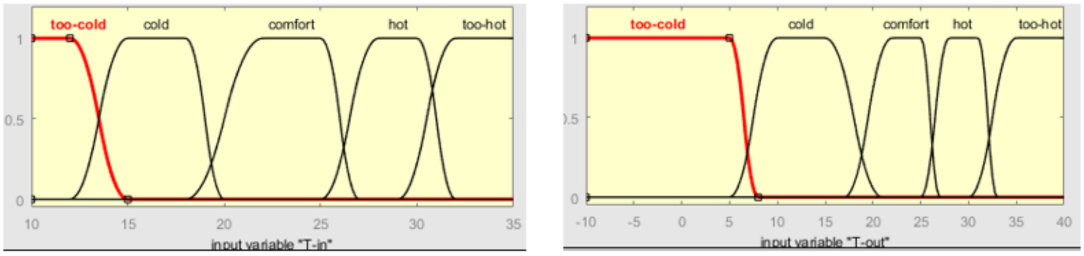


Figure 3.10: T_{indoor} (left) and $T_{outside}$ (right) fuzzyfication.

The output variables were the same with the first fuzzy case. The overview of the second fuzzy case could be seen in the following table. It represents the inputs, outputs and defined rules. Besides, in the Table 3.9, the diagram of the fuzzy logic system, which explains the relations between inputs and outputs, is shown.

Table 3.9: The overview of the second fuzzy scenario.

	Input		Rules	Output
	Indoor Temperature	Outdoor Temperature		Set-point Temperature
Very Cold	Below 15°C	Below 8°C	25 rules	-
Cold	12-20°C	5-21°C		-
Comfort	18-27°C	17-27°C		-
Hot	25-32°C	25-33°C		-
Very Hot	Upper than 29°C	Upper than 30°C		-
Heating Mode	-	-		22-25°C
Cooling Mode	-	-		23-26°C

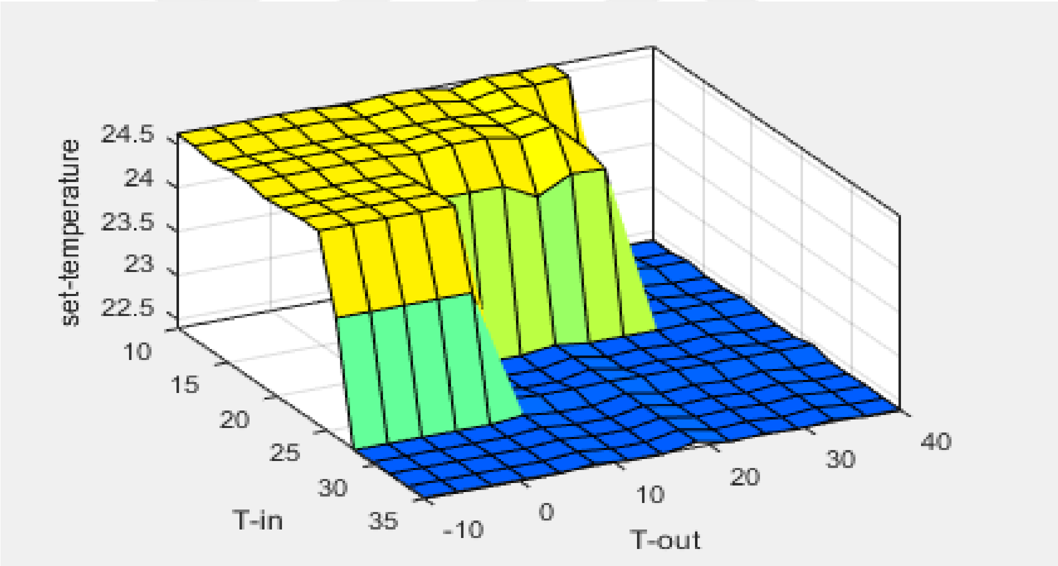


Figure 3.11: Input-output mapping of the fuzzy logic system.

Actually, Figure 3.11 summarizes the fuzzy logic’ working scheme of this case. The blue regions represent the low set points according to the inside and outside temperatures situation, while the yellow regions indicate the high set points. The greenish colors display the transition set points that were decided by the Fuzzy logic. This part was the most significant, because there were no particular values like the high and low set-points. The values could be changed in the previously defined range.

In this scenario, the main objective was to see the dynamic set-point changes according to outside and indoor temperatures. For this purpose firstly hourly and secondly monthly results were evaluated.

Firstly, two days, one of the hottest for heating season and one of the coldest for cooling season, were selected to track the hourly changes of the setpoints as it represented in the Figure 3.12 and 3.13.

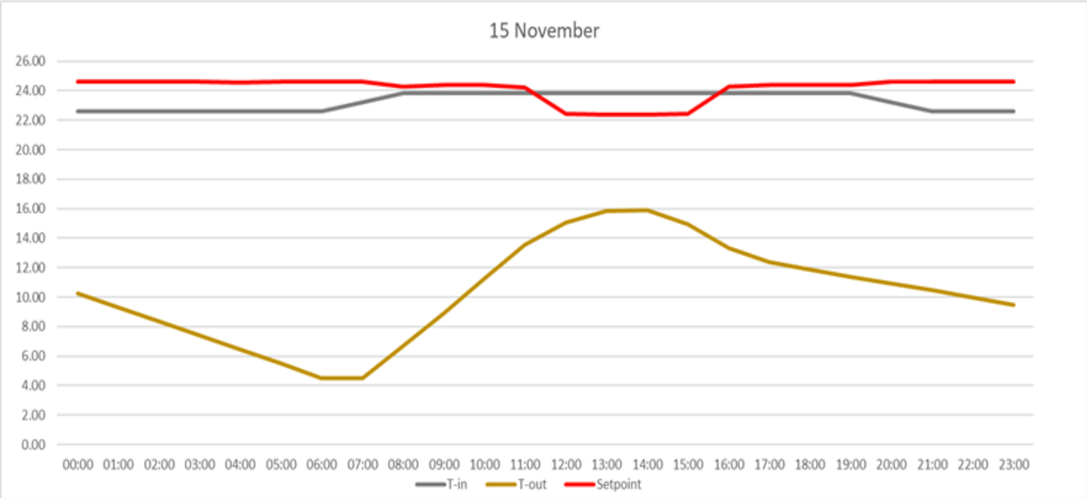


Figure 3.12: Hourly set-point changes in the day of heating season.

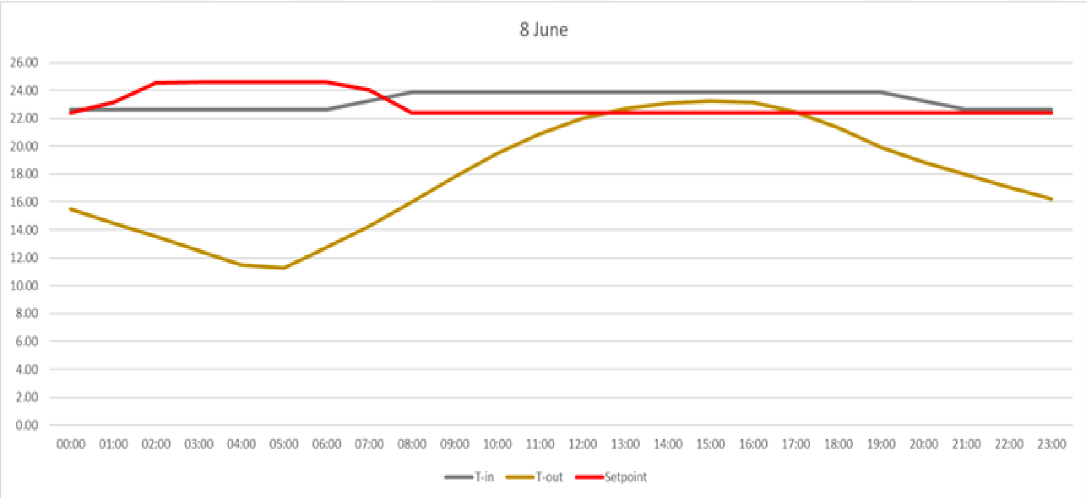


Figure 3.13: Hourly set-point changes in the day of cooling season.

It is clearly seen from the graphs that the setpoints vary according to the T_{in} and T_{out}. In the heating day, the setpoint got the highest degree with 24.62 °C when the T_{out} was 4.50 °C. The minimum set-point value was 22.38 °C. The range of the set-points were between 22.38 °C and 24.62 °C for that day and it can take any value in that range.

Secondly, the monthly results were obtained from the second fuzzy case were represented on the Table 3.10. After the T_{in} was included instead of $T_{collector}$ to the fuzzy case, the energy performance of the scenario was improved. As in the previous scenarios, the results were shown for per month as heating, cooling and total energy consumption.

Table 3.10: Second fuzzy scenario results.

	Heating Consumption [kWh]	Cooling Consumption [kWh]	Total Consumption [kWh]
January	290,537.24	0.00	290,537.24
February	233,942.50	0.00	233,942.50
March	198,446.90	0.00	198,446.90
April	128,533.29	0.00	128,533.29
May	56,811.74	21,575.56	78,387.30
June	0.00	55,966.86	55,966.86
July	0.00	105,795.16	105,795.16
August	0.00	96,875.45	96,875.45
September	0.00	41,379.09	41,379.09
October	81,097.90	10,823.05	91,920.95
November	180,987.15	0.00	180,987.15
December	260,576.99	0.00	260,576.99
Total	**1,430,933.71**	**332,415.17**	**1,763,348.89**
Total [kWh/m^2]	**79.02**	**18.36**	**97,38**

3.5 Comparative Results

Several simulations were performed to obtain the results. For this purpose, firstly a baseline model was created. Later, diverse codes were written on the MATLAB to run the simulations according to conditions of scenarios. Then, these .m files were imported into the TRNSYS model and simulations were run. Consequently, the results were obtained to compare the scenarios. The comparisons were made considering the annual heating energy consumption and cooling energy consumption. The monthly cumulative heating and cooling energy consumptions of the scenarios were compared in this section.

The annual heating consumptions obtained from each scenario is shown in the Figure 3.14. The blue, red, purple and green line express the base case, ICT, first fuzzy and second fuzzy scenarios respectively.

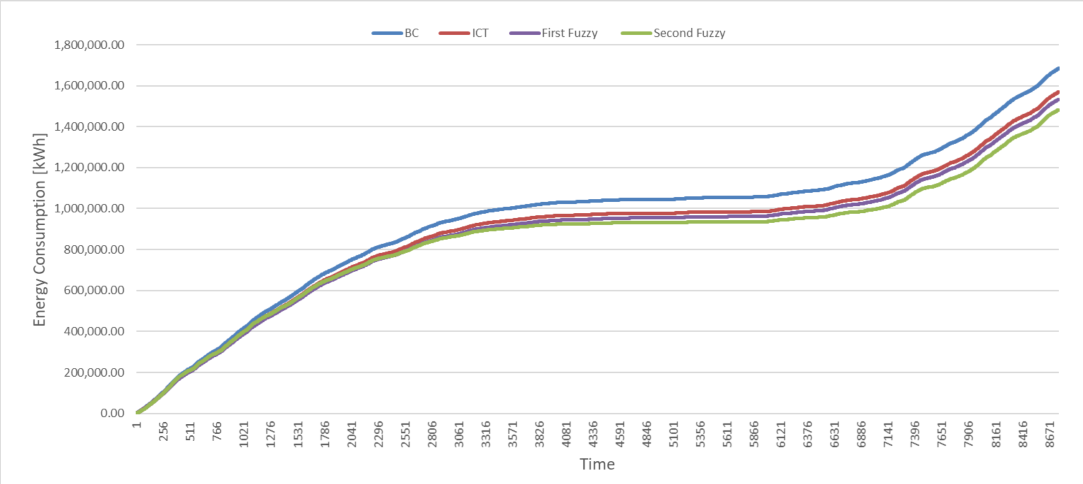


Figure 3.14: Annual comparison of the heating energy consumptions of the scenarios.

When looking the previous figure, for the heating consumption, it can be easily seen that firstly the curves were increased because of heating needs, then remained constant for a while due to no heating needs in summer months and, finally increased again. The most savings were earned from the second fuzzy logic strategy. The total heating energy consumption was 1,596,422.97 kWh in the base case, 1,497,655.14 kWh in the ICT, 1,463,126.45 kWh in the first fuzzy case and 1,430,933.71 kWh in the second fuzzy case. It means that the most savings were obtained from the second fuzzy case with 10.37%. In the Table 3.11 and 3.12, heating energy consumptions and obtained savings can be seen.

Table 3.11: Comparison of the heating energy consumptions.

	Heating Energy Consumptions [kWh]			
	Base-case	ICT	First fuzzy	Second fuzzy
January	303,202.70	289,531.50	289,262.11	290,537.24
February	249,616.19	237,292.17	235,865.43	233,942.50
March	221,334.72	207,787.07	203,414.68	198,446.90
April	154,243.38	141,950.94	135,916.54	128,533.29
May	77,368.80	68,191.45	62,663.37	56,811.74
June	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00
September	0.00	0.00	0.00	0.00
October	105,454.31	94,566.60	87,125.51	81,097.90
November	204,229.37	191,403.48	185,426.25	180,987.15
December	280,873.49	266,931.92	263,452.56	260,576.99
Total	1,596,422.97	1,497,655.14	1,463,126.45	1,430,933.71
Total [kWh/m^2]	88.16	82.71	80.80	79.02

Table 3.12: Obtained heating savings from the scenarios.

	Savings [%]					
	ICT - BC	1.fuzzy-BC	2.fuzzy-BC	1.fuzzy-ICT	2.fuzzy-ICT	2.fuzzy-1.fuzzy
January	4.54.	4.60	4.21	0.09	-0.35	-0.44
February	4.94	5.51	6.28	0.06	1.41	0.82
March	6.12	8.10	10.34	2.10	4.50	2.44
April	7.97	11.88	16.67	4.25	9.45	5.43
May	11.86	19.01	26.57	8.11	16.69	9.34
June	0.00	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00
September	0.00	0.00	0.00	0.00	0.00	0.00
October	10.32	17.38	23.10	7.87	14.24	6.92
November	6.28	9.21	11.38	3.12	5.91	2.39
December	4.96	6.20	7.23	1.30	2.38	1.09
Total	**6.19**	**8.35**	**10.37**	**2.31**	**4.46**	**2.20**

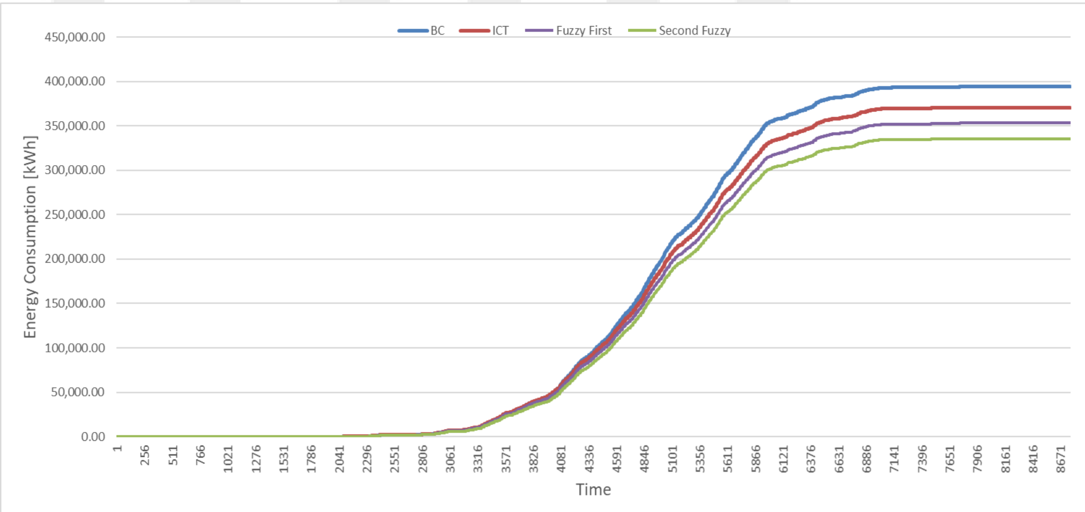


Figure 3.15: Annual comparison of the cooling energy consumptions of the scenarios.

When looking at the cooling consumption on the Figure 3.15, from June to September, the ranges were started to broaden, and then remained stable until end of the year. But in the transition months and April, a small increase was seen. The total cooling energy consumption of the base case, ICT, first fuzzy and second fuzzy scenarios were 390,512.63 kWh, 366,863.95 kWh, 349,344.28 kWh and 332,415.17 kWh respectively. The saving is about 23,648.68 kWh for ICT, 41,168.35 kWh for first fuzzy and 58,097.46 kWh for second fuzzy scenario for one year according to simulations. The Table 3.13 and 3.14 summarizes the cooling energy consumptions and the savings.

Table 3.13: Comparison of the cooling energy consumptions.

	Cooling Energy Consumptions [kWh]			
	Base-case	ICT	First fuzzy	Second fuzzy
January	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00
March	0.00	0.00	0.00	0.00
April	0.00	0.00	0.00	0.00
May	24,327.35	24,619.04	22,911.27	21,575.56
June	64,894.98	61,793.51	58,179.54	55,966.86
July	124,370.08	115,051.30	111,221.41	105,795.16
August	115,054.80	106,119.52	101,146.23	96,875.45
September	49,650.32	46,743.49	43,947.48	41,379.09
October	12,215.09	12,537.09	11,938.37	10,823.05
November	0.00	0.00	0.00	0.00
December	0.00	0.00	0.00	0.00
Total	**390,512.63**	**366,863.95**	**349,344.28**	**332,415.17**
Total [kWh/m^2]	**21.57**	**20.26**	**19.29**	**18.36**

Table 3.14: Obtained cooling savings from the scenarios.

	Savings [%]					
	ICT - BC	2.fuzzy-BC	1.fuzzy-BC	2.fuzzy-ICT	1.fuzzy-ICT	2.fuzzy-1.fuzzy
January	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00
March	0.00	0.00	0.00	0.00	0.00	0.00
April	0.00	0.00	0.00	0.00	0.00	0.00
May	-1.20	5.82	11.31	6.94	12.36	5.83
June	4.78	10.35	13.76	5.85	9.43	3.80
July	7.49	10.57	14.94	3.33	8.05	4.88
August	7.77	12.09	15.80	4.69	8.71	4.22
September	5.85	11.49	16.66	5.98	11.48	5.84
October	-2.64	2.27	11.40	4.78	13.67	9.34
November	0.00	0.00	0.00	0.00	0.00	0.00
December	0.00	0.00	0.00	0.00	0.00	0.00
Total	**6.06**	**10.54**	**14.88**	**4.78**	**9.39**	**4.85**

As a consequence, the results of this study showed us how the automation systems affect the building' energy performance. The savings were calculated for both heating and cooling consumption separately. The austerities come from the ICT were 6.19% for heating and 6.06% for cooling. Finally, the key purpose of this study was to perform a dynamic hourly simulation and it was achieved by the implementation of the Fuzzy logic. The hourly set-point changes were shown in two different seasonal days. It was seen that the set-point dynamically varied in the interval of 2-3 °C. Besides, the savings were obtained with only changes on the set-points. According the results, the saving on heating consumption between Fuzzy and Base Case scenarios which was the highest saving, was about 10.37% (~166,000 kWh). The highest saving for the cooling consumption was nearly 14.88% (58,000 kWh) for Fuzzy and Base Case scenario. These results indicate that the dynamic set-points improve the energy saving which could be simulated accurately. The Table 3.15 summarizes the obtained heating sand savings from each scenario.

Table 3.15: Summary of the total heating and cooling savings.

	Heating Saving	Cooling Saving
Basecase	-	-
ICT-Basecase	6.19%	6.06%
First fuzy-Basecase	8.35%	10.54%
Second fuzzy-Basecase	10.37%	14.88%
First fuzzy-ICT	2.31%	4.78%
Second fuzzy-ICT	4.46%	9.39%
Second fuzzy-First fuzzy	2.20%	4.85%

Lastly, the highest savings obtained from the second fuzzy scenario which was reached 10.37% (~166,000 kWh) for heating and 14.88% (58,000 kWh) for cooling with total about 224,000 kWh for one year. Inclusively, with the application of the automation systems, remarkable falls on the energy consumption of the buildings could be accomplished, especially large-scale buildings because of their high degree of energy consumption and multiple mechanical systems usage. This chapter demonstrates a method to follow to improve the effect of the automation systems.

4. CASE 2 – CALIBRATION OF ICT MODEL

In the second case, a calibration process will be tried to perform. For this purpose, the model created in the CASE 1 working with the ICT system control strategy was chosen to be calibrated. Because, the mechanical system of the actual building works based on the ICT control strategy. This is the reason why the ICT model was chosen. While these operations are carried out, measurements are also made by the placed sensors in the building. Some of these measurements are as follows; heating and cooling consumption [kWh], outside temperature [°C], inside temperature [°C]. These measurements have a significant importance, because the model will be calibrated based on them. By comparing the simulated results and the measurements, the accuracy of the model is evaluated. While evaluating it, MBE and CVRMSE values are calculated. If these values provide the calibration criteria published by ASHRAE, the model may be considered as calibrated. But if not, then the input parameters of the model are changed continuously until the values provide the criteria. After the calibrated model is obtained, the simulation is run, and the realistic energy performance of the simulation is got. As a last step, the second fuzzy scenario mentioned in the CASE 1 is applied to the calibrated model to see the real effect of the fuzzy.

4.1 Measurements

As mentioned before, measurements have an important role in the calibration process. The accurate and desired quality of these measurements directly affects the calibration process. Therefore, extra attention should be given to this process.

In this case, it was decided to calibrate the generated model according to the energy performance of the building. Therefore, heating and cooling energy consumption of the building were monitored and collected separately for each mechanical system. That is, which mechanical system consumes more energy, and whichever comes in and out is easily visible from these data. Furthermore, another nice aspect of these measurements is that measurements are carried out on hourly basis. This allows us to make more precise evaluations. In addition, the sensitivity of the placed sensors is 100-kwh. In other words, if the consumption does not reach 100 kwh, consumption will be 0 for that hour, and if it exceeds 100-kwh, it will be 100-kwh for that hour. As a result, every 100-kwh consumption of the building can be seen on hourly basis.

However, these consumptions cannot always be measured on an hourly basis as expected. Because sometimes there may be problems with the connection or the sensors, which may interfere with the measurements. In such cases, missing data may occur and may corrupt data integrity. These missing data may sometimes need to be filled individually, depending on the data state.

In our case, such breaks were very frequent, and the hourly calibration might not be accurate. Moreover, there was a lot of fluctuations in daily data. Therefore, it was decided to perform a monthly calibration. However, in the latest model, an evaluation was made based on daily data as an extra.

On the other hand, it is necessary to give information about the duration of measurements taken from the building. In our case, sensors were installed in the building at the beginning of 2018. However, in the first months we have encountered sensor and connection problems. Therefore, we concluded that the measurements we received were incomplete and not accurate. In addition, the building has been stayed empty for a long time due to renovation work, and renovation works continued until late May 2018. With the beginning of June 2018, the old people started to settle in the building and the building started to work at full capacity. Therefore, it was decided to use the measurements after June in the calibration process. These measurements continued until the end of November 2018.

To sum up, we had approximately 11 months of measured heating and cooling energy consumptions. However, the accuracy of the data until the end of May was controversial. Therefore, there was only 6 months of measured data was usable. 4 of these 6 months were cooling season data, and the remaining 2 were heating season data. A summary of the measured data from the building can be seen in the Figure 4.1. The red backgrounds in the graph represent heating months, and the blue backgrounds represent the cooling months.

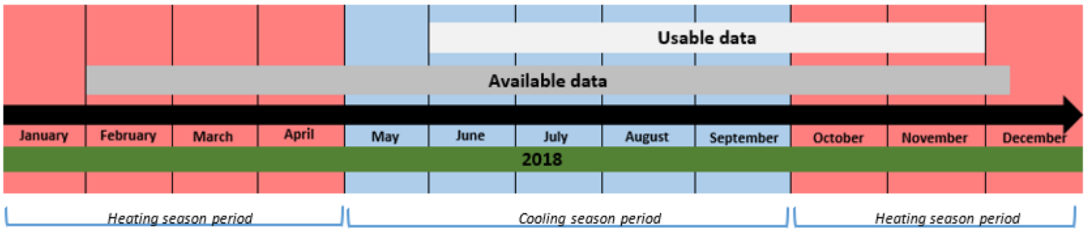


Figure 4.1: Measured data summary.

4.2 Improvements for Calibration

In this section, the iterative operations which was performed to get the results of the simulation closer to the measured data is be explained. As a first step of iterative operations, the most influential inputs that will be modified should have determined. To detect these inputs, it is advised to perform a sensitivity analysis in the literature. But instead of performing sensitivity analysis, in our study, we have used the inputs that had been already proved as effective in the literature. Table 4.1 summarizes the inputs used in this study.

Table 4.1: Used inputs and ROV's.

Variable Description	Existing Value	Source	ROV	Min. Value	Max. Value
External wall U-value	0.330 W/m^2K	Design documents	15%	0.281 W/m^2K	0.380 W/m^2K
Below grade wall U-value	0.950 W/m^2K	Design documents	15%	0.410 W/m^2K	0.554 W/m^2K
Windows U-value	1.600 W/m^2K	Design documents	15%	1.360 W/m^2K	1.840 W/m^2K
Infiltration rate	1.1 ac/h	Design documents	15%	0.935 ac/h	1.265 ac/h
Cooling set-point	26 ˚C	Sensor data	2%	25.48 ˚C	26.52 ˚C
Heating set-point	24 ˚C	Sensor data	2%	23.58 ˚C	24.42 ˚C

As it could be seen from the Table 4.1, 6 inputs were determined to modify. Then a ROV was defined for each input based on their source, as mentioned Figure 2.5. As a consequence, each input had a min. value and max. value. It means that the inputs' values could be changed in that range. In the next section, the obtained results from inputs varied according to the ranges in the Table 4.1 is explained.

4.2.1 Iterative model improvement

In our study, the final model was provided after 4 iterations as the calibration criteria defined by ASHRAE. In this section, firstly, the results of the existing model are presented, and the errors are calculated. Then the revisions are explained, and the results are presented. Finally, the obtained errors are compared in the last heading to see the achieved improvement.

4.2.1.1 Existing model (ICT model)

The specifications and modelling process of the existing model was explained in detail in section "CASE 1 – ICT Scenario". The hourly heating and cooling energy consumptions were obtained from TRNSYS and converted to daily and monthly basis. Later on, they compared with the measurements. The measurements and the simulation results were represented in the Figure 4.2. The consumptions of the June-September interval were for cooling while the consumptions of the October-November were for heating.

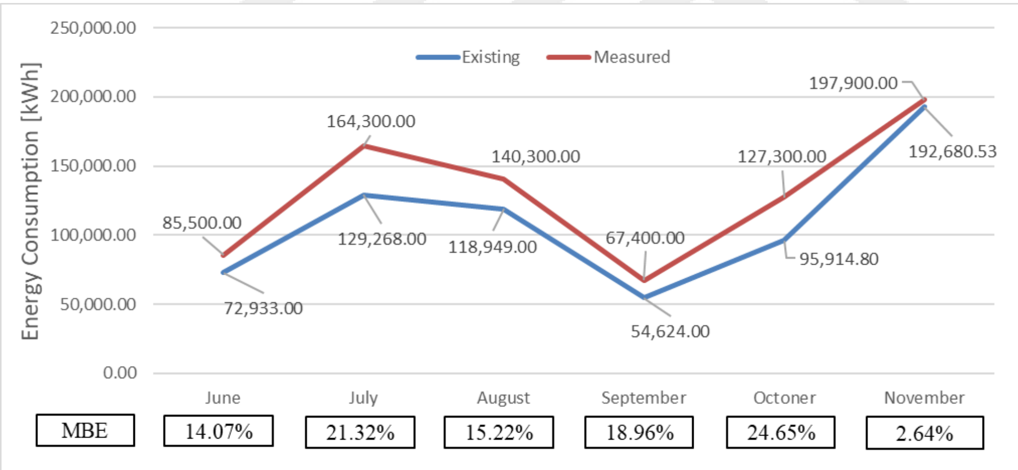


Figure 4.2: Comparison of the existing simulation model results with the measurements.

When the results were compared, it can be easily seen that the simulation results were considerably low. According to figure, the simulation consumptions should be increased. Also, although it was the first model, November provided the calibration criteria with 2.64% MBE.

On the other hand, it should be looked at the heating period, cooling period and total errors to evaluate the model. The Table 4.2 summarizes the calculated errors of the first model. The bold values mean that it provides the calibration criteria.

Table 4.2: Errors of the first model.

	MBE	CVRMSE
Cooling period	17.86%	19.57%
Heating period	11.26%	***13.84%***
Total	15.12%	17.19%

4.2.1.2 Version 1 – External wall U-value

When the first model results were evaluated, it can be clearly seen that the simulation results were always lower that the measured values. In order to increase the simulation results, some changes should have done on the model. These changes could be done by changing the input parameters represented in the Table 4.1. In the version 1, the external wall U-value was increased from 0.326 W/m^{2}K to 0.340 W/m2K to rise the simulation consumptions up. As it expected and represented in the Figure 4.3, the simulation results were increased because of the alteration on the external wall U-value.

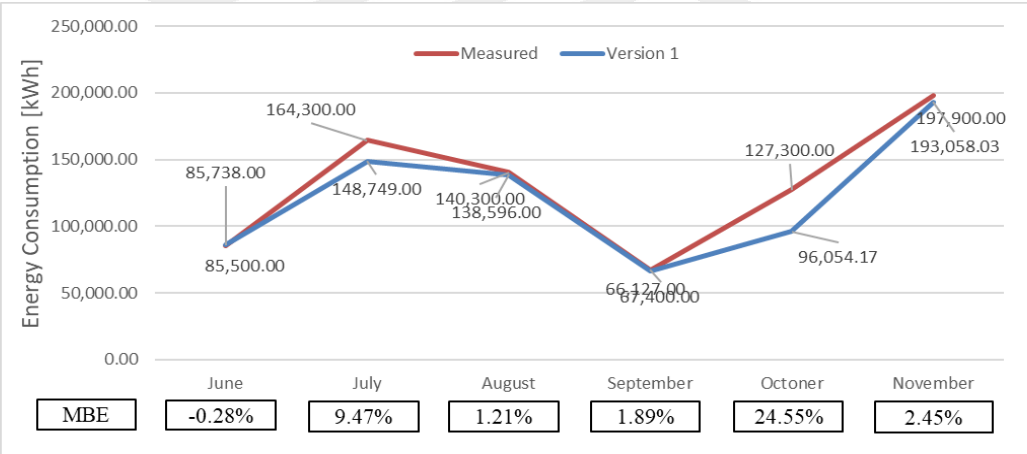


Figure 4.3: Comparison of version 1 results with the measurements.

In the first version, most of the simulation results were got closer the measured values except July and October. Especially, in June, August and September, there was almost no difference while in October, the difference was considerably high when compared to the other months.

Table 4.3: Errors of the version 1.

	MBE	CVRMSE
Cooling period	***4.00%***	***6.86%***
Heating period	11.10%	***13.75%***
Total	6.95%	***11.05%***

The Table 4.3 shows that All CVRMSE values were provided the calibration criteria even in the version 1, while only the cooling MBE was provided it. The total MBE value was really close the criteria. However, still some improvements should be done to ensure the calibration criteria totally.

4.2.1.3 Version 2 – Ground floor U-value

As it can be seen in the version 1, there was a high difference on October. The simulation result of October was still less than the measured one and it had to be increased. With the aim of it, the ground floor U-value was changed from 0.478 W/m^{2}K to 0.502 W/m^{2}K. It was increased, because we wanted to rise the results up. The obtained results with the change of the ground floor U-value could be seen in the Figure 4.4.

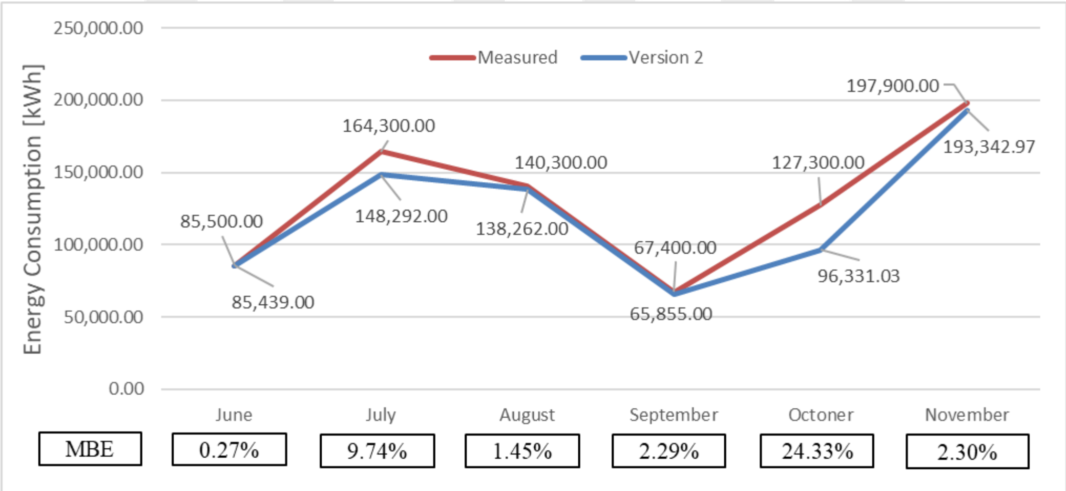


Figure 4.4: Comparison of version 2 results with the measurements.

In this version, even the ground floor U-values was changed, there was not a significant change on the results. They were almost the same with the version 1. The MBE value of October was only reduced from 24.55% to 24.33%. This drop was not solved our problem. Also, the errors of the cooling period were increased except June.

Table 4.4: Errors of the version 2.

	MBE	CVRMSE
Cooling period	***4.30%***	***7.09%***
Heating period	10.92%	***13.61%***
Total	7.05%	***11.03%***

As it can be seen from the Table 4.4, in the second version, the results were not changed in the way that it expected. The errors were quite same with the version 1. Because of the insufficient change on the results of this version, there was still needs for improvements on the model.

4.2.1.4 Version 3 – Infiltration rate

In the version 3, one of the most important factors on the buildings' energy performance, infiltration rate, was edited. It was modified from 1.1 ac/h to 1.2 ac/h because the energy consumptions in the months which had the high errors were still less than the measured values.

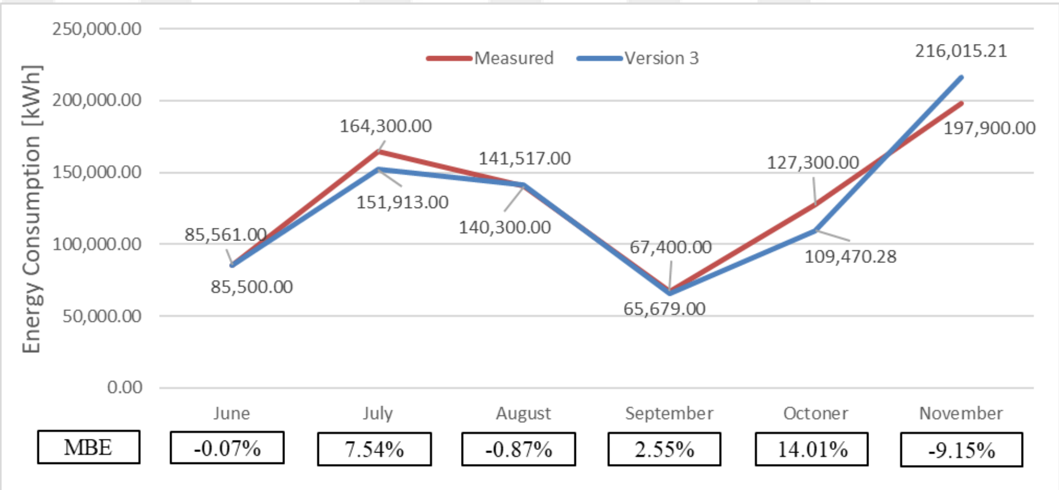


Figure 4.5: Comparison of version 3 results with the measurements.

When looked the Figure 4.5, it was seen that the consumptions in the cooling season were not changed much while the consumptions in the heating season were increased considerably. In October, the MBE was 24.33% in the v2, and now it was improved to 14.01%. On the other hand, in November, the MBE was 2.30% in the v2, while it was -9.15% in the v3. It means that after the change on the infiltration rate, the model was underestimating the October consumption, while overestimating the November consumption. This estimating problem was a serious problem, because until now, it was tried to increase the simulation results to catch the measured values. But now, one of the consumptions of the months was high and the other one was low. Therefore, after this change, it will be tried to find the optimum MBE values for both October and November.

Table 4.5: Errors of the version 3.

	MBE	CVRMSE
Cooling period	***2.80%***	***5.49%***
Heating period	***-0.09%***	***11.05%***
Total	***1.60%***	***8.87%***

In the Table 4.5**,** the results prove that the model could be considered as calibrated because all of the values ensured the calibration criteria. Particularly, MBE values were quite good. Also, CVRMSE values were acceptable.

4.2.1.5 Version 4 – Windows U-value

Even though the monthly calibration criteria were ensured in the v3, when looked on the monthly basis, still there was a problem on the consumptions in the heating period. In order to find the optimum MBE value for the October and November, the windows U-value was changed from 1.600 W/m^{2}K to 1.750 W/m^{2}K. The results of this version were represented in the Figure 4.6.

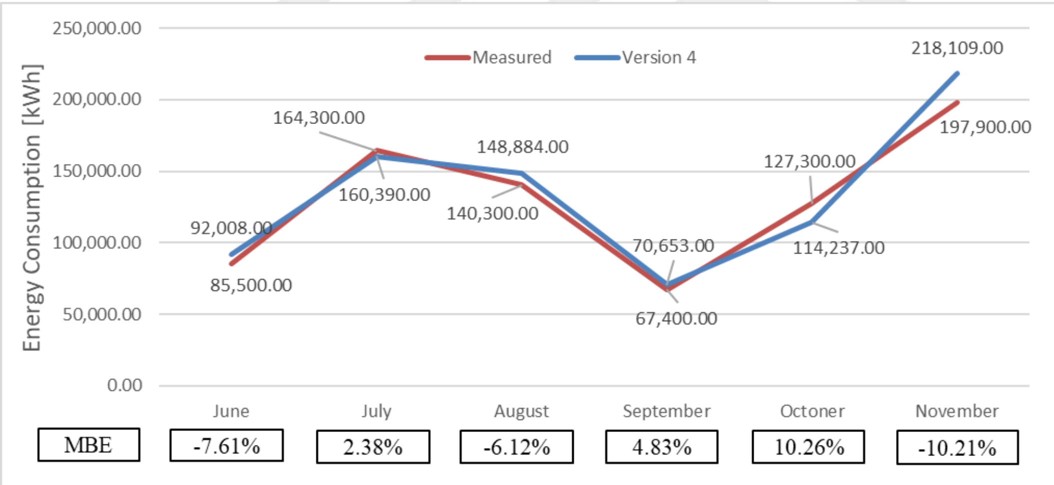


Figure 4.6: Comparison of version 4 results with the measurements.

Now, the MBE values for October and November might be considered as optimized. Because after now, whatever it is changed, one of the MBE value was going to be increased while the other one was going to be decreased. Nevertheless, most of the MBE values in the cooling season were changed in a bad way except July, it was considered this model as the final one. In the next section, the reason why this model was considered as the final model even though some of the MBE values were worse than the v3, will be explained. The MBE and CVRMSE values for the final model could be seen in the Table 4.6.

Table 4.6: Errors of the version 4.

	MBE	CVRMSE
Cooling period	***-3.16%***	***5.21%***
Heating period	***-2.20%***	***10.46%***
Total	***2.76%***	***8.40%***

4.2.2 Error check – Comparison of the errors

In this section, the obtained error values in the previous heading are going to be compared and discussed. It will be like a summary of the results. Also, there will be some explanations about the overestimating and underestimating problems. In the Table 4.7 and Table 4.8, obtained errors so far were summarized.

Table 4.7: MBE values of the versions.

	Existing	Version1	Version 2	Version 3	Version 4
Cooling period	17.86%	***4.00%***	***4.30%***	***2.80%***	***-3.16%***
Heating period	11.26%	11.10%	10.92%	***-0.09%***	***-2.20%***
Total	15.12%	6.95%	7.05%	***1.60%***	***-2.76%***

Table 4.8: CVRMSE values of the versions.

	Existing	Version1	Version 2	Version 3	Version 4
Cooling period	19.57%	***6.86%***	***7.09%***	***5.49%***	***5.21%***
Heating period	13.84%	13.75%	13.61%	***11.05%***	***10.46%***
Total	17.19%	11.05%	11.03%	***8.87%***	***8.40%***

As a consequence of this case, the results prove that even the first model was close the calibration criteria. The errors were minimized as much as possible with the calibration process. The biggest drops were obtained in the version 1. In the version 2, the results were not changed as it expected. While the errors were increased in the cooling period, they were decreased in the heating period. However, they were not satisfactory changes. Version 3 had very good results when looked the MBE and CVRMSE values, especially MBE values were almost zero. But the problem in this version was the huge differences in the October and November. The simulation consumptions in the October were less than the measurements, on the other hand in November, the consumptions were higher than the measurements. It was tried to find the optimum errors for both months, therefore version 4 was performed. In the last version, these errors were 10.26% and -10.21% respectively. After this version, we have stopped the calibration process, because whatever it is changed, one of the errors of the months were going to increase while the other one was going to decrease.

Consequently, it was proposed a solution to see the reason of the underestimating and overestimating problems. It was thought that this problem could be cause from the weather data. Because, in the simulation, the historical weather data was used, and it could be the reason. That is why, the heating degree days were calculated for both the historical weather data and real weather data and then, compared to each other to see if the reason of the problem was it or not. The Table 4.9 represents the HDD and CDD of the months.

Table 4.9: Examination of the HDD and CDD of the months.

	CDD		HDD	
	Real	Simulation	Real	Simulation
June	19.7	18.5	-	-
July	79.1	65.0	-	-
August	88.4	97.3	-	-
September	15.1	21.6	-	-
October	-	-	60.5	50.4
November	-	-	154.6	177.7

The Table 4.9 supports our thoughts because the minus and plus MBE values of the months were in parallel with the CDD and HDD values. Especially, for the heating consumption, there was a significant difference between measured and simulated values in the October and November. In October, the simulated consumptions were less than the measured one, and when looked the Table 4.9, it was obvious that the HDD for simulation was also less than the real one.

After this explanation, as a further step, the daily MBE and CVRMSE values were calculated for the calibrated model. The results were represented in the Table 4.10.

Table 4.10: Daily MBE and CVRMSE values for the calibrated model.

	N_p [days]	Average consumption [kWh]	MBE	CVRMSE
Cooling period	122	3,750.00	***-3.16%***	***27.17%***
Heating period	61	5,315.00	***-2.20%***	***24.18%***
Total	183	4,272.00	***-2.76%***	***26.10%***

The daily results showed us that MBE values were quite good while CVRMSE values were in the expected range but not in a good position. But when the weather data difference was considered, these values could be acceptable.

4.3 Results (Calibrated)

One of the main purposes of this study was to see the annual energy performance of the building. It was possible to perform an annual simulation to get the one-year data after the calibrated mode was obtained.. The Figure 4.7 and Table 4.11 show the annual energy consumptions of the building.

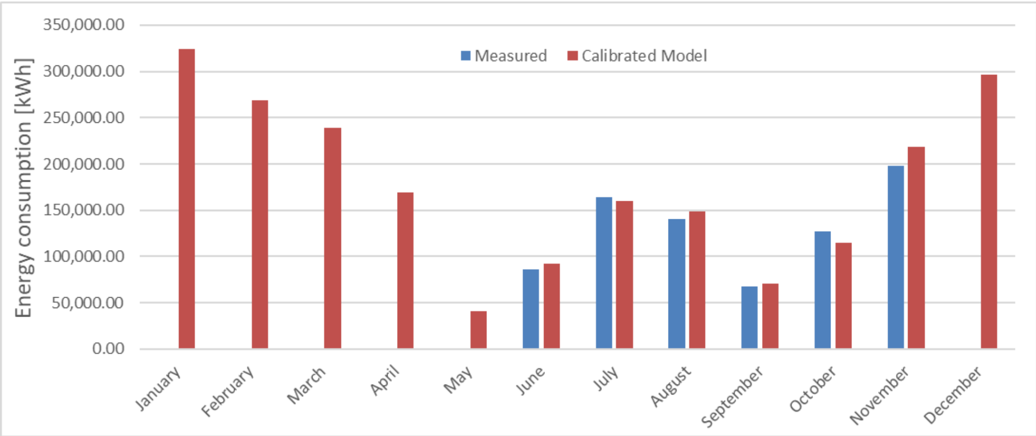


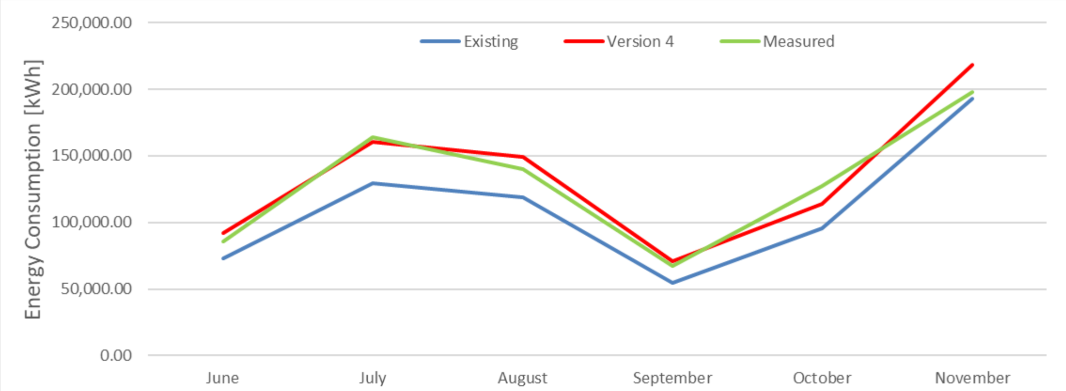
Figure 4.7: Annual energy consumption of the building.

In the figure, the consumptions in the May-September interval were for cooling and the rest was for heating. The blue and red columns represent the real-time measurements and the consumptions of the calibrated model respectively.

Table 4.11: Monthly energy consumptions.

	Measured [kWh]	Simulated [kWh]
January	-	324,503.00
February	-	268,374.00
March	-	238,878.00
April	-	169,172.00
May	-	40,463.00
June	85,500.00	92,008.00
July	164,300.00	160,390.00
August	140,300.00	148,884.00
September	67,400.00	70,653.00
October	127,300.00	114,237.00
November	197,900.00	218,109.00
December	-	296,745.00

Overall, the main purpose of this study was to perform a calibration process and obtain the annual energy performance of the building. The calibration was achieved by performing several processes, and the annual energy performance of the building was obtained consequently. The Figure 4.8 shows the improvement accomplished by the calibration.



	June	July	August	September	October	November
MBE-existing	14.70%	21.32%	15.22%	18.96%	24.65%	2.64%
MBE-version 4	-7.61%	2.38%	-6.12%	4.83%	10.26%	-10.21%

Figure 4.8: The comparison of the first model and the last model with the measurements.

The green line represents the real-time measurements, blue one is the existing model consumptions and the red one is the calibrated model consumptions. As it can be seen from the figure, in the first model all of the consumptions were less than the measurements. According to this information, we have made improvements on the model and obtained the calibrated model which is represented with red color in the figure.

4.4 Second Fuzzy Scenario (Calibrated)

After the calibrated model is obtained, fuzzy scenario might be integrated into the calibrated model to see the actual effect of this control strategy. The same procedure was followed with the "3.4.2 – Second fuzzy scenario". In this section, only the results will be represented, and the achieved savings will be evaluated. The energy performance of this model is shown in the Table 4.12.

Table 4.12: Comparison of ICT-2.Fuzzy scenario results (calibrated).

	ICT Consumption [kWh]	Fuzzy Consumption [kWh]	Saving
January	324,503.00	325,276.00	-0.24%
February	268,374.00	264,257.00	1.53%
March	238,878.00	227,830.00	4.62%
April	169,172.00	152,843.00	9.65%
May	40,463.00	35,190.00	13.03%
June	92,008.00	83,033.00	9.75%
July	160,390.00	147,343.00	8.13%
August	148,884.00	135,903.00	8.72%
September	70,653.00	62,639.00	11.34%
October	114,237.00	97,619.00	14.55%
November	218,109.00	205,917.00	5.59%
December	296,745.00	289,445.00	2.46%
Total	**2,142,419.00**	**2,027,300.00**	**5.37%**
Total [kWh/m^2]	**118.31**	**111.95**	**5.37%**

5. CASE 3 – COMPARATIVE RESULTS

5.1 The Comparison of the Calibrated and Uncalibrated Model Results

The previous chapters, both calibrated and uncalibrated energy performances were obtained. In this chapter, these results were evaluated by comparing them. Firstly, the energy performance of the calibrated and uncalibrated ICT strategy was discussed. The comparison results were shown in the Figure 5.1 and Table 5.1.

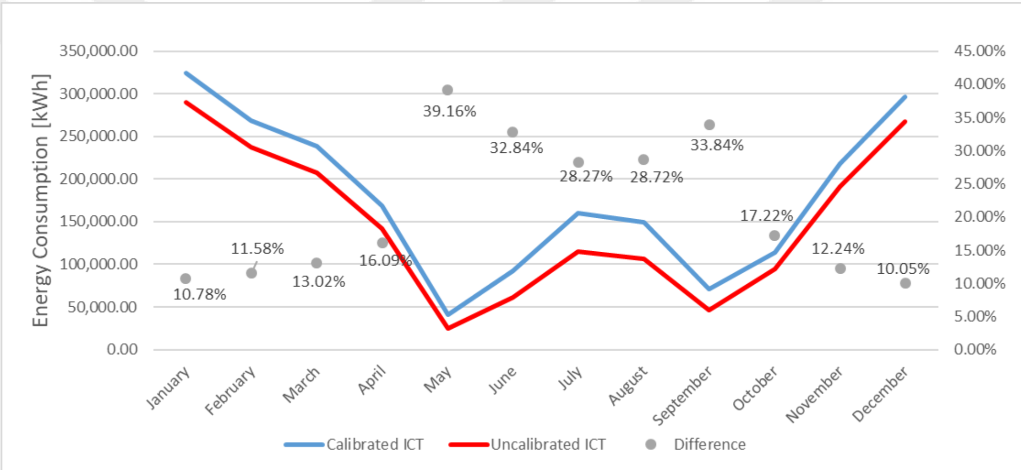


Figure 5.1: Comparison of the calibrated and uncalibrated ICT model.

Table 5.1: Comparison of the calibrated and uncalibrated ICT models' results.

	ICT Consumption Calibrated [kWh]	ICT Consumption Uncalibrated [kWh]	Difference
January	324,503.00	289,531.51	10.78%
February	268,374.00	237,292.17	11.58%
March	238,878.00	207,787.07	13.02%
April	169,172.00	141,950.94	16.09%
May	40,463.00	24,619.04	39.16%
June	92,008.00	61,793.51	32.84%
July	160,390.00	115,051.30	28.27%
August	148,884.00	106,119.52	28.72%
September	70,653.00	46,743.49	33.84%
October	114,237.00	94,566.60	17.22%
November	218,109.00	191,403.48	12.24%
December	296,745.00	266,931.92	10.05%
Total	**2,142,419.00**	**1,783,790.55**	**16.74%**
Total [kWh/m^2]	**118.31**	**98.50**	**16.74%**

As it was represented in the Figure 5.1 and Table 5.1, the calibrated model had higher consumptions than uncalibrated one. It means that the first (uncalibrated) model underestimated the consumptions. Later, with the improvements done, the results were raised to the consumptions which similar to actual consumptions. The maximum differences were observed in the transient months (May and September). Also, the differences in the cooling season were higher than they were in the heating seasons. Therefore, it might be said that the cooling consumptions were affected more than the heating consumptions, from the calibration process.

As it was done in ICT, the same procedure was also followed in the second fuzzy scenario. The comparison results were represented in the Figure 5.2 and Table 5.2.

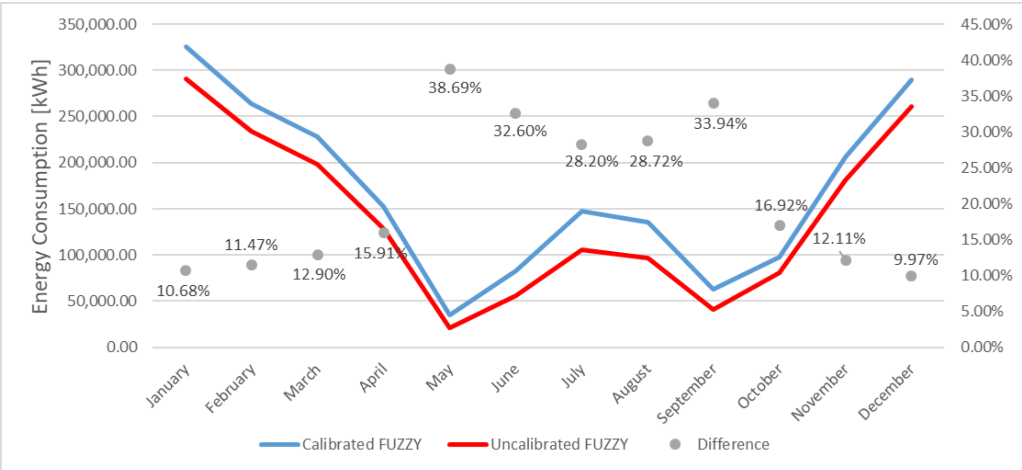


Figure 5.2: Comparison of the calibrated and uncalibrated Fuzzy model.

Table 5.2: Comparison of the calibrated and uncalibrated Fuzzy models' results.

	Fuzzy Consumption Calibrated [kWh]	Fuzzy Consumption Uncalibrated [kWh]	Difference
January	325,276.00	290,537.24	10.68%
February	264,257.00	233,942.50	11.47%
March	227,830.00	198,446.90	12.90%
April	152,843.00	128,533.29	15.91%
May	35,190.00	21,575.56	38.69%
June	83,033.00	55,966.86	32.60%
July	147,343.00	105,795.16	28.20%
August	135,903.00	96,875.45	28.72%
September	62,639.00	41,379.09	33.94%
October	97,619.00	81,097.90	16.92%
November	205,917.00	180,987.15	12.11%
December	289,445.00	260,576.99	9.97%
Total	**2,027,300.00**	**1,695,714.09**	**16.36%**
Total [kWh/m^2]	**111.95**	**93,64**	**16.36%**

It was seen that the second fuzzy results were paralleled with the ICT results, and this parallelism could be understood from the similarity between the figures of ICT and Fuzzy. The peak differences were in the same months again, and also the cooling consumptions were affected more than the heating consumptions as it was experienced in the ICT. The total difference between the calibrated and uncalibrated model was 18.31 kWh/m^2 which equals to 16.36%.

5.2 Improved Results and Obtained Savings

The results of the first case showed that how the automation systems affect the building's energy performance. The savings were calculated for both the heating and cooling consumptions of each scenario and represented in the following table. The energy performances of the base-case scenario were 88.16 kWh/m^2 for heating and 21.57 kWh/m^2 for cooling. The austerities come with the application of ICT strategy were 6.19% for heating and 6.06% for cooling. The heating and cooling energy performances were improved to 82.71 kWh/m^2 and 20.26 kWh/m^2 respectively. After the first fuzzy case, the savings were 10.54% for cooling and 8.35 % for heating. With the second fuzzy scenario application, these consumptions have dropped slightly. The most important factor why the savivngs were decreased was the change of the input variable. With the addition of the indoor temperature as an input, the savings were improved to 14.88% for cooling and 10.37% for heating. The Figure 5.3 represents how much savings were obtained from the scenarios.

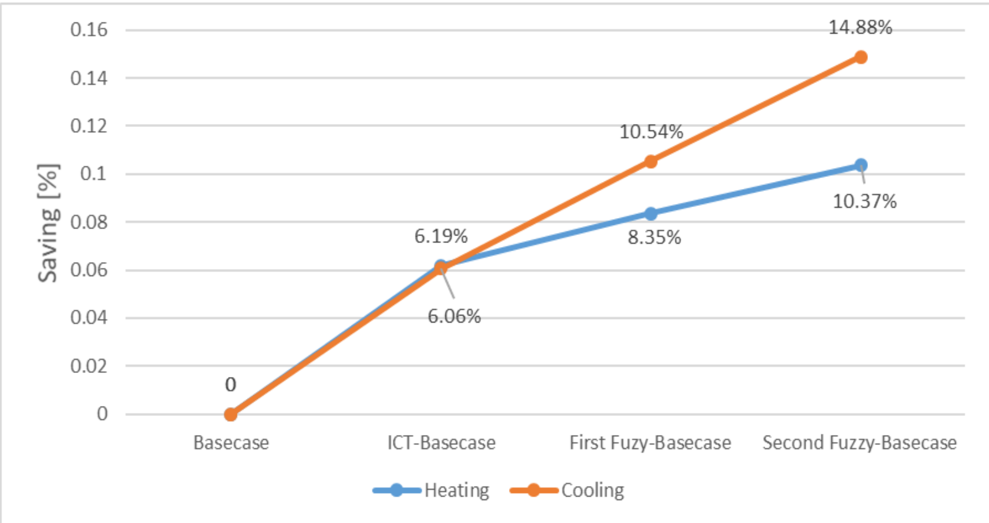


Figure 5.3: Obtained savings.

Overall savings of second fuzzy scenario, which was reached the highest point with 10.37% for heating and 14.88% for cooling, was considerably high. These savings were approximately equal to 166,000 kWh decrease in the heating and 58,000 kWh in the cooling energy consumption. In addition, significant reductions in the energy consumption of buildings, especially in large-scale buildings, due to the high energy consumption and the use of a large number of mechanical systems, may be achieved by the application of automation systems.

In the second case, the MBE and CVRMSE values were evaluated. The MBE and CVRMSE were 15.12% and 17.19% in the existing ICT model, respectively. They were not provided the calibration criteria therefore some revisions were made on the model. The revisions were; changing the external wall U-value, ground floor U-value, infiltration rate and windows U-value. After these revisions, in the 4th model, the values were decreased to -2.76% for MBE and 8.40% for CVRMSE. In the Figure 5.4 and Figure 5.5, the improvements are represented.

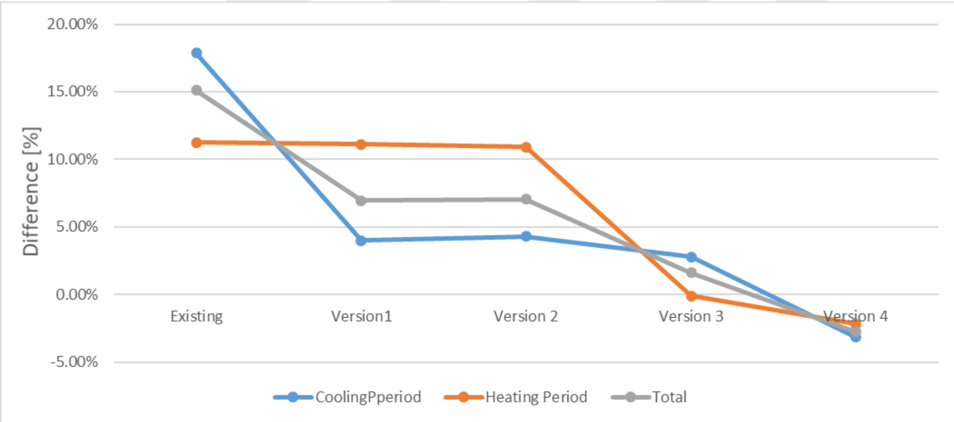


Figure 5.4: Achieved improvements on MBE values.

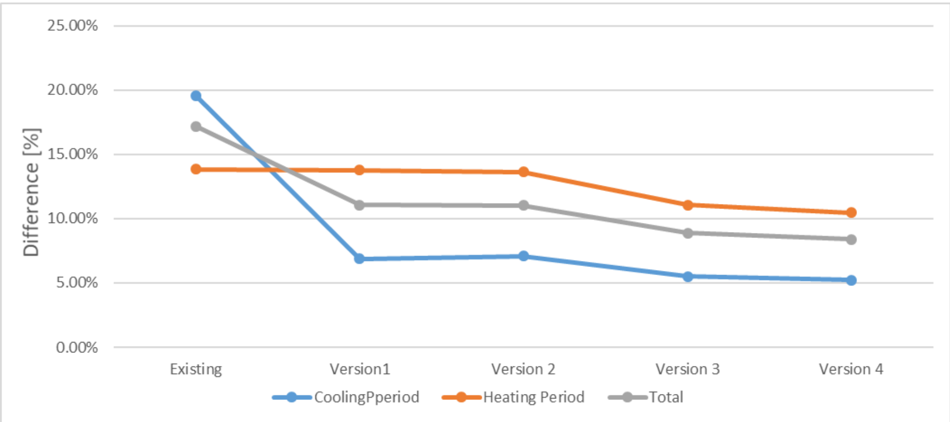


Figure 5.5: Achieved improvements on CVRMSE values.

Overall, the main purpose of the second case was to perform a calibration process and it was achieved by performing several processes. The calibration process has a great significance in the energy performance modelling. Because, nowadays, the energy performances of the buildings are usually needed to make calculations for economical or any other indicators. When the annual measurements are not reachable or obtainable, with the usage of short-term measurements, the created models can be calibrated, and the annual energy performance may be obtained easily. Besides, it gives us opportunity to understand how the adjustments would affect the building's energy performance without applying to the actual building.

6. CONCLUSION

In the thesis, the energy performance analyses of large scales building' mechanical system under different control strategies, and the calibration process in terms of energy performance of the same building was performed by using short-term measurements from the building. A comprehensive methodology of 3 steps has been developed to enable these two processes to be performed. The steps were improving the energy performance of the building, calibration of the energy performance model of the building and the comparison of the results.

In the first case, three different control strategies, which were base-case, ICT and fuzzy, were applied through to mechanical system of the building model. The base-case scenario was a simple control scenario that controls the building's mechanical systems, the ASHP, WSHP and boiler, and operates depending on the outlet water temperature of the solar collectors. In the second scenario, the base-case scenario was improved by increasing the number of inputs to two. The additional input was outside air temperature. With the increasing number of inputs, the way the scenario works was became a little more complicated to improve the energy performance. In the fuzzy scenario, it was aimed to be performed a dynamic hourly simulation by changing the set-point values within a certain range instead of using fixed seasonal set-points. Firstly, a fuzzy logic working system, that works depending on the outside temperature and outlet water temperature of the solar collector, was formed in order to reach the purpose of the scenario. Then, instead of using outlet water temperature of the solar collector, indoor temperature was used as an input variable. By doing this, the energy performance of the simulation models improved considerably. After, the energy performances of each scenario were obtained and compared to evaluate the results.

In the second case, the heating and cooling energy consumption measurements from the building were done to perform the calibration process. The measurements covered almost all of 2018. However, only six months, from June to November, of the measured data were usable for calibration process. The model that works based on the ICT control strategy, was chosen to be calibrated, because the mechanical system of the actual building was working based on that control strategy. While performing the calibration, the MBE and CVRMSE error indicators that reveal the error between the model and the measurements, were used. These values must meet the calibration criteria set by ASHRAE to be able to say that the model was calibrated. The model inputs were revised to bring the MBE and CVRMSE values of the model into the desired range. After 4 revision, the error values were decreased to requested range, and the model was considered as calibrated.

In general, in the thesis, on the computer environment, it was highlighted that how much the automation systems would affect the energy performance of the building, and more realistic results could be obtained by the calibration process. It is important to increase and encourage the number of such practices, which are gradually starting to find themselves in the sector nowadays.

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