THERMAL RETROFITTING ON TRADITIONAL BUILDINGS WITH EXTERIOR HALL (*SOFA*): URBAN AND RURAL HOUSES OF MUĞLA

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ABSTRACT

THERMAL RETROFITTING ON TRADITIONAL BUILDINGS WITH EXTERIOR HALL (*SOFA*): URBAN AND RURAL HOUSES OF MUĞLA

Sustaining functional continuity of historical buildings is a commonly acknowledged conservation strategy and thermal retrofitting interventions applied on these buildings has complemental potentials to this strategy as these interventions can be designed to increase the thermal satisfaction of occupants. The aim of this thesis is to examine the thermal behavior of a common historical building type in Anatolia, the traditional houses with exterior hall, and to determine enhancement potentials of possible thermal interventions which will not cause loss of heritage values. Method of the study consists of on-site thermal measurements and transient thermal analysis of case studies utilizing the software *DesignBuilder*. Case studies were selected from both urban and rural sub-settlements of Muğla City in order to detect possible effects of prevailing microclimates. With the results obtained, it was demonstrated the retrofitting interventions of thermal insulation works in roofs and floors between storeys, airtightness measures, addition of secondary glazing to window frames and the addition of closed circulation corridors provide significant improvements in thermal performance of the cases. According to simulation analyses, it was specified that these interventions would save 38.0% of the total building energy use in the urban and 49.4% in the rural sub-settlements. These improvement percentages can even be increased to more than 80% when the integration of a new HVAC system such as ground-source heat pump is implemented. Consequently, it was determined the traditional houses with exterior hall have significant potentials for thermal enhancements which renders the application of thermal interventions as a capable conservation strategy.

ÖZET

DIŞ SOFALI GELENEKSEL YAPILARDA ISIL İYİLEŞTİRMELER: KENTSEL VE KIRSAL MUĞLA KONUTLARI

Tarihi yapıların işlevsel sürekliliğinin sağlanması için önlemler alınması, restorasyon uygulamalarında yaygın olarak kullanılan önemli bir koruma stratejisidir. Bu yapılar için önerilecek ısıl iyileştirme müdahaleleri ise yapı enerji kullanımında tasarruf ve kullanıcı ısıl konforunda iyileşme sağlayarak bu strateji bağlamında tamamlayıcı potansiyellere sahiptir. Bu tezin amacı, Anadolu'da yaygın bir tarihi yapı tipi olan dış sofalı geleneksel konutların ısıl davranışını incelemek ve bu incelemeye dayalı olarak bu tür yapıların miras değerinde kayıplara neden olmayacak olası ısıl müdahalelerin iyileştirme potansiyellerini belirlemektir. Çalışmanın yöntemi, örnek yapılarda uygulanmış yerinde ısıl ölçümlerden ve yapıların *DesignBuilder* yapı simülasyon yazılımı kullanılarak yürütülmüş zamana bağlı ısıl analizlerinden oluşmaktadır. Örnek yapılar, olası mikroklima koşullarının etkilerinin de değerlendirilebilmesi için Muğla Kenti'nin kentsel ve kırsal alt yerleşmelerinden seçilmiştir. Elde edilen ısıl simülasyon sonuçlarıyla, çatıda ve katlar arası döşemelerde uygulanacak ısıl yalıtım uygulamalarının, hava sızdırmazlık önlemlerinin, pencerelere çift cam eklenmesinin ve özgün durumda doğrudan dış hava koşullarına açılan odaların kapalı bir dolaşım koridoruyla birbirine bağlanmasının yapıların ısıl performansında önemli iyileştirmeler sağladığı gösterilmiştir. Bu müdahalelerin birlikte uygulandığında, kentsel alt yerleşme için bina toplam enerji kullanımında % 38.0, kırsal alt yerleşmede ise % 49.4 oranında tasarruf sağladığı belirlenmiştir. Bu iyileştirme yüzdelerinin, yapılarda toprak kaynaklı ısı pompası gibi yüksek verimli bir ısıtma / soğutma sisteminin entegrasyonu da sağlanabildiğinde % 80'in üstüne çıkabildiği görülmüştür. Sonuç olarak, dış sofalı geleneksel Anadolu konutunun ısıl iyileştirme konusunda önemli bir potansiyele sahip olduğu ve bu türden iyileştirmeleri sağlayabilecek olası müdahalelerin de etkili bir koruma stratejisi olarak değerlendirilmesi gerektiği belirtilmiştir.

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CHAPTER 1

INTRODUCTION

Historical buildings, which constitute an important part of the existing building stock[1], began to be studied in the researches focused on their thermal characteristics by late 1970s (Prömmel, 1978). Since the early studies, thermal enhancement of architectural heritage that is based on the specification of measures and interventions to reduce the energy consumption of historical buildings has been a significant research topic (Prömmel, 1978; Johnsen, 1980; Theis, 1982; Gail, 1983; Jankovich, Puccetti, 1983; Butera, D'Orso, Farruggia, Rizzo, Silvestrini, 1985). The attention on the topic is seen to be intensified especially in the last decade (Martínez-Molina, Tort-Ausina, Cho, Vivancos, 2016; Lidelöw, Örn, Luciani, Rizzo, 2018) in parallel with recent administrative and legal steps taken in energy efficiency policies especially in the developed countries (e.g. by the incentives of European Union, 2010; European Union, 2012; European Union, 2018). With the researches on energy enhancement of historical buildings, energy retrofitting interventions that do not risk the heritage value of historical buildings are being studied regarding their impact on heritage values and their enhancement capabilities. While in the early studies, the main theoretical focus was on the contradiction between thermal intervention practices and the preservation of heritage values of historical buildings[2]; in recent years, it has begun to be argued that such interventions can be designed as a conservation strategy for the protection of architectural heritage. This argument is based on the idea that thermal interventions have the potential to make historical buildings functionally more attractive by providing enhancements on their energy performance, reduction on energy consumptions and increase in the thermal comfort for their occupants. In other words, by making the buildings thermally efficient, their environmental impacts will be reduced and the thermal needs of the occupants will

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[1] "In Europe (EU 27, Croatia, Norway, Switzerland, and Turkey) the percentage of buildings older than 1945 vary between 6.1 % (Turkey) and 47.4 % (Luxembourg) with a mean value of 23.1 %" (EFFESUS, 2013).

[2] For addressing this contradiction, ICOMOS France published the declaration called "Concilier performance énergétique et qualité patrimoniale" in 2008 for pointing out the need for strategies for reconciling energy-efficiency interventions and value conservation of architectural heritage. (ICOMOS France, 2008)

be fulfilled according to the modern living standards. By this course, functional continuity of the heritage buildings will be maintained and consequently they will be conserved. Sustaining the functional continuity of historical buildings is a commonly acknowledged conservation strategy. With this strategy, sociocultural value of the historical buildings can be safeguarded as they are maintained as an active participant of the contemporary society and as a result, their cultural significances are conserved as the buildings are regularly monitored and preserved by their occupants. ICOMOS' Charter on the Built Vernacular Heritage (1999), specifically addressed this strategy saying "The appreciation and successful protection of the vernacular heritage depend on the involvement and support of the community, continuing use and maintenance" (ICOMOS, 1999 / General Issues-Article 2) and with the phrase of "Adaptation and reuse of vernacular structures should be carried out in a manner which will respect the integrity of the structure, its character and form while being compatible with acceptable standards of living…" (ICOMOS, 1999 / Guidelines in Practice-Article 5). In this charter (ICOMOS, 1999), it is important that the emphasis of functional continuity is presented in parallel to the satisfaction of the occupants. Also in Declaration of Amsterdam (Council of Europe, 1975), the recommendations of "It has been proved that historical buildings can be given new functions which correspond to the needs of contemporary life" and "…afford functions to buildings which, whilst corresponding to the needs of contemporary life, respect their character and ensure their survival" were depicted as a direct reference to the strategy of sustaining functional continuity on historical buildings. Additionally, in International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964) of ICOMOS / Article 5, it is said that "The conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable but it must not change the lay-out or decoration of the building…" which points out the benefit and framework for the continuity of use. Therefore, in order to be established as a conservation strategy, thermal intervention practices should be designed with regards to the balance of three variables which are:

- establishing considerable thermal enhancement rates,
- conserving heritage values,
- safeguarding occupant satisfaction.

There are also complementary arguments that consider safeguarding the functional continuity of historical buildings as a sustainable urbanization strategy itself as it reduces the need for new constructions. These views point out the extent of extra energy sources that would be spent for new constructions as opposed to the readily possessed embodied energy that is inherent in historical buildings (Munarim et al., 2016; Lidelöw et al., 2019).

1.1. Problem Definition

Traditional houses establish significant assets of historical settlements as representing identity, documentary, historic, aesthetic, architectural, townscape and social values. Moreover, they constitute large portions of their settlements resulting in economic significance as complementary to their cultural importance. Conserving and conveying this cultural heritage to next generations depend on the functional continuity of the buildings. For safeguarding of functional continuity; improving spatial capabilities by energy analyses and thermal enhancements have the potential for raising user thermal comfort and reducing energy consumptions which assists upgrading of historical buildings to the thermal needs of contemporary adaptive uses. However; overly-demanding thermal interventions have significant risks of causing value loss due to possible architectural and constructional alterations. As a result, there occurs the need for balancing energy-efficient retrofitting, conservation of architectural heritage and thermal comfort of their occupants. In order to establish such balance, case-specific and precise thermal examinations must be conducted and solutions must be specified accordingly.

Traditional houses demonstrate a wide variety of architectural types due to the technological level of the period in which they were constructed, specific expectations of their original users and their financial resources, diversity of urban, geographical and climatic contexts, dissimilarities in socio-cultural preferences and available local construction materials. For this reason, each heritage building possesses distinct characteristics of values, potentials, strengths and weaknesses. Architectural conservation works which begin with the process of documentation refer to these characteristics and assess them in the final decision-making procedures. As in the documentation of constructional, structural, and functional features; thermal characteristics of a traditional building must also be evaluated in order to establish case-sensitive restoration interventions that are realistically applicable to the specific buildings. As a result, determining thermal characteristics of these buildings and designing case-specific interventions are becoming commonly acknowledged conservation strategies that need specialized studies.

1.2. Aim and Scope of the Study

The aim of this thesis is to examine thermal characteristics of traditional houses with exterior hall (*sofa*[3]) which constitute a common building type among the architectural heritage of Anatolia and based on this examination, to determine enhancement potentials of possible thermal retrofitting interventions in order to develop conservation decisions to sustain the functional continuity of these buildings. Within the scope of the thesis, studied thermal retrofitting interventions were chosen to be focusing on the enhancements of building envelopes rather than HVAC solutions and rearrangement of occupant behaviors. With this study, these questions were tried to be answered:

- Do dissimilar parameters such as urban form and prevailing microclimatic conditions affect the thermal behavior of traditional houses located in urban and rural sub-settlements of the same city?
- What are the possible thermal retrofitting interventions that can be implemented on traditional houses without risking any value loss on their heritage significance?
- And what are the enhancement rates of these thermal interventions?

In-depth survey on introduction of modern HVAC (heating, ventilation, and air conditioning) systems to historical buildings, constructional detail design for thermal retrofitting interventions, problem of interstitial condensation that can be caused by the change of hygrothermal behavior of historical structures and the financial extent of thermal retrofitting works are out of the research scope.

This study was conducted under these two hypothesis:

1. Traditional houses with exterior hall (*sofa*) have considerable potentials as to be enhanced in their thermal performance with retrofitting interventions that do not risk their heritage values.

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[3] In the scope of this study, the term *sofa* is used for a distinguished space of Anatolian traditional houses rather than for its use in English language as a type of furniture. This space which is one of the most dominant elements that affect the plan arrangement and type of traditional houses, serves both as a circulation area and as a closed or semi-open multi-functional volume (Eldem, 1986; Kuban, 1995).

2. Even in the same city, dissimilar microclimatic conditions and the urban form that are observed in different sub-settlements, significantly affect the thermal behavior of buildings.

1.3. Literature Survey

Among the scholars, the interest in the topic of thermal analyses regarding historical buildings began by late 70s and early 80s (Prömmel, 1978; Johnsen, 1980; Theis, 1982; Gail, 1983; Jankovich, Puccetti, 1983; Butera, D'Orso, Farruggia, Rizzo, Silvestrini, 1985). And this interest has become significantly more evident in the last decade (Martínez-Molina, Tort-Ausina, Cho, Vivancos, 2016; Lidelöw, Örn, Luciani, Rizzo, 2018). This rise of interest seems to be parallel with the recent administrative and legal steps taken in energy efficiency policies especially in the developed countries (European Union, 2010; European Union, 2012; European Union, 2018). The main study areas regarding the topic of energy analyses on historical buildings are:

- Improving energy efficiency and thermal comfort,
- Analyzing interior conditions for the conservation of artwork (presented in historical buildings),
- Determining possible effects of climate change on architectural heritage,
- Defining hygrothermal behavior of historical construction materials for conservation,
- Defining the energy requirements of historical settlements and specific building types in order to establish a data base for policy makers and
- Specifying sustainable design strategies that have been utilized in historical buildings in order to be adapted for the betterment of contemporary architecture.

Improvement of energy efficiency and thermal comfort on historical buildings is the most dominant study area for researchers (Morelli et al., 2012; Moran et al., 2014; Arumägi et al., 2014; Ben et al., 2014; López et al., 2014). In these quantitative studies, sets of retrofitting[4] measures were tested for their enhancement rates in order to define

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[4] The term retrofitting is defined by ASHRAE as "modification of existing equipment, systems, or buildings to incorporate improved performance, updated operation, improved energy performance, or all three" (https://www.ashrae.org/technical-resources/authoring-tools/terminology, access date: 08.09.2019)

their effects to the thermal behavior of historical buildings for deciding the benefits and necessity of their implementation (Ascione et al., 2011; Berardinis et al., 2014; Ciulla et al., 2016; Rodrigues. et al., 2017a; Duarte et al., 2019).

The studies that specifically analyze interior conditions of historical buildings generally examine the buildings that are used as museums or buildings that are significant with integrated artwork (e.g. wall paintings, sculptures) in their design (Bernardi et al., 2000; Cataldo et al., 2005; Loupa et al., 2006; Bencs et al., 2007; Zítek, Vyhlídal, 2009). These studies generally monitor and predict temperature, humidity and air speed values as well as contaminant presence of the interior spaces with on-site readings and thermal simulations so as to establish design strategies for balancing the preservation of artworks and sustaining thermal comfort for visitors.

Determining possible effects of climate change on architectural heritage is another research topic that generally utilize predicted future weather data in their analyses (Sabbioni, Brimblecombe and Cassar, 2012; Huijbregts, Kramer, Martens, van Schijndel and Schellen, 2012; Lankester et al., 2012; Leissner et al., 2015). These studies aim to determine the possible foreseen changes in thermal behavior of a building for the conservation of historical construction material. The studies use methodology parallel to the researches aiming to prevent the historical construction fabric to deteriorate from hygrothermal alterations (Abuku, Janssen, Roels, 2009; Johansson, Geving, Hagentoft, Jelle, Rognvik, Kalagasidis and Time, 2014) which seek to specify the humidity and temperature changes affecting constructional assemblies to foresee possible decay mechanisms such as biological formations and interstitial condensation.

Defining the energy requirements of historical settlements and specific building types is another common research topic that is conducted in order to establish a data base for policy makers (Fabbri, Zuppiroli and Ambrogio, 2012; Moran, Natarajan and Nikolopoulou, 2012). These studies seek to complement urban / energy planning of historical districts with mapping and statistical work.

Specifying sustainable design strategies that have been utilized in historical buildings is another research area. The studies on this topic seek to define thermal characteristics of historical buildings such as in the parameters of material choice, solar orientation, district planning and natural ventilation in order to be adapted to contemporary architecture designs for the betterment of thermal behavior (Hatamipour, Abedi, 2008; Zhai, Previtali, 2010; Kacher, 2013; Li, You, Chen, Yang, 2013; Khalili et al., 2014; Tang, Nikolopoulou, Zhang, 2014). These studies are generally conducted with quantitative and qualitative comparisons of historical and modern buildings in the same settlement pointing out climate-responsive characteristics of the former.

The studies on the thermal examination of historical buildings are generally conducted with the analysis methods of building modeling and thermal simulations, GIS (Geographical Information Systems) mapping and statistical calculations. These methods utilize the data on thermal characteristics of historical buildings such as energy consumption, thermal comfort status, temperature and humidity distribution, hygrothermal behavior of building envelopes and thermophysical characteristics of construction materials. These data are specified by the tools such as:

- Examination of building envelopes (e.g. thermography, heat flux readings),
- Monitoring of interior and exterior conditions, (e.g. atmospheric readings, temperature and humidity measurements, blower door airtightness tests),
- Laboratory works on construction materials (e.g. for the specification of thermophysical properties such as thermal conductivity, specific heat and density) and
- Occupant surveys (e.g. on spatial utilization patterns, thermal satisfaction, energy consumption).

The studies are held through cases in a variety of building functions. Traditional houses seem to be the most common building type (Cantin et al., 2010; Omar et al., 2011; Li et al., 2012; Harrestrup et al., 2015; Requena-Ruiz, 2016) which is followed by religious monuments (Tiwari et al., 1995; Samek et al., 2007; Martins et al., 2014; Varas-Muriel et al., 2014; Woroniak et al., 2014; Bughrara et al., 2017). Aside from these building types, educational buildings (Lipska et al., 2012; Buvik et al., 2014; Ascione et al., 2015), museums (Camuffo et al., 1999; La Gennusa et al., 2005; Balocco et al., 2007; Corgnati et al., 2009; Rota et al., 2015) and libraries (Fabbri et al., 2014; Coşkun et al., 2017) are also studied. The scales of study cases differ from single construction elements such as walls, windows and roofs (Stazi et al., 2013; Yazicioğlu, 2013; Pisello, 2015) to single building scale (Cardinale et al., 2013; Bellia et al., 2015), settlement scale (Fabbri et al., 2012; Bajracharya, 2014; Gigliarelli et al., 2014; Eriksson et al., 2014; Arumägi et al., 2015), country scale (Nguyen et al., 2011) and even to international / regional contexts (Alev et al., 2014). It can be observed that international research projects are mostly conducted in European countries. Among these projects:

- The project *EFFESUS* (Energy Efficiency for EU Historic Districts' Sustainability / 09.2012-08.2016) was a research project investigating the energy efficiency of European historic urban districts and developing technologies and systems for its improvement[5].
- The Project *3encult* (Efficient Energy for EU Cultural Heritage / 10.2010-3. 2014) focused on energy efficient retrofitting of architectural heritage more in the single structure scale[6].
- The *Climate for Culture* Project (2009-2014) sought after a continent scale methodology to foresee the effects of climate change on historical structures of Europe.
- The *Co₂olBricks* Project (12.2010-12.2013) studied on technical, administrative and educational issues concerning reduction in energy consumption of historical buildings especially at cities of Baltic Sea Region[7].
- The *SECHURBA* (Sustainable Energy Communities in Historic Urban Areas / 09.2008-02.2011) Project considered historical buildings on a community level and aimed to develop ways to encourage energy efficiency practices and renewable energy systems into these communities and set best practice examples[8]. Project has also resulted in a publication called *SECHURBA Guide - Sustainable Energy Communities in Historic Urban Areas* (2011).
- The *HELTH* (Healthy and Energy-efficient Living in Traditional Rural Houses / 05.2010-04.2013) Project aimed to develop optimal solutions concerning how traditional rural houses may be renovated to achieve healthy and energy-efficient living conditions[9].
- The *RENERPATH* (2011-2012) Project aimed to establish an energy rehabilitation methodology based on new and non- intrusive techniques for the energy analysis. It has been applied to public and private heritage buildings in the Spain and in Portugal[10].

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[5] http://www.effesus.eu/, access date: 30.05.2017

[6] http://www.3encult.eu/en/project/Info.html, access date. 30.05.2017

[7] http://www.co2olbricks.eu/index.php?id=43, access date : 14.09.2018

[8] https://ec.europa.eu/energy/intelligent/projects/en/projects/sechurba, access date 14.09.2018

[9] https://www.keep.eu/project/5298/healthy-and-energy-efficient-living-in-traditional-rural-houses, access date: 14.09.2018.

[10] https://www.cartif.com/en/international-projects/european/interreg/item/989-renerpath.html, access date: 14.09.2018.

- The *ReFoMo* (Reduced Footprints of Monumental Structures, Landscapes & Buildings / 2013-2015) Project's objectives were to assess the demand, products and services for climate-proof refurbishment of historical buildings[11].
- *RIBuild* (2015-2019) Project's purpose is to reduce energy consumption in historical buildings with main focus on installation of internal thermal insulation in historical buildings while maintaining their architectural and cultural heritage[12].
- *New4Old* (New energy for old buildings / 2007-2010) Project aimed to promote the integration of renewable energy and energy efficiency technologies into historical buildings, and to create a European-wide network of Renewable Energy Houses in the member States of the European Union[13].

In parallel to these projects, many institutes began to prepare scientific standards in order to contribute to the field of thermal analyses and retrofitting on historical buildings. Some of these documents are:

- *EN 15759-1: Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship* (CEN, 2011)
- *EN 16883: Conservation of cultural heritage - Guidelines for improving the energy performance of historic buildings* (CEN, 2017)
- *Guideline 34P: Energy Guideline for Historical Buildings and Structures* (ASHRAE, 2017b)

Very similar to these standards, there are examples of books, guides and regulations that were prepared by national and local administrations. Examples to these texts are:

- The report *Making Your Historic Building Energy Efficient* (Wilson et al., 2007) for Boulder City of Colorado / USA,
- The report *Advice Series: Energy Efficiency in Traditional Buildings* for the City of Dublin in Ireland (Paul Arnold Architects, 2010),
- The publication *The Secretary of the Interior' s Standards for Guidelines for Rehabilitating Historic Buildings* (Grimmer, Hensley, Petrella, Tepper, 2011) for USA,

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[11] https://refomo.eu/, access date: 14.09.2018.

[12] https://www.ribuild.eu/, access date: 14.09.2018.

[13] https://ec.europa.eu/energy/intelligent/projects/en/projects/new4old, access date: 14.09.2018.

- The guide *Warmer Bath - A guide to improving the energy efficiency of traditional homes in the city of Bath* (Anderson & Robinson, 2011) in UK,
- The regulation *Energy Efficiency and Historic Buildings - Application of Part L of the Building Regulations to historic and traditionally constructed building* (Historic England, 2012a) for UK,
- The guide of *Short Guide Fabric Improvements for Energy Efficiency in Traditional Building* of Historic Scotland (Historic Scotland, 2013),
- The guide *Retrofitting historic buildings for sustainability* (Built Environment City Planning Delivery Unit, 2013) for the city of Westminster in UK,
- The guide *Improving Energy Efficiency in Historic Cornish Buildings* published by Cornwall Council in Ontario / Canada, (Richards, Smith, 2014)
- The guide *Planning Responsible Retrofit of Traditional Buildings* by Sustainable Traditional Buildings Alliance (STBA) for UK (May, Griffiths, 2015). And
- The guide *Building Resilience: Practical Guidelines to Sustainable Rehabilitation of Buildings in Canada* (MTBA Mark Thompson Brandt Architect & Associates Inc., 2016) for Canada.

These texts which examine and evaluate local architectural tradition and climatic conditions focus on the balance between sustainable usage and the conservation of architectural heritage and also propose technical and financial solutions for the historical building users in coherence with their national conservation legislations.

Majority of academic publications on thermal analysis of historical buildings present the studies on the architectural heritage of European nations as Italy and UK being the leading countries followed by Spain. And China is a non-European country contributing to the literature with significant intensity (Martínez-Molina, et al., 2016). Most recently, there is an emerging interest among the scholars of Turkey as well. Among these studies, in their work, Ulukavak Harputlugil and Çetintürk (2005) specified the interior conditions of a traditional house in Safranbolu with thermal simulations and determined its thermal comfort status. In her study, Dizdar (2009) specified the thermal comfort and occupant satisfaction status of new and traditional houses in Diyarbakır using interviews with the users. In her research, Kırmızıdağ Çiçek (2009) specified the thermophysical properties of the construction materials used on a 15th century Ottoman bath in Ankara, determined its original interior microclimatic conditions and thermal insulation characteristics of the building envelope as well as the negative effects of recent restoration works using on-site measurements, laboratory works and calculations on heat and water vapor transfer. In his work, Basaran (2011) determined the interior conditions of a domed Harran House in Urfa and specified the thermal comfort status of its spaces with on-site thermal measurements and heat transfer calculations. In the study of Temur (2011), heating and cooling energy requirements of three traditional houses in Edirne were specified and compared using thermal simulations. In her work, Terim (2011) specified the relationship between local wind flow patterns, natural ventilation and the design parameters of traditional houses in Alaçatı / İzmir with the main focus of their co-operative influence on the spatial thermal comfort status using on-site thermal / air-flow measurements and CFD (Computational Fluid Dynamics) simulations. In their study, Arpacıoğlu and Töre (2012) evaluated the effects of recent restoration works to the thermal behavior of a monumental building (*Divanhane*) in İstanbul using thermal simulations. In her study, Taçoral (2012) specified the thermal comfort status and energy requirements of a traditional house in Kemaliye / Erzincan using occupant interviews and thermal simulations. In his work, Şahin (2013) evaluated the effects of some thermal retrofitting measures to the energy consumption of a traditional house in İzmir using on-site measurements and dynamic simulations. In his study, Yazicioglu (2013) compared the thermal performance and environmental impact of using traditional wooden shutters and contemporary aluminum shutters. In their work, Bekleyen, Dalkılıç and Özen (2014) specified the thermal conditions of open, semi-open and closed spaces of a traditional house in Mardin with on-site thermal measurements and evaluated the thermal comfort status of these spaces. In her study, Çelikyürek (2017) compared the thermal behavior and the energy consumption of a historical Turkish Bath in İzmir for two heating scenarios of original hypocaust heating and contemporary alternative underfloor heating systems using CFD simulations. In their work, Bughrara, Arsan and Akkurt (2017) specified the effect of underfloor heating to the thermal comfort status of a historical mosque in İzmir using on-site thermal measurements and dynamic simulations. In their study, Coşkun, Gülhan, Şahin, Arsan and Akkurt (2017) specified the indoor conditions of a historical library in Tire / İzmir with on-site thermal measurements and dynamic simulations in order to determine the chemical, mechanical and biological degradation risks on the manuscript collection of the building. And in her work, Ulu (2018) analyzed the effects of some thermal retrofitting measures on the energy consumptions of a group of traditional houses located in İzmir using dynamic simulations. The cases evaluated in these studies cover building types ranging from traditional houses to historical monuments. However; there is a lack of research specially focusing on the traditional houses with exterior *sofa* which is one of the most common building types of Anatolian architectural heritage that this thesis seeks to fulfill with case-specific analyzes.

1.3.1. Studies on Thermal Retrofitting of Historical Houses

As a comparative work to evaluate the outcome of this thesis, some selected studies on thermal retrofitting of historical buildings were assessed in more detail. For the sake of a valid comparison, these studies were chosen among the works evaluating historical buildings with residential function, which are located in Mediterranean countries that have relatively similar climatic conditions to the case studies of this thesis.

In the study analyzing a palace (Palazzo dell'Aquila Bosco-Lucarelli) located in Benevento / Italy that is recently used for commercial and educational purposes, thermal effects of some enhancement measures were determined. The study conducted in-field analyses of endoscopies, core samplings and heat flux measurements in order to specify the thermal specifications of building envelopes and used dynamic thermal simulations prepared in *EnergyPlus* software in order to predict the energy consumption of the building. The simulations were validated by model calibration works. Tested thermal enhancement measures were change of HVAC temperature set points that resulted in 10% energy saving, repairs and weather-stripping works on windows for infiltration reduction that resulted in 11% savings, partial application of wall insulation that yielded 2% savings and HVAC upgrading of replacing the present old gas heater with a new system with heat recovery that provided 5% savings. In addition to these results, a whole package of better resulting measures was also simulated as applied together and a total 22% reduction in annual energy consumption was specified. These energy consumption simulations were also complemented with cost-optimization and building energy certification analyses (Ascione et al., 2011).

In the study examining a traditional house in the village of Sant'Eusanio Forconese - L'Aquila / Italy, the effects of thermal insulation work with different materials to the energy consumption of the case study building were evaluated. The tested materials were EPS, Aerogel, VIP vacuum insulating panel, insulation plaster, traditional plaster, glass wool and OSB oriented strand board. The methodology of the study involves on-site investigations of thermography and thermo-flux-meter analysis, and dynamic thermal simulations complemented with technical and economic compatibility check. With the results of the simulations, the application of glass wool within a platform frame was suggested to be the best insulation solution with 53.4% energy saving, while thermal plaster was demonstrated to show the worst performance with 15.8% saving (Berardinis et al., 2014).

In the study which evaluated five cases of a traditional housing type, *Kulla* in Kosovo, thermal improvement scenarios were tested for each historical building. The study utilized on-site thermal measurements and thermal simulation works on *TAS* software. Thermal simulations were validated by model calibration process. With simulations, retrofitting measures of thermal insulation works on roofs and walls as well as changing the original windows with energy efficiency designs were tested. For heating seasons, retrofitting results were given as reduction in the heating loads and for summer, the results were given as reduction in overheating hours. The study suggested 58.3-67.2% reduction in heating loads by insulation on walls, 2.4-10.2% reduction by insulation on the roofs and 0.7-2.3% reduction by window replacement. When all retrofitting measures were applied together, a total 68.9-71.8% reduction in heating loads was specified (Deralla, 2014).

In the study examining a 18th century baroque palace (Palazzo Gallenga Stuart) located in Perugia / Italy, energy savings provided by HVAC upgrading measures were specified. The study used energy models and simulations conducted in *EnergyPlus* software. Tested HVAC upgrading measures were the disposal of the outdoor condensing units and the maintenance of the existing radiators, substitution of the old boiler with a more effective ground-source heat pump plant and installation of a system for the heat storage. According to simulation results, approximately 57% savings in primary energy consumption for heating and cooling were calculated (Pisello et al., 2014).

In the study evaluating a traditional house in İzmir / Turkey, the effects of different thermal retrofitting measures were examined. Energy consumption of the case study was specified using thermal model and dynamic simulations prepared with *DesignBuilder* software. The model was validated by calibration work utilizing on-site dry bulb temperature measurements. The tested retrofitting measures were weather stripping works, upgrading of heating system, use of thermostat control for HVAC equipment, attic floor insulation, wall insulation, roof insulation, ground floor insulation and window replacement. These measures were grouped according to their impact to the authentic features of the building. Consequently, there defined 3 retrofitting packages as package 1 having no impact and package 3 being the most detrimental. With simulation results, it was demonstrated that the most beneficial measure was replacing the heating system with air-source heat pumps that yielded in 24.8% energy saving followed by discarding the auxiliary heating resulted in 14.1% saving, use of natural gas boiler resulted in 12.2% saving, indoor temperature control resulted in 7.1% saving, interior wall insulation resulted in 4.7% saving, exterior wall insulation resulted in 3.9%, weather stripping works resulted in 1.1% saving, roof insulation resulted in 0.9% saving, attic floor insulation resulted in 0.7% saving, replacing the windows resulted in 0.5% saving and ground floor insulation that resulted in 0.5% saving. When these measures were simulated as applied together within the retrofitting packages, 35% saving for Package 1, 41% saving for Package 2 and 53% saving for Package 3 were suggested (Şahin et al., 2015).

In the study comparatively analyzing two historical house types in Italy from early 20th century, one being attached to neighboring blocks from its two sides (Sample A) and one from one side (Sample B), thermal effects of some retrofitting measures were specified for four different Italian cities of Cagliari, Rome, Milano and Palermo with distinct microclimatic conditions. To evaluate the energy requirements of the cases, dynamic simulations conducted in *TRNSYS* software were used. Energy analyzes were also complemented by economic feasibility assessments. The tested retrofitting measures were insulation works on walls and roofs, window replacement and different combinations of these three measures as applied together. For sample A, the simulation results suggested best savings on primary energy demands as 44.6% for Palermo, 44.7% for Cagliari, 56.7% for Rome and 69.0% for Milano. For sample B, best savings were given as 44.1% for Palermo, 44.8% for Cagliari, 47.7 for Rome and 48.9% for Milano (Ciulla et al., 2016)

In the study which examined a 16th century, large scale residential complex (Villa Mondragone) in Italy, effects of some thermal refurbishment solutions in the heating season were evaluated. The study conducted on-site ambient measurements of air temperature and humidity as well as utilizing dynamic building simulations validated by model calibration work. Building simulations were carried out with *IDA ICE 4.5* software. The tested refurbishment solutions were enhancements on window frames and insulation works on walls and partially on the floors. By simulations results, it was specified that approximately 42% energy savings by window enhancements and 64% savings by insulation work could be obtained for heating season (Cornaro et al., 2016).

In the study analyzing a Renaissance-style palace (Palazzo Gravina) in Naples / Italy, saving rates of thermal retrofitting measures in regards to the primary energy required for building heating were specified. Energy consumption of the building was determined by thermal modeling and dynamic simulations prepared with *DesignBuilder* software. Thermal models were validated by calibration work and the energy analyzes were accompanied with economic feasibility assessments. Tested retrofitting measures were wall insulation which resulted in 13.8% energy saving, roof insulation which resulted in 1.01% saving, replacement of windows which resulted in 40.2% saving and replacing heating equipment with condensing boiler which yielded in 32.8% saving. By cost optimal analyses, insulation works were deemed to be non-feasible. Consequently, by a final simulation that tested the effect of interventions only on windows and on heating system applied together, a total 59% saving was suggested (Ascione et al., 2017).

In the study evaluating a 19th century house in Coimbra / Portugal which has been used as an office building, the effects of different occupancy scenarios and physical retrofitting measures to the energy demand of the building were specified. This work was also complemented with life-cycle cost assessments and eco-efficiency analyses. Energy behavior of the house was determined by a dynamic simulation model that was prepared in software, *EnergyPlus*. Tested occupancy scenarios were determined by the variations of alternative HVAC set point temperatures, different occupant numbers and spatial utilization schedules. These scenarios were based on the re-establishment of the building as a residence again rather than maintaining its current function as an office building. The scenarios were categorized in two main sets of residential-low occupancy and residential-high occupancy levels. Integrated in these scenarios, insulation works on roofs and walls were accepted as physical thermal interventions. With simulations, it was demonstrated that with changing the use of the building to a low-occupancy residence, the energy demand for heating increases between 46% and 65%, and cooling demand decreases between 39% and 72%. While high-occupancy residence scenario increases both heating and cooling demands between 69% and 76%, and between 11% and 32% respectively (Rodrigues. et al., 2017a).

In the study comparatively analyzing two historical residences from early 20th century, a single-family house and an apartment building located in the historical city center of Coimbra / Portugal, effects of thermal insulation works applied on walls and roofs in different thicknesses were examined. In addition to energy saving potential of these measures, environmental impacts of the measures were also determined by life cycle assessments. Energy consumption rates of the houses were calculated using building modeling and dynamic simulations carried on with *EnergyPlu*s software. With the results of the simulations, it was demonstrated that for single-family house, approximately 48% energy saving could be provided for heating and 3% saving could be established for cooling. And for apartment building, 23% energy saving could be provided for heating and 60% saving could be obtained for cooling (Rodrigues et al., 2017b).

In the study examining a group of traditional houses within same neighborhood in İzmir / Turkey, thermal effects of some retrofitting measures were evaluated. Thermal requirements of the case studies were calculated using dynamic simulations conducted on *DesignBuilder* software. Tested retrofitting measures were weather-stripping works, thermal insulation on walls, floor and roofs, addition of secondary glazing to windows, use of oriels as sun space, rescheduling window shutters and night time ventilation. According to their impact on the buildings, these measures were grouped in 2 retrofitting packages of the 1st having no impact and the 2nd possessing low-risk. The packages were demonstrated to cause dissimilar results for different cases. For package 1, the highest saving rate was reported to be 31% and the lowest was 8%. For the package 2, the highest saving rate was calculated 66% and the lowest rate was 35% (Ulu, 2018).

In the study focusing on two historical residential / commercial buildings built in late 19th / early 20th century in Catania / Italy; the effects of thermal and seismic retrofitting measures were evaluated in an integrated methodology. This methodology covered the works of historic and architectural surveys for defining the features of the cases and application of the Italian *Guidelines for the improvement of energy efficiency in cultural heritage* (2015) for evaluating their energy performances. For thermal calculations, the software *Masterclima Aermec software v.1.4*5 that is based on a monthly-steady-state method was used. The tested thermal retrofitting measures were the insulation works on terraces, vaults and roofs, replacement of window glasses with double glazing and use of thermal plaster partially on the facades. With possible implementation of these measures, 20.8% to 38.4% reduction in winter energy demand and 17.4% to 39.4% reduction in summer energy use were specified (Moschella. et al., 2018).

In the study comparatively evaluating two 18th century historical buildings with residential / commercial function in Lisbon / Portugal, effectiveness of some passive and active retrofitting measures were determined. Energy requirements and thermal comfort status of the buildings were specified by thermal modeling with *IFC Builder 2018* software and dynamic simulations conducted in *Cypetherm Eplus 2018* program that runs in the engine of *EnergyPlus* software. Tested passive measures were suggested as rescheduling the operation (opening / closing) of openings and shutters, replacing windows and applying insulations on roofs and walls. Tested active measures were given as upgrading of DHW (domestic hot water) systems, installation of photovoltaic and solar thermal systems and upgrading of current HVAC system with selected alternatives. For buildings, simulations of passive retrofitting measures applied as a whole package resulted in reduction of energy demand for heating between 51.84% and 52.05%, and for cooling between 63.49% and 70.48%. However, by considering complementary thermal comfort analyses, this package was deemed to be insufficient. Selected HVAC packages displayed reductions on the primary energy consumption for heating and cooling between 73.37% and 86.74%. Upgrading measures on DHW systems yielded in savings between 68.18% and 78.18% on the primary energy consumptions on DHW. When photovoltaic systems, new HVAC system and DHW upgrading were simulated as applied together, for one case building 83.11% reduction in final energy demand was calculated. For the other case building, the results of this arrangement was suggested more dramatic as it was claimed that this retrofitting arrangement provided a zero energy building even producing 40% more output energy when all its energy demands were fulfilled (Duarte et al., 2019).

In these quantitative studies, sets of retrofitting measures were tested for their enhancement rates in order to define their effects to the energy consumption of historical buildings for deciding the benefits and necessity of their implementation. Thermal retrofitting measures that are examined in these studies can be categorized according to their scopes as:

- The interventions on building envelope such as weather-stripping applications, thermal insulation works on walls, floors and roofs, and upgrading or replacing the windows and the doors,
- The interventions on HVAC (Heating, Ventilating and Air Conditioning) systems and building services (e.g. artificial lighting, domestic hot water-DHW) such as upgrading original HVAC equipment, installation of new systems and integration of renewable energy sources (e.g. micro renewable systems such as solar panels),
- Rearrangement of occupancy patterns regarding spatial utilization schedules and intensity.

Among these retrofitting measures, the thermal insulation works on walls and roofs were seen to be the most frequently evaluated interventions followed by the replacement of windows and the introduction of new HVAC systems. On the contrary, rearrangement of occupancy patterns was only observed in one case study (Rodrigues. et al., 2017a). Testing all or a sub-set of thermal interventions, studies result in a large variation of saving rates regarding building energy use (Table 1 lists the studies according to their energy saving percentages) that range from 20s% (Ascione et al., 2011) to 80s% (Duarte et al., 2019). Some scholars argue that historical buildings can be upgraded to nearly zero-energy buildings and moreover they can even produce more energy than their consumption by the integration of micro renewable systems such as Photovoltaic solar panels (Duarte et al., 2019).

Table 1. Example studies and their results of overall thermal enhancement percentages

Reference Study	Scope of Retrofitting Measures	Overall Energy Saving Percentage	Location of Case Study
Ascione et al., 2011	Building envelope, HVAC systems	22%	Benevento / Italy
Ulu, 2018	Building envelope	31%	İzmir / Turkey
Ascione et al., 2015	Building envelope, HVAC systems	38%	Benevento / Italy
Şahin et al., 2015	Building envelope, HVAC systems	35%-41%	İzmir / Turkey
Berardinis., 2014	Building envelope	53.4%	L'Aquila / Italy
Pisello et al., 2014	HVAC systems	57%	Perugia / Italy
Ascione et al., 2017	Building envelope, HVAC systems	59%	Naples / Italy
Ciulla et al., 2016	Building envelope	48.9%-69%	Palermo, Cagliari, Rome, Milano / Italy
Duarte et al., 2019	Building envelope, HVAC systems	83.1%-140%	Lisbon / Portugal
* For saving percentages, best results that were suggested by the studies were presented in the table.			

The diversity of energy saving rates presented in these studies mostly originates from the fact that the case studies demonstrate an extensive variety of building types with different architectural / constructional characteristics while being located across a large geography. However, variety of different retrofitting measure sets that are proposed in these studies and the differences on their analysis and evaluation methods also enhance this diversity which consequently show that proposing thermal retrofitting measures as to be applied on historical buildings needs case-specific analyzes and evaluations as no generic solutions can be applied to all buildings.

CHAPTER 2

METHODS AND TOOLS

The method of the study consists of on-site thermal measurements and transient thermal analysis of case studies that is the determination of their thermal characteristics that changes over time. All analyses are conducted by the processes of virtual modeling and thermal simulations using building energy performance software. In order to be used in these processes, data sets that define the building attributes had been constructed by preliminary works of site surveys, laboratory works and literature survey.

2.1. Thermal Analyses and Building Performance Software

Thermal analysis of a building is a quantitative study that determines the thermal behavior of the building that is related to the amount, rate and time-dependent change of energy transfer between its inner spaces and the outer environment. With this analysis, thermal characteristics of a building such as heating and cooling loads, temperature and humidity distributions and thermal comfort status of its spaces can be determined.

For thermal analyses, this study utilizes building performance software that enables virtual modeling and dynamic thermal simulation of the case study buildings. Virtual model of a building is a numerical, 3-dimensional representation of a building indicating both physical (building geometry, construction, weather conditions etc.) and social (occupancy) attributes. Virtual simulation is the numerical animation of this model in a desired time period with the parameters that affect its thermal behavior. Time dependent thermal variables such as values of interior air temperature, relative humidity, thermal comfort status, heat gains / losses and fuel consumption are the outputs of energy simulations. These outputs can be acquired for single spaces as well as for the whole building as totals or averages. For the simulation work of this study, *DesignBuilder v5.4.0.21* software was used as it has a detailed architectural modeling interface and its simulations run on *EnergyPlus* engine, which is a free, open source and a regularly updated program that is commonly utilized in academic works (e.g. Boyano et al., 2013, Shabunko et al., 2016). Thermal analyses of the study focus mainly on the variables of annual heating / cooling loads and primary energy consumptions as building totals and the thermal comfort status of each individual space.

2.1.1. Thermal Comfort Model

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as "the condition of the mind in which satisfaction is expressed with the thermal environment" (ASHRAE, 2004). By this definition, as being one of the dominant factors for users to feel satisfied, thermal comfort status is an important characteristic of a space that needs to be determined. Moreover, there is a direct relation between thermal comfort status and the energy requirement of a space as thermal satisfaction of occupants dictates the HVAC demands. Therefore, this study conducted works on specification of thermal comfort status of case studies within its analysis stages.

For the specification of thermal comfort, two main approach models are observed commonly. These models are:

1. Heat-Balance (Rational) Model and
2. Adaptive Model.

2.1.1.1. Heat-Balance (Rational) Model

This model is based on the experimental works and calculations regarding heat-exchange between human body with its surrounding environment (ASHRAE, 2017a). The model has been developed by researchers such as Macpherson (1962) who determined six factors that affect human thermal comfort. Four of these variables are indices based on measurement of physical factors such as:

- air temperature,
- air velocity,
- relative humidity,
- mean radiant temperature.

And two of them are indices based on human preferences such as:

- clothing insulation (In unit *clo* - m^2 °C/ W),

- activity level[14] (Djongyang et al., 2010, Yang et al. 2014).

With quantified values of these variables, Fanger (1973) constructed formulas of The Predicted Mean Vote (PMV) and The Predicted Percentage of Dissatisfied (PPD) in order to calculate this thermal sensation. PMV is the index that predicts the mean value of the votes of a large group of people on thermal sensation (ASHRAE, 2004). This index is formulated as in Equation (2.1).

$$\mathrm{PMV} = [0.303 \exp(-0.036M) + 0.028]L \tag{2.1}$$

where M is rate of metabolic generation per unit DuBois surface area[15],
L is the thermal load on the body (ASHRAE, 2017a).

Using PMV values that derives from this formula, general consensus of the people regarding a specific thermal environment can be foreseen. For example, ASHRAE (2004) defines a seven scale chart of the PMV values which was developed for use in quantifying people's thermal sensation such as:

+3 hot
+2 warm
+1 slightly warm
0 neutral
-1 slightly cool
-2 cool
-3 cold

In parallel, PPD is the index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV (ASHRAE, 2004). The

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[14] Activity level or as defined in ASHRAE (2004) as metabolic rate is the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface and it is expressed in met (W/m^2) units.

[15] "The surface area of a nude body was given by D. DuBois in 1916 as

$$A_s = 0.202m^{0.425}\, h^{0.725}\ (\mathrm{m}^2)$$

Where m is the mass of the body in kg and h is the height in m" (Çengel, 2003) relationship of PMV and PPD can be calculated by the Equation (2.2) and demonstrated by the chart in Figure 1.

$$PPD = 100 - 95 \exp[-(0.03353PMV^4 + 0.2179PMV^2)] \qquad (2.2)$$

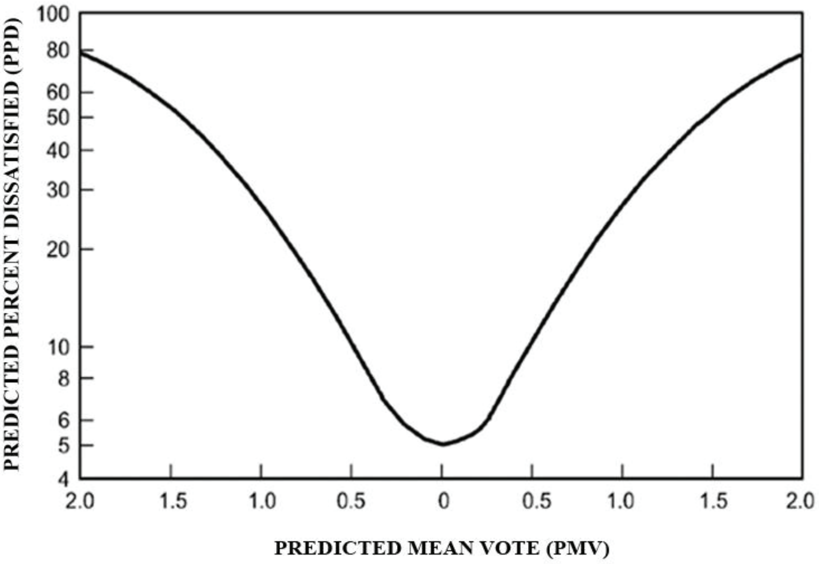


Figure 1. PMV / PPD correlation chart (ASHRAE 2017a)

2.1.1.2. Adaptive Model

Adaptive model accepts that people orientate themselves to their thermal environments by means of physiological, behavioral and psychological adaptations (Roaf et al., 2010). These adaptations manifest themselves on adjustments of conscious actions such as altering clothing, posture, activity schedules or levels, rate of working, eating patterns, ventilation, air movement, and interior temperature preferences (ASHRAE, 2017a). Therefore, as accepting a certain amount of tolerance provided by user behaviors, adaptive model relates indoor design temperatures or acceptable temperature ranges to especially outdoor meteorological or climatological parameters (Figure 2) rather than six specific variables of air temperature, air velocity, relative humidity, mean radiant temperature, clothing insulation and activity level that Heat-balance Model directly focuses on.

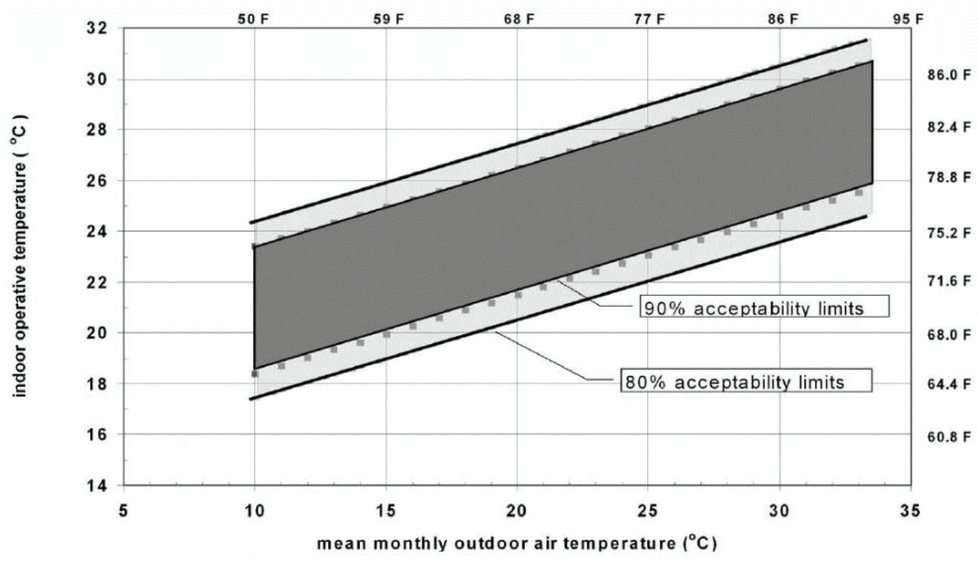
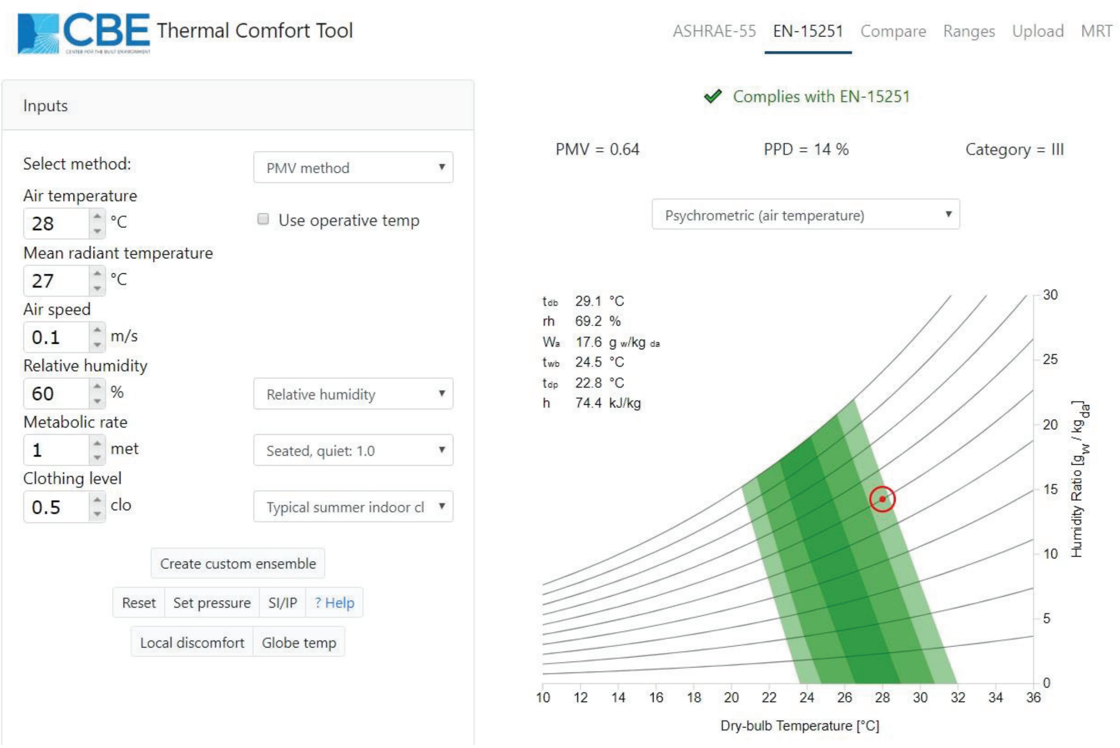


Figure 2. Acceptable operative temperature ranges for naturally conditioned spaces according to Adaptive Model (ASHRAE, 2004)

For the thermal comfort analyses, this study utilized Heat-balance Model as it provides more detailed and specific results regarding PMV and PPD calculations working on a wider range of thermal variables such as metabolic rate and clothing insulation that Adaptive Model does not directly refer to. Moreover, Standard EN 15251 (CEN, 2007) was used to evaluate thermal comfort calculations as it defines different expectation categories for different building categories such as:

> - *Category I defines high level of expectation and is recommended by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons,*
> - *Category II defines normal level of expectation and should be used for new buildings and renovations,*
> - *Category III defines an acceptable, moderate level of expectation and may be used for existing buildings and*
> - *Category IV covers values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.* (CEN, 2007)

For this study, category III was chosen to determine the comfort status of historical buildings. The standard suggests PMV tolerance interval of -0.7 / +0.7 for category III buildings. Figure 3 demonstrates an example interactive web tool using Fanger PMV Model and Standard EN-15251 to determine thermal comfort.



Select method: PMV method

Air temperature: 28 °C

☐ Use operative temp

Mean radiant temperature: 27 °C

Air speed: 0.1 m/s

Relative humidity: 60 % (Relative humidity)

Metabolic rate: 1 met (Seated, quiet: 1.0)

Clothing level: 0.5 clo (Typical summer indoor cl)

✓ Complies with EN-15251

PMV = 0.64

PPD = 14 %

Category = III

t_{db} 29.1 °C
rh 69.2 %
W_a 17.6 g_{w}/kg_{da}
t_{wb} 24.5 °C
t_{dp} 22.8 °C
h 74.4 kJ/kg

Figure 3. Example of an interactive web tool[16] demonstrating Fanger PMV Model and Standard EN-15251 to determine thermal comfort.

2.2. Workflow of the Study

General research structure of this study (Figure 4), which is based on the flow of the data between its work phases, consists of four main consecutive stages of:

- Data Collection,
- Specification of Model Variables,
- Modeling and Simulations,
- Results and Discussion

In the data collection stage, necessary information on the architectural, functional and constructional features of the case studies were gathered in order to specify the modeling variables. With these variables, building models were prepared and defined to the analyses software for thermal simulations. And the output of these simulations were evaluated in the results and discussion stage.

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[16] http://comfort.cbe.berkeley.edu/EN, access date: 26.11.2019.

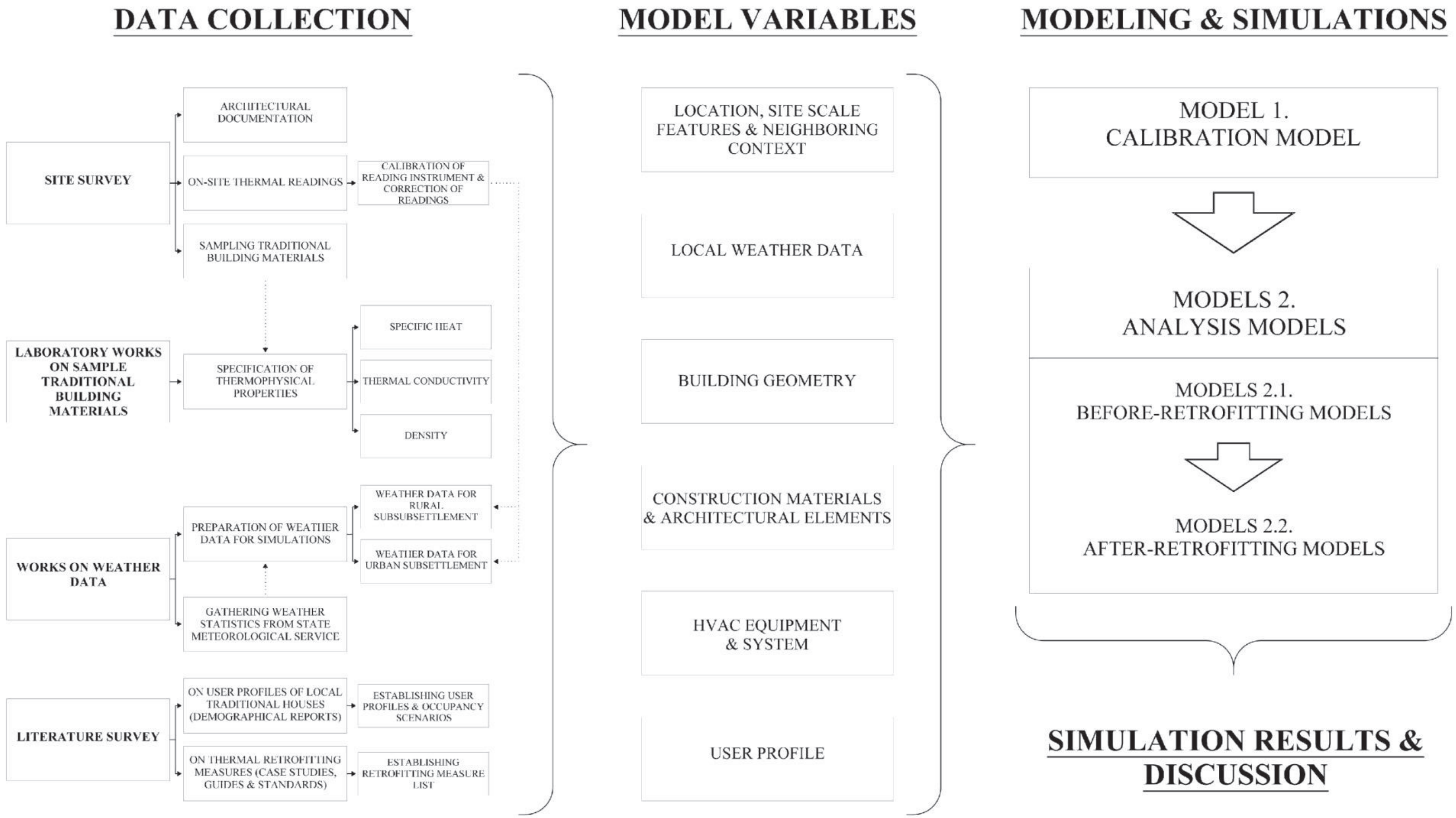

Figure 4. Workflow of the study

2.2.1. Data Collection

Data collection stage was conducted to gather necessary information to specify the model variables for the simulations of case study buildings. This stage consisted of:

1. Site Survey,
2. Laboratory Works on Properties of Sample Traditional Building Materials,
3. Works on Weather Data and
4. Literature Survey

2.2.1.1. Site Survey

Site survey is composed of the works on:

- Architectural documentation of the case study buildings,
- Whole-year, on-site thermal readings of air temperature and relative humidity at case study buildings and
- Sampling of traditional building materials which are to be examined for their thermophysical properties.

In architectural documentation phase, on-site examinations were conducted in order to collect necessary information about the case study buildings regarding their geometry, architectural elements, construction techniques, building materials, landscape elements, site planning and neighborhood. This stage was carried out with methods of architectural sketching, hand-measurements and photography. In addition to architectural documentation, on-site thermal readings of air temperature and relative humidity values were collected in the case study buildings. These readings were later used in weather data preparation and model calibration phases. Planned as a whole-year thermal monitoring of case studies, the readings were taken from April 2017 till March 2018. The data loggers, *Onset HOBO U12-012* were used in readings. These instrument have measuring intervals of -20 to 70°C for temperature and 5% to 95% for relative humidity. Their reading accuracy is maximum ±0.35°C for temperature and maximum ±2.5% for relative humidity[17]. In positioning of data loggers throughout the buildings, safeguarding ongoing

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[17] http://www.onsetcomp.com/products/data-loggers/u12-012, access date: 03.06.2017.

readings from the effects of direct sunlight and protection of the instrument from rain penetration were the main concerns (Figure 5).

Figure 5. Location of data logger at Gürsel House

For case studies, in Sönmezer House (Figure 6), both inside and outside readings could be taken and in Gürsel House (Figure 7), only the outside readings could be gathered due to unmonitorible spatial utilization schedules in this building, the rooms of which are seldom used as activity halls for Muğla University.

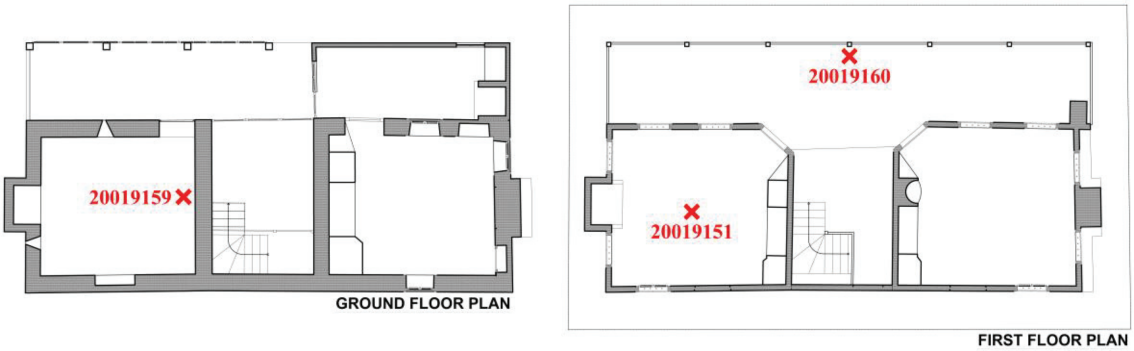

Figure 6. Locations and designations of data loggers on Sönmezer House

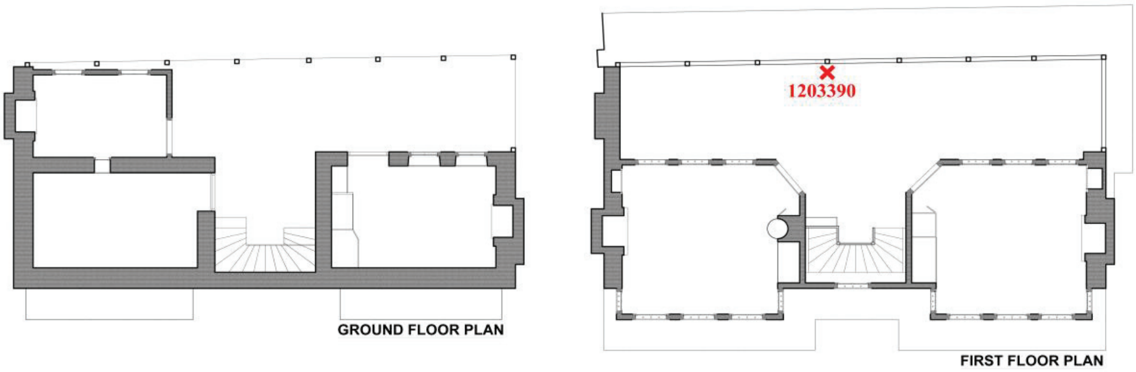

Figure 7. Location and designation of data logger on Gürsel House

For eliminating possible reading errors; the data loggers were subjected to calibration tests by the end of on-site reading stage. The tests were taken in Calibration Laboratory of İzmir Chamber of Mechanical Engineers (MMO KALMEM) in July 2018. For the tests, instruments were put inside of pre-calibrated thermal chambers (Figure 8 and Figure 9) and monitored for a period of time. In these chambers, thermal conditions were manipulated with precision controls and the readings of data loggers were examined if they match the chambers' conditions.

Figure 8. Chamber for temperature calibration tests

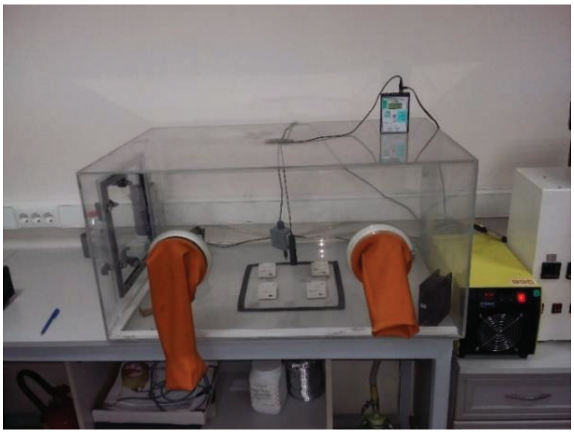

Figure 9. Chamber for relative humidity calibration tests

At the end of examinations, a report that presents the comparison of chamber conditions to the data logger readings was established for each instrument. With these reports, reading differences on 10, 20 and 30°C for temperature and 14.9%, 52.4% and 79.9% for relative humidity were acquired. And with the aid of *Excel* software, calibration formulas were constructed for each data logger (Appendix A). The readings of all data loggers were recalculated with these formulas before being used in further stages (Figure 10 and Figure 11).

Datalogger 20019160 Calibration Measurements-Temperature		
Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
9.8	10.0	10.0
19.9	20.0	20.0
30.0	30.0	30.0

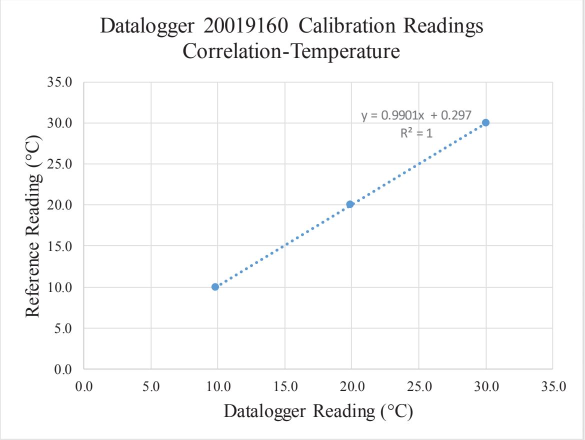

Figure 10. Temperature readings and calibration formula for data logger 20019160

Datalogger 20019160 Calibration Measurements-Relative Humidity		
Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
20.2	14.9	14.9
53.5	52.4	52.5
81.3	79.9	80.2

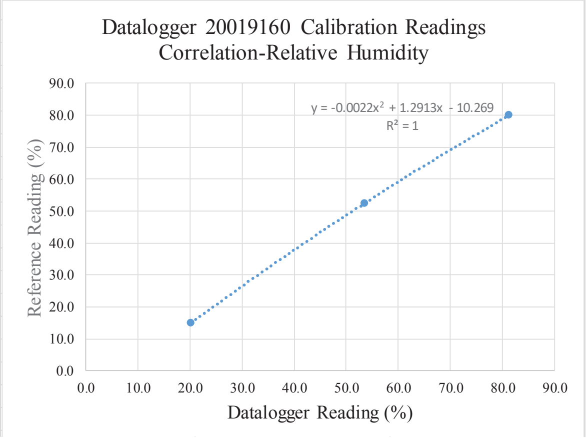

Figure 11. Relative humidity readings and calibration formula for data logger 20019160

With the outside thermal measurements that were taken on the case studies, it was specified that for both temperature and relative humidity, changes between nighttime and daytime are evidently more pronounced in Karabağlar / rural sub-settlement than the urban center. In other words, rural sub-settlement is more prone to change for its thermal conditions while urban center is more stable. According to the measurements, annual average temperature value is 15.9°C for Sönmezer House while it is measured as 16.7°C for Gürsel House. In parallel, annual average relative humidity value is 65.4% for Sönmezer House while it is 61.1% for Gürsel House. For whole year, temperature measurements change between -2.2°C and 37.8°C in Sönmezer House and between -0.5°C and 37.6°C in Gürsel House (Figure 12) as relative humidity values change between 12% and 100% for Sönmezer house and between 22.2% and 91.3% for Gürsel House (Figure 13). On daily basis, the difference is seen more evident. Figure 14 and Figure 15 show the difference on monthly average daily change of temperature and relative humidity values for an example month, September when this difference is observed most significantly (Please see Appendix B for temperature and Appendix C for relative humidity values recorded on the other months). Figure 14 demonstrates that temperature difference between the measurements on case studies even reach more than 4°C in the hours of morning as Figure 15 show the difference in relative humidity values can get more than 16%. Referring to this differentiation in thermal conditions, weather data for each case studies were prepared separately utilizing specific on-site measurements for the corresponding building. Methodology of this process will be introduced in detail by the coming section Works on Weather Data.

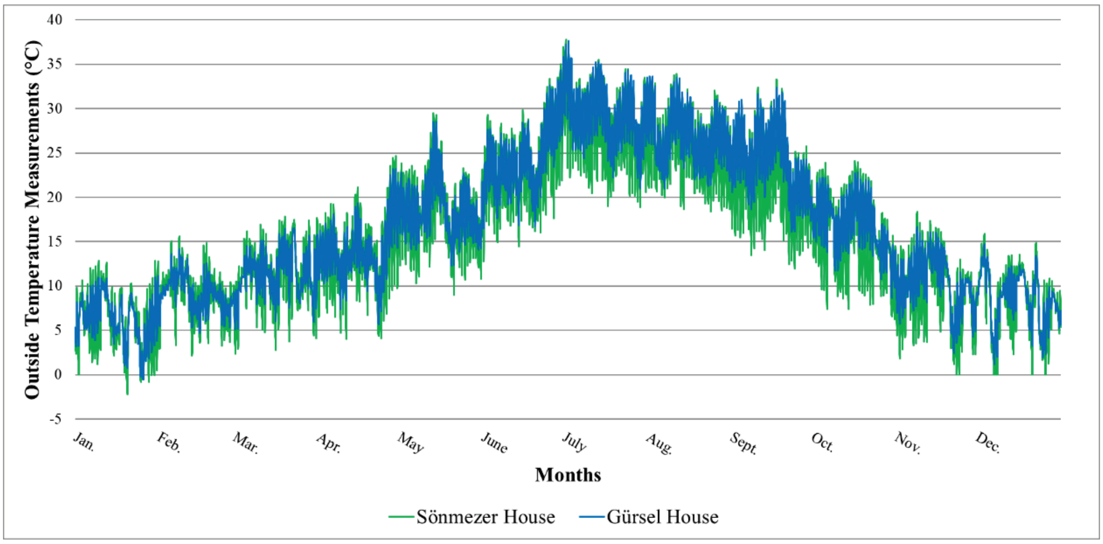

Figure 12. Annual comparison of outside temperature measurements taken on case studies from April 2017 till March 2018

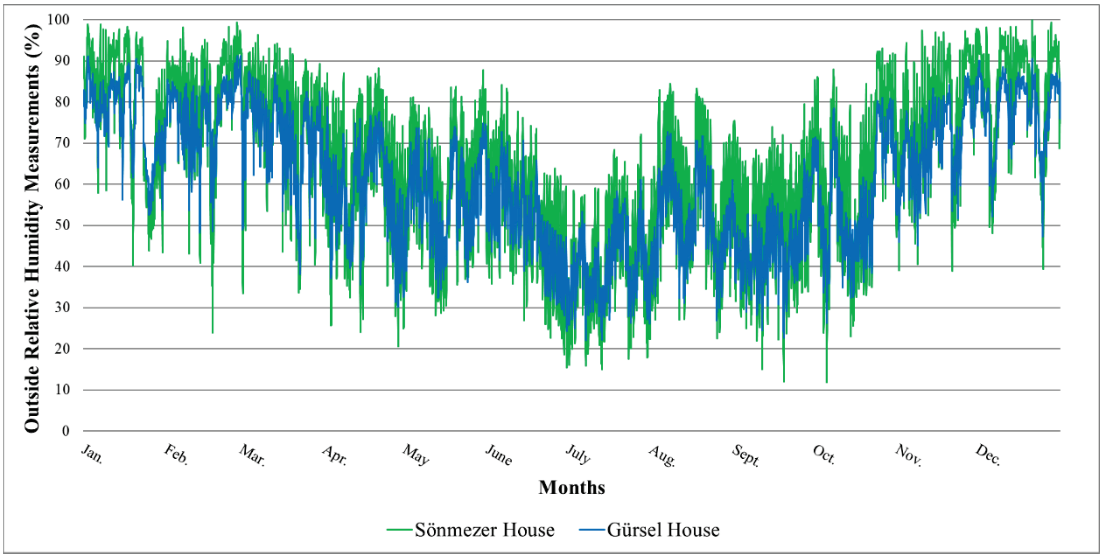

Figure 13. Annual comparison of outside relative humidity measurements taken on case studies from April 2017 till March 2018

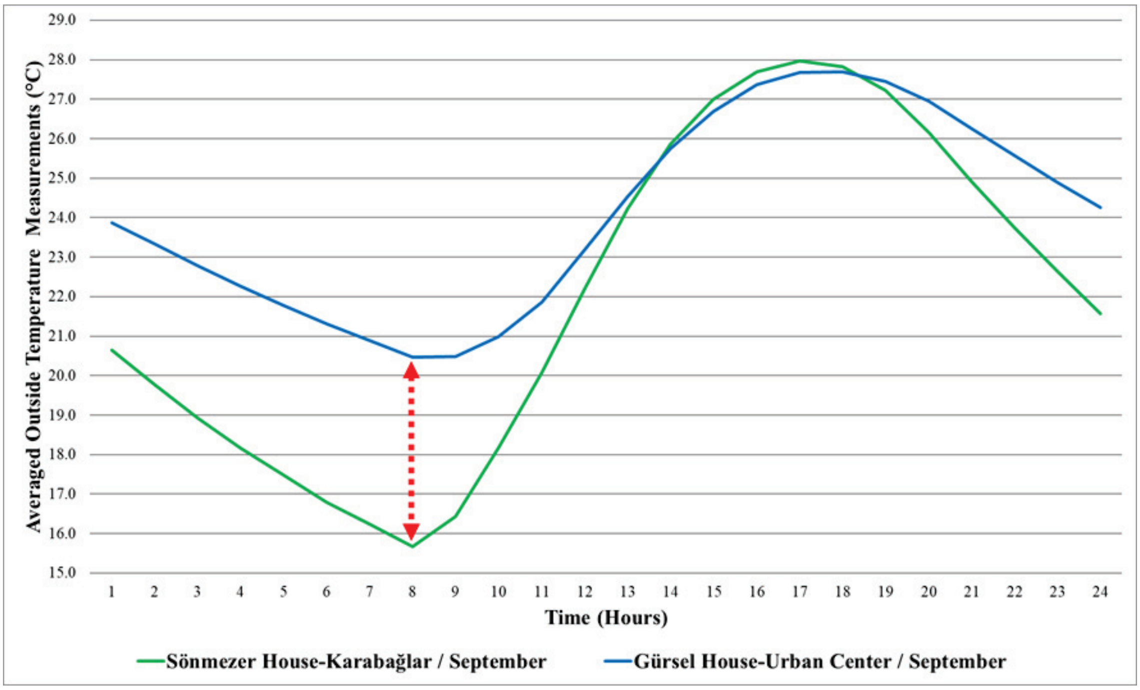

Figure 14. Comparison of monthly average daily outside air temperature change on case studies / hourly averaged data of the measurements taken on the month of September. Red arrow indicates the difference.

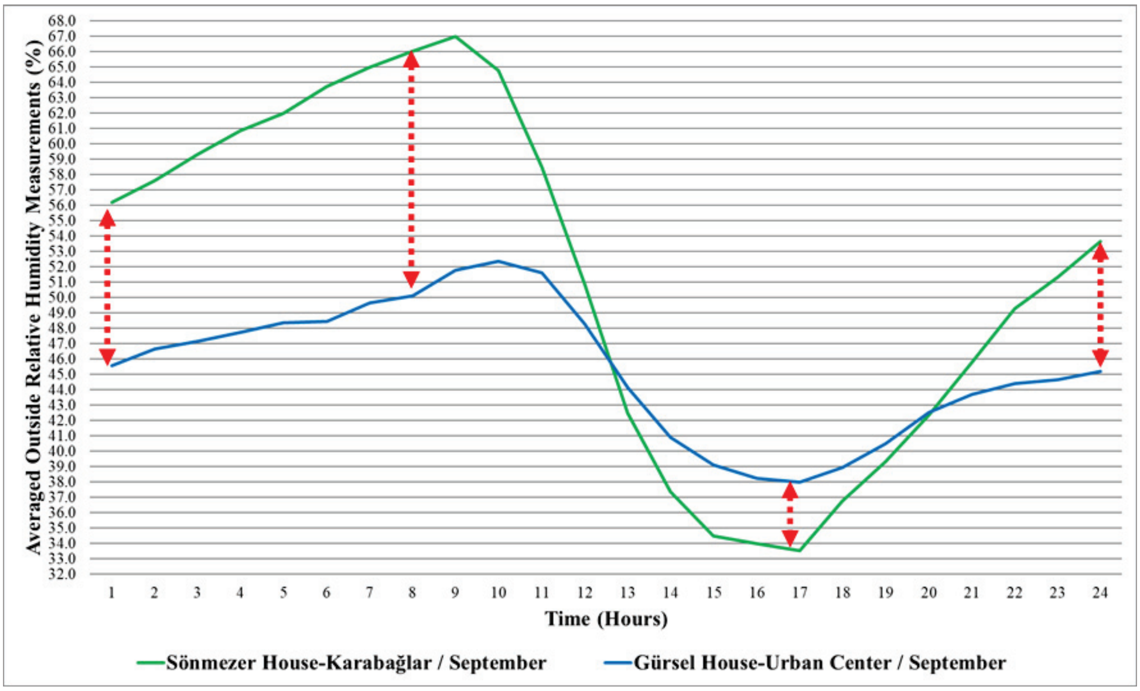

Figure 15. Comparison of monthly average daily outside relative humidity change on case studies / hourly averaged data of the measurements taken on the month of September. Red arrows indicate the difference.

2.2.1.2. Laboratory Works on Properties of Traditional Building Materials

Thermal simulations process thermophysical properties (specific heat[18], thermal conductivity[19] and density[20]) of building materials (plaster, stone, timber, brick and roof tile) in order to represent constructional sections (walls, roofs and floors) and architectural elements (windows and doors) in transient thermal analyses. As building tradition and available local raw materials may vary greatly from one settlement to another; standards and libraries that were prepared for contemporary building materials cannot be used to define traditional building materials. Therefore; sample materials were collected from historical structures and their properties were determined by laboratory analyses. As the case study buildings were unsuitable for material sampling; the traditional building in Karabağlar, 208 Block / Lot 13 (Figure 16 and Figure 17) was used as the source structure for construction materials. It was assumed that materials used in this structure were similar to the case studies as this structure resembles the case study buildings in plan type (2 spaces in each floor that are accessed through exterior *sofa*s), structural design (stone masonry walls on lower level and timber frame / infill walls on upper floors) and constructional detailing. The construction materials that were collected and analyzed for their thermophysical properties are:

- Interior plaster,
- Exterior plaster,
- Ceiling and flooring timbers,
- Masonry stone wall and
- Roofing tiles.

As being a highly brittle and fragile material, the infill within timber frames (construction of upper floor walls) that is the mixture of adobe mortar, organic fibers, and stone / brick pieces could not be sampled and analyzed. Therefore, thermophysical properties of this part was modeled by the values from literature (Ulukavak Harputlugil et al., 2005).

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[18] Specific heat (c-J/kg°C) is a physical property of matter that is defined as the energy required to raise the temperature of a unit mass of a substance by one degree (Çengel, 2003).

[19] Thermal conductivity (k or λ-W/m K), is the property of a material that is defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference (Çengel, 2003). This coefficient changes with temperature.

[20] Density (ρ-kg/m^3) is a physical property of matter that is the amount of mass per unit volume.

Figure 16. The building in Karabağlar, 208 block / lot 13 (front facade photograph)

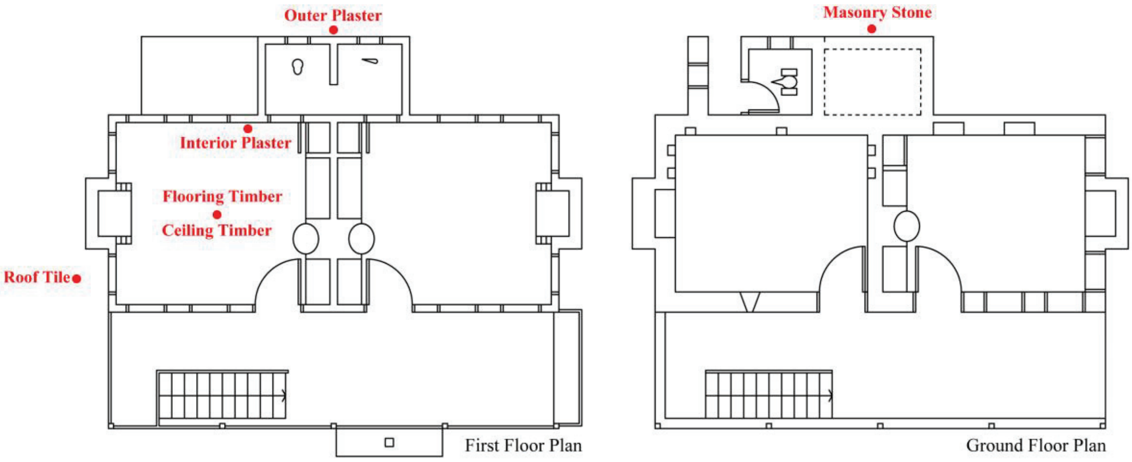

Figure 17. Plan drawings of the building in Karabağlar, 208 block / lot 13 showing the locations of material samplings

Before laboratory measurements, Sample materials were coded depicting the address of their source building, material types and their locations within the structure. For instance; code *K-208-13-W-1-C* represents a wood sample from the building in Karabağlar, on Block 208 and Lot 13. The sample is from 1st floor ceiling (Figure 18). (Please see Appendix D for images of the other sample construction materials.)

Figure 18. Wood sample (*K-208-13-W-1-C*)

After the collection and coding of sample traditional building materials; thermal conductivity and specific heat tests were conducted at IZTECH Geothermal Energy Research and Application Center and density measurements were held at IZTECH Material Conservation Laboratory of Architectural Restoration Department. In order to minimize errors, all measurements were applied in parallel readings and final results are the arithmetic averages.

Thermal conductivity values were measured by reading equipment, KEM QTM 500 (Figure 19) that works with hot wire probes. Measurement sensitivity for this device is 5 %[21].

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[21] http://geocen.iyte.edu.tr/cihaz-bilgileri/, access date: 02.06.2017

Figure 19. Thermal conductivity meter

Specific heat values of the samples were measured in differential scanning calorimeter (TA Instruments Q-10 /Figure 20). As the value of this physical property varies with temperature change; for modeling value assumptions, readings at 15.6°C (that is the annual air temperature average of last 20 years at Muğla) were accepted as the specific heat values of the construction materials (Figure 21).

Figure 20. Differential scanning calorimeter[22]

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[22] http://www.tainstruments.com/pdf/oldDSC.pdf, access date: 05.06.2017.

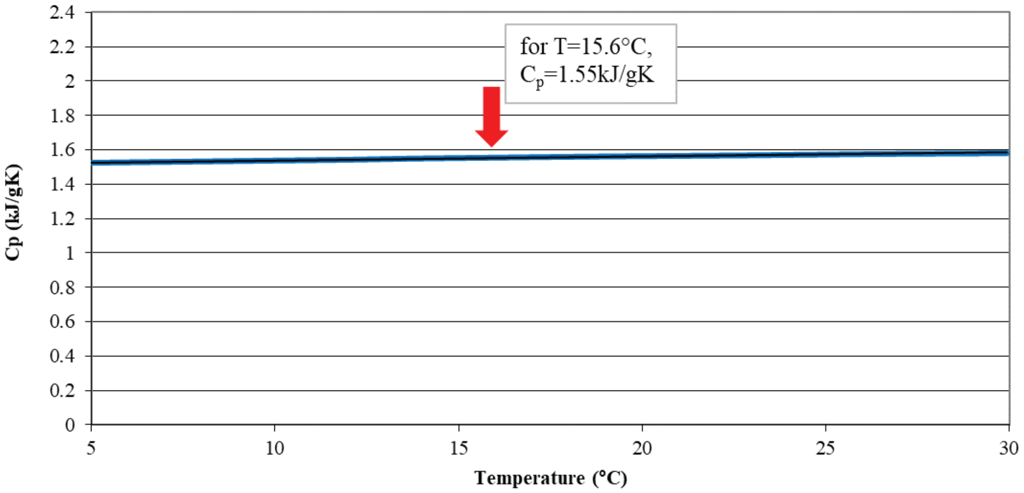

Figure 21. Specific heat reading chart for sample material K-208-13-S-1-O (red arrow indicates the value at 15.6 °C)

Density values for water-submerging samples (stone, roof tile and plaster) were determined by standard test methods (RILEM, 1980). For each material sample, two parallel specimens were tested and the results were averaged. An oven at low temperatures (40°C) was used to dry the specimens for 24 hours. Their dry weights (M_{dry}) were measured with precision balance (AND HF-3000G). Following that; specimens were submerged in distilled water and entirely saturated by a vacuum oven (Lab-Line 3608-6CE). Saturated weights (M_{sat}) and Archimedes weights (M_{arch}) were measured by hydrostatic weighing in distilled water using the precision balance. Densities (D) of samples were calculated with the Equation 2.3 below:

$$D(\mathrm{g/cm^3}) = M_{\mathrm{dry}} / (M_{\mathrm{sat}} - M_{\mathrm{arch}}) \tag{2.3}$$

Density values of timber specimens were determined according to the standard *TS 2472- Wood - Determination of Density for Physical and Mechanical Tests* (Turkish Standards Institution, 1976)[23]. In this procedure, firstly, the timber specimens were dried

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[23] Parallel measurements and standard specimen dimensioning procedures could not be followed as timber samples could only be acquired in small quantities.

in the oven (at 103°C according to Efe et al., 2011) until their weights became constant providing the difference between consecutive weight measurements are equal to or less than 0.5% of the weight of the specimen. Then their weights (M_{dry}) were measured by precision balance (AND HF-3000G) and dimensions (for calculation of dry volume-V_{dry}) were determined by digital caliper. Densities *(D*) of samples were calculated with the Equation 2.4 below:

$$D(\text{g/cm}^3) = M_{\text{dry}} / V_{\text{dry}} \tag{2.4}$$

By the laboratory analyses, Table 2 was prepared to be used for the introduction of traditional construction materials to the modeling software.

Table 2. Thermophysical properties of sample construction materials

Material Code	Density (kg/m³)	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)
K-208-13-P-I-B (Interior Plaster)	1738	0.72	1430
K-208-13-P-O-R (Outer Plaster)	1779	0.81	1100
K-208-13-S-1-O (Masonry Stone Wall)	2596	3.09	1550
K-208-13-T (Roof Tile)	1532	0.48	770
K-208-13-W-1-F (Flooring Timber)	673	0.19	2190
K-208-13-W-1-C (Ceiling timber)	615	0.14	1500
Adobe Infill Within Timber Frame (Ulukavak Harputlugil et al., 2005)	1650	0.70	900

2.2.1.3. Works on Weather Data

As being one of the major factors on thermal behavior of buildings, weather conditions of the case study settlements must be determined and introduced to the simulation software in the form of quantified weather data (in *.epw* format for *DesignBuilder*). For Muğla, which –in tradition- has been living in two separate sub-settlements of urban and rural characteristics with distinct microclimatic conditions (Eroğlu, 1939, Ekinci, 1985, Koca, 2004, Çınar, 2004) as it was also stated by on-site thermal measurements presented earlier in Site Survey Section; specification of weather data was conducted separately for the case studies located on those sub-settlements.

For *EnergyPlus* simulations, weather data sets consist of hourly averages of whole year weather variables of:

1. Air temperature (°C),
2. Dew point temperature (°C),
3. Relative humidity (%),
4. Atmospheric Pressure (Pa),
5. Solar Radiation Values (Direct normal radiation, Diffuse horizontal radiation & Horizontal infrared radiation intensity from sky – Wh/m²),
6. Wind direction (°),
7. Wind speed (m/s),
8. Sky cover (scale of 10),
9. Visibility (km),
10. Present weather observation & present weather code,
11. Snow depth (cm),
12. Days since last snow and
13. Liquid precipitation depth (mm)[24]

In order to determine these variables; 3 data sources were used together:

a. On-site thermal readings: Whole year exterior readings of air temperature and relative humidity were taken on both case study buildings. Using these readings dew point temperatures could also be calculated by the *DesignBuilder* software.

b. Averaging of official weather statistics: Because of lack of proper equipment, all weather variables could not be collected on-site. In order to specify these unreadable variables; official weather statistics of Turkish State Meteorological Service were requested for the last 20 years. For the values of wind speed, wind direction, direct normal radiation, diffuse horizontal radiation, atmospheric pressure and sky cover, official statistics could be acquired and averaged as hourly annual data sets. For scalar quantities of wind speed, atmospheric pressure, radiation values and sky cover, arithmetic means

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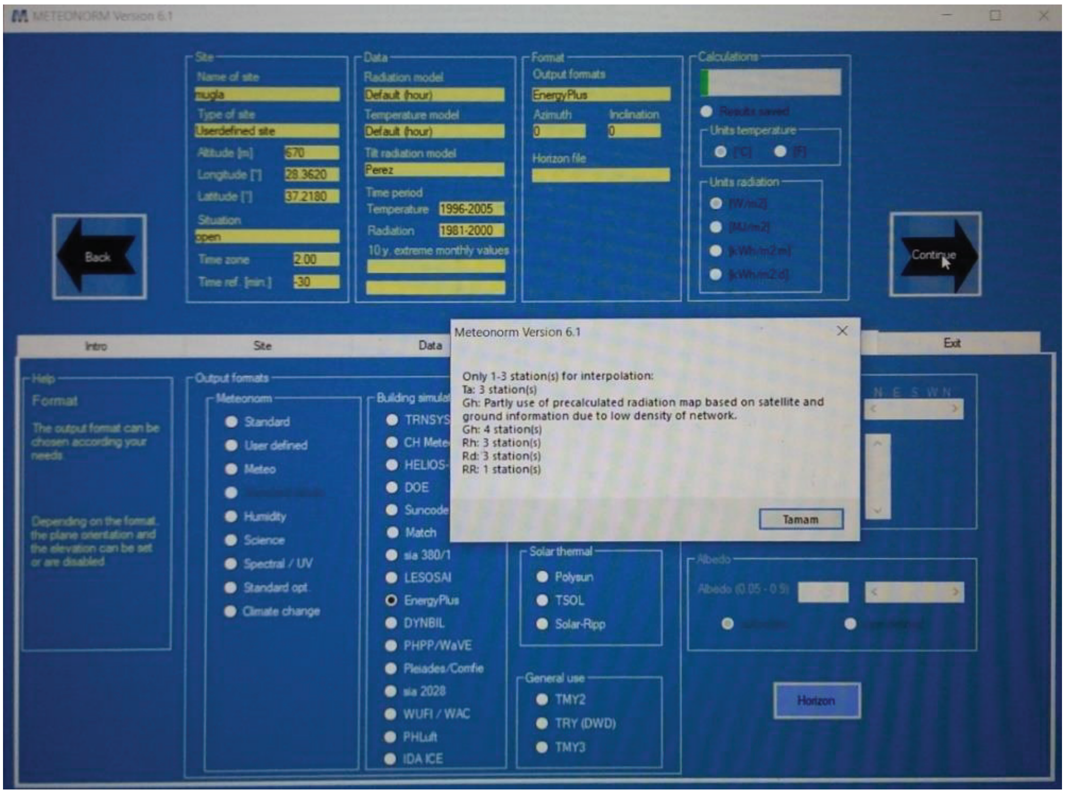
[24] https://energyplus.net/sites/default/files/pdfs_v8.3.0/AuxiliaryPrograms.pdf (access date: 28.05.2018).

is used for averaging; for wind direction (which is a vectorial quantity) trigonometric functions were used[25].

c. Using weather data software: For the variables that could not be read on-site or be averaged from official statistics; weather data software, *Meteonorm v.6.1* was used (Figure 22). These variables are horizontal infrared radiation intensity from sky, visibility, present weather observation, weather code, snow depth, days since last snow and liquid precipitation depth.



Site
Name of site: mugla
Type of site: Userdefined site
Altitude [m]: 670
Longitude [°]: 28.3620
Latitude [°]: 37.2180
Situation: open
Time zone: 2.00
Time ref. [min.]: -30

Data
Radiation model: Default (hour)
Temperature model: Default (hour)
Tilt radiation model: Perez
Time period
Temperature: 1996-2005
Radiation: 1981-2000

Format
Output formats: EnergyPlus
Azimuth: 0
Inclination: 0

Meteonorm Version 6.1

Only 1-3 station(s) for interpolation:
Ta: 3 station(s)
Gh: Partly use of precalculated radiation map based on satellite and ground information due to low density of network.
Gh: 4 station(s)
Rh: 3 station(s)
Rd: 3 station(s)
RR: 1 station(s)

Tamam

Figure 22. Screen capture of *Meteonorm* software processing weather data for Muğla

Using these three sources, weather data for the simulation analyses were prepared according to the workflow shown in Figure 23. This method was used for its benefit of enhancing virtual (software) data to a more realistic set by the introduction of on-site thermal readings and averages of official weather statistics. In this method, firstly, a virtual data set was produced with the help of weather data software. This virtual data set

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[25] By the methodology suggested by Earth Observing Laboratory(USA). (https://www.eol.ucar.edu/content/wind-direction-quick-reference. Access date: 20.03.2018)

which needs refinement with actual thermal readings was used as an initial data template. Then some of the weather variables (in our case, radiation values, atmospheric pressure, cloud cover, wind speed and wind direction) on this template were replaced by averaged climate statistics that had been gathered from Turkish State Meteorological Service. This course established the secondary template. Following that, on-site air temperature, and relative humidity readings were overlapped onto the data of this secondary template. And by this course; final simulation weather data was established.

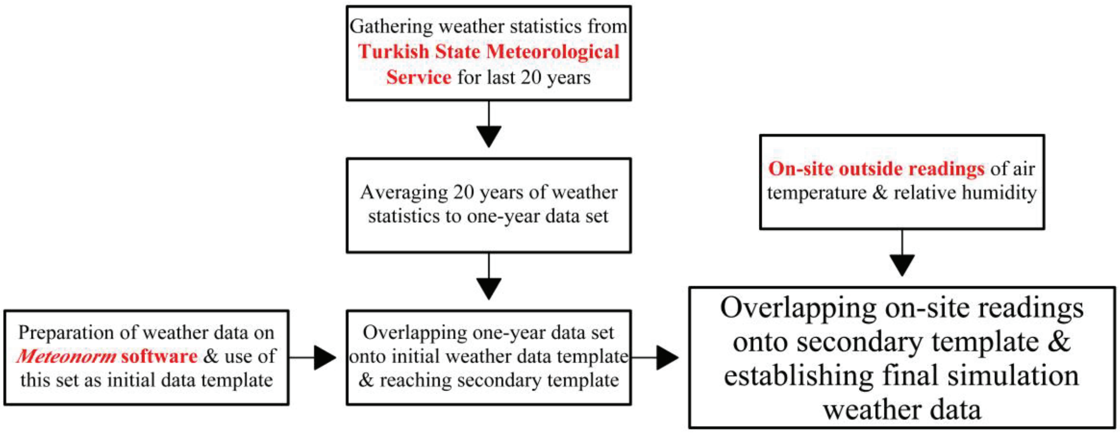

Figure 23. Methodology of weather data preparation

2.2.2. Specification of Model Variables

In this stage, variables of location, site scale features, neighboring context, local weather data, building geometry, constructional materials and architectural elements, HVAC equipment and systems as well as user profile were determined by the information conveyed from data collection stage in order to be introduced to the analysis software for the realistic representation of case study buildings.

2.2.3. Modeling & Simulations

In Modeling & Simulations stage, model variables that were established by the data conveyed from Data Collection stage were used. This stage covers the works on Calibration Model (Model. 1) and Analyses Models (Models. 2.1 & 2.2):

- Model 1. Calibration Model was prepared to examine the reliability of model variable assumptions and the analyses software. This stage determines at what percentage the models are able to represent the real conditions of the buildings. This work could be conducted only on one case study (Sönmezer House) where both interior and exterior on-site thermal measurements could be taken as the inputs of the calibration process.
- Models 2. Analyses Models were arranged in two phases of:
    1. Models 2.1. Before-Retrofitting Models were created to determine at what capability traditional heating equipment (fireplaces) ensure thermal comfort without thermal retrofitting. By this analysis, it could be established if the case buildings require thermal interventions.
    2. Models 2.2 After-Retrofitting Models were produced by adding retrofitting measures to the Models 2.1. By these models, enhancement rates of retrofitting measures were determined.

2.2.4. Results and Discussion

Results and Discussion stage is based on the quantitative comparison of thermal simulation results. The result sets that were utilized in the comparisons are building totals of annual heating and cooling loads and annual primary energy consumptions.

2.3. Limitations and Assumptions

This study was realized under these limitations and assumptions:

- As *DesignBuilder* software was used for modeling and simulation works, the results and analyses following these stages demonstrate the precision level within the capabilities and limitations of *DesignBuilder* software. Some examples for software limitations are:
    - With the software, it is only possible to define summertime / wintertime intervals on a monthly basis rather than daily basis and
    - Clothing insulation values can only be defined as a constant value throughout the whole summer or winter time permitting no change between days and nights.

These limitations affected especially the fine-tuning of PMV analyses.

- Model calibration work could only be conducted on one case study (Sönmezer House) and could not be realized on Gürsel House due to the fact that the occupancy pattern of this building could not be determined as it is rarely opened and used. However, it was assumed that the reliability of the model of Gürsel House is high as Sönmezer House's because both models were established by the same modeling variables and assumptions.
- Parallel comparative measurements regarding specification of thermophysical properties of sample construction materials were limited as only small quantity of samples could be collected.
- Thermal retrofitting measures that are proposed on architectural heritage cover an extensive collection of intervention types that can be categorized according to their target groups such as:
    - on building envelopes,
    - on HVAC systems and
    - on occupant behaviors (Lidelöw et al., 2018).

As the main focus of this study is the interventions on building envelopes (constructional and architectural elements), the interventions on HVAC systems and occupant behavior were not studied in detail. However, enhancement rates of some example HVAC interventions were specified in comparison to the rates of envelope retrofitting measures. The aim of this course was to be able to compare enhancement rates of envelope retrofitting measures to the rates of more comprehensive interventions such as introduction of new HVAC systems to the case studies rather than defining an ideal HVAC system for the buildings which necessitates additional analyses that are not in the scope of this study (e.g. CFD- Computational Fluid Dynamics analyses).

CHAPTER 3

CASE STUDY SETTLEMENT AND BUILDINGS

The building type, which this study examined, was chosen to be the traditional houses with exterior *sofa* which is one of the most common building types among Anatolian traditional houses (Eldem, 1986; Kuban, 1995) as they have been built in a wide geography, especially from The central part of Anatolia to its Western coasts (Kuban, 1995). The *sofa* part in these buildings, which is a characteristic traditional space, is one of the most dominant elements that affect the design and type of traditional houses just like the room numbers and their plan arrangements. This space serves both as a circulation area and as a multi-functional volume (Eldem, 1986; Kuban, 1995).

Figure 24. An example traditional house with exterior *sofa* in Kula / Manisa (Source: Kuban, 1995)

In addition to this intensity, in the Balkans, where the Ottoman Empire reigned, architectural traces of these buildings can also be observed (Figure 25). And moreover, this building type, which has been arranged with the combination of open, semi-open and closed spaces, recaps a common spatial practice (Figure 26) of Central and Middle Eastern Asian cultures (Kuban, 1995) even resembling the houses of Hittite and Hellenistic eras (Eldem, 1986).

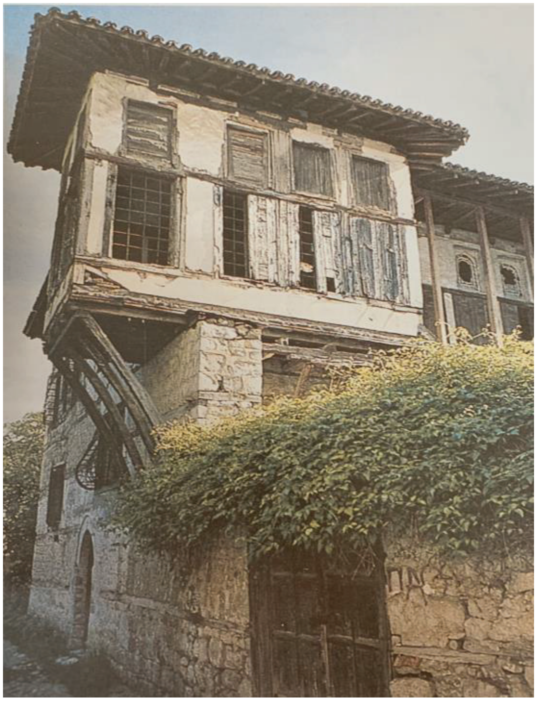

Figure 25. An example traditional house with exterior *sofa* / Bassaras Mansion in Kastoria / Greece (Source: Kuban, 1995)

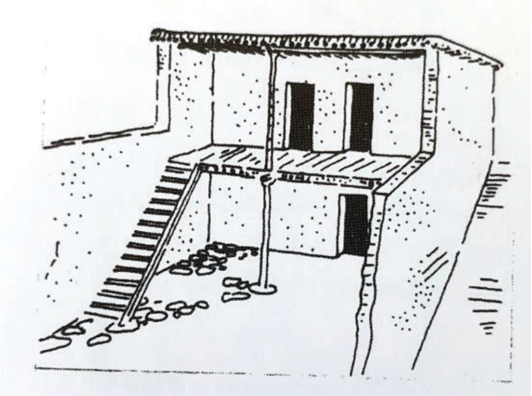

Figure 26. Restitution of a Hittite House in high resemblance to exterior *sofa* houses in spatial organization (Source: Naumann, 1955)

Traditional houses with exterior *sofa*s have generally been constructed within a courtyard and their plan is arranged with multi-functional unit rooms (Figure 27) having fireplaces and multi-purpose service walls that open directly to the *sofa*s.

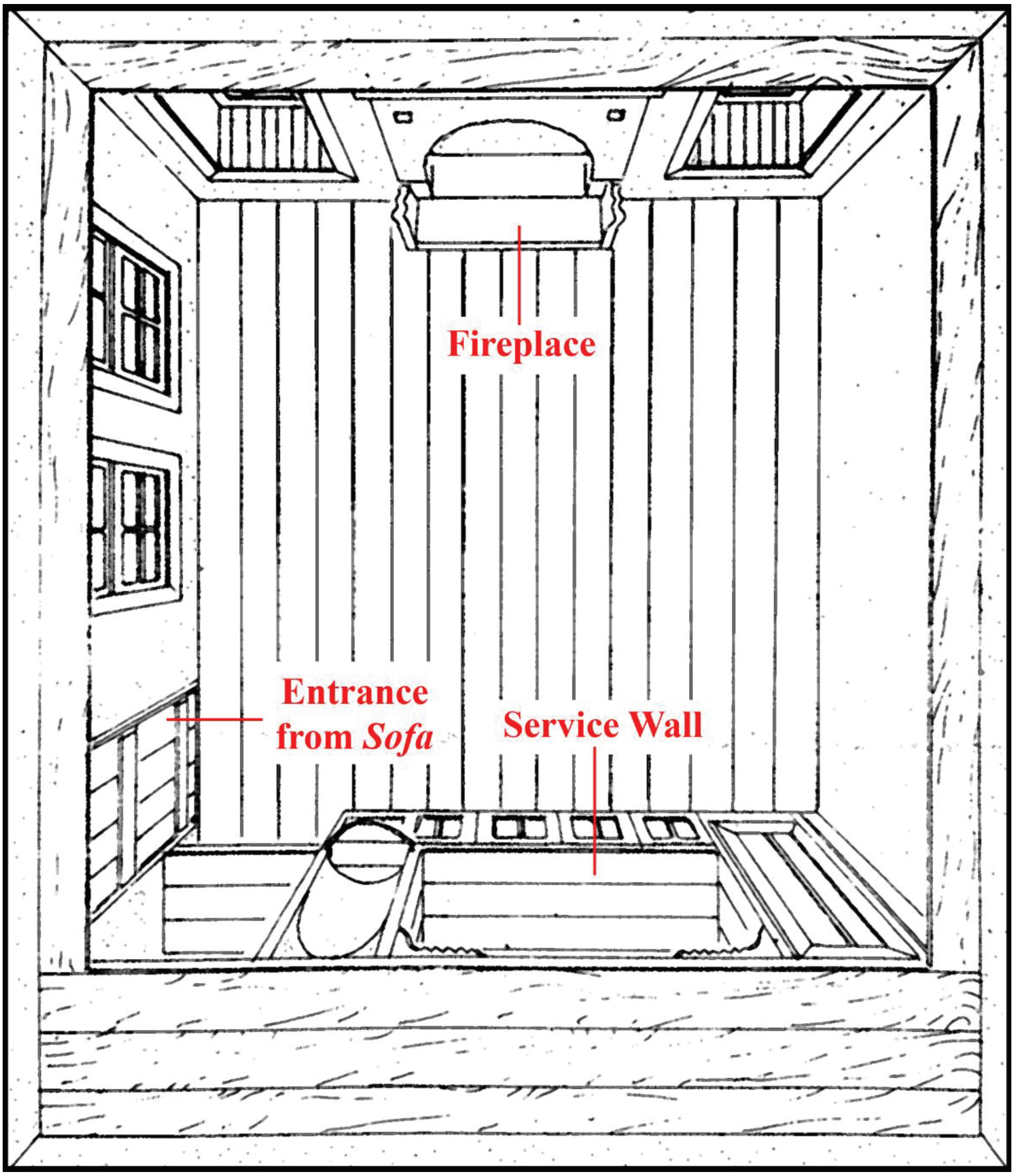

Figure 27. Plan perspective drawing of an example multi-functional room of a traditional Muğla house demonstrating the general layout of the space with architectural elements such as fireplace and multi-purpose service wall (Source: Aladağ, 1991).

These rooms have been used for living, gathering, reception, eating and sleeping functions. And in seasons when the weather was suitable, these functions were carried out also to the *sofa*s (Kuban, 1995). As complementary to these main spaces, outbuildings which had service spaces such as kitchens, toilets and storage rooms have been constructed in the courtyards (Figure 28).

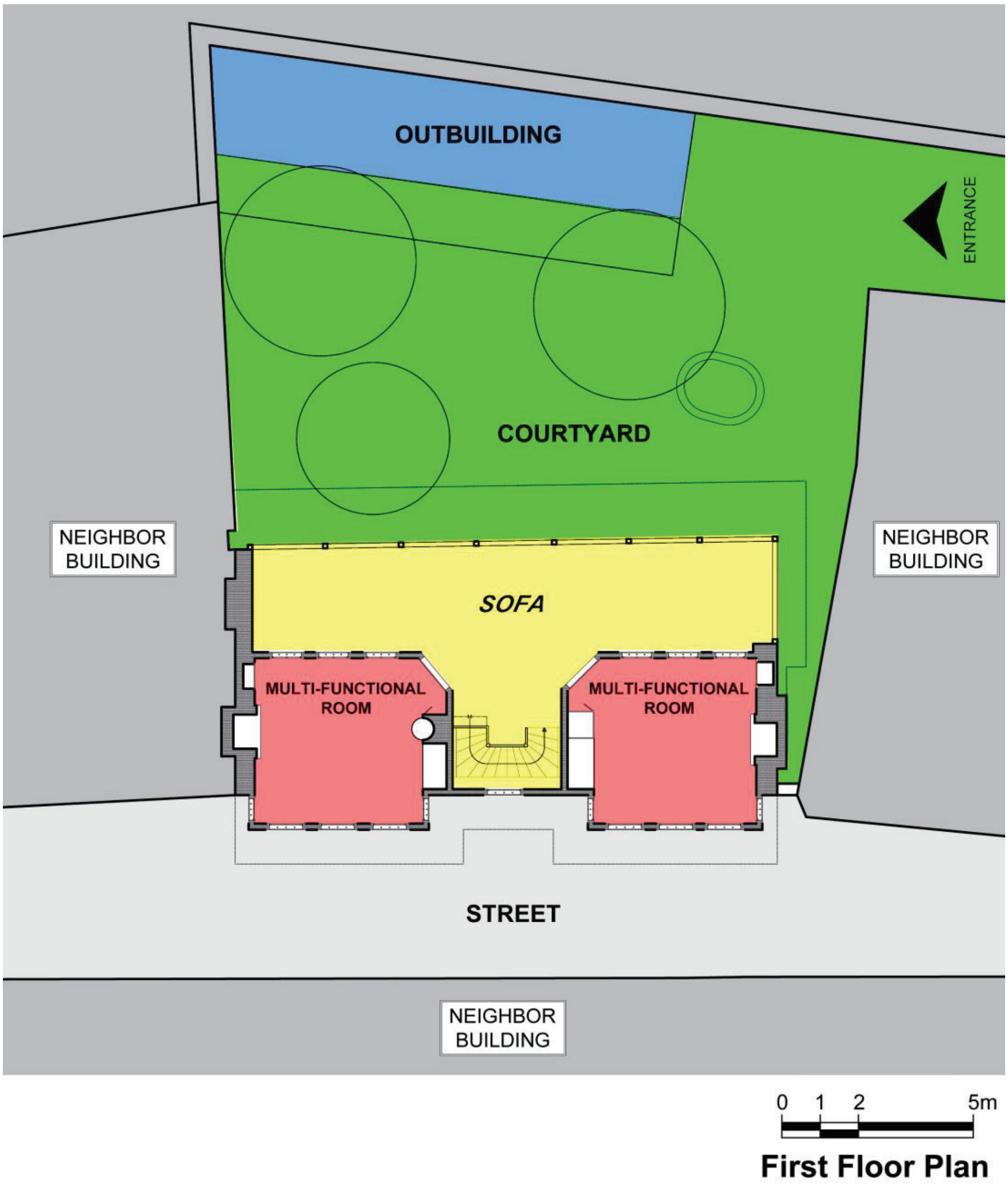

Figure 28. A typical example of spatial organization on traditional houses with exterior *sofa*s-Gürsel House / Muğla. Red hatches indicate multi-functional rooms, yellow hatch indicates sofa, green hatch represents courtyard and blue hatch shows outbuilding.

3.1. Muğla City

As a historical city that possesses a well-conserved reserve of traditional houses most of which have been constructed with exterior *sofas*[26], Muğla was chosen as the case study settlement of this thesis. Furthermore, urban (historical city center) and rural (Karabağlar District) sub-settlements of this city, which demonstrate distinct microclimatic conditions (Eroğlu, 1939, Ekinci, 1985, Koca, 2004, Çınar, 2004), enabled examination of the effects of these conditions on the thermal behavior of traditional houses.

3.1.1. Location

Muğla city (more recently called as Menteşe city) is the administrative center of Muğla Province on the south-west of Anatolia / Turkey (Figure 29). The city had been founded on Muğla Plain with an average 655 m. altitude (Figure 30).

Figure 29. Location of Muğla province in Turkey[27]

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[26] According to Değer (2012) buildings with exterior *sofa*s constitute 63 % of the traditional housing stock of Muğla.

[27] Base map Source: https://www.harita.gov.tr/urun-216-haritasi.html&katid=14 access date: 03.10.2016.

Figure 30. Location of Muğla City within the province[28]

3.1.2. Climate

According to Köppen–Geiger Climate Classification System[29], weather conditions of Muğla city are referred as *Csa (Typical Mediterranean Climate)* type which is defined as temperate climate with dry and hot summers (Figure 31 and Figure 32). As complementary to this classification, which demonstrate a general and a global scale comparison of different climate types within a large scale resolution, a more recent and local standard, *TS 825 / Thermal Insulation Requirements for Buildings* (Turkish Standards Institution, 2008) suggests a more detailed mapping and locates Muğla in 2nd Degree Day Region marking its climatic differences from its geographical vicinity (Figure 33).

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[28] Base map Source: http://www.hgk.msb.gov.tr/tematik-haritalar# access date: 03.10.2016.

[29] This system is a widely used, vegetation-based, empirical climate classification system developed by Wladimir Köppen and Rudolf Geiger. (Yılmaz et al., 2018)

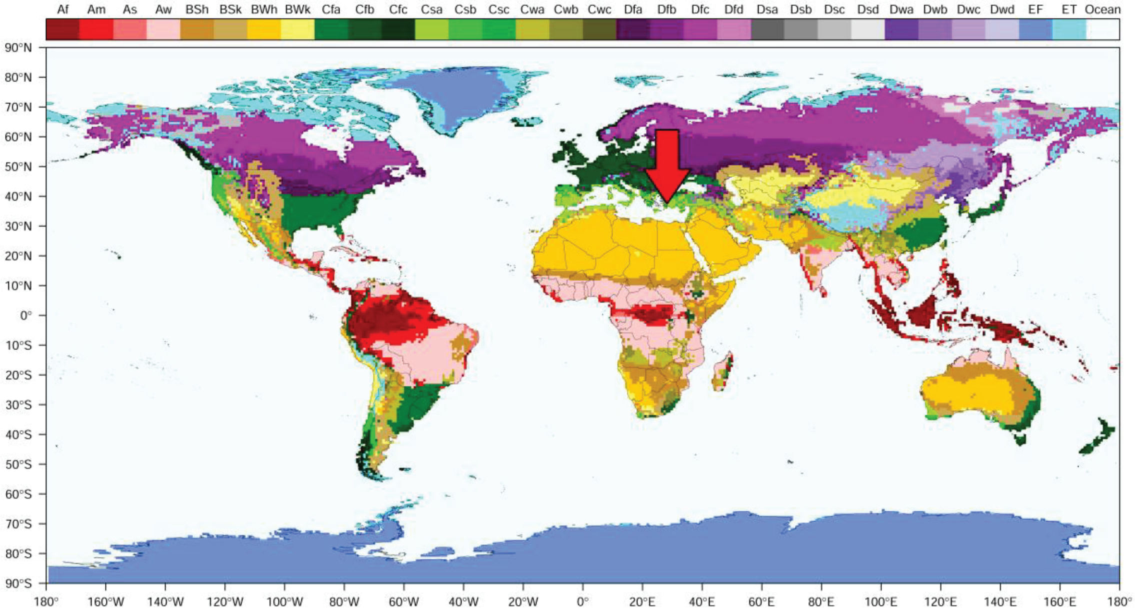

Figure 31. Map of Köppen–Geiger Climate Classification System representing data between 1986 and 2010[30]. Red arrow marks the location of Muğla City.

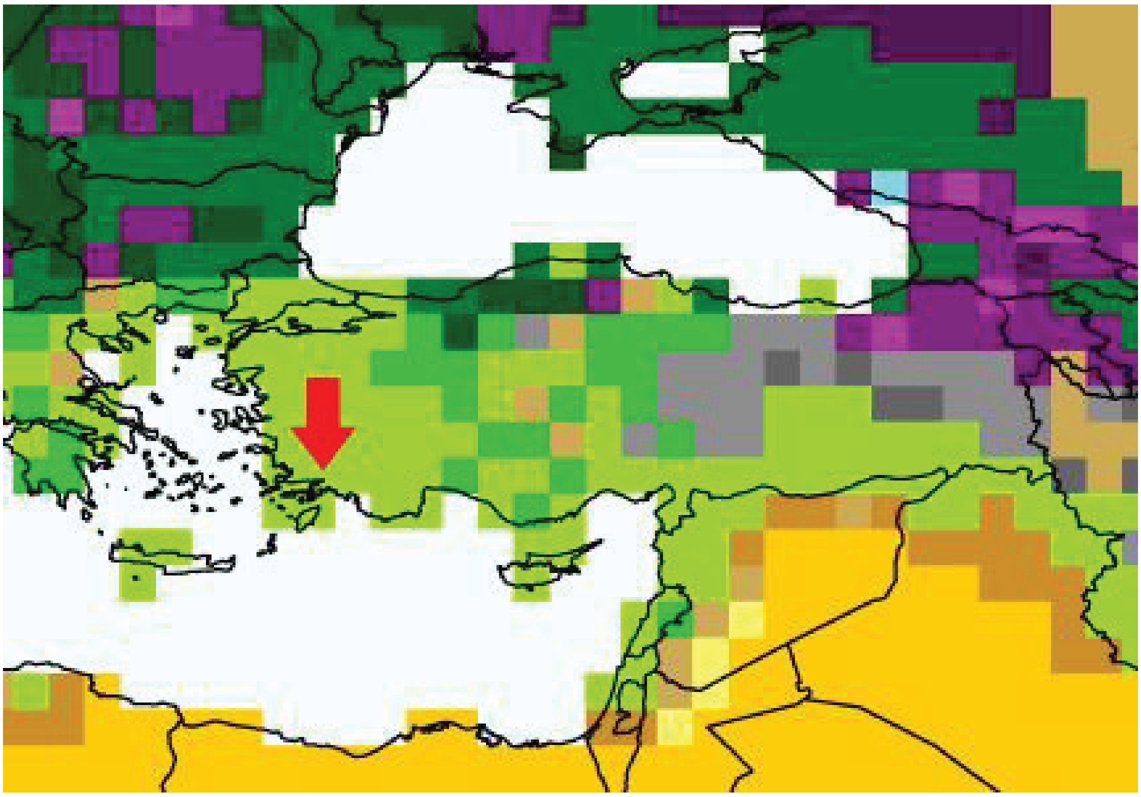

Figure 32. Map of Köppen–Geiger Climate Classification System / focused on Turkey. Red arrow marks the location of Muğla City.

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[30] http://koeppen-geiger.vu-wien.ac.at/present.htm, access date: 16.08.2018.

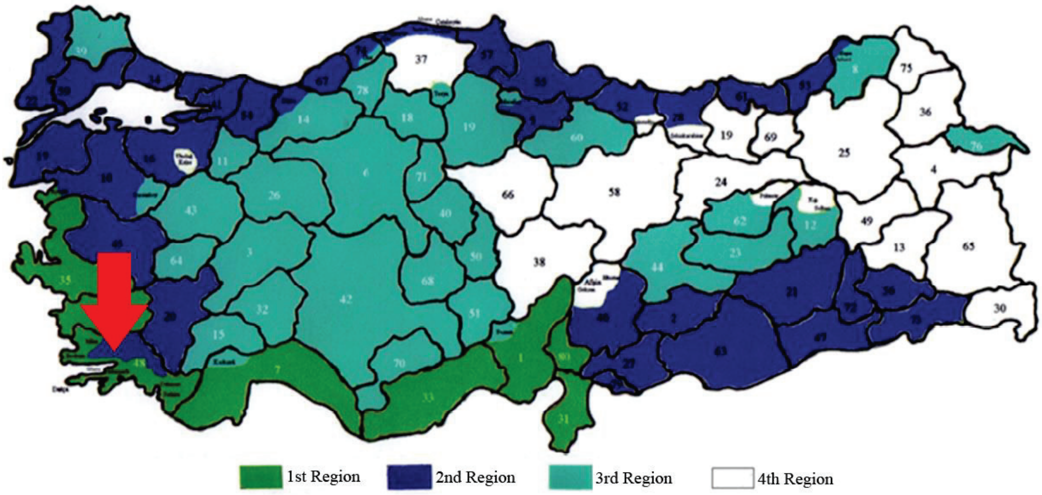

Figure 33. Map of degree-day regions according to TS825 (2008). Red arrow marks the location of Muğla City.

Figure 34 and Figure 35 demonstrate whole year hourly averages of air temperature and relative humidity values for Muğla. Figure 36 shows wind direction diagram. These charts were prepared with data gathered from Turkish State Meteorological Service. According to the charts, it is seen that temperature values vary between 0°C and 35°C with annual average of 15.6°C; relative humidity values oscillate between 20% and 97% with annual average of 63.4% and the prevailing wind direction for Muğla is northwest.

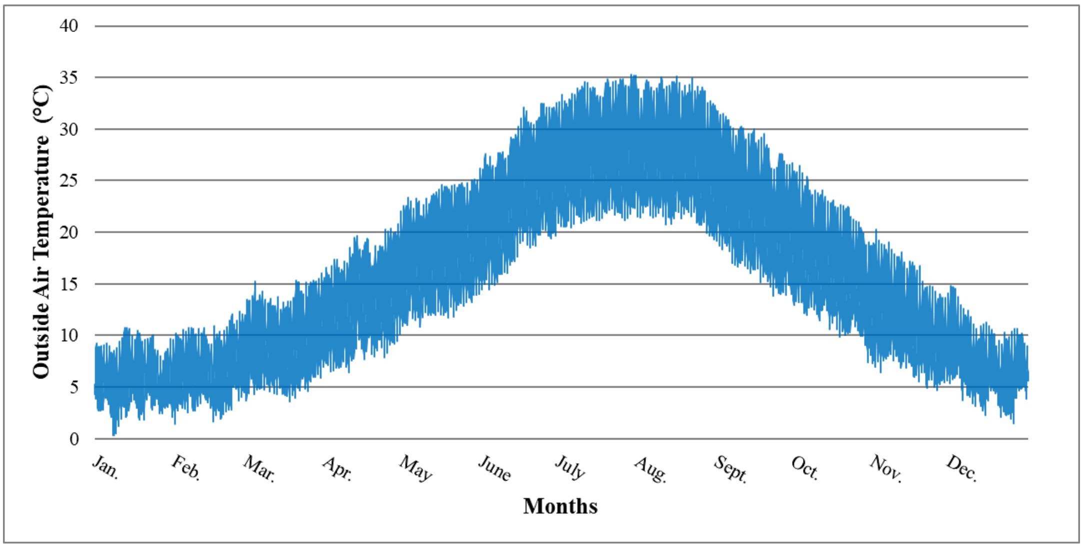

Figure 34. Whole year hourly averages of outside temperature values for Muğla City (average of last 20 years)

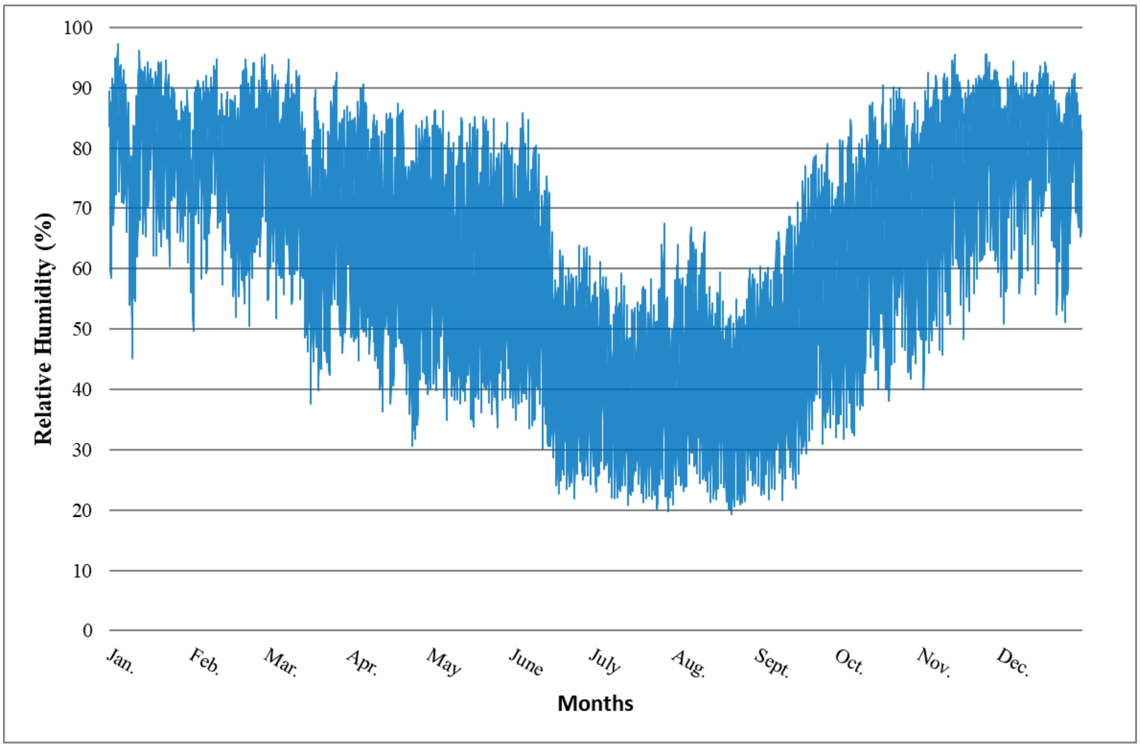

Figure 35. Whole year hourly averages of relative humidity values for Muğla City (average of last 13 years)

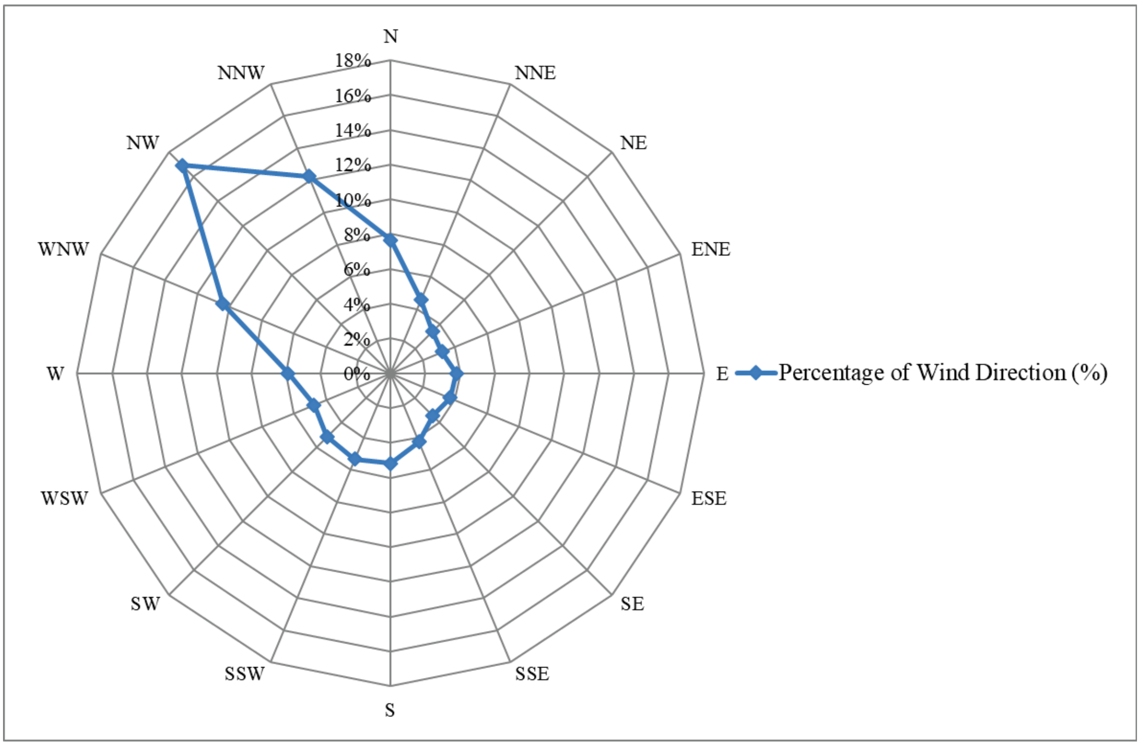

Figure 36. Wind direction diagram for Muğla City (Average of Last 13 Years)

Muğla City is also known for its significant rainfall (Figure 37) in contrast to the other parts of Turkey (after Rize-Artvin Region) which is assumed to provide distinct microclimatic characteristics to its rural zones (Koca, 2004). Average annual total rainfall amount for Muğla Province is 1126 mm [31].

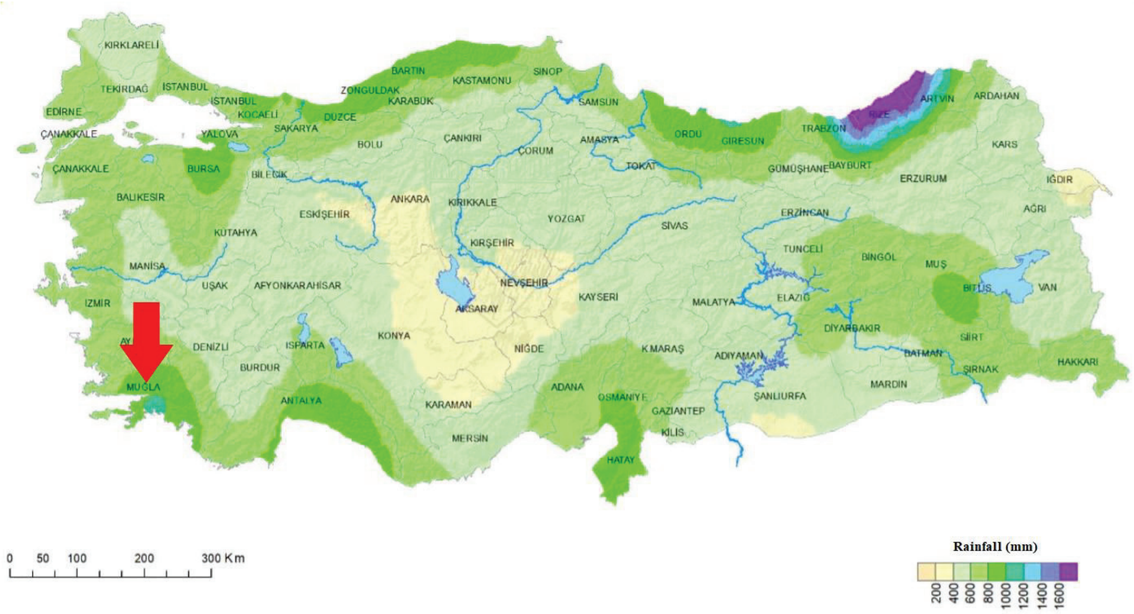

Figure 37. Map demonstrating annual rainfall averages in Turkey / data of 1981-2010[32]

3.1.3. Historic and Traditional Background

The geographical area that is defined by the boundaries of modern Muğla Province roughly refers to the historical region that had been known as Caria in antiquity. In chronological order, the region is known to have been ruled by civilizations of Lydians (6th c. BC.), Persians (6-4th c. BC.), Macedonians (4-2nd c. BC.), Romans (2nd c. BC. – 4th c. AD.), Byzantines (4-9th c. AD.) and Abbasids (9th c. AD.) until 9th century AD. Caria had been taken back from Abbasids by Byzantines in 9th century and their reign had continued until the region was conquered by the Turks in 13th century. Until 15th century, Menteşe Principality was dominant in the area and from 15th century to 20th century, Ottomans ruled the region. Today, the province of Muğla is within the boundaries of

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[31] https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=H&m=MUGLA, access date: 16.10.2019.

[32] https://mgm.gov.tr/, access date: 16.10.2019.

Turkish Republic. Although the exact foundation date of Muğla city is unknown, it is assumed to have been in the pre-Hellenistic period (Mete, 2005).

In tradition, with annual spring and fall migrations, Muğla city has been living in a two-spaced urban pattern (Figure 38). The historical city center that is located at the north-east of the Muğla Plain, on the outskirts of Asar Mountain has been a sloped and dense winter settlement (Figure 39). Whereas; Karabağlar District which is situated at south-east of Muğla Plain has been serving as the loosely built summer settlement of the city (Figure 40).

The literature on city history (Eroğlu, 1939, Ekinci, 1985, Tekeli, 2006) points out roughly the duration from May to September as the inhabitance period of Karabağlar. The district is the lowest area of Muğla plain which has a remarkable annual rainfall. By the help of this rainfall, Karabağlar possesses a very fertile soil by the accumulation of productive alluvial deposits that are refreshed by consecutive rainy seasons in each year. Consequently; Muğla summer settlement has been used as the agricultural production area of the city (Koca, 2004). Both the historical city center and Karabağlar is protected by urban conservation site registrations (Figure 41 and Figure 42).

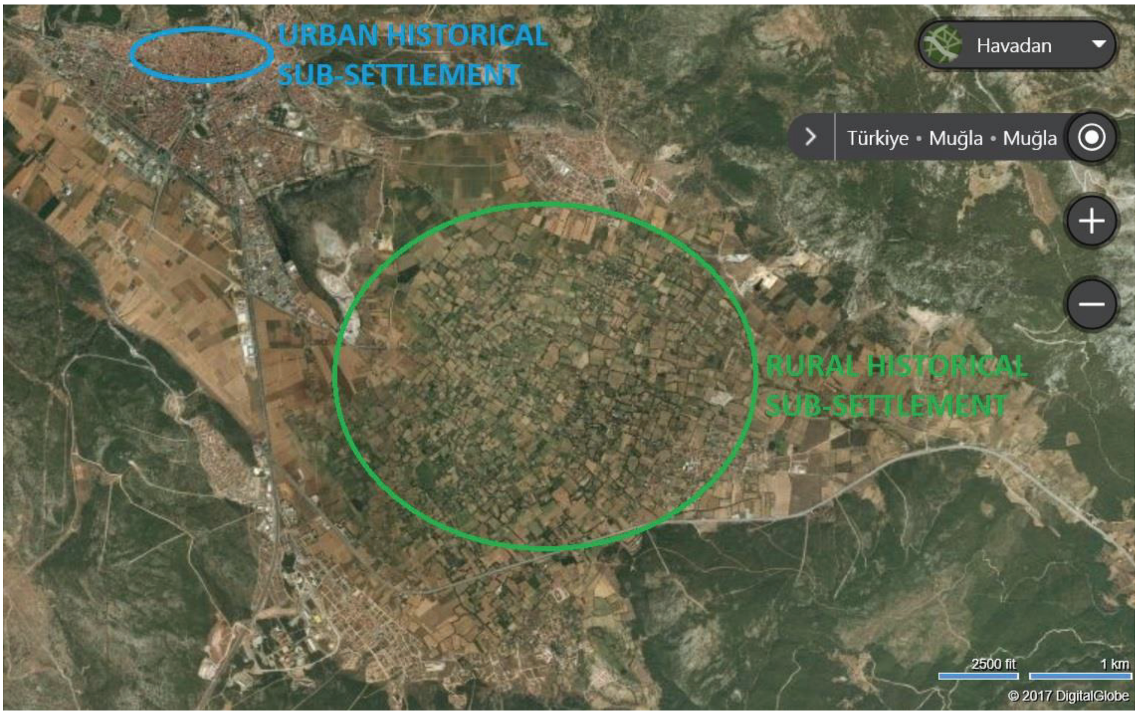

Figure 38. Historical sub-settlements of Muğla[33]

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[33] https://www.bing.com/maps, accessed in 11.12.2017.

Figure 39. Historical city center of Muğla - October 2019 (as seen from south)

Figure 40. Rural sub-settlement of Muğla / Karabağlar – October 2019 (as seen from west)

Figure 41. Muğla conservation plan (Source: Muğla/Menteşe Municipality)

Figure 42. Muğla / Karabağlar conservation plan (Source: Muğla/Menteşe Municipality)

3.2. Case Study Buildings

For selecting case study buildings, representation of traditional houses with exterior *sofa*s was the main criteria. In addition to that, cases were chosen both from urban and rural sub-settlements in order to detect the possible effects of prevailing microclimatic conditions and urban form to the thermal behavior of case studies.

For the analyses, Gürsel house in the historical urban center and Sönmezer house in Karabağlar (rural sub-settlement) were selected as case study buildings. For the sake of comparison, both buildings were chosen among the structures that were constructed in similar plan organization, constructional features, scale and solar orientation. The main difference between the buildings is that Sönmezer house is situated on a plain topography with few neighboring masses around it whereas Gürsel house is located on an upper altitude (49 m higher) on an inclined topography within a very dense urban tissue. The distance between the buildings is 5.6 km (Figure 43).

Figure 43. Location of case study buildings (pink mark indicates Gürsel House and blue mark points out Sönmezer house)[34]

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[34] base map: https://www.bing.com/maps, accessed in 11.12.2017.

3.2.1. Gürsel House

Gürsel house is a traditional building constructed in the second half of 1800s (Figure 46). The building, which had lost its dwelling function over time was donated to Muğla Sıtkı Koçman University in 2008 by the original owners, Gürsel Family. More recently, the building is used infrequently and hosts activities for the university.

The building is located in a dense neighborhood of Hamamönü District, (357 Block / 8 Lot) at historical urban city center on 670 m altitude (Figure 47). Building faces a street on south and opens to its courtyard on north. Neighboring block on its west is attached to the building and neighbor on the east is very close to building in few meters.

The building has two storeys with exterior *sofa*s and *eyvan*s on both floors (Figure 44 and Figure 45). Its staircase is designed on the *eyvan*[35]. All ground floor walls are in stone masonry construction (41 to 60 cm wall thickness) and 1st floor have stone masonry walls (51 to 55 cm wall thickness) on east and west sides, and timber frame / adobe infill walls (averaging 16 cm in thickness) on south and north sides of the plan. (Please refer to Table 3 and Table 4 for constructional features of the building in detail)

The building has three rooms on the ground floor and two rooms on the upper floor. At ground floor, the room on the northwest is a later partial enclosing of *sofa*. The room at the east (G-2) is a multi-functional space with a fireplace. Flooring and ceiling material of this room is timber. The room opens to *sofa* with a door on its north façade which also has two windows. The room on the west (G-3) seems to have been designed as a storage space with no fireplace and a very small wall opening (rather than large windows) on its north façade. In the original design, the room is thought to have compact soil flooring which has been changed to a stone floor in a recent restoration work. The ceiling material of this space is timber. On the 1st floor, both rooms (F-2 and F-3) have fireplaces and designed very extraverted with their large windows on north and south facades. The rooms seem to have been designed as multi-functional spaces. Both flooring and ceiling material of these rooms is timber. The area of the windows is significantly more pronounced on the upper floor (Table 5). And like the spaces on ground floor, all closed spaces directly open to the *sofa* that is directed approximately 6° east of north direction.

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[35] *Eyvan* is a rectangular planned traditional space open at one side.

Table 3. Constructional sections according to the rooms / flooring, ceiling and north wall-Gürsel House

	Flooring		**Ceiling**		**North Wall**	
	Construction Layers (from inner to outer)	**U-Value**[36]	**Construction Layers (from inner to outer)**	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**
G-2 (Living Room in Retrofit Analyses)	Wood Flooring (2cm) + Air Cavity (5cm) + Lime Mortar Bedding (10cm) + Compact Soil (Restitution)	1.32 W/m²K	Wood Flooring (2cm)	3.35 W/m²K	White Wash + Stone Wall (41cm) + White Wash	3.09 W/m²K
G-3 (Kitchen & Bathroom in Retrofit Analyses)	Stone Flooring (3cm) + Lime Mortar Bedding (10cm) + Compact Soil (Restitution)	1.80 W/m²K	Wood Flooring (2cm)	3.35 W/m²K	White Wash + Stone Wall (45cm) + White Wash	2.97 W/m²K
F-2 (Parents Room in Retrofit Analyses)	Wood Flooring (2cm)	3.35 W/m²K	Wood Flooring (2cm)	3.35 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (11cm) + Outer Plaster (2.5cm) + White Wash	2.42 W/m²K
F-3 (Children Room in Retrofit Analyses)	Wood Flooring (2cm)	3.35 W/m²K	Wood Flooring (2cm)	3.35 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (11cm) + Outer Plaster (2.5cm) + White Wash	2.42 W/m²K
Roof	Wood Flooring (2cm)	3.35 W/m²K	Wood Sheathing (2cm) + Air Gap (2cm) + Clay Tile (1cm)	2.78 W/m²K	NA	NA

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[36] U-values of the constructional sections of case studies are given as calculated by *DesignBuilder*.

Table 4. Constructional sections according to the rooms / east, south and west walls-Gürsel House

	East Wall		**South wall**		**West Wall**	
	Construction Layers (from inner to outer)	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**
G-2 (Living Room in Retrofit Analyses)	White Wash + Stone Wall (55cm) + White Wash	2.71 W/m²K	White Wash + Stone Wall (60cm)	2.60 W/m²K	White Wash + Stone Wall (45cm) + White Wash	2.97 W/m²K
G-3 (Kitchen & Bathroom in Retrofit Analyses)	White Wash + Stone Wall (49cm) + White Wash	2.86 W/m²K	White Wash + Stone Wall (60cm)	2.60 W/m²K	White Wash + Stone Wall (55cm) + White Wash	2.71 W/m²K
F-2 (Parents Room in Retrofit Analyses)	White Wash + Stone Wall (55cm) + White Wash	2.71 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (11cm) + Outer Plaster (2.5cm) + White Wash	2.42 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (11cm) + Outer Plaster (2.5cm) + White Wash	2.42 W/m²K
F-3 (Children Room in Retrofit Analyses)	White Wash + Inner Plaster (2.5cm) + Adobe Infill (11cm) + Outer Plaster (2.5cm) + White Wash	2.42 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (11cm) + Outer Plaster (2.5cm) + White Wash	2.42 W/m²K	White Wash + Stone Wall (51cm) + White Wash	2.81 W/m²K

Table 5. Opening surface area percentages in the facades of Gürsel House

	Ground Floor				
	North Facade	East Facade	South Facade	West Facade	Total
Total Facade Surface Area (A1) m²	31.7	11.1	31.7	10.7	85.2
Total Opening Surface Area (A2) m²	4.7	0.0	0.0	0.0	4.7
Opening Surface Area Percentage (A2/A1)	15.0%	0.0%	0.0%	0.0%	5.6%
	1st Floor				
	North Facade	East Facade	South Facade	West Facade	total
Total Facade Surface Area (A1) m²	39.5	16.5	38.1	15.7	109.9
Total Opening Surface Area (A2) m²	11.8	0.9	8.3	0.9	22.0
Opening Surface Area Percentage (A2/A1)	30.0%	5.6%	21.7%	5.8%	20.0%

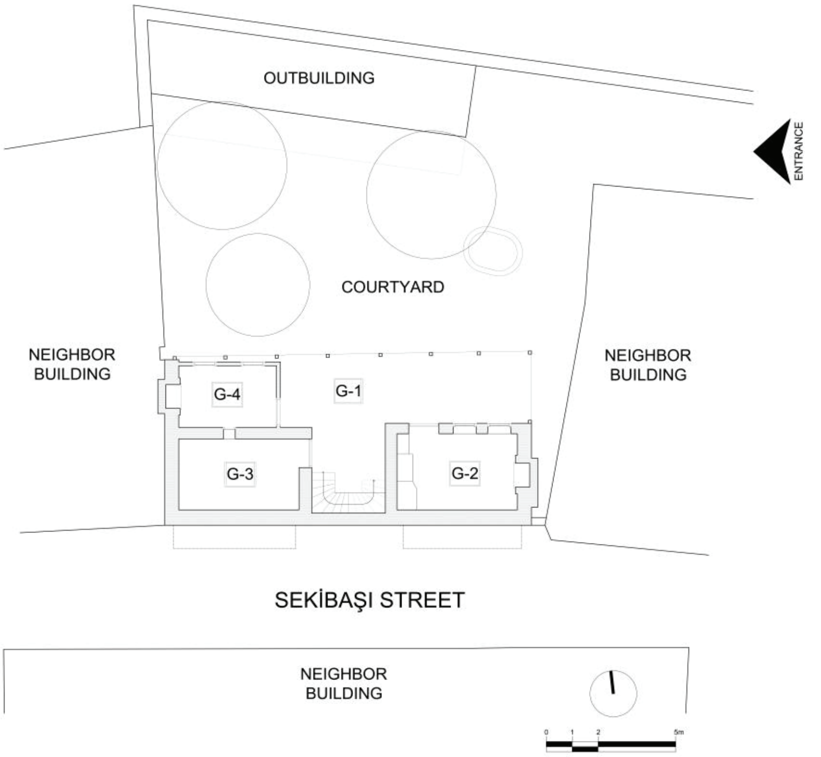

Figure 44. Gürsel House measured drawings (ground floor plan)

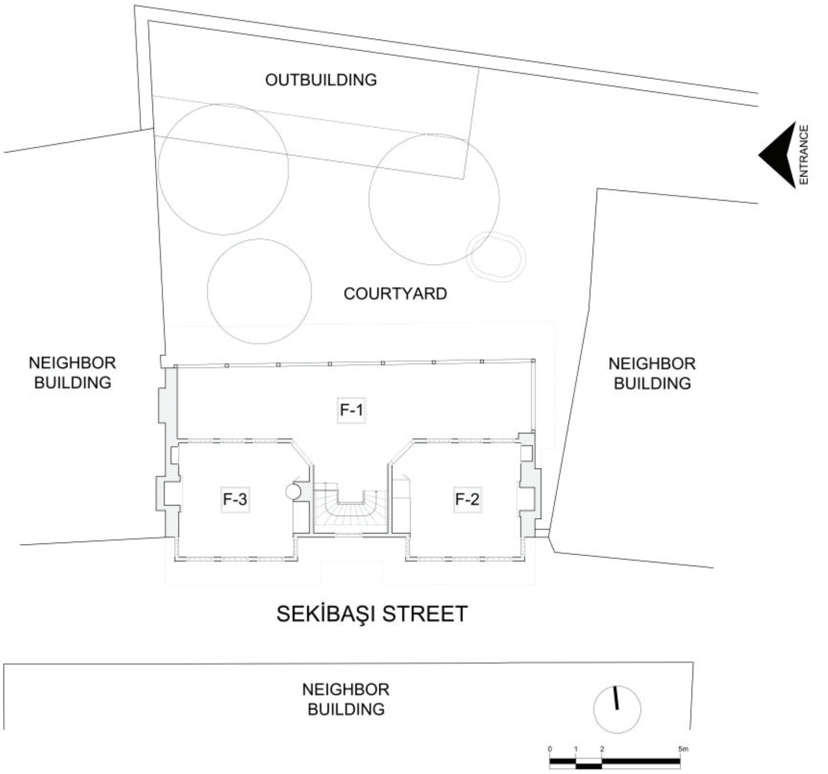

Figure 45. Gürsel House measured drawings (first floor plan)

Figure 46. Gürsel House north facade facing courtyard

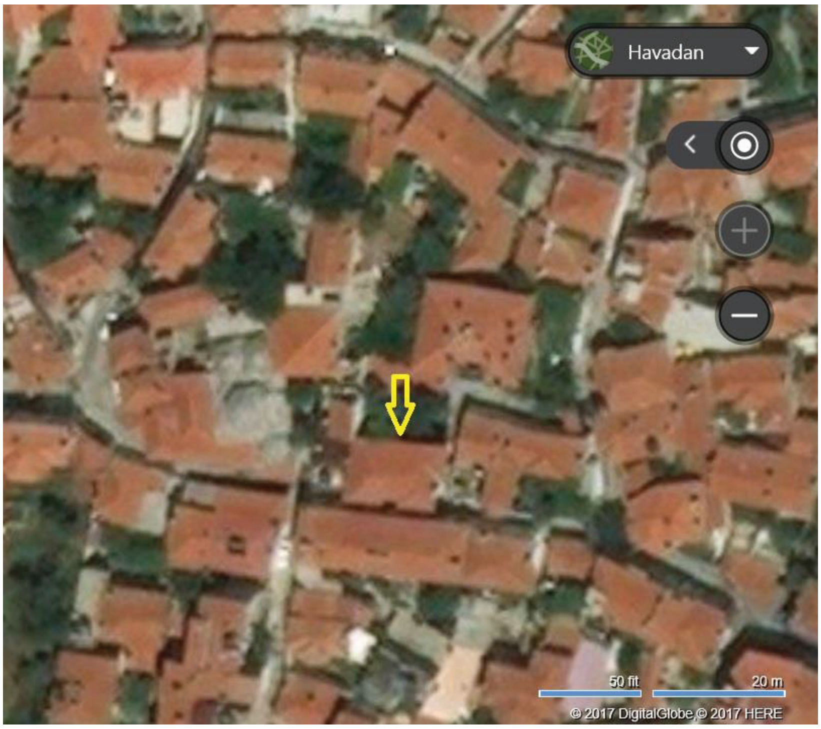

Figure 47. Aerial view of Gürsel House[37]

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[37] https://www.bing.com/maps, accessed in 11.12.2017.

3.2.2. Sönmezer House

Sönmezer House is a traditional rural house that was constructed in early 1900s (Figure 50). In time, the building has become a rarely used weekend house. It is located on the loosely-built, rural sub-settlement of Muğla that is Karabağlar (Figure 51). The building is on Süpüroğlu Neighborhood, at 240 Block / Lot 3 and situated on 621 m altitude.

The building -with its outbuildings- faces a street on south and opens to its garden on north. The neighborhood can be characterized as a low density agricultural zone of building blocks within large gardens. The building is surrounded by outbuildings on south, east and west. The outbuilding on the south was built with traditional construction elements of stone masonry walls. The one on the east is a reconstruction of an earlier outbuilding and the one on the west is a later addition.

Sönmezer House has two storeys with exterior *sofa*s and *eyvan*s on both floors (Figure 48 and Figure 49). Its staircase is designed on the *eyvan*. Ground floor walls are in stone masonry structure (walls with 45 cm average thickness) and 1st floor is in a hybrid structure of timber frame and adobe infill walls (average of 15 cm thickness). (Please refer to Table 6 and Table 7 for constructional features of the building in detail)

The building has three closed rooms on the ground level and two closed rooms on the upper level. At the ground floor, the room on the northeast is a later partial enclosing of *sofa*. The room at the east (G-3) is a multi-functional room with a fireplace. Flooring and ceiling material of this room is timber. This room opens to *sofa* with a door on its north façade. This façade also has 2 windows. The room also opens to east and south through windows. The room on the west (G-2) seems to have been designed as a storage space with no fireplace and very small wall openings (rather than large windows) on its north and west façades. The room has compact soil flooring and ceiling material is timber. On the 1st floor, the room on the east (1F-3) seems to have been designed as a multi-functional room. It has no fireplace and designed very extraverted with large windows on north, east and south facades. The room on the west (1F-2) also seems to have been designed as a multi-functional room. It has a fireplace and designed with large windows on north, east and south facades. Both flooring and ceiling material of these rooms is timber. The area of the windows is significantly more pronounced on the upper floor

(Table 8). Like the spaces on ground floor, all closed spaces directly open to the *sofa* that is directed approximately 32° east of north direction.

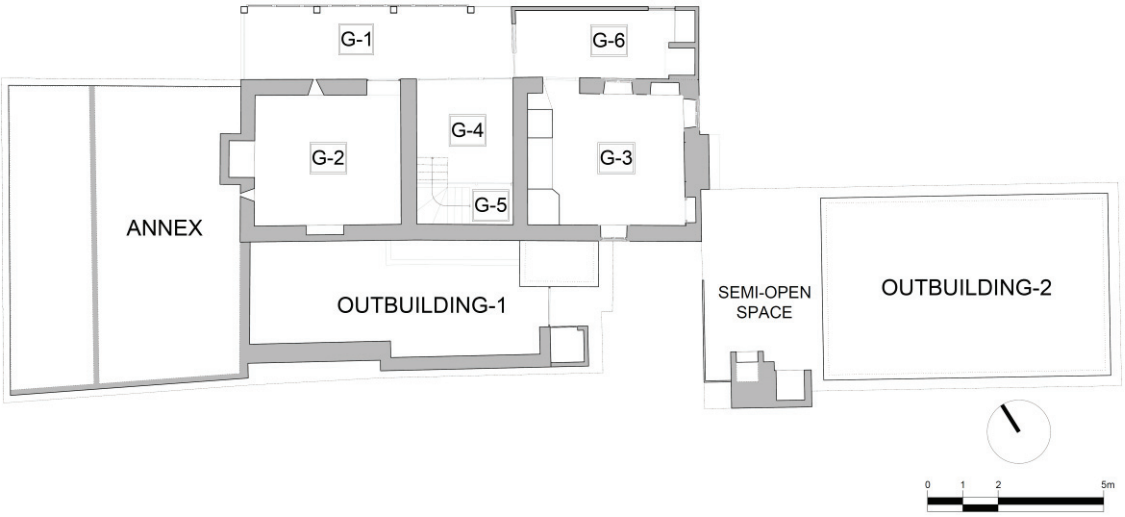

Figure 48. Sönmezer House measured drawings (ground floor plan)

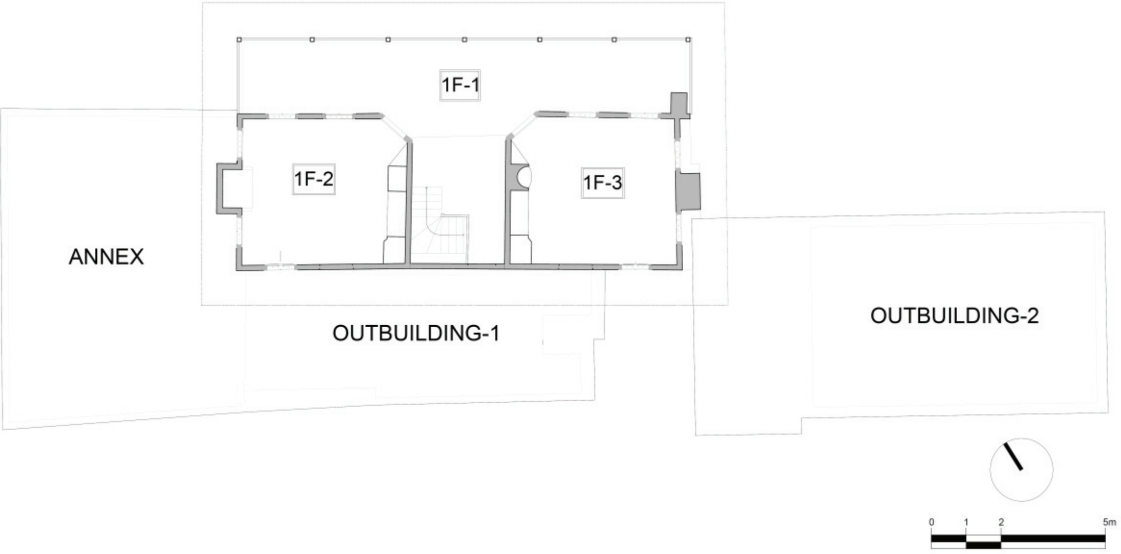

Figure 49. Sönmezer House measured drawings (first floor plan)

Table 6. Constructional sections according to the rooms / flooring, ceiling and north wall-Sönmezer House

	Flooring		**Ceiling**		**North Wall**	
	Construction Layers (from inner to outer)	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**
G-3 (Living Room in Retrofit Analyses)	Wood Flooring (2cm) + Air Cavity (5cm) + Lime Mortar Bedding (10cm) + Compact Soil (Restitution)	1.40 W/m²K	Wood Flooring (2cm)	6.73 W/m²K	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K
G-2 (Kitchen & Bathroom in Retrofit Analyses)	Stone Flooring (3cm) + Lime Mortar Bedding (10cm) + Compact Soil (Restitution)	1.93 W/m²K	Wood Flooring (2cm)	6.73 W/m²K	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K
1F-3 (Parents Room in Retrofit Analyses)	Wood Flooring (2cm)	6.73 W/m²K	Wood Flooring (2cm)	6.73 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K
1F-2 (Children Room in Retrofit Analyses)	Wood Flooring (2cm)	6.73 W/m²K	Wood Flooring (2cm)	6.73 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K
Roof	Wood Flooring (2cm)	6.73 W/m²K	Wood Sheathing (2cm) + Air Gap (2cm) + Clay Tile (1cm)	3.13 W/m²K	NA	NA

Table 7. Constructional sections according to the rooms / east, south and west walls- Sönmezer House

	East Wall		**South wall**		**West Wall**	
	Construction Layers (from inner to outer)	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**	**Construction Layers (from inner to outer)**	**U-Value**
G-3 (Living Room in Retrofit Analyses)	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K
G-2 (Kitchen & Bathroom in Retrofit Analyses)	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K	White Wash + Stone Wall (45cm) + White Wash	3.37 W/m²K
1F-3 (Parents Room in Retrofit Analyses)	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K
1F-2 (Children Room in Retrofit Analyses)	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K	White Wash + Inner Plaster (2.5cm) + Adobe Infill (10cm) + Outer Plaster (2.5cm) + White Wash	2.13 W/m²K

Table 8. Opening surface area percentages in the facades of Sönmezer House

	Ground Floor				
	North Facade	East Facade	South Facade	West Facade	Total
Total Facade Surface Area (A1) m²	24.3	10.9	24.6	10.9	70.7
Total Opening Surface Area (A2) m²	6.2	1.1	0.9	0.1	8.4
Opening Surface Area Percentage (A2/A1)	25.6%	10.4%	3.5%	1.3%	11.8%
	1st Floor				
	North Facade	East Facade	South Facade	West Facade	total
Total Facade Surface Area (A1) m²	34.0	14.4	32.4	14.4	95.3
Total Opening Surface Area (A2) m²	8.1	2.4	4.8	2.4	17.7
Opening Surface Area Percentage (A2/A1)	23.8%	16.7%	14.8%	16.6%	18.6%

Figure 50. Sönmezer House north facade

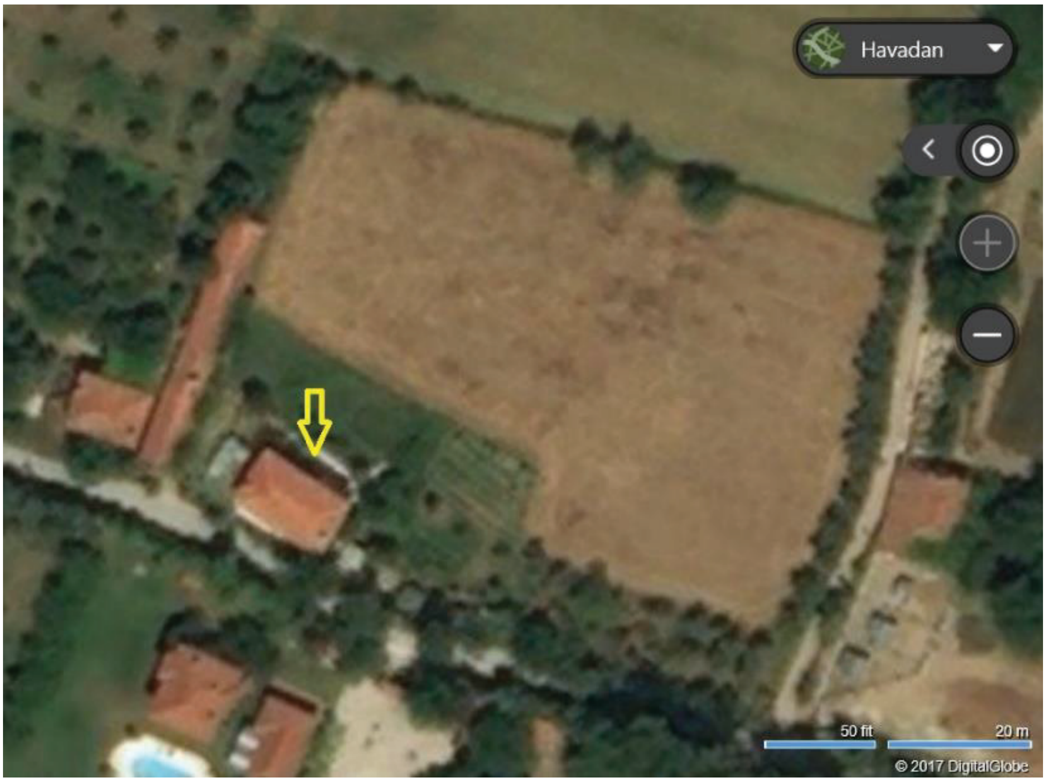

Figure 51. Aerial view of Sönmezer House [38]

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[38] https://www.bing.com/maps, accessed in 11.12.2017.

CHAPTER 4

MODELS AND SIMULATIONS

In this chapter, firstly, the variables and the assumptions, which were accepted in forming the thermal models of the case study buildings, are explained in Section 4.1. Following that, the process and the results of model calibration stage are presented in Section 4.2. And lastly, the analyses models, which were used to determine the enhancement rates of the thermal retrofitting measures, are introduced in detail in Section 4.3.

4.1. Model Variables

For thermal simulations to represent the thermal behavior of the case study buildings realistically, modeling variables that best refer to the actual conditions of the buildings must be introduced to the analysis software. These variables, which are prepared as quantified data and as a set of program inputs, define the physical and functional aspects of the buildings as well as their geographical and urban context as to be processed by the building performance software (*DesignBuilder*) in the thermal calculations. The variables[39] that this study specified to be used in the modeling stage can be summarized as:

- Location, site scale features and surroundings,
- Local weather data,
- Building geometry,
- Constructional features and architectural elements,
- HVAC equipment and systems and
- User profile

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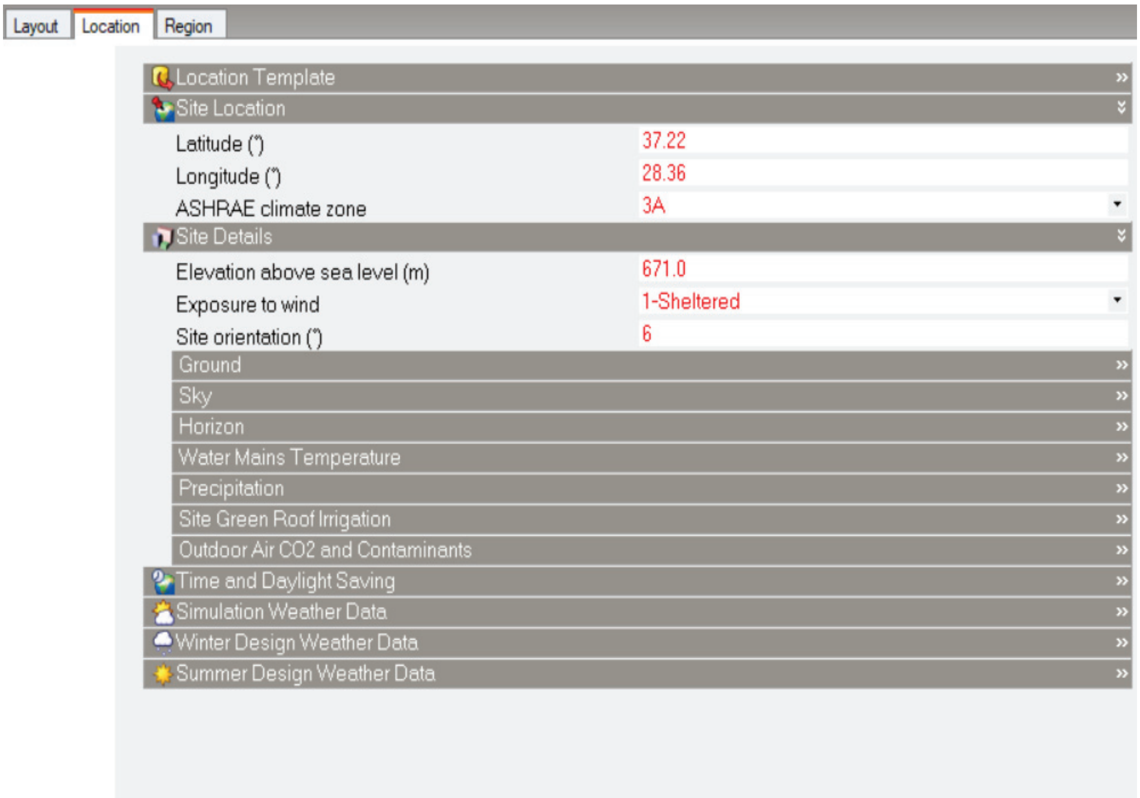
[39] For the variables that are not mentioned in this chapter like the artificial lighting settings and DHW (Domestic hot water) consumptions, default settings of the software were used for simulations.

4.1.1. Location, Site Scale Features and Surroundings

The geographical locations of the buildings were introduced to the analysis software by their actual altitude, latitude and longitude[40] values (Figure 52). For Gürsel House these values are 671m, 37.22° and 28.36°, and for Sönmezer House, the values are 622m, 37.19° and 28.4°, respectively. In addition, the virtual models of the buildings were created with their surrounding neighboring blocks and landscape elements (e.g. trees and garden walls) in order to be able to simulate the effects of these elements to the thermal behavior of the case study buildings regarding shadowing, solar reflections and air-flow manipulation (Figure 53 and Figure 54 demonstrate the model of Gürsel House and Figure 55 and Figure 56 show the model for Sönmezer House).



Latitude (°)	37.22
Longitude (°)	28.36
ASHRAE climate zone	3A
Elevation above sea level (m)	671.0
Exposure to wind	1-Sheltered
Site orientation (°)	6

Figure 52. Interface of *DesignBuilder* to introduce locational features of the buildings (case of Gürsel House)

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[40] The altitude values of the case studies were gathered from Muğla Municipality and *Google Earth* application was used to specify latitude and longtitude values.

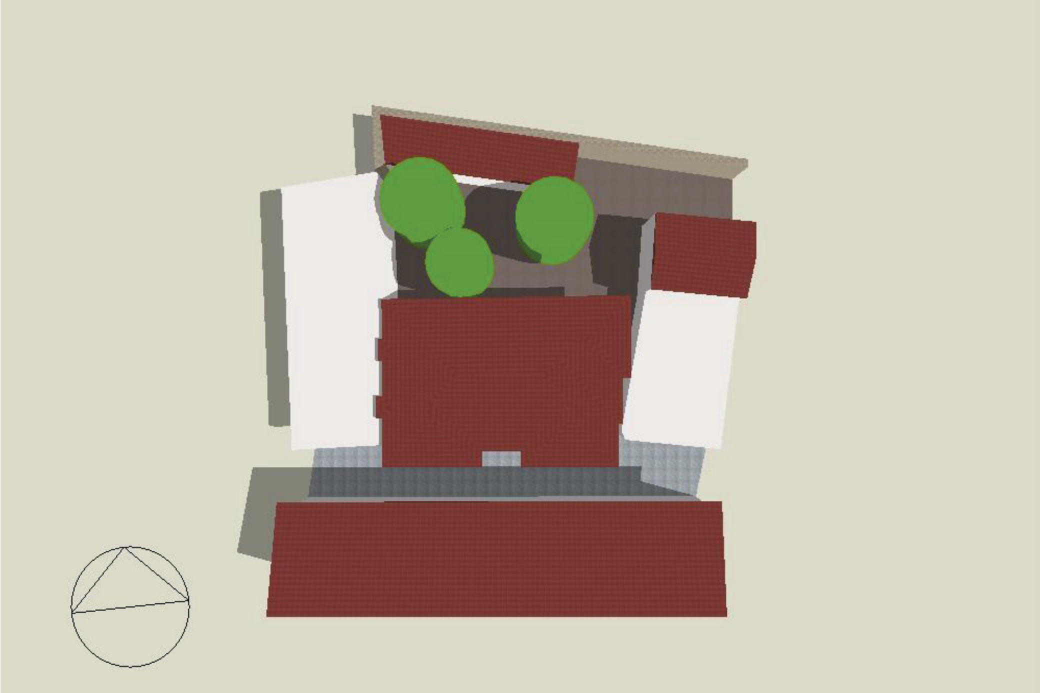


Figure 53. Top view of the virtual model for Gürsel House showing surrounding neighbor blocks, courtyard and street surfaces and landscape elements of trees and courtyard wall

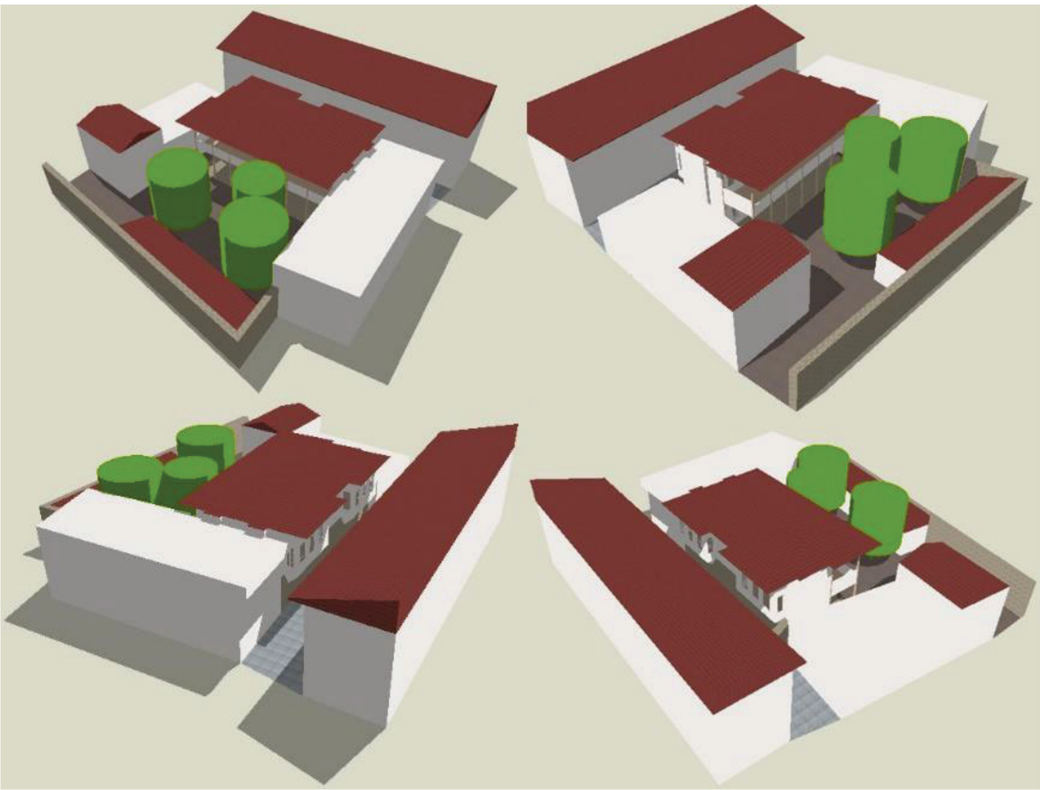


Figure 54. Axonometric perspective views of the virtual model for Gürsel House

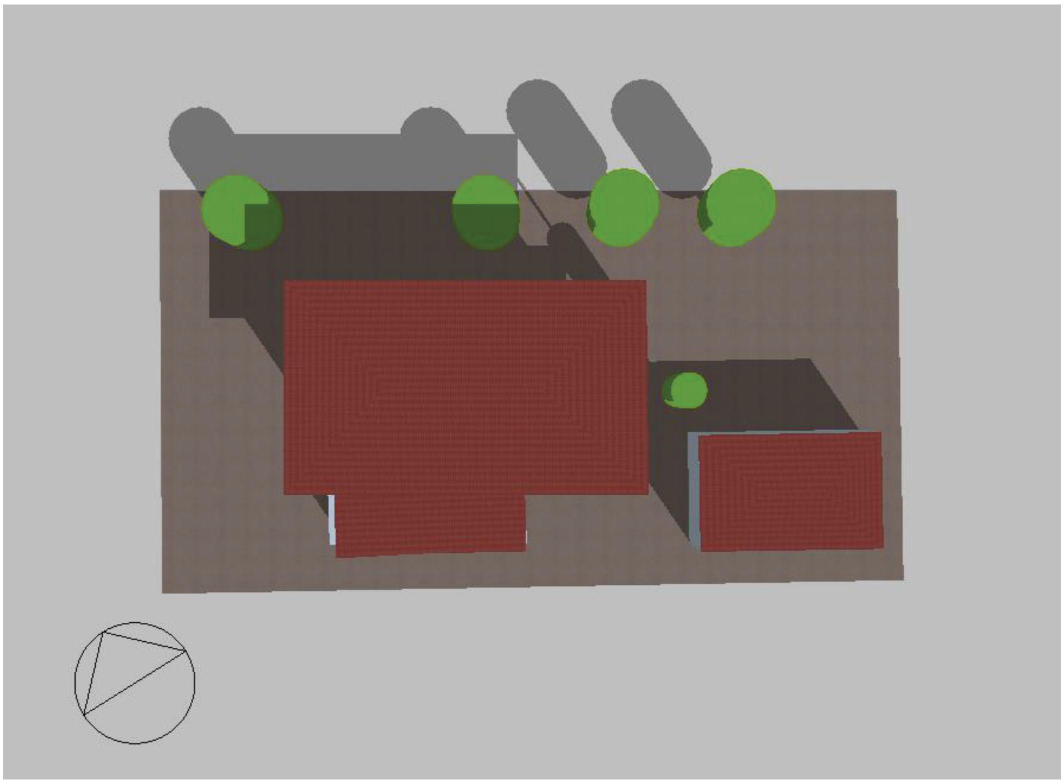


Figure 55. Top view of the virtual model for Sönmezer House showing surrounding outbuildings, and trees.

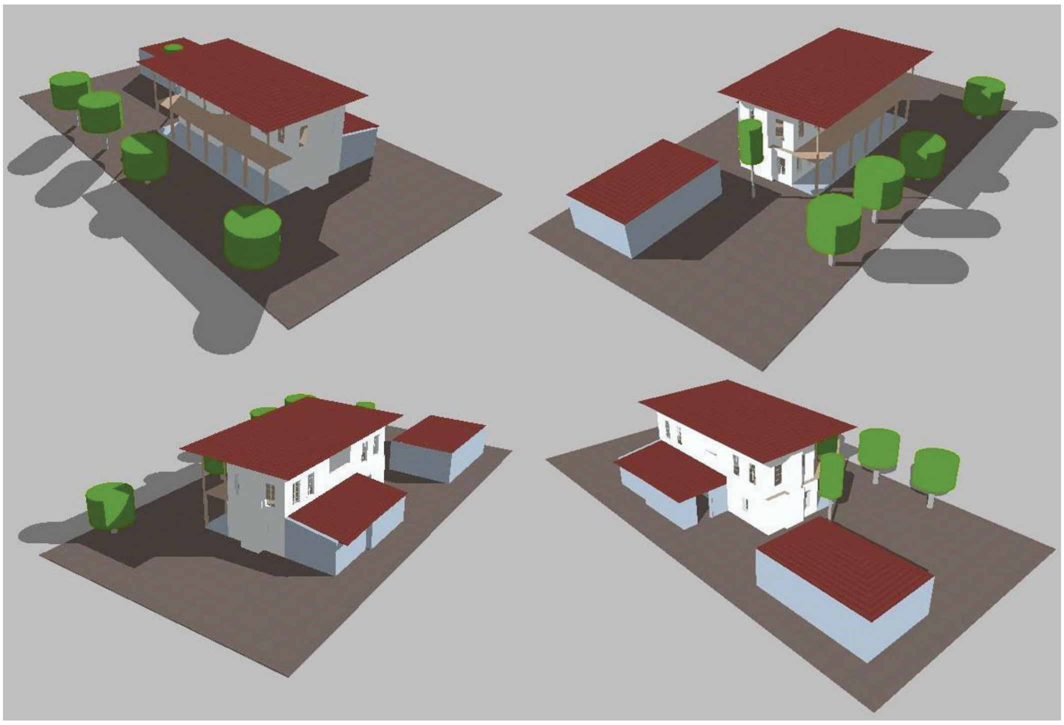


Figure 56. Axonometric perspective views of the virtual model for Sönmezer House

4.1.2. Local Weather Data

With the method described in Chapter 2 / Works on Weather Data, local weather data were prepared and introduced to analysis software for each building separately in order to detect the possible effects of different microclimates that the case buildings are exposed. These data were introduced to the model in *.epw* file format (Figure 57). Moreover, monthly ground temperature averages, which had been gathered from these weather files, were inserted to the models providing no default ground temperature was used for simulations.

Hourly weather data: muglhourEPWCSV

Day of week for start day: 8-Use weather file

☑ Use weather file snow and rain indicators

Figure 57. Interface of *DesignBuilder* to define simulation weather data (case of Gürsel House)

4.1.3. Building Geometry

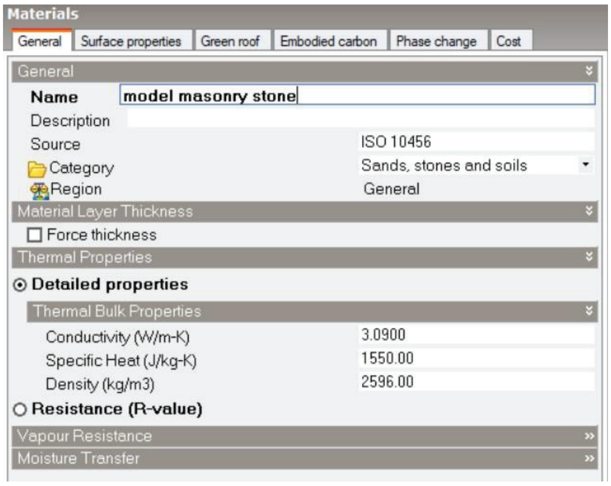
Using the architectural data gathered on site survey, firstly, 2-dimensional measured drawings for each case study were prepared on the program, *Autodesk AutoCAD 2019* (student version). And following that, 3-dimensional geometry of the case buildings were introduced to *DesignBuilder* software with its modeling interface using the CAD drawings in .dxf format as drawing guides. In order to establish more detailed simulation results, all closed spaces of the buildings were defined separately in the models rather than assuming the whole building as a single thermal zone. And no thermal zone is defined for open and semi-open spaces such as *eyvan*s, *sofa*s and courtyards (Figure 58).

Figure 58. North facade of the Gürsel House model

4.1.4. Constructional Features and Architectural Elements

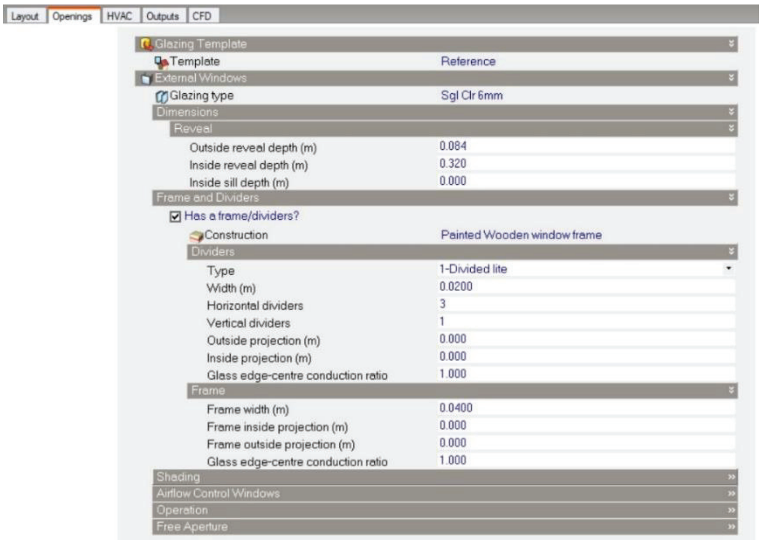
Thermophysical properties (specific heat, thermal conductivity and density) of the building materials were introduced to models by the values that had been measured in laboratory works on sample building materials (Figure 59). Architectural elements (e.g. openings such as windows and doors) were introduced to the software by modeling interface and detailed attributes for each element were inserted through openings tab (Figure 60). The attributes for windows are:

- Glazing type, thickness and number of layers,
- Dimension and material data for frames and dividers,
- Reveal and projection measurements,
- Shading equipment (e.g. drapes, blinds, shade rolls) and
- Operation (time intervals when the windows are opened and closed)



Name: model masonry stone
Description:
Source: ISO 10456
Category: Sands, stones and soils
Region: General
☐ Force thickness
● Detailed properties
Conductivity (W/m-K): 3.0900
Specific Heat (J/kg-K): 1550.00
Density (kg/m3): 2596.00
○ Resistance (R-value)

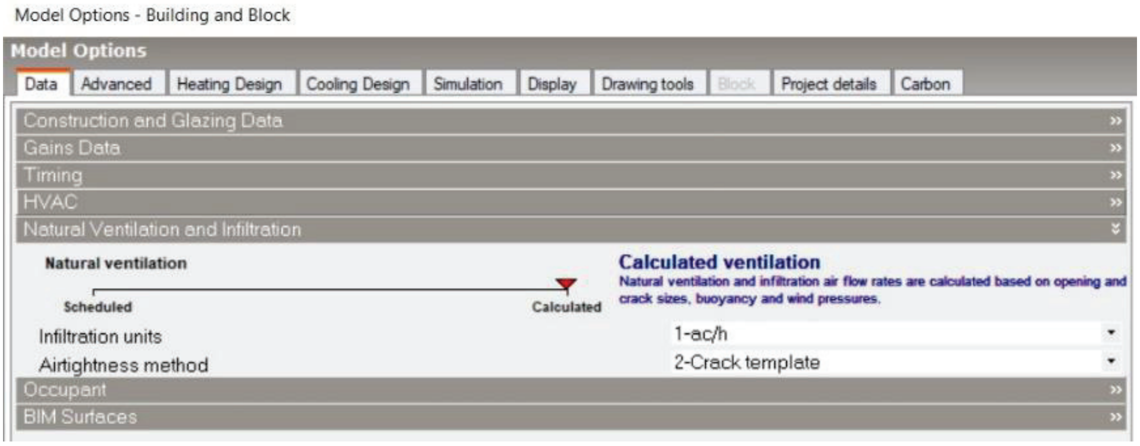
Figure 59. *DesignBuilder* material introduction interface under construction tab (example: masonry stone wall)



Template: Reference
Glazing type: Sgl Clr 6mm
Outside reveal depth (m): 0.084
Inside reveal depth (m): 0.320
Inside sill depth (m): 0.000
☑ Has a frame/dividers?
Construction: Painted Wooden window frame
Type: 1-Divided lite
Width (m): 0.0200
Horizontal dividers: 3
Vertical dividers: 1
Outside projection (m): 0.000
Inside projection (m): 0.000
Glass edge-centre conduction ratio: 1.000
Frame width (m): 0.0400
Frame inside projection (m): 0.000
Frame outside projection (m): 0.000
Glass edge-centre conduction ratio: 1.000

Figure 60. *DesignBuilder* openings tab for windows (example: northern windows on ground floor of Gürsel House)

In *DesignBuilder* software, general crack template of the rooms, which can be defined as the resistance of construction and architectural elements to air leakage, is set through a scale of five categories defined as excellent, good, medium, poor and very poor. For the case buildings, this template was assumed to be poor. And natural ventilation / infiltration option was selected to be calculated meaning the software calculates infiltration / exfiltration rates in detail according to model attributes rather than processing pre-assumed air flow values (Figure 61).



Calculated ventilation

Natural ventilation and infiltration air flow rates are calculated based on opening and crack sizes, buoyancy and wind pressures.

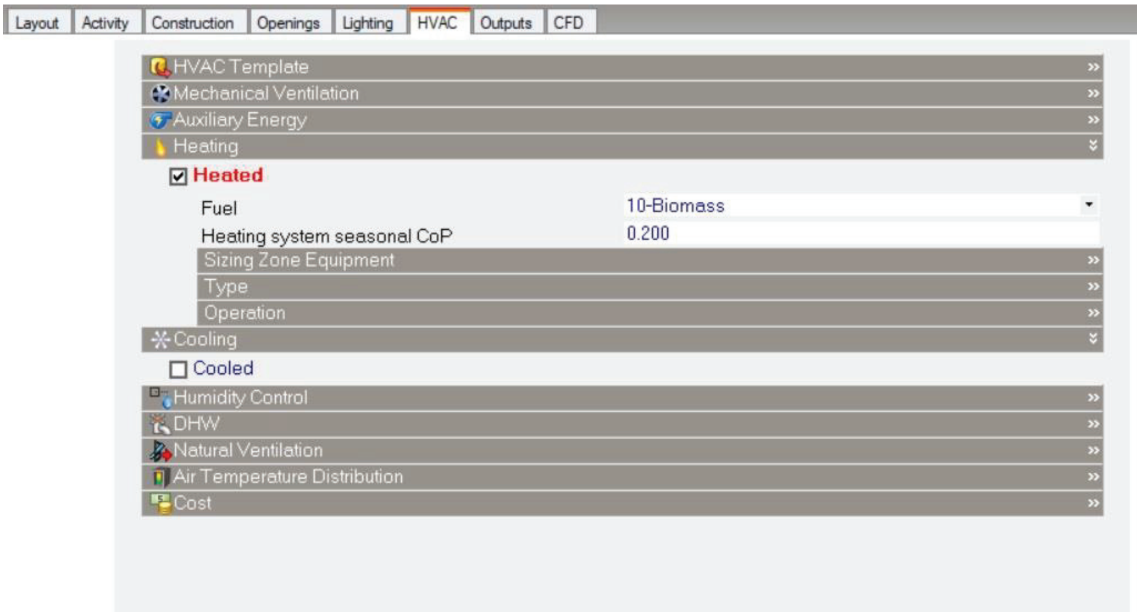
Infiltration units: 1-ac/h

Airtightness method: 2-Crack template

Figure 61. *DesignBuilder* model options tab showing calculated ventilation preference

4.1.5. Heating and Cooling Equipment

DesignBuilder software has the HVAC (Heating Ventilation and Air Conditioning) tab for the introduction of heating / cooling systems to the models. Using this tab, HVAC systems are defined by their fuel type, COP (coefficient of performance) values and operational schedules (Figure 62).



☑ **Heated**

Fuel: 10-Biomass

Heating system seasonal CoP: 0.200

☐ Cooled

Figure 62. *DesignBuilder* HVAC tab showing heating preference for the rooms of case studies for original state analyses (Models 2.1)

4.1.5.1. Energy Output of Traditional Heating Equipment

In order to calculate the heating output rate of the traditional fireplaces following formula (4.1) was used:

$$A*B*C*D = \text{Heating Output Rate} \qquad (4.1)$$

where A is Combustion Heat Output of Unit Mass Wood,
B is Mass of Wood Burnt in Unit Time and in Unit Volume,
C is Volume of Fireplace Combustion Chamber and
D is Heating / Burning Efficiency

For the calculations, it was assumed that

- Combustion heat output of 1 kg wood is 14210 kJ/kg according to Speight (2011).
- 12.33 kg of wood burns in 1 hour in a traditional fireplace having a combustion chamber of 1 m^3 volume as 1.85 kg wood was calculated to burn in 1 hour in a traditional fireplace with a 0.15 m^3 combustion chamber by Calvo et al. (2014).
- Heating / Burning Efficiency of traditional open fireplaces is 20% according to Taylor et al. (2005), Anderson et al. (2011) and Arnold et al. (2013).
- Burning wood amount is linearly proportional to the volume of the combustion chambers on each fireplace of the case study buildings (As combustion chamber volumes of the fireplaces in Sönmezer house are same and 0.5 m^3 and it varies in Gürsel house fireplaces between 0.29 m^3 and 0.41 m^3)

With the formula (4.1), heating output rates were calculated for each fireplace of the case study buildings (Table 9).

Table 9. Energy output rates of traditional fireplaces at the case buildings

Fireplace 1 & Fireplace 2 in Sönmezer House (0.5 m^3)	Fireplace 1-Living Room in Gürsel House (0.29 m^3)	Fireplace 2-Parents Room in Gürsel House (0.32 m^3)	Fireplace 3-Children Room in Gürsel House (0.41 m^3)
4.87 kW	**2.82 kW**	**3.12 kW**	**3.99 kW**

4.1.6. User Profile

In traditional lifestyle, Muğla houses had been utilized either with 5-6 member nuclear families or with 7-8 member extended families[41] that depended on a family-scale economy mostly based on agricultural production (Keleş, 2002). However, the studies on current user trends like the report of Oktik and Öztürk (2007) demonstrate a very different family structure for the traditional house users. According to this report[42]:

- Dominant family trend in traditional houses is nuclear family that generally consists of 4 people (as 2 parents and 2 children).
- 60 % of the houses have only 1 working person and 74 % of the women are housewives meaning that generally father is the only working person.
- Agricultural production seems completely abandoned as only 0.5 % of the inhabitants are presented to be farmers.

This dramatic change in living trends are also perceived in the case buildings of this study. Both case buildings are no longer used in their original density and function as Sönmezer House is a rarely used weekend house and the rooms of Gürsel House seldom function as activity halls for Muğla University. For this reason, in order to define functional schedules for the rooms of case buildings, demographical facts presented in literature (Oktik et al., 2007) and the architectural potential of the traditional houses (two rooms on ground level and two rooms on 1st floor) were considered. The schedules were prepared regarding specific room functions, their daily utilization frequency and the user density. While establishing schedules, these assumptions were considered:

- As the user family profile of the traditional houses changed greatly over time, new adaptive re-functioning decisions must be made.
- As opposed to the traditional multi-functional nature of the unit spaces of the houses, which seems to have originated from the needs of more crowded traditional families, new functions of the rooms can be defined more specific such as living room, bedroom etc.(Figure 63 and Figure 64).
- From ground level to the upper floors, functions of the rooms are selected in a gradation from semi-private to the private which led to the upper floors have the bedrooms and the ground levels have living, dining and cooking functions.

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[41] The number of the family members demonstrate the situation in 19th century (Keleş, 2002).

[42] Survey of this study was held in 2006 interviewing 915 inhabitants of Muğla Urban Conservation Site.

- The service spaces such as kitchens and toilets, which in tradition had been located in outbuildings outside the main buildings, were inserted inside the main buildings for protecting users which otherwise might be exposed to direct weather conditions while performing these functions (e.g. in tradition, users had been walking through the rain in order to reach the toilet).
- The spaces that were designed originally as agricultural storage spaces were converted into wet cores including kitchens and bathrooms as the need for agricultural stocking disappeared in time.
- Rooms with fireplaces on ground level which may be regarded as a more semi-private location are used both for living and dining rooms as they can also function for guest acceptance.
- At least 8 hour of daily sleeping time is scheduled for each person.
- Father is the only person working in the family and the mother is housewife.
- Children are assumed to attend school from 16th of September to 14th of June and have summer holidays from 15th June until 15 September.
- For weekend afternoons, all family is accepted to be out of the house for social and recreational activities.
- For week day afternoons, housewife is out of the house for social and recreational activities.

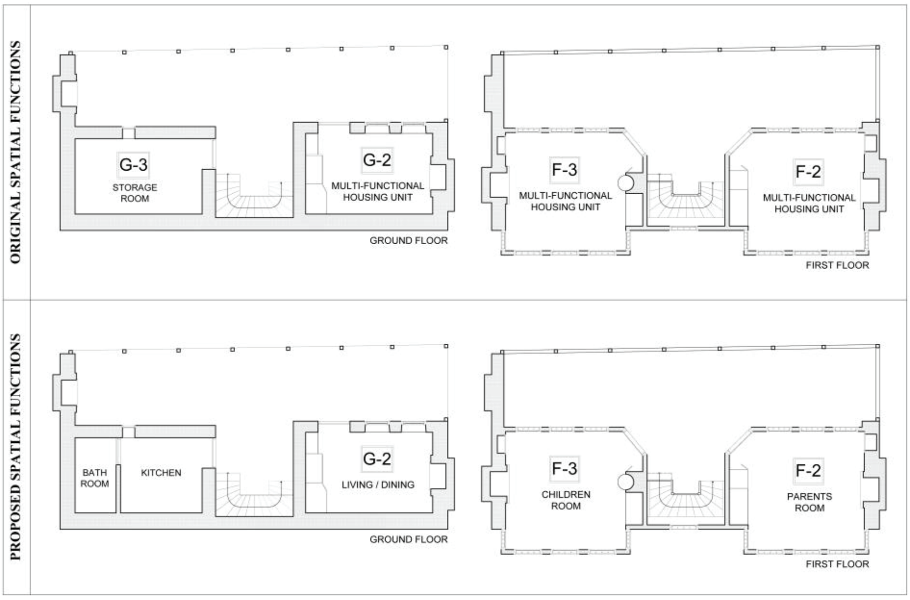

Figure 63. Proposed spatial functions for the model of Gürsel House in comparison to the original utilization

Figure 64. Proposed spatial functions for the model of Sönmezer House in comparison to the original utilization

By these assumptions, time schedules for each space covering separately the weekday (Table 11) and the weekend / holiday (Table 12) intervals were prepared and introduced to the analysis software. House appliances were also defined in the required spaces with utilization schedules as they contribute to thermal status of the rooms (Table 10). The schedules for house appliances are prepared in parallel to the spatial use pattern.

Table 10. Energy use of household appliances[43]

Room	Equipment	Power	Amount
Living room	Tv	150 Watt	1
Children Bedroom	Notebook pc	25 Watt	2
Kitchen	Washing machine	255 watt	1
	Dishwasher	330 Watt	1
	Refrigerator	225 Watt	1
	Oven	1500 Watt	1

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[43] https://www.energy.gov/energysaver/save-electricity-and-fuel/appliances-and-electronics/estimating-appliance-and-home, access date: 01.03.2019.

Table 11. Spatial occupancy schedules – weekdays (grey hatches indicate occupancy hours)

Time	Ground Floor Kitchen			Ground Floor Bathroom			Ground Floor Living Room			1st Floor Parents Bedroom			1st Floor Children Bedroom		
	Father	Mother	Children	Father	Mother	Children	Father	Mother	Children	Father	Mother	Children	Father	Mother	Children
0:00-0:30										▨	▨				▨
0:30-1:00										▨	▨				▨
1:00-1:30										▨	▨				▨
1:30-2:00										▨	▨				▨
2:00-2:30										▨	▨				▨
2:30-3:00										▨	▨				▨
3:00-3:30										▨	▨				▨
3:30-4:00										▨	▨				▨
4:00-4:30										▨	▨				▨
4:30-5:00										▨	▨				▨
5:00-5:30										▨	▨				▨
5:30-6:00										▨	▨				▨
6:00-6:30										▨	▨				▨
6:30-7:00		▨													
7:00-7:30							▨	▨	▨						
7:30-8:00								▨							
8:00-8:30								▨							
8:30-9:00								▨							
9:00-9:30								▨							
9:30-10:00								▨							
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18:15-18:30		▨				▨									
18:30-19:00							▨	▨	▨						
19:00-19:30							▨	▨	▨						▨
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22:00-22:30							▨	▨							▨
22:30-23:00										▨	▨				▨
23:00-23:30										▨	▨				▨
23:30-24:00										▨	▨				▨

* This schedule illustrates the actions of father and mother for the weekdays of whole year whereas it demonstrates the actions of childeren from 15th September to 15th June when the schools are open.

Table 12. Spatial occupancy schedules – weekends & holidays (grey hatches indicate occupancy hours)

Time	Ground Floor Kitchen			Ground Floor Bathroom			Ground Floor Living Room			1st Floor Parents Bedroom			1st Floor Children Bedroom		
	Father	Mother	Children	Father	Mother	Children	Father	Mother	Children	Father	Mother	Children	Father	Mother	Children
0:00-0:30										▨	▨				▨
0:30-1:00										▨	▨				▨
1:00-1:30										▨	▨				▨
1:30-2:00										▨	▨				▨
2:00-2:30										▨	▨				▨
2:30-3:00										▨	▨				▨
3:00-3:30										▨	▨				▨
3:30-4:00										▨	▨				▨
4:00-4:30										▨	▨				▨
4:30-5:00										▨	▨				▨
5:00-5:30										▨	▨				▨
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7:00-7:30										▨	▨				▨
7:30-8:00										▨	▨				▨
8:00-8:30										▨	▨				▨
8:30-9:00		▨													
9:00-9:30							▨	▨	▨						
9:30-10:00							▨	▨							▨
10:00-10:30							▨	▨							▨
10:30-11:00							▨	▨							▨
11:00-11:30		▨					▨								▨
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22:00-22:30							▨	▨	▨						
22:30-23:00										▨	▨				▨
23:00-23:30										▨	▨				▨
23:30-24:00										▨	▨				▨

4.2. Calibration Model (Model 1)

Calibration of a model is the test of credibility which examines capabilities of analysis software and reliability of constructional assumptions, weather data, architectural representation and introduction of the site scale features. This stage determines at what percentage the model will be able to represent the real conditions of the building. The data that were utilized in this process were on-site thermal measurements of the interior spaces and outside conditions of the case study building that in this study were chosen to be the temperature values. The study assumes the calibration work that takes place in one case study building can be generalized for similar case studies that utilize similar modeling variables and analysis software. Consequently, not all the case studies were tested by calibration work but Sönmezer House in where both the interior and exterior temperature readings could be collected was chosen as the subject of model calibration work.

Figure 65 summarizes model calibration process. In this process, outside on-site temperature readings are inserted within weather data to the model of the case study building. The model is simulated and simulation results of interior thermal values are compared to the actual interior on-site readings and proximity percentage of these data sets determines the success of calibration (Figure 65).

Comparison of actual and virtual values are conducted through analysis methods that are defined in ASHRAE Guideline 14 (2002) that suggests using the statistical tools of Mean Bias Error-MBE, Root Mean Square Error-RMSE and Coefficient of Variation of Root Mean Square Error-CV(RMSE) that are depicted in equations 4.2, 4.3 and 4.4[44].

$$\text{Mean Bias Error} = \left(\frac{(\sum_{i=1}^{n} Residual_{\mathrm{i}})}{n}\right)\ \% \tag{4.2}$$

$$\text{Root Mean Square Error} = \left[\frac{\sum_{i=1}^{n}\ |t_i - o_i|^2}{n}\right]^{1/2}\ \% \tag{4.3}$$

$$\text{Coefficient of Variation of Root Mean Square Error} = \left(\frac{\mathrm{RMSE_{period}}}{\mathrm{A_{period}}}\right)\ \% \tag{4.4}$$

---

[44] Equations were interpreted from the study of Şahin et al. (2015).

According to guideline (ASHRAE, 2002), when hourly data is used if MBE and CV(RMSE) values are within ±10% and 30% respectively; it is accepted that the model is calibrated that is its representation capability is high.

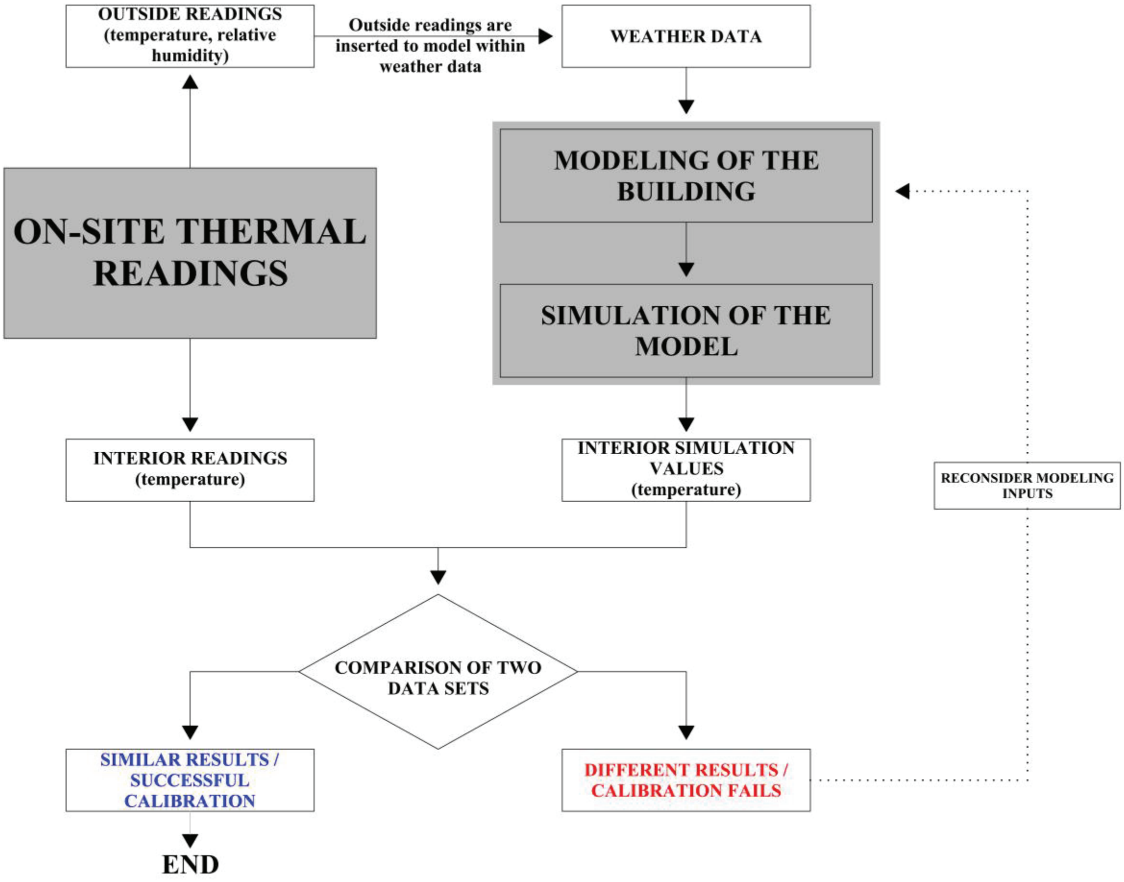

Figure 65. Model calibration process

In order to test the simulation success of different type of rooms with distinguished constructional features (walls, floors and ceilings), architectural elements and location within building, the calibration tests were conducted on two dissimilarly constructed rooms on different floors of case building as:

- Room G-2 is on ground floor with thick (45 cm) stone walls (Figure 66) and
- Room 1F-2 is on first floor with thin (15 cm) timber skeleton-adobe infill walls (Figure 67).

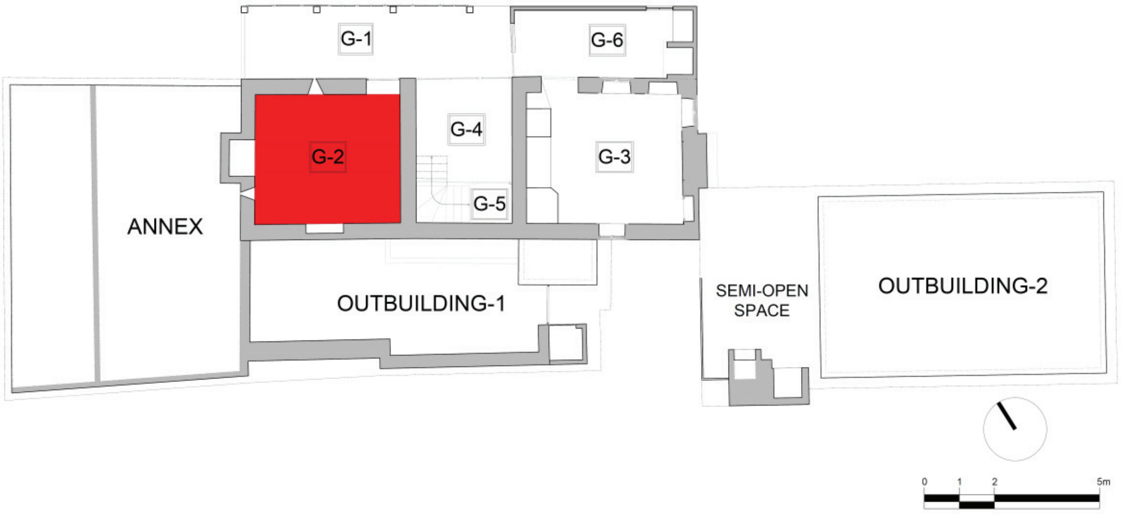

Figure 66. Location of room G-2 (Red hatch) on ground floor

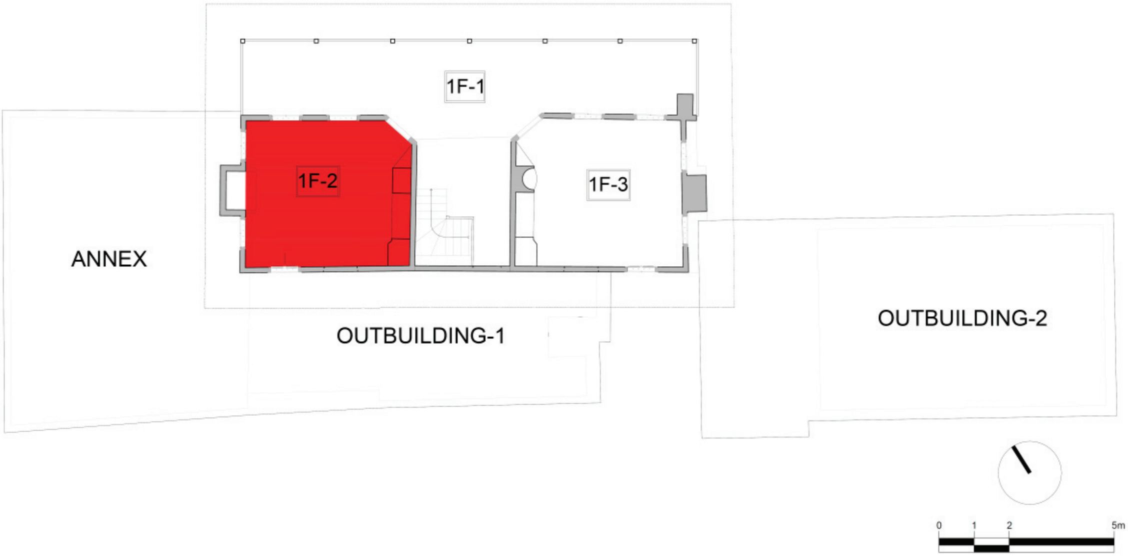

Figure 67. Location of room 1F-2 (red hatch) on first floor

With model variables that were determined in data collection stage, model of Sönmezer House (Figure 68) was prepared depicting the building in its current state of no occupancy and no heating / cooling system that are the status while collecting on-site readings.

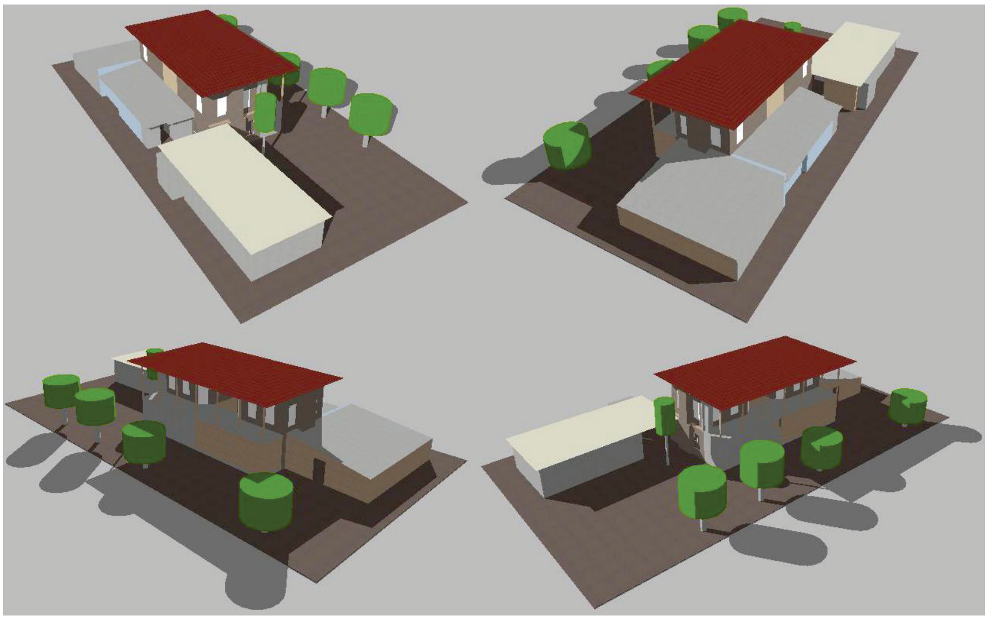

Figure 68. Axonometric perspective views of the calibration model

After the whole year simulations, Coefficient of Variation of Root Mean Squared Error-CV (RMSE) and Mean Bias Error-MBE values for room G-2 were calculated as 12.1 and -9.1 respectively which comply with ASHRAE Guideline 14 (2002). (Please refer to Figure 69 for the comparison of simulations result air temperature values and on-site readings)

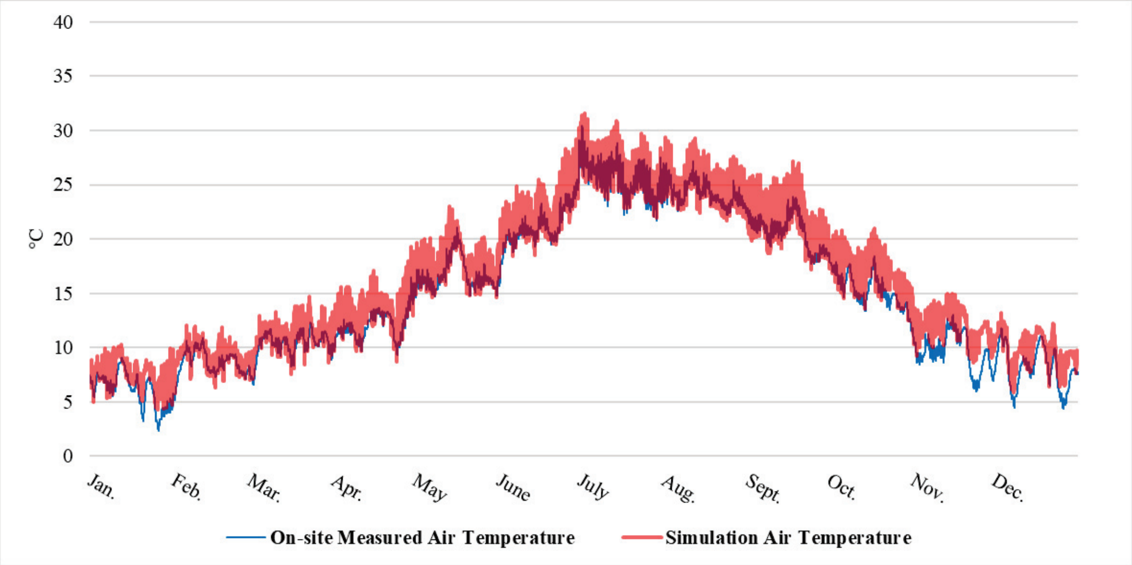

Figure 69. Comparison of simulation air temperature values to on-site readings for room G-2

Similar to the case of room G-2, calibration of 1F-2 was also successful. For this room, Coefficient of Variation of Root Mean Squared Error-CV (RMSE) and Mean Bias Error-MBE values were calculated as 10.4 and -7.4 respectively. (Please refer to Figure 70 for the comparison of simulations result air temperature values and on-site readings)

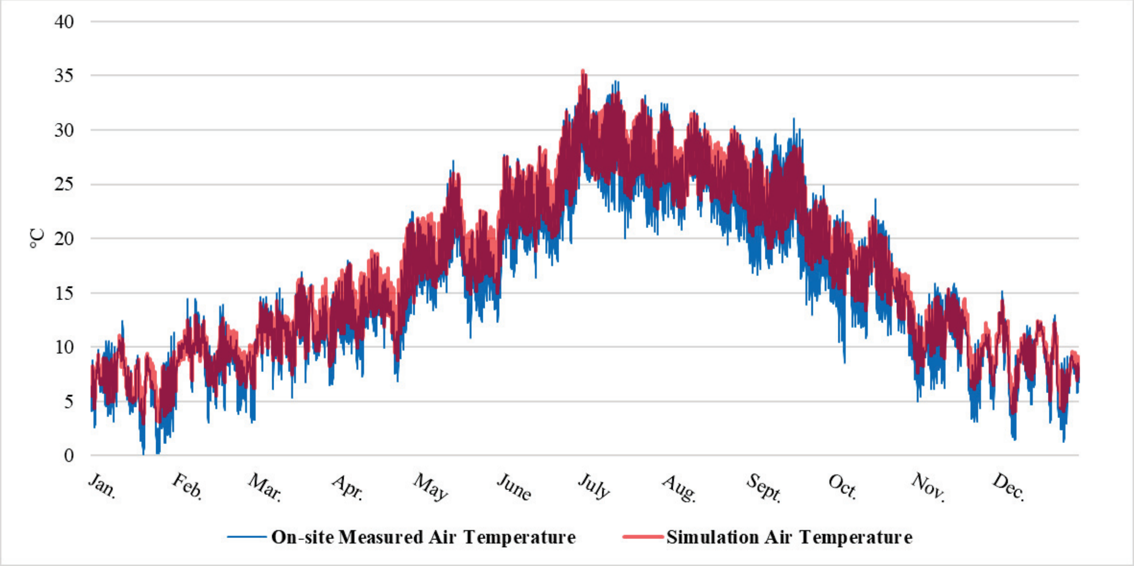

Figure 70. Comparison of simulation air temperature values to on-site readings for room 1F-2

As the result of calibration work, model assumptions and the capability of simulation software could be regarded as reliable to be used in the further analyses.

4.3. Analysis Models (Models 2)

For the thermal analyses, both case buildings were modeled as if they have been restored according to their original states. This led to the removal of later addition rooms on their ground floors and the new annex structure to the east of Sönmezer House. In addition to that, some minor changes had to be made on the models of buildings as architectural necessities in order to increase their functional potential as to be used by contemporary users. These proposed changes are:

- Service spaces such as kitchens and toilets, which in traditional planning have been located outside the buildings, were replaced inside the buildings and original storage rooms were altered to become wet spaces. Consequently, original compact soil floorings of storage rooms were changed to stone covering.

- Glazed inner frames were added to the windows on the upper floor of Sönmezer house which were originally designed unglazed and open directly to the outside weather conditions when their shutters are opened.

Utilizing the models of the case studies, thermal analyses were designed in 2 phases of:

- Models 2.1. Before-Retrofitting Models and
- Models 2.2. After-Retrofitting Models

4.3.1. Before-Retrofitting Models (Models 2.1)

Models 2.1 were used to determine at what capability traditional heating equipment (fireplaces) ensure thermal comfort without thermal retrofitting. Accordingly, it can be established if the case buildings require thermal interventions. The buildings are modeled in their restitution-oriented, basic restored states by the assumptions that were explained in the beginning of this chapter (Please refer to section 4.1). Heating systems were introduced only to the rooms which originally have fireplaces and no cooling system was selected as there is none in their original. Fuel type of the fireplaces were selected as biomass (e.g. wood) and the combustion efficiency of this equipment is accepted to be 20 % (Taylor et al. 2005, Anderson et al 2011 and Arnold et al. 2013). In order to prevent strong fluctuations on thermal status of the rooms, fireplaces were assumed to be working all the time. The simulation results were evaluated room by room rather than building averages in order to establish a more detailed analysis. Models 2.1 stage is conducted as a series of analyses which support each other in a row. For first simulations, buildings were modeled with occupancy and without heating and cooling. The users are equipped in clothes with *clo* values of 1.0[45]. The aim of this simulation set is to find out when the users require summer clothes through PMV analysis as *DesignBuilder* –in default-assigns 6 months of winter clothing and 6 months of summer clothing which in fact, is unrealistic. The simulation results as exemplified in the case of the living room in Gürsel House (Figure 71) point out the interval from July to August as summer clothing period as PMV values on these months accumulate over the hottest boundary of the comfort

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[45] Default setting of the software for winter clothing insulation value is 1.0 and for summer, it is 0.5. These values are used for the PMV analyses of this study.

zone. This period is defined to software as summer clothing period as to be processed in the following analyses. This simulation set is repeated by introducing summer clothing to the model and changes on PMV values of summertime were indicated in Figure 72.

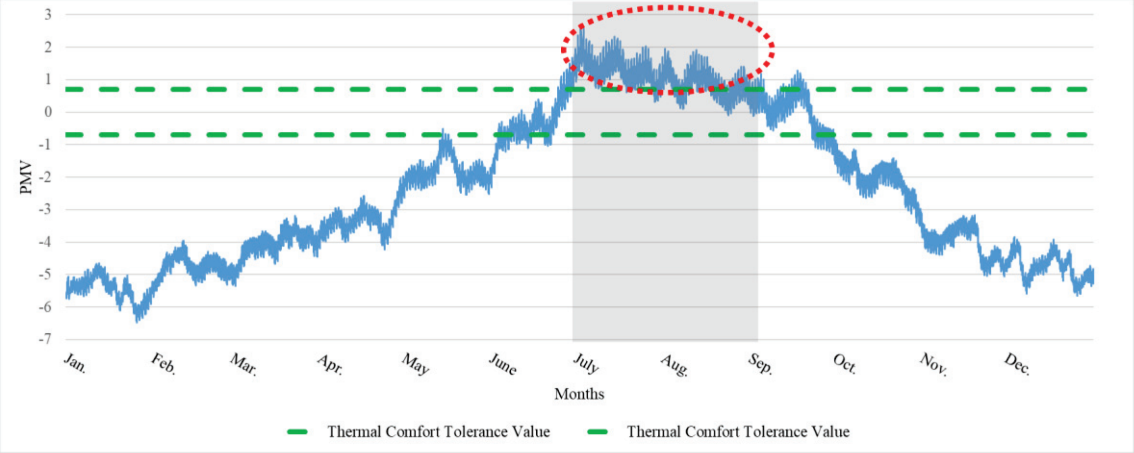

Figure 71. First simulation results for the living room of Gürsel House. The interval between horizontal green lines demonstrates the PMV comfort zone (-0.7 / +0.7) defined by Standard EN 15251 (2007), vertical grey hatch is the summer clothing period and red circle points out the accumulation of PMV values over +0.7 boundary.

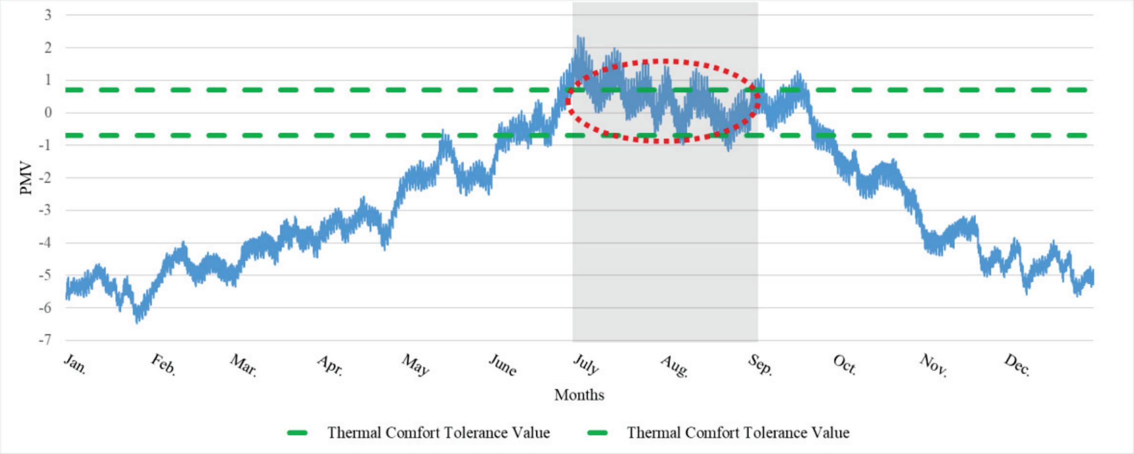

Figure 72. First simulation results with the introduction of summer clothing for the living room of Gürsel House. The interval between horizontal green lines demonstrates the PMV comfort zone (-0.7 / +0.7) defined by Standard EN 15251 (2007), vertical grey hatch is the summer clothing period and red circle points out the change of summer PMV values in comparison to previous simulation.

Second simulations were conducted to find out the minimum heating load that is needed to maintain comfortable spaces. For these simulations, heating system was introduced to the rooms which originally had fireplaces and none is added to the kitchens and bathrooms as well as Room 1F-3 (parents room / please refer to section 3.2.2 for floor plans) of Sönmezer House which did not have heating equipment in their original design. Temperature control for the heating is selected to be operative temperature. A series of trial and error simulations were conducted as heating set point for operative temperature of the rooms were manipulated to result in the best PMV values. These trials ended when the PMV values pass over the -0.7 level (coldest boundary of comfort zone defined by EN 15251-2007). By this action, minimum heating energy requirements were determined for each room. Following that, energy requirements (heating loads) of the rooms were compared to the output capabilities of traditional fireplaces that were presented in the Energy Output of Traditional Heating Equipment section. As an example, Figure 73 demonstrates the simulation results for the living room of Gürsel house. According to this chart, with heating output rate of 2.82 kW, traditional fireplace in this room is insufficient to maintain thermal comfort especially on the months of January, February and December. Simulation results of the other rooms in the case studies display very similar outcomes (Please refer to Appendix H / Figure 209 - Figure 216 for simulation results of the rooms in Gürsel House and to Appendix I / Figure 217 - Figure 223 for simulation results of the rooms in Sönmezer House).

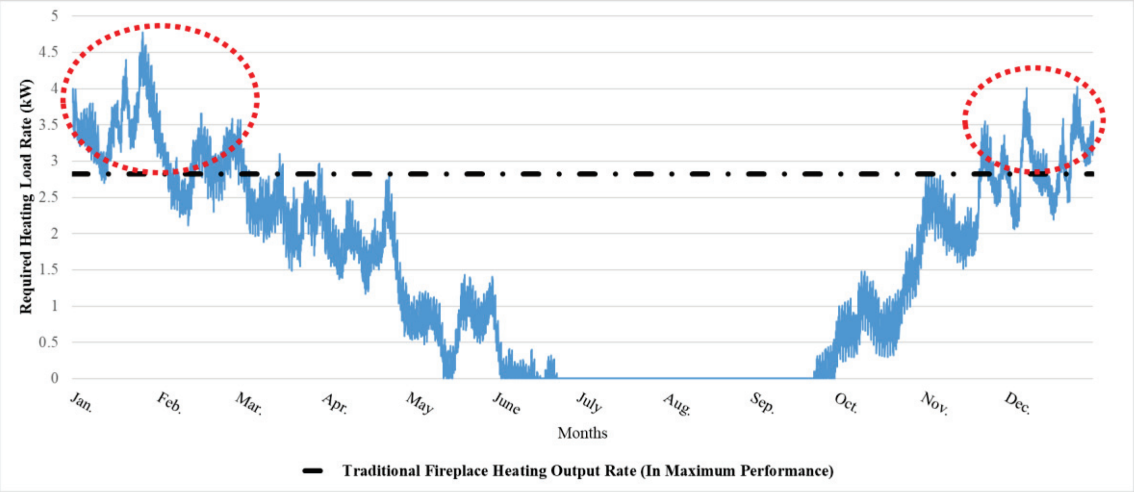

Figure 73. Second simulation results for the living room of Gürsel House. Chart shows that with heating output rate of 2.82 kW, traditional fireplace in this room is insufficient especially on the months of January, February and December.

By the guidance of these results, it was concluded that even in their rooms that originally have heating equipment, case study buildings lack to maintain whole year thermal comfort especially under more extreme weather conditions of summer and wintertime when analyzed for current occupancy scenarios and modern thermal standards. However, this fact does not suggest that these houses have been poorly designed and built. On the contrary, it only demonstrates that in their original design, they have been the architectural products for a different life style and comfort expectancies of their past users. Nevertheless, as user expectancies seem to have been increased through time that is documented by thermal comfort standards (e.g. ASHRAE, 2004; EN 15251, 2007), these buildings need to be upgraded with thermal interventions without causing any loss in their heritage values.

4.3.2. After-Retrofitting Models (Models 2.2)

These models were produced by adding retrofitting measures to the Models 2.1. In order to specify the final set of measures that are to be tested for their thermal enhancement capabilities, first an extensive initial list of measures (Figure 75) was established as an outcome of related literature survey conducted on standards, guides and case studies (e.g. Historic England, 2012a; ASHRAE, 2017b; CEN, 2017). Then, the measures on this initial list were re-evaluated and eliminated according to the architectural conservation principals with main emphasis on the concepts of:

- Reversibility[46] (Historic England, 2012a, BSI, 2013, ASHRAE, 2017b, CEN, 2017) of the intervention,
- Safeguarding aesthetic and constructional integrity[47] (BSI, 2013, ASHRAE, 2017b, CEN, 2017) of the building concerning its character-defining features on both exterior facades and interior spaces,
- Preserving authenticity[48] (Historic England, 2012a, BSI, 2013, ASHRAE, 2017b, CEN, 2017) of constructional features such as material, detailing and workmanship,

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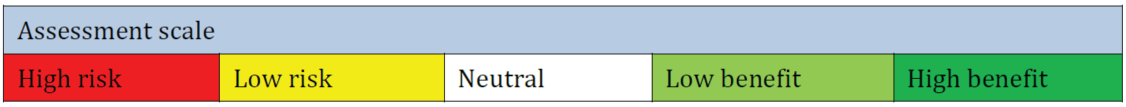
[46] Reversibility is defined by CEN (2017) as “extent to which an intervention can be undone without damage to the building.”
[47] Integrity is defined by CEN (2017) as “extent of physical or conceptual wholeness of a building.”
[48] Authenticity is defined by CEN (2017) as “extent to which the identity of a building matches the one ascribed to it.”

- Compatibility[49] (Historic England, 2012a, CEN, 2017) of the new interventions to the authentic features of the building regarding physical and visual harmony.
- Planning minimum intervention[50] (ICOMOS, 2003) in order to restrain the extent of possible changes occurring on traditional building as result of a possible retrofitting measure.

In parallel, the measures that were defined by ASHRAE (2017b) as EEMs (Energy Efficiency Measures) with *detrimental impacts* that are "those that result in identifiable, irreversible change or damage to the building, loss of historic integrity, or loss or alteration of character-defining features." and the measures that were defined by CEN (2017) in *High Risk* (Figure 74) category were removed from the intervention list of this study. Consequently, the insulation works on walls (regarding both interior and exterior surfaces) were excluded as these implementations risk visual integrity of exterior and / or interior facades by possible losses on the texture, color and ornamentation of the building surfaces in addition to deformations on façade and room proportions. In parallel, replacement of original windows with modern energy-efficient designs were omitted as this course will evidently cause loss of authentic detailing, design and material of original windows. And installation of on-site micro-renewable energy systems such as solar panels and domestic wind turbines were taken out as extensive and distinctive equipment of these systems may jeopardize aesthetic integrity both on building and settlement scales.



Assessment scale				
High risk	Low risk	Neutral	Low benefit	High benefit

Figure 74. Assessment scale for thermal measures according to CEN (2017)

The interventions regarding user behavior and the building services (e.g. lighting) were not tested in analyses as the scope of this study focuses mainly on the interventions concerning architectural and constructional elements of traditional buildings.

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[49] Compatibility is defined by CEN (2017) as "extent to which one material can be used with another material without putting heritage significance or stability at risk."

[50] Regarding the minimum intervention principle, in ICOMOS (2003) / Article 3.5, it is recommended "Each intervention should be in proportion to the safety objectives set, thus keeping intervention to the minimum to guarantee safety and durability with the least harm to heritage values."

Scope of Retrofitting Measure	Application Point of Retrofitting Measure			Description of Retrofitting Measure	Impact of Retrofitting Measure on Heritage Value	Document(s) Refering to Retrofitting Measure
Physical	Building Envelope	Opaque Surfaces	Walls	Thermal insulation (inner surface)	Irreversible when applied on ornate surfaces; risks visual integrity of inner facades; jeopardizes room proportions, architectural elements and detailing	Changeworks (2008), Historic England (2012), ASHRAE (2017)
				Thermal insulation (outer surface)	Irreversible when applied on ornate surfaces; risks visual integrity of building facades; jeopardizes architectural elements and detailing	Changeworks (2008), Historic England (2014), ASHRAE (2017)
				Thermal insulation (within section)	Irreversible when authentic building fabric is replaced and / or applied with sprayed material; risks deterioration as its long-term chemical / physical performance is hard to be monitored	Historic England (2012), ASHRAE (2017)
			Roofs	Thermal insulation (rafter level)	Reversible when not applied with sprayed foam material	Historic England (2016), ASHRAE (2017)
				Thermal insulation (attic floor)	Reversible when not applied with sprayed foam material	Changeworks (2008), Historic England (2012), ASHRAE (2017)
			Ground Floor / Foundation	Thermal insulation (outer surface)	Reversible when original flooring material can be removed and relocated without damage	Changeworks (2008), ASHRAE (2017)
				Thermal insulation (inner surface)	Risks visual integrity and architectural elements (e.g. doors) of inner spaces	Changeworks (2008), ASHRAE (2017)
		Openings	Windows	Re-installing lost elements (shutters, drapes etc.)	Reversible	Changeworks (2008), Historic England (2012), ASHRAE (2017)
				Replacing original windows with modern designs	Irreversible due to loss of authentic architectural elements	Changeworks (2008), ASHRAE (2017)
				Weather-stripping	Reversible when care is taken not to lose original detailing	Changeworks (2008), Historic England (2012), ASHRAE (2017)
				Addition of solar filtering films to existing glazing	Reversible when not applied on ornate and / or rare glass types	Currie etal. (2014), ASHRAE (2017)
				Installing additional glazing	Reversible when care is taken not to lose original detailing	Changeworks (2008), Heath etal. (2010), Historic England (2012), ASHRAE (2017)
				Use of thick, heavy curtains	Reversible	Changeworks (2008)
				Re-scheduling opening frequencies & timing of windows & shutters in order to optimize interior thermal conditions, natural lighting and ventilation (e.g. Nighttime ventilation)	Reversible	Changeworks (2008), Paul Arnold Architects (2010), Michael etal. (2017)
			Doors	Weather-stripping	Reversible when care is taken not to lose original detailing	Changeworks (2008), Historic England (2012), ASHRAE (2017)
			Chimney Flues	Closing chimney flues	Reversible when temporary solutions (e.g. chimney baloons) can be applied	Changeworks (2008), Historic England (2012)
	Inner Partitions	Opaque Surfaces	Floors between storeys	Thermal insulation (on surfaces)	Risks visual integrity and architectural elements (e.g. doors) of inner spaces	ASHRAE (2017)
				Thermal insulation (within section)	Reversible when not applied with sprayed foam material	Historic England (2012), ASHRAE (2017)
	Semi-open / Open spaces	Building Entrances		Constructing glazed draught lobbies for entrance doors (Interpreted as partial enclosing of *Sofa* s in this study)	Reversible when care is taken not to lose original detailing & construction material	Changeworks (2008)
	Building Services, Domestic Appliances & Energy Source	HVAC / DHW / Lighting / Domestic Appliances		Installation of new energy-efficient systems and equipment	Reversible when extreme caution is taken not to lose authentic features because of wiring / piping works and new HVAC equipment installation	Changeworks (2008), Historic England (2013), ASHRAE (2017)
		Introduction of renewable energy systems		Installation of micro-renewable energy systems (solar panels, domestic wind turbine)	May risk visual integrity both on building and urban scales	Hummelt (2014), Cabeza etal. (2018)
Functional	Closed Spaces	Spatial Use		Re-scheduling occupancy frequency and intensity of spaces	Reversible	Ben etal. (2014)

Figure 75. Initial list for retrofitting measures

From the initial list (Figure 75), following interventions were chosen to be tested in further simulations:

- Weather stripping,
- Introducing operating (opening and closing) schedules for windows and shutters in order to manipulate solar gain and natural ventilation.
- Addition of second glazing to windows,
- Application of thermal insulation on roofs, in floors between storeys and on ground floors,
- Addition of closed, glazed corridors as a circulation space between rooms that originally open directly to outside weather conditions (through exterior *sofa*s) and
- Introduction of new HVAC system to the buildings.

In this list, the measures, except for the interventions regarding HVAC systems, constitute the retrofitting package called as Set-1 which is the main focus of this analysis stage. The alternatives that were tested in the context of HVAC systems are referred to as Set-2 and this set was studied only to able to compare enhancement rates of simple envelope retrofitting measures (Set-1) to the rates of more comprehensive interventions such as introduction of new HVAC systems to historical structures. In parallel, Set-2 analyses were not conducted in order to specify best solution HVAC proposals for the case studies which necessitates additional research like CFD (Computational Fluid Dynamics) simulations and analyses on hygrothermal behavior of constructional sections that are not in the scope of this study.

All retrofitting measures were examined for their enhancement percentages in comparison to the thermal performance of the base models with no thermal interventions. These comparisons were presented both in graphical charts and numerical tables. The main thermal variable that is the subject of these comparisons is the annual primary energy consumption that is calculated by multiplication of annual fuel consumption per unit area (kWh / m^2) with fuel to primary energy conversion factors. These factors are assumed 1.00 for biomass and 3.31 for grid electricity. However, the variables of annual total heating and cooling loads were also examined in order to evaluate the effects of thermal interventions specific to summer and wintertime seasons. In the scope of this study, heating and cooling loads can be defined as the amount of final energy required to condition the spaces independent from the type of HVAC system and the fuel consumption is total energy requirement calculated in regards to the HVAC system's efficiency and its fuel type.

Base building models of this stage are assumed to be having HVAC equipment that current occupants utilize. The heating device for the base case is accepted to be low-efficiency stove of biomass fuel that is observed in Sönmezer House (Figure 76) and cooling instrument is supposed to be air-conditioner (Samsung T-Series / Boracay / 12K BTU) that is employed in Gürsel House (Figure 77). Efficiency of stove is taken 30% (average value of 20% and 40%) as suggested by ASHRAE (2016) and COP of air conditioner is taken as 3.21 as specified in Samsung Air Conditioner Catalog (2012).

Figure 76. Biomass stove that is used in Sönmezer House

Figure 77. Air-conditioner that is used in Gürsel House

For cooling and heating set points, temperatures of 22°C for heating in winter and 25°C for cooling in summer that are proposed as approximate values by ASHRAE (2017b) were tested for their capability to sustain thermal comfort for the rooms of case buildings. However, it was observed that these set points cannot provide continuous thermal comfort. Therefore, a set of trial and error simulation work (as applied in Models 2.1 Stage) was conducted to find out the HVAC set points for each room of the case buildings. In this work, temperature set points for heating and cooling for each room is manipulated through a series of simulations and the temperature values that create best results for PMV values are accepted as set points for the rooms. As an example of this work, Figure 78 demonstrates the thermal comfort status of the living room in Gürsel House when HVAC set points are defined according to ASHRAE (2017b). In comparison, Figure 79 shows the simulation results of trial and error work. While ASHRAE (2017b) set points lack to maintain the room inside PMV tolerance limits (-0.7

/ +0.7) suggested by EN 15251 (2007); trial and error work ensures thermal comfort for the majority of the time. Momentary value fluctuation over and under the tolerance limits (in Figure 79) occurred due to the constraints of the *DesignBuilder* software such as summertime interval can only be defined on monthly basis (instead of daily basis) and clothing insulation values can only be defined constant during the whole day as same value for daytime and nighttime clothing. Consequently, fine tuning of the PMV values could be conducted within the limits of software (Please refer to Appendix J and K / Figure 224 - Figure 233 for Gürsel House and Appendix L and M / Figure 234 - Figure 243 for Sönmezer House regarding PMV analyses of the other case study rooms).

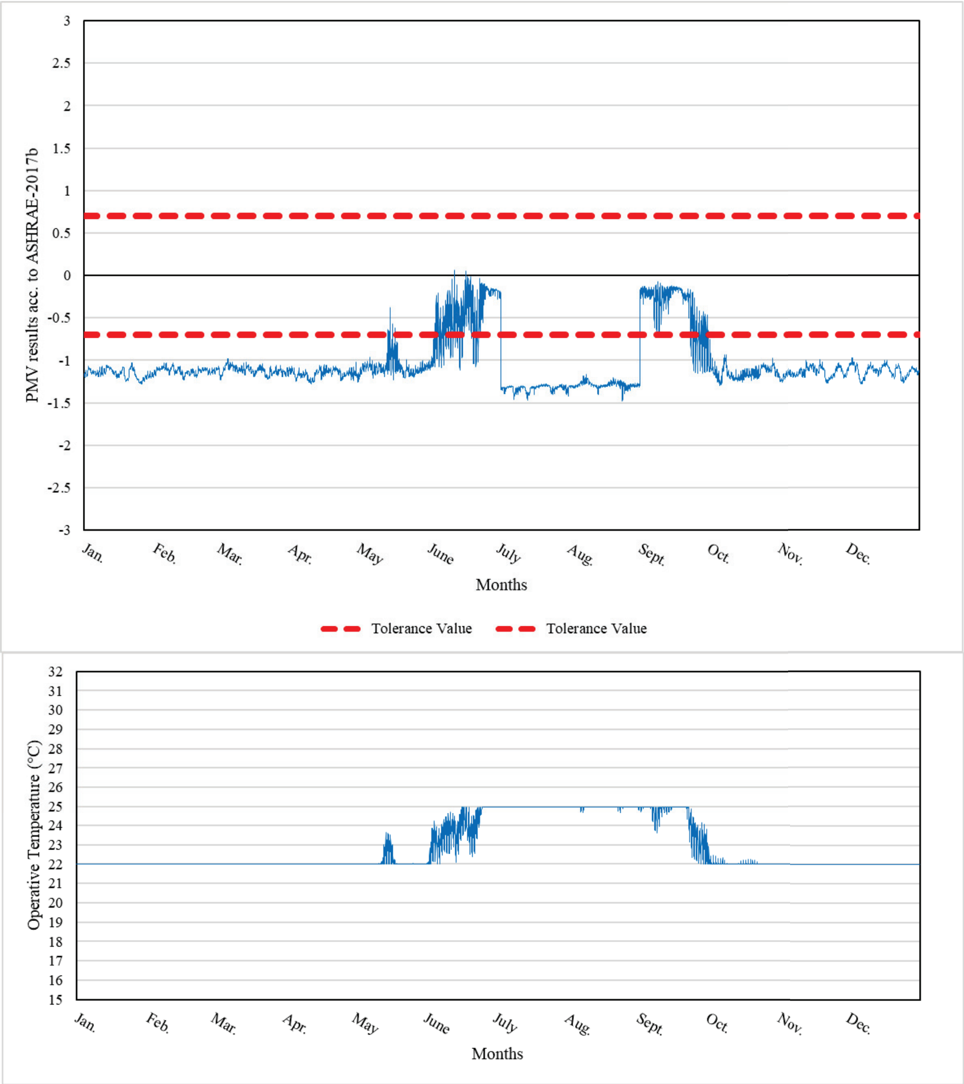

Figure 78. Thermal comfort status of the living room in Gürsel House when HVAC set points are chosen according to ASHRAE (2017b). Upper chart demonstrates PMV values and lower chart shows annual operative temperature distribution that occurs in the room.

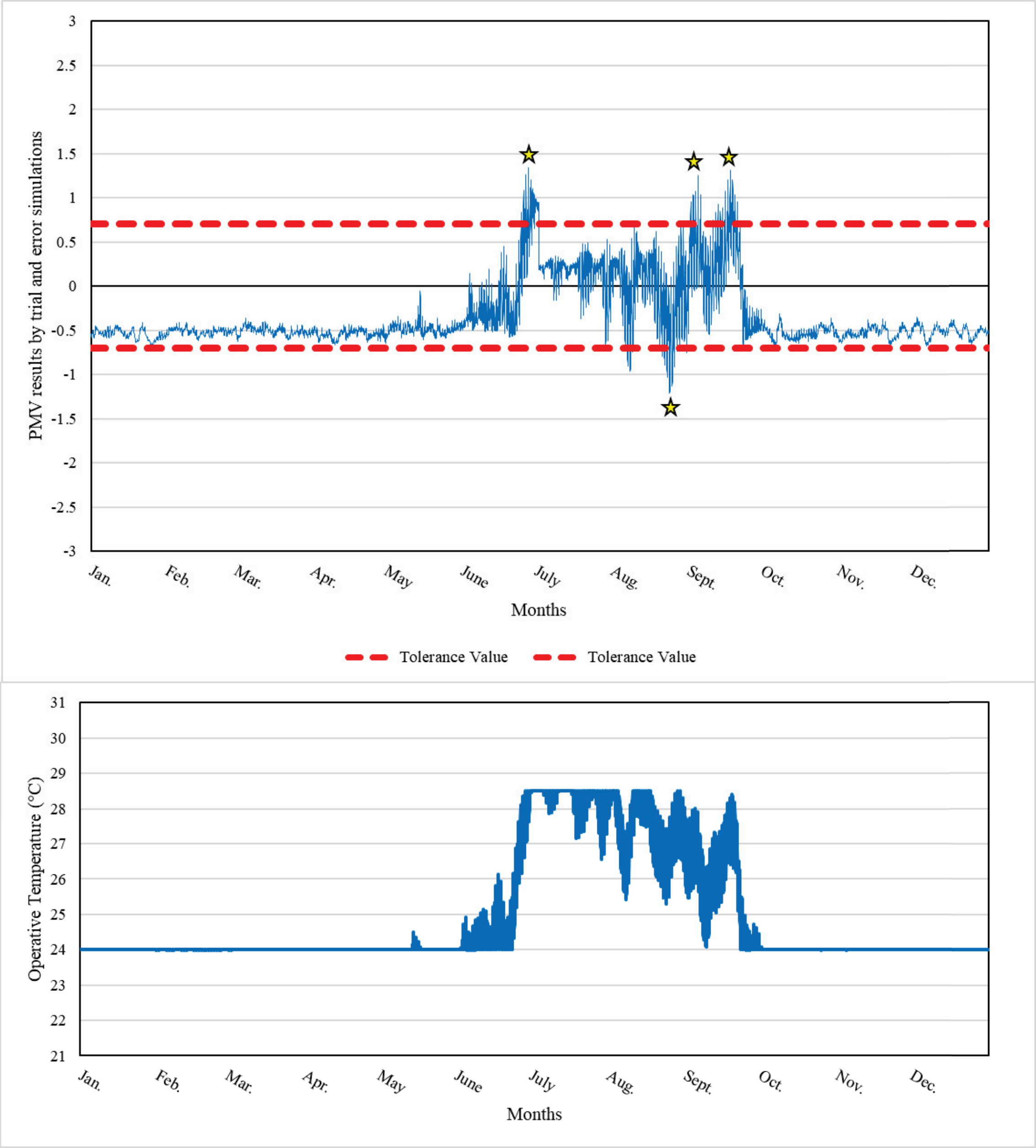

Figure 79. Thermal comfort status of the living room in Gürsel House when HVAC set points are specified through trial and error simulations. Upper chart demonstrates PMV values and lower chart shows annual operative temperature distribution that occurs in the room. The values out of the tolerance limits marked by stars occurred due to the limitations of simulation software such as the inability to define user clothing values for day and nighttime differently.

With the results of this simulation set, specified operative temperature ranges that result in best PMV values for the rooms of Gürsel House are demonstrated in Table 13 and the ranges that result in best PMV values for the rooms of Sönmezer House are demonstrated in Table 14. Theses tables indicate that even in the same building, room by room HVAC set point preferences might require adjustments with significant differences. For instance, this difference was determined to be very evident in the comparison of kitchen (16°C - 24.5°C) and the children room (27°C - 31.5°C) of Gürsel House. This outcome was considered to be the result of dissimilar physical and functional attributes of each room such as:

- Thermophysical properties of constructional envelopes (case studies have thicker stone masonry walls on the ground floors with higher thermal mass than the thinner timber / adobe walls on the upper floors. This difference also manifest itself as dissimilarity on the radiant temperatures distributions on the inner surfaces of walls that influence the consequential operative temperature values),
- window to wall ratio (this ratio is more pronounced on the upper floors – please refer to Table 5 and Table 8 in Chapter 3),
- location within the buildings (upper floors are more prone to heat transfer through the roofs rather than lower floors that are in proximity with the ground level),
- heat gains based on occupancy and household appliances (e.g. this factor is especially more valid for the kitchens as they accommodate ovens, dishwasher and fridges with higher energy outputs – please refer to Table 10 in Chapter 4).

As opposed to these dissimilarities between the rooms of the same buildings, corresponding rooms of the case studies do not display evident differences in their HVAC requirements (Table 13 and Table 14).

Table 13. Operative temperature ranges that result in best PMV values for the rooms of Gürsel House

Gürsel House				
Living Room (Ground Floor)	Children Room (First Floor)	Parent Room (First Floor)	Kitchen (Ground Floor)	Bathroom (GroundFloor)
24°C - 28.5°C	27°C - 31.5°C	25°C - 30°C	16°C - 24.5°C	21°C - 25.5°C

Table 14. Operative temperature ranges that result in best PMV values for the rooms of Sönmezer House

Sönmezer House				
Living Room (Ground Floor)	Children Room (First Floor)	Parent Room (First Floor)	Kitchen (Ground Floor)	Bathroom (GroundFloor)
24°C - 29°C	26.5°C - 31.5°C	26°C - 30°C	16°C - 26°C	21°C - 25.5°C

CHAPTER 5

RESULTS AND DISCUSSION

In this section, simulation results of the building models which were established with modeling variables introduced in previous sections will be discussed. Firstly, the energy consumption status of base models will be specified. Then simulation results of each retrofitting measure will be presented and in the last part, enhancement rates of these measures will be compared.

5.1. Energy Consumption of Base Models

Before conducting further analyses, energy consumptions of the base models were determined and compared in order to detect possible differences on the thermal requirements of case buildings. According to this evaluation, Sönmezer House (located on the rural sub-settlement) was observed to consume significantly more energy than Gürsel House (situated in urban center). Simulation results demonstrate 16.2% difference in annual primary energy consumption as Gürsel House consumes 3423.86 kWh / m² and Sönmezer House uses 3980.10 kWh / m² as annual building totals[51] (Figure 80 and Table 15), 5.4% difference in heating loads (Figure 81 and Table 16) and 29.9% difference in cooling loads (Figure 82 and Table 17). As the case buildings were selected in similar plan organization, solar orientation, construction material and scale; the difference in their energy consumption must be resulted from their location within city, the microclimatic conditions that occur at these locations and the surrounding urban context (dense and loose neighboring fabric).

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[51] These values demonstrate the simulation results when HVAC temperature set points were determined with room by room PMV analyses and HVAC systems were assumed working continuous through the whole day in order to prevent deep PMV fluctuations that disrupt the thermal comfort status of the rooms. A comparative simulation set was also conducted with HVAC set points suggested by ASHRAE (2017b) and assuming HVAC systems are working only when the rooms were in use (intermittent schedules for HVAC systems) and as a result, building total annual primary energy consumptions were calculated as 608.02 kWh / m² for Gürsel House (as opposed to 3423.86 kWh / m²) and 680.92 kWh / m² for Sönmezer House (as opposed to 3980.10 kWh / m²). This significant difference seen between the results of two simulation sets point out the necessity for further studies on the standardization of HVAC and occupancy assumptions to be applied on the thermal simulations of historical buildings.

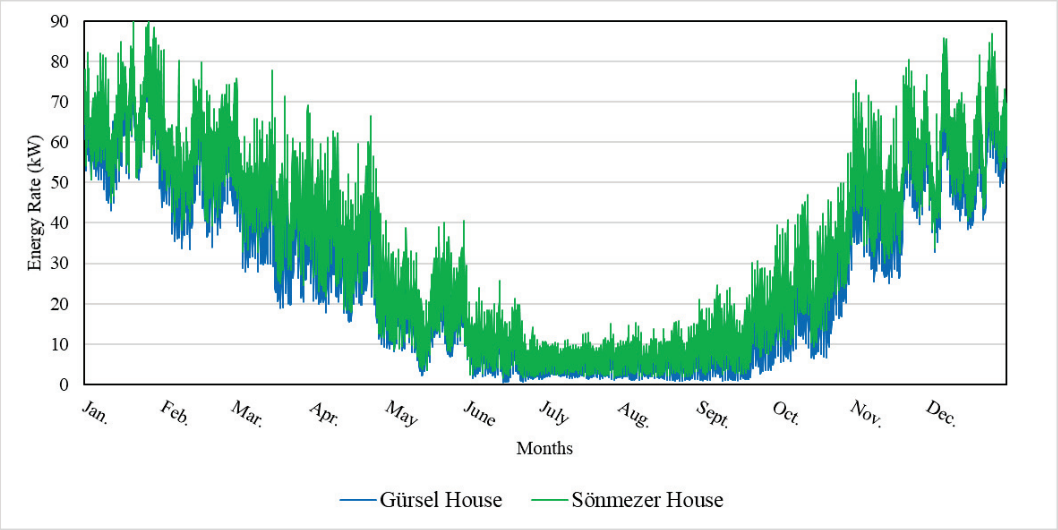

Figure 80. Comparison of base models of the case buildings for annual primary energy consumption rates

Table 15. Comparison of base models of case buildings for annual primary energy consumption

Base Models	Gürsel House	Sönmezer House	Difference in Energy Consumption
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3980.10	**16.2%**

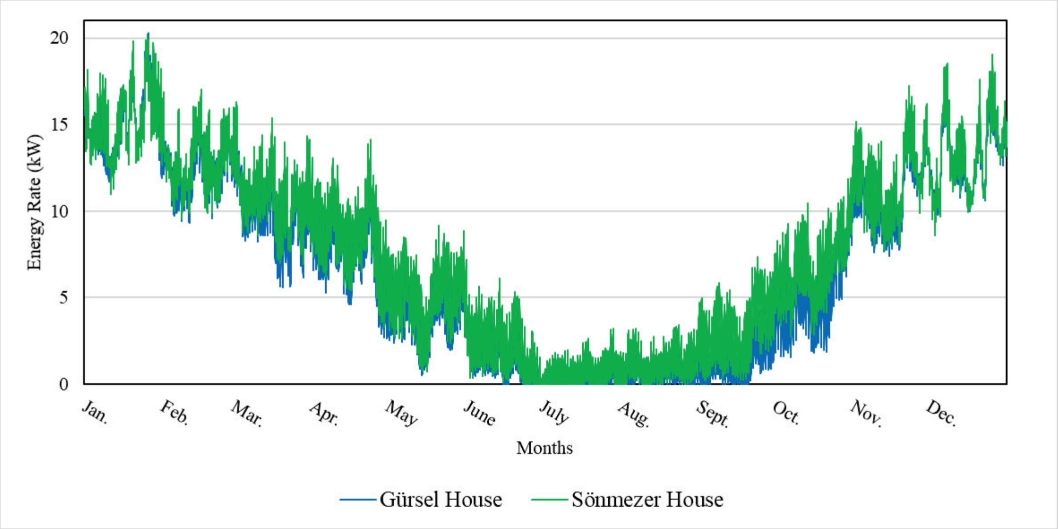

Figure 81. Comparison of base models of case buildings for annual heating load rates

Table 16. Comparison of base models of case buildings for annual heating load

Base Models	Gürsel House	Sönmezer House	Difference in Annual Heating Load
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	913.40	**5.4%**

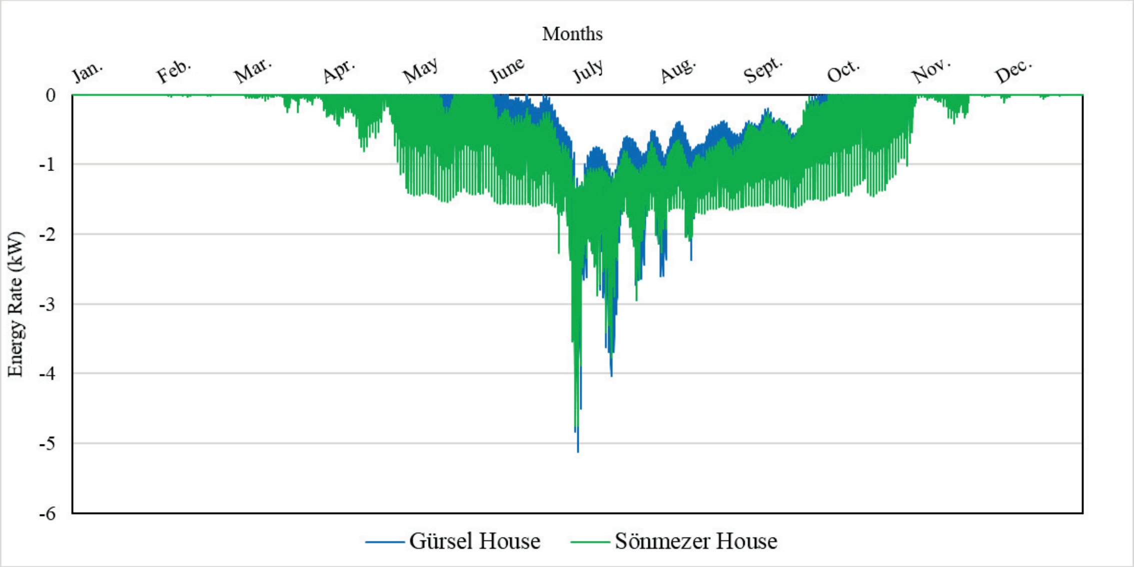

Figure 82. Comparison of base models of case buildings for annual cooling load rates

Table 17. Comparison of base models of case buildings for annual cooling load

Base Models	Gürsel House	Sönmezer House	Difference in Annual Cooling Load
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-44.37	**29.9%**

In addition to this difference, it was also determined that the houses utilize considerably more energy for heating than cooling which makes heating season as the dominant factor in their total energy consumption. The ratio of heating load to cooling load is roughly 25 to 1 for Gürsel House and 20 to 1 for Sönmezer House (Figure 83).

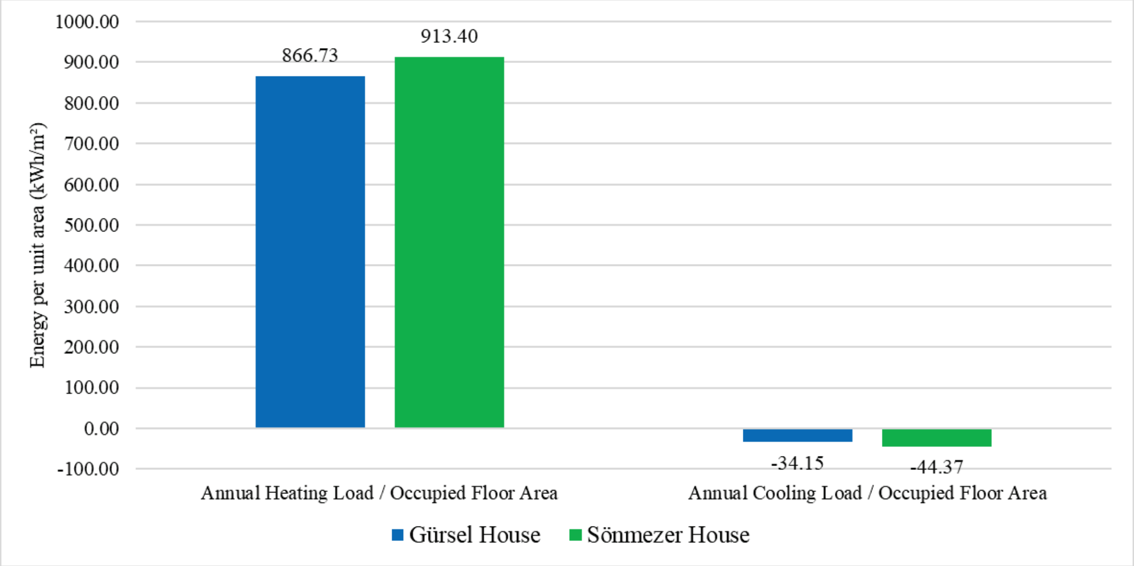

Figure 83. Comparison of annual heating and cooling loads of the base models

5.2. Results of Retrofitting Simulations

In this section, thermal enhancement percentages of each retrofitting intervention were demonstrated with charts and corresponding tables regarding the whole building annual primary energy consumption and the annual heating / cooling loads. The enhancement percentages were calculated by comparing the simulation results of building models with applied interventions to the base models of no intervention.

5.2.1. Weather-stripping

In order to determine thermal enhancement percentage of a possible weather-stripping implementation on the openings (windows and doors) and constructional features (e.g. cracks) of the case buildings; crack template of the building models were assumed to be enhanced from poor category to medium. By this course, changes in fresh air rates that are depicted in Figure 84 and Figure 85 were observed.

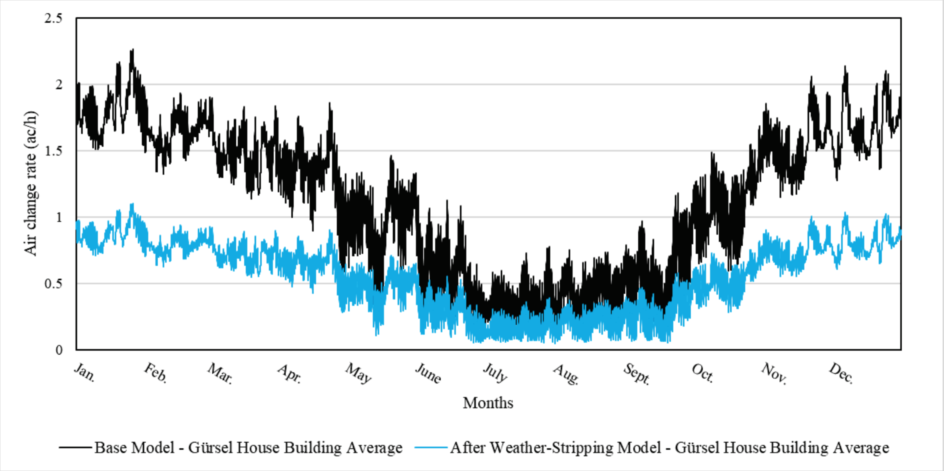

Figure 84. Air change per hour (ACH) rates before and after weather-stripping for Gürsel House (building average)

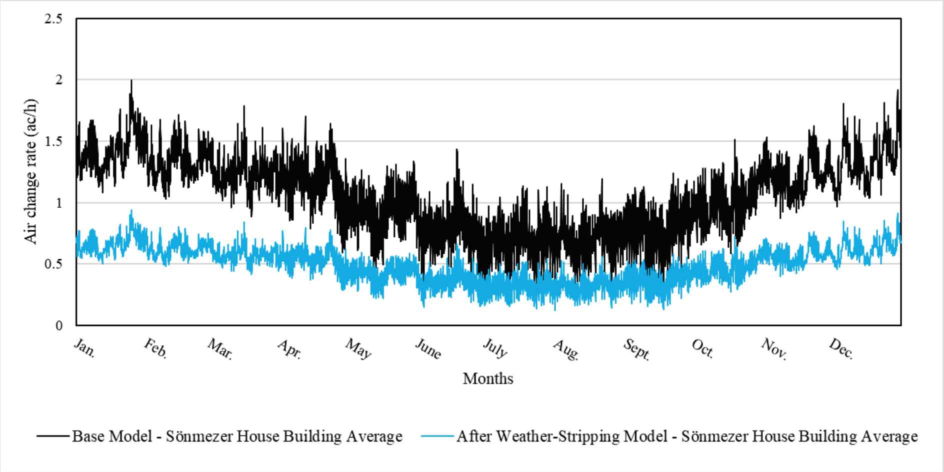

Figure 85. Air change per hour (ACH) rates before and after weather-stripping for Sönmezer House (building average)

As the result of simulations, for Gürsel House, 7.8% enhancement in annual primary energy consumption (Figure 86 and Table 18), 9.6% enhancement in annual total heating load (Figure 87 and Table 19) and 1.6% enhancement in annual total cooling load can be achieved (Figure 88 and Table 20).

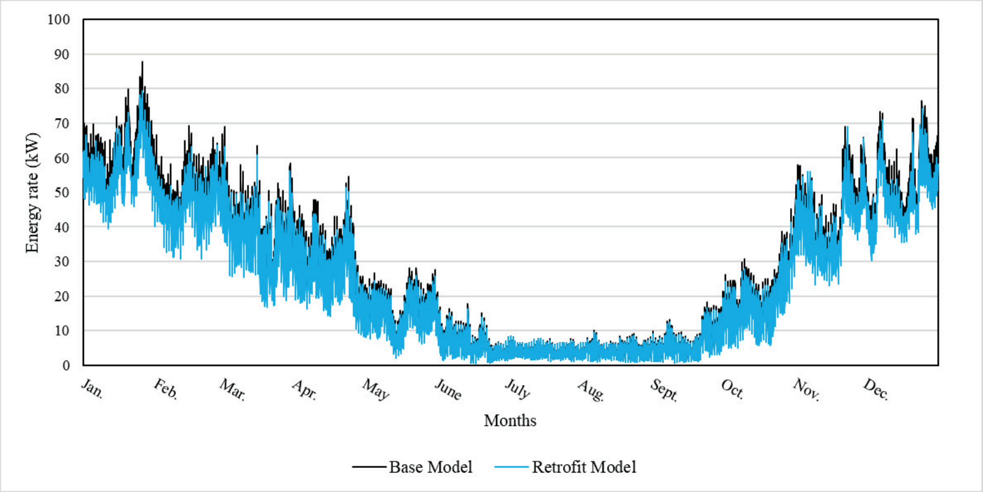

Figure 86. Comparison of base and retrofit models for primary energy consumption rates - Gürsel House / weather-stripping

Table 18. Comparison of base and retrofit models for primary energy consumption - Gürsel House / weather-stripping

Weather-stripping / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3157.23	**7.8%**

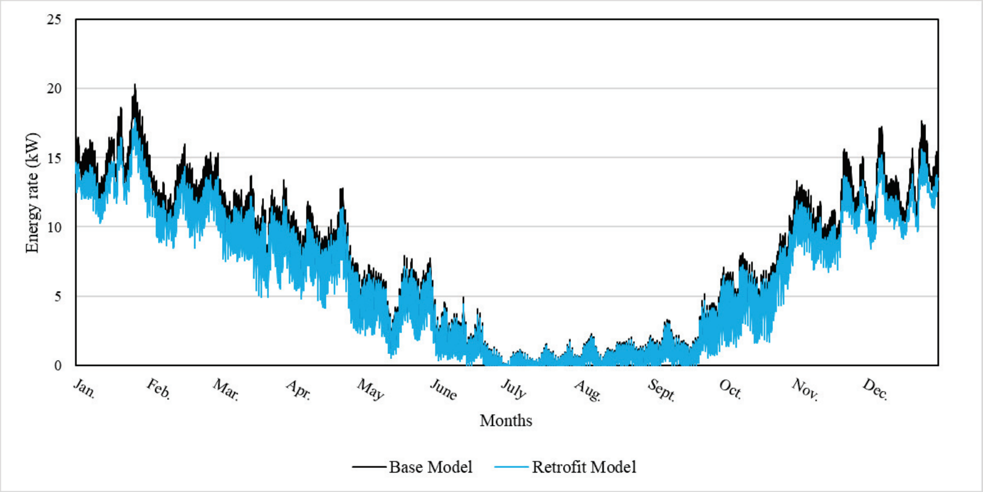

Figure 87. Comparison of base and retrofit models for heating load rates - Gürsel House / weather-stripping

Table 19. Comparison of base and retrofit models for heating load - Gürsel House / weather-stripping

Weather-stripping / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	783.57	**9.6%**

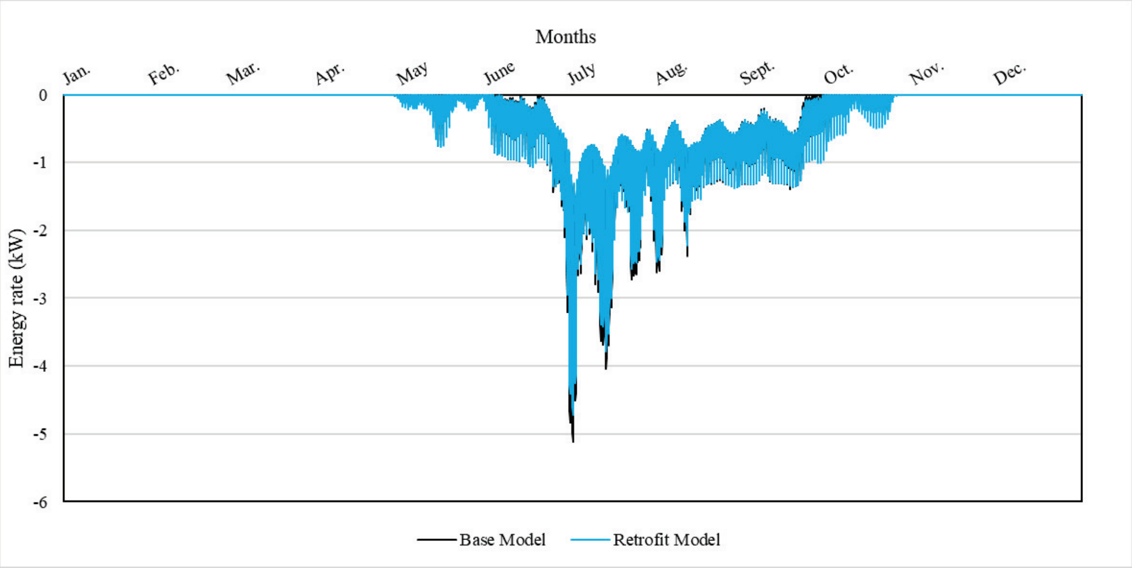

Figure 88. Comparison of base and retrofit models for cooling load rates - Gürsel House / weather-stripping

Table 20. Comparison of base and retrofit models for cooling load - Gürsel House / weather-stripping

Weather-stripping / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-33.59	**1.6%**

Similarly, for Sönmezer House, 6.8% enhancement in annual total primary energy consumption (Figure 89 and Table 21), 9.9% enhancement in annual total heating load (Figure 90 and Table 22) and 0.1% enhancement in annual total cooling load can be achieved (Figure 91 and Table 23).

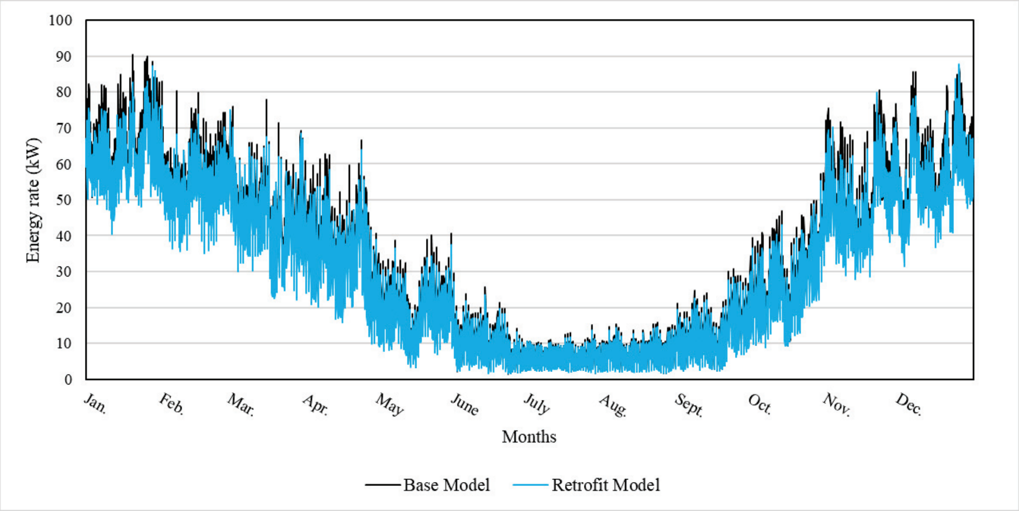

Figure 89. Comparison of base and retrofit models for primary energy consumption rates - Sönmezer House / weather-stripping

Table 21. Comparison of base and retrofit models for primary energy consumption - Sönmezer House / weather-stripping

Weather-stripping / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3708.13	**6.8%**

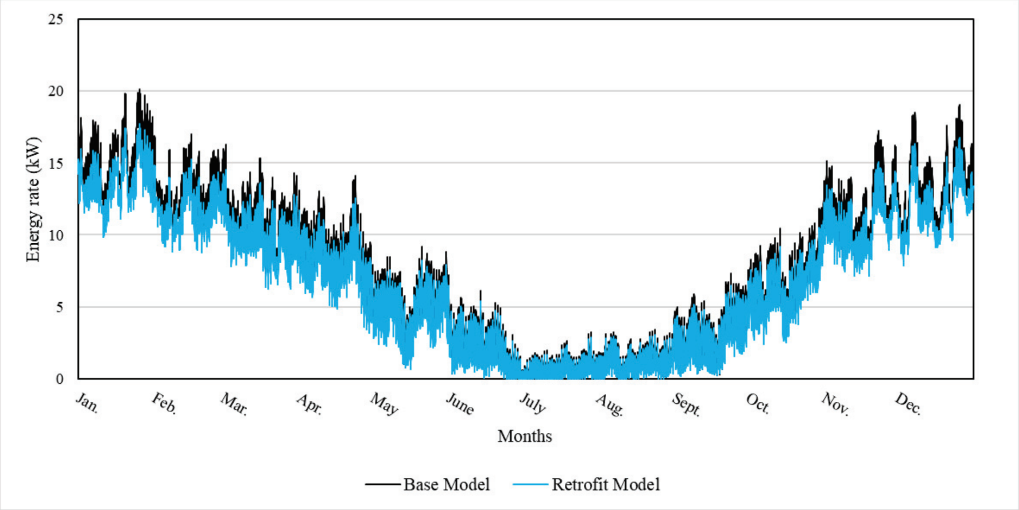

Figure 90. Comparison of base and retrofit models for heating load rates - Sönmezer House / weather-stripping

Table 22. Comparison of base and retrofit models for heating load - Sönmezer House / weather-stripping

Weather-stripping / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	823.21	**9.9%**

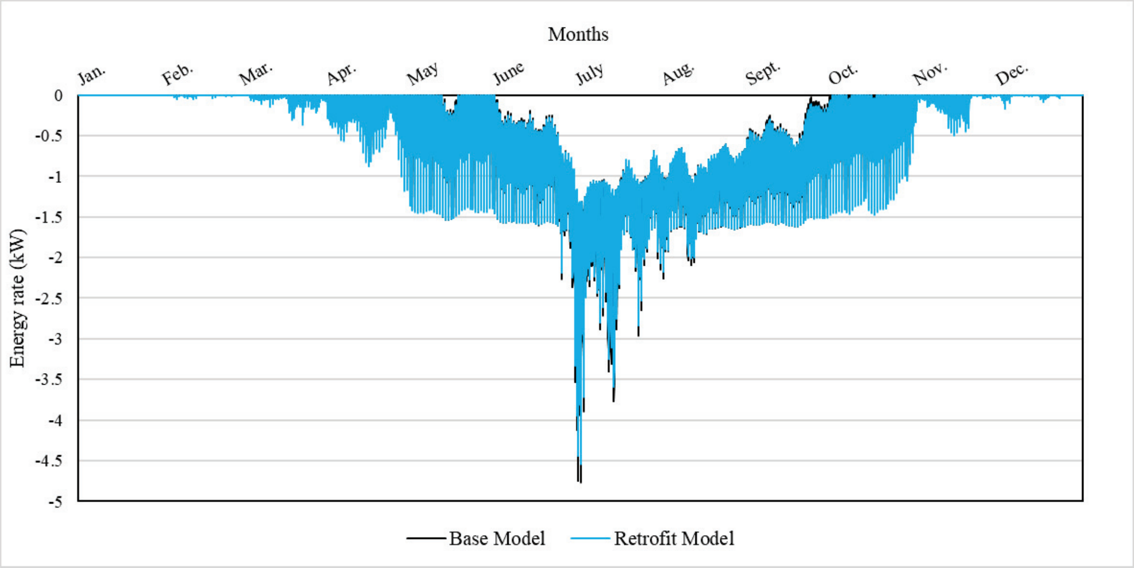

Figure 91. Comparison of base and retrofit models for cooling load rates - Sönmezer House / weather-stripping

Table 23. Comparison of base and retrofit models for cooling load - Sönmezer House / weather-stripping

Weather-stripping / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-44.32	**0.1%**

5.2.2. Operation (Opening / Closing) Control for Window Shutters

In order to reduce solar gain in summer and heat loss in winter through windows; an operation schedule for window shutters was prepared and introduced to the models. According to this schedule (Appendix N), shutters are simulated closed in summer daytime and winter nighttime while left open in summer nighttime and winter daytime. Nighttime is assumed to be the interval from sun set to sun rise and daytime is assumed to be the interval from sun rise to sun set. Monthly averaged times of sun set and sun rise were calculated using the online data provided by Boğaziçi University Kandilli Observatory and Earthquake Research Institute[52]. As *DesignBuilder* software cannot offer traditional shutter elements in building models, "window blinds with low-reflectivity slats" option (under Openings / Shading) was used instead.

With the simulations utilizing the shutter operation schedules, for Gürsel House, 0.5% enhancement in annual total primary energy consumption (Figure 92 and Table 24), 0.2% enhancement in annual total heating load (Figure 93 and Table 25) and 5.3% enhancement in annual total cooling load can be achieved (Figure 94 and Table 26).

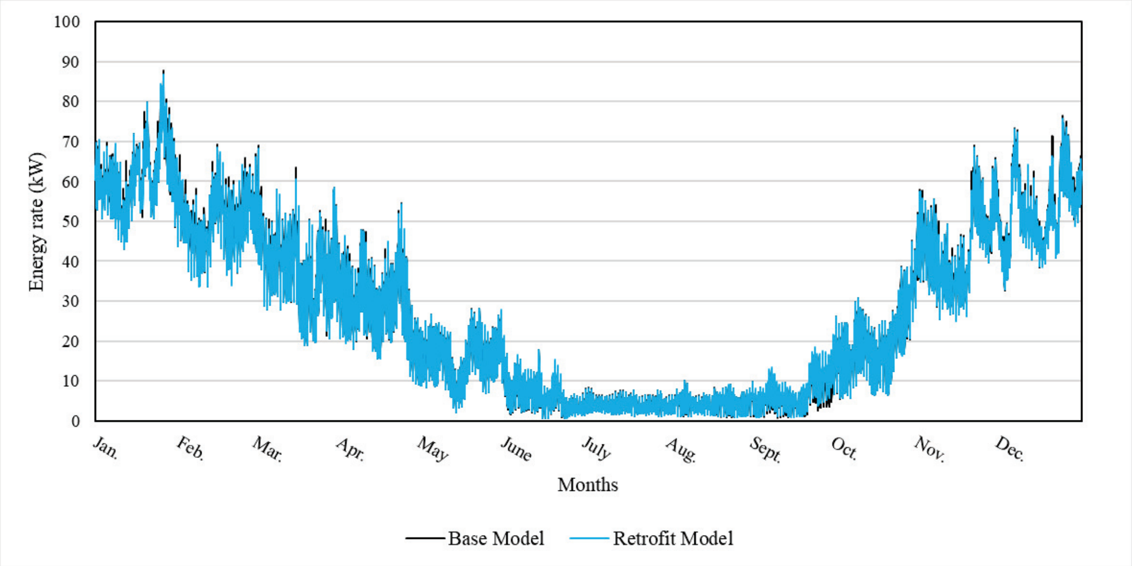

Figure 92. Comparison of base and retrofit models for primary energy consumption rates - Gürsel House / window shutter operation control

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[52] Data was taken from http://www.koeri.boun.edu.tr/astronomy/dogus-batis/Mugla.htm. Access date: 10.05.2019.

Table 24. Comparison of base and retrofit models for primary energy consumption - Gürsel House / window shutter operation control

Window Shutter Operation Control / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3407.29	**0.5%**

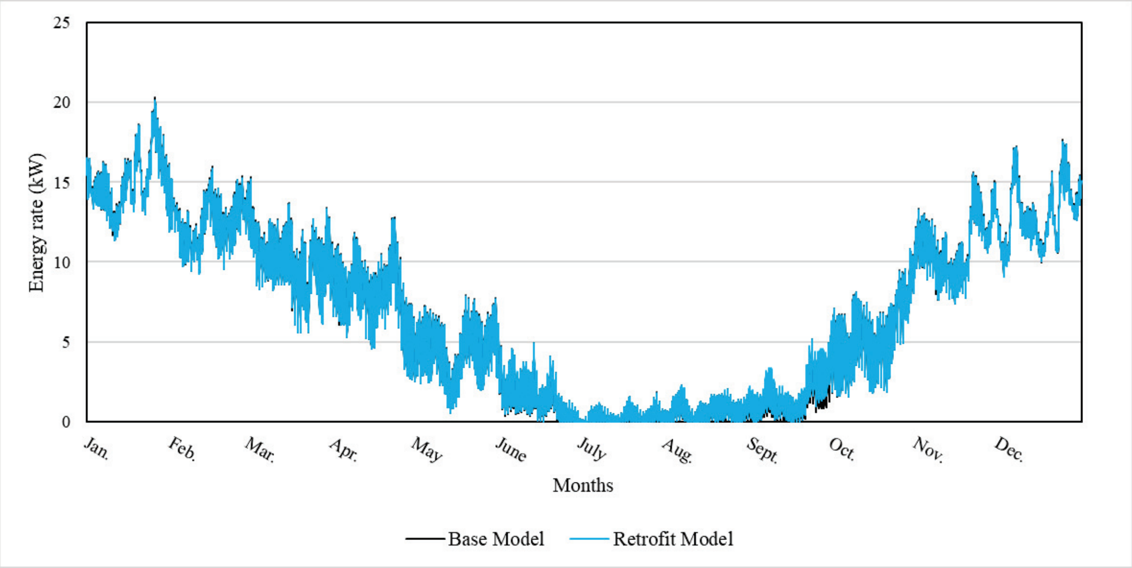

Figure 93. Comparison of base and retrofit models for heating load rates - Gürsel House / window shutter operation control

Table 25. Comparison of base and retrofit models for heating load - Gürsel House / window shutter operation control

Window Shutter Operation Control / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	864.94	**0.2%**

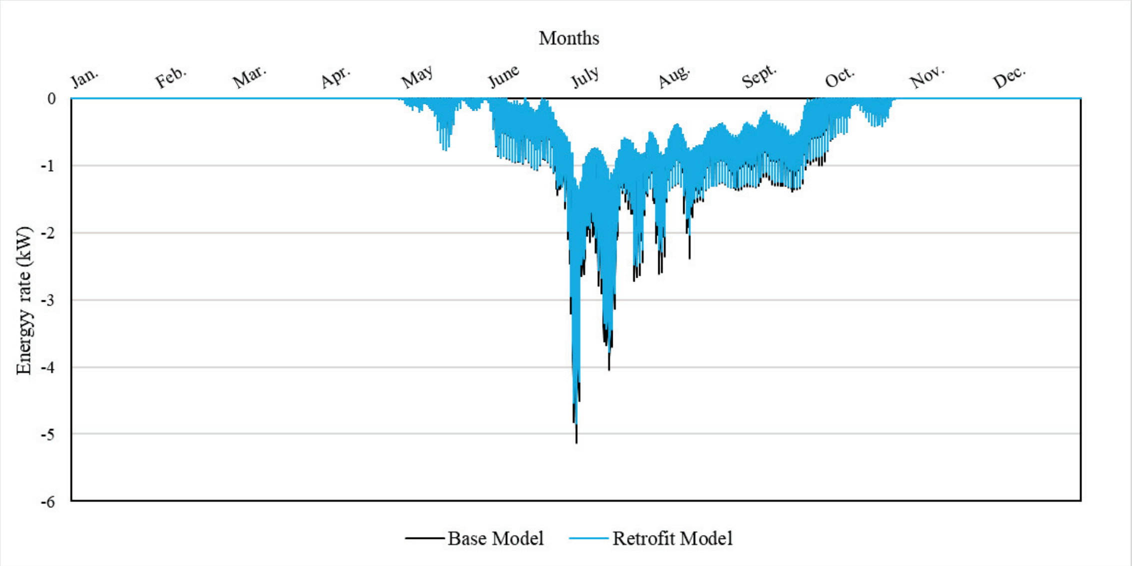

Figure 94. Comparison of base and retrofit models for cooling load rates - Gürsel House / window shutter operation control

Table 26. Comparison of base and retrofit models for cooling load - Gürsel House / window shutter operation control

Window Shutter Operation Control / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-32.34	**5.3%**

For Sönmezer House, 0.4% enhancement in annual total primary energy consumption (Figure 95 and Table 27), 0.1% enhancement in annual total heating load (Figure 96and Table 28) and 5.8% enhancement in annual total cooling load can be achieved (Figure 97 and Table 29). With these results, it can be seen that the control of window shutter operation -while reducing cooling loads of summer for both case buildings- results in minimal effect on the overall energy consumptions.

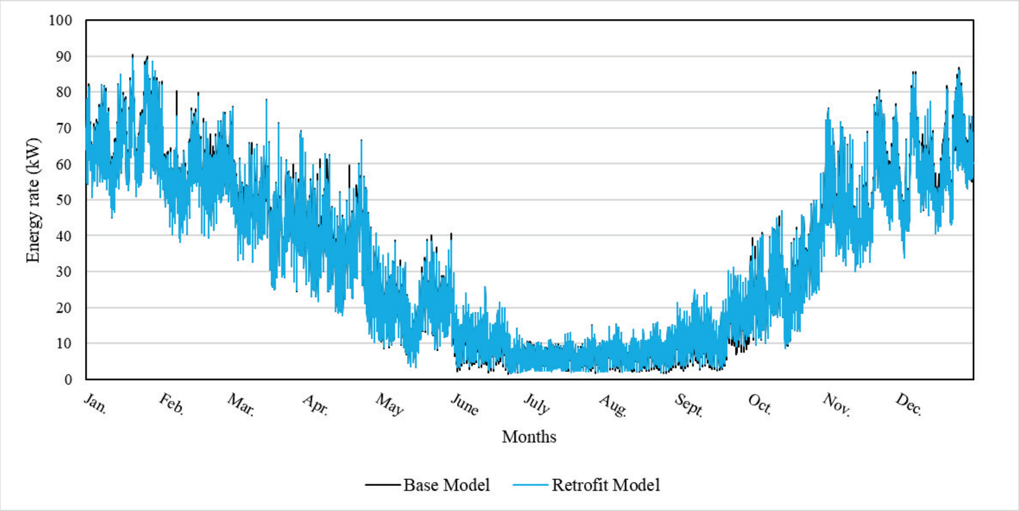

Figure 95. Comparison of base and retrofit models for primary energy consumption rates - Sönmezer House / window shutter operation control

Table 27. Comparison of base and retrofit models for primary energy consumption - Sönmezer House / window shutter operation control

Window Shutter Operation Control / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3963.24	**0.4%**

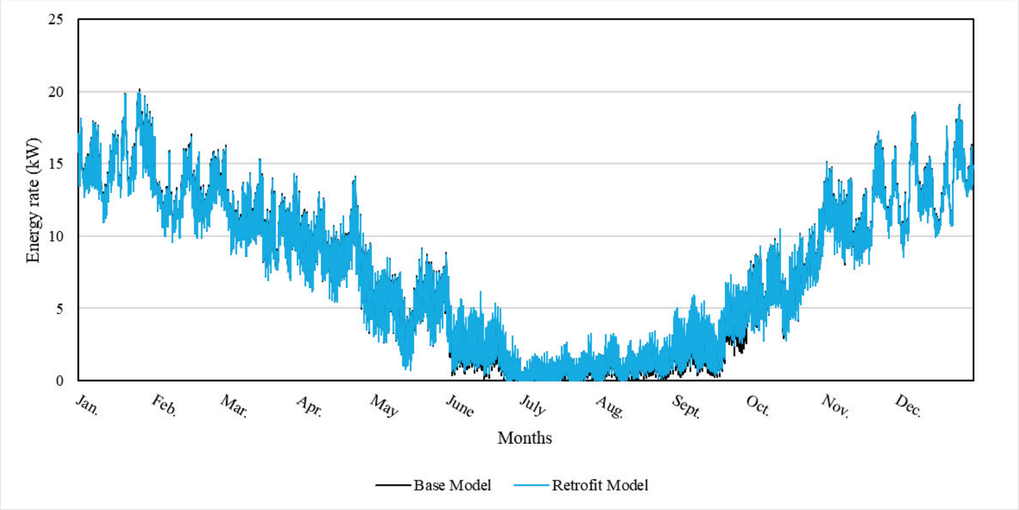

Figure 96. Comparison of base and retrofit models for heating load rates - Sönmezer House / window shutter operation control

Table 28. Comparison of base and retrofit models for heating load - Sönmezer House / window shutter operation control

Window Shutter Operation Control / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	912.64	**0.1%**

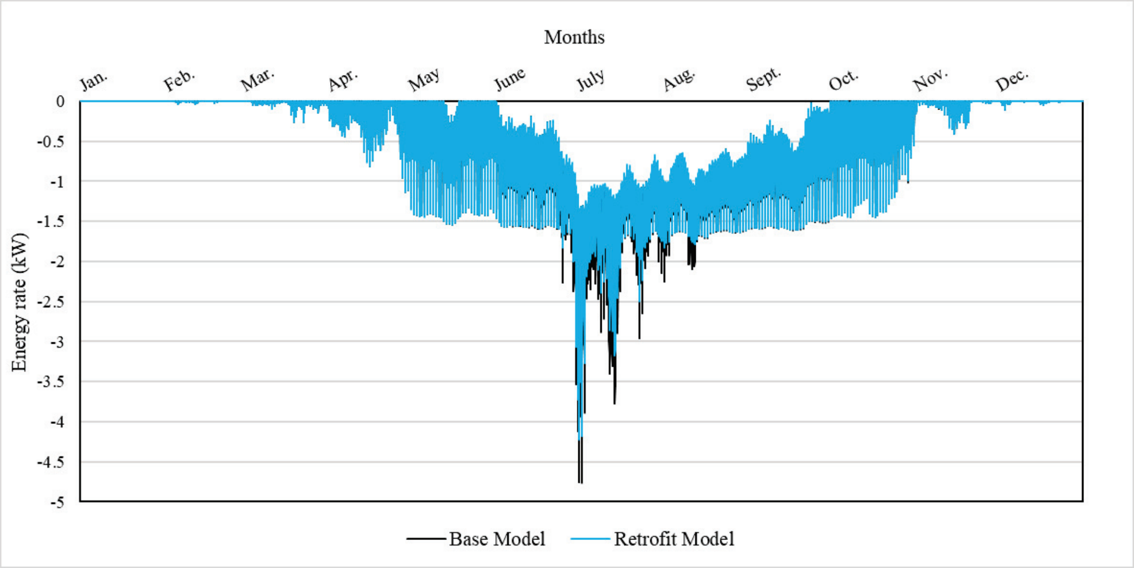

Figure 97. Comparison of base and retrofit models for cooling load rates - Sönmezer House / window shutter operation control

Table 29. Comparison of base and retrofit models for cooling load - Sönmezer House / window shutter operation control

Window Shutter Operation Control / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-41.78	**5.8%**

5.2.3. Operation (Opening / Closing) Control for Windows

In order to reduce cooling loads in summer by directing cool nighttime ventilation into the rooms through windows; (Michael et al., 2017). an operation schedule for windows was prepared and introduced to the models. According to this schedule (please see Appendix N), windows are simulated closed in all wintertime and left open only in summer nighttime. Similar to the shutter operation schedules; nighttime is assumed to be the interval from sun set to sun rise and monthly averaged times of sun set and sun rise were calculated using the data provided by Boğaziçi University Kandilli Observatory and Earthquake Research Institute.

With the simulations utilizing the window operation schedules, for Gürsel House, 0.6% enhancement in annual cooling load is achieved (Figure 100 and Table 32), however the intervention caused consumption of 2.0% more annual fuel (Figure 98 and Table 30) and 2.4% increase in the annual heating load (Figure 99 and Table 31).

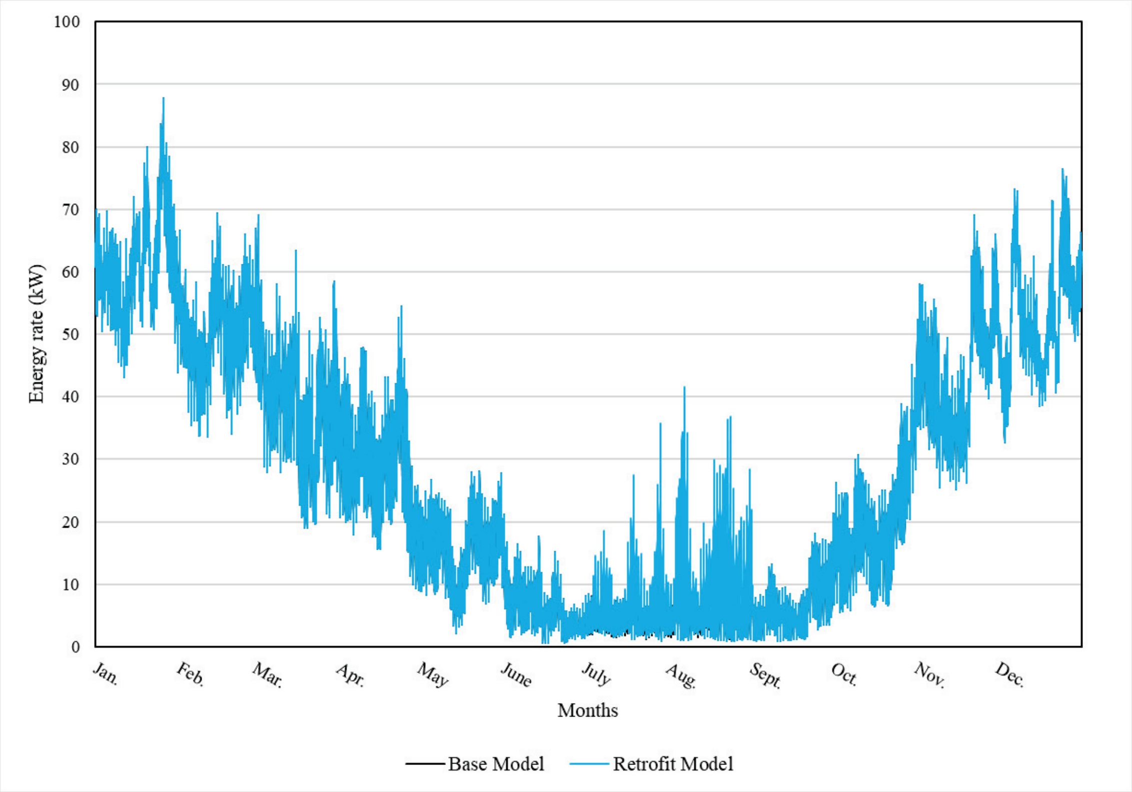

Figure 98. Comparison of base and retrofit models for primary energy consumption rates - Gürsel House / window operation control

Table 30. Comparison of base and retrofit models for primary energy consumption - Gürsel House / window operation control

Window Operation Control / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3491.99	**-2.0%**

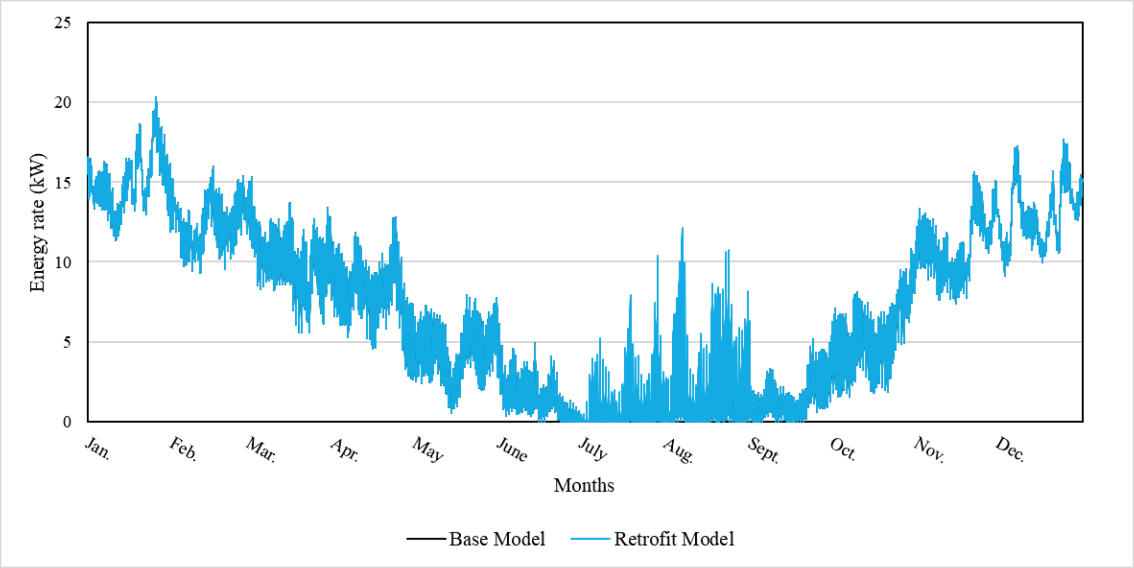

Figure 99. Comparison of base and retrofit models for heating load rates - Gürsel House / window operation control

Table 31. Comparison of base and retrofit models for heating load - Gürsel House / window operation control

Window Operation Control / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	887.12	**-2.4%**

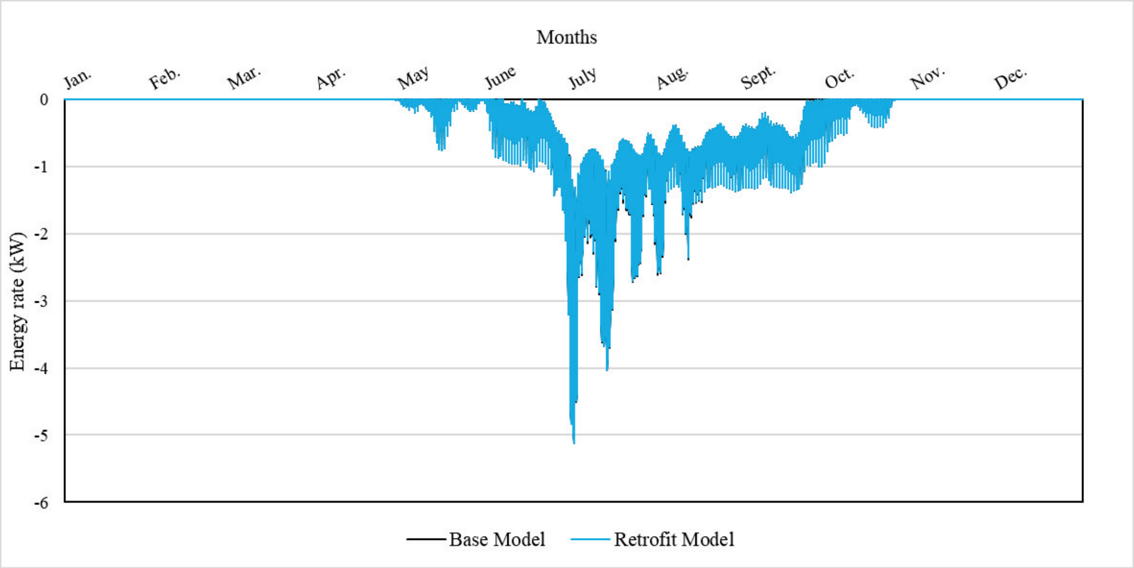

Figure 100. Comparison of base and retrofit models for cooling load rates - Gürsel House / window operation control

Table 32. Comparison of base and retrofit models for cooling load - Gürsel House / window operation control

Window Operation Control / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-33.93	**0.6%**

For Sönmezer House, window operation schedules caused nearly no effect on energy demands. Using simulations, 0.0% enhancement in annual total primary energy consumption (Figure 101 and Table 33) and 0.1% enhancement in annual total heating load (Figure 102 and Table 34) is observed. The intervention even results in 0.1% increase in the cooling load (Figure 103 and Table 35).

As the results indicate no or negative effect on the thermal behavior of the case building, window operation control can be specified as an unsuitable intervention for the exterior-*sofa* houses of the studied region.

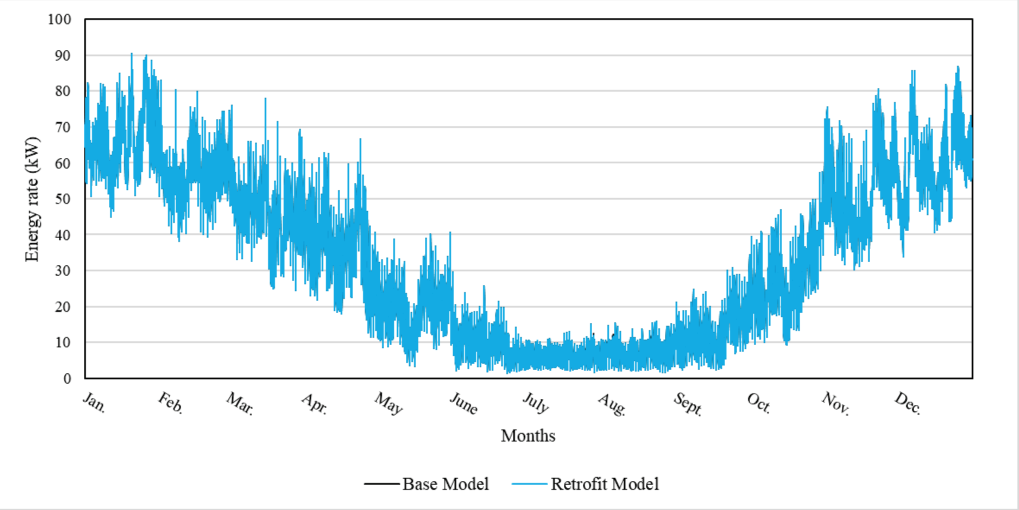

Figure 101. Comparison of base and retrofit models for primary energy consumption rates - Sönmezer House / window operation control

Table 33. Comparison of base and retrofit models for primary energy consumption - Sönmezer House / window operation control

Window Operation Control / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3978.31	**0.0%**

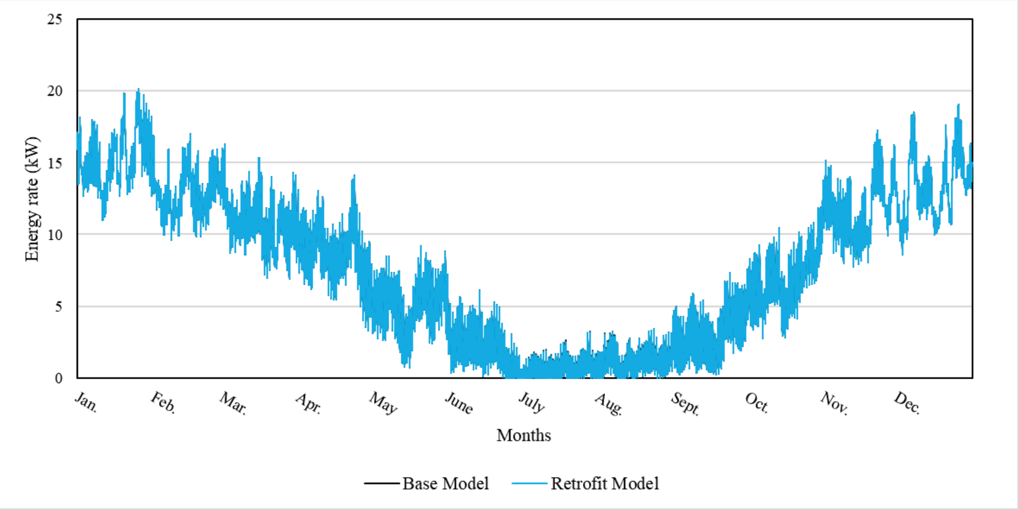

Figure 102. Comparison of base and retrofit models for heating load rates - Sönmezer House / window operation control

Table 34. Comparison of base and retrofit models for heating load - Sönmezer House / window operation control

Window Operation Control / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	912.85	**0.1%**

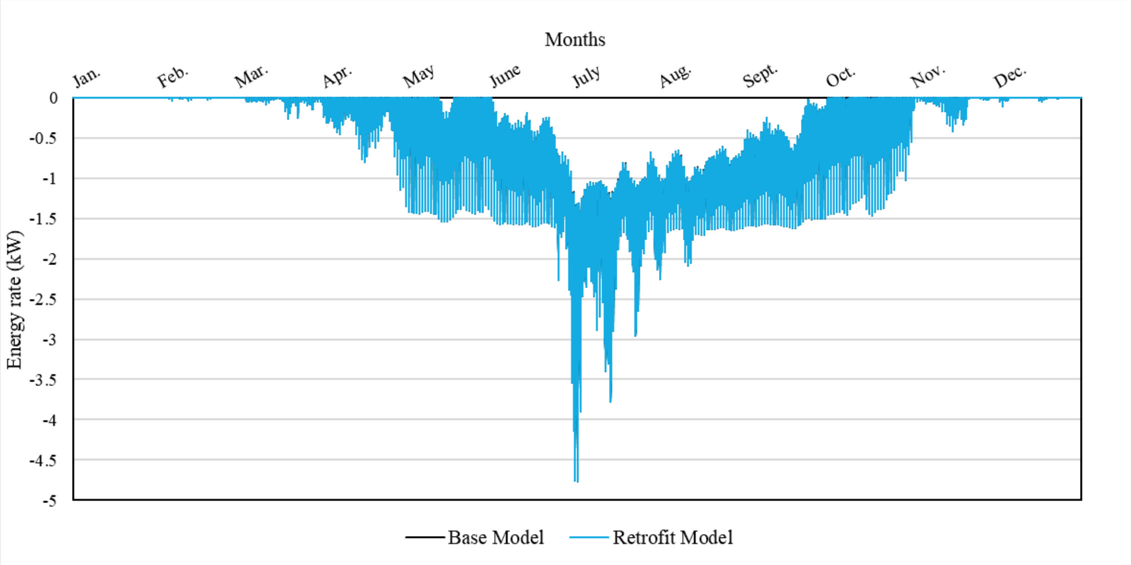

Figure 103. Comparison of base and retrofit models for cooling load rates - Sönmezer House / window operation control

Table 35. Comparison of base and retrofit models for cooling load - Sönmezer House / window operation control

Window Operation Control / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-44.39	**-0.1%**

5.2.4. Addition of Second Glazing to the Windows

In order to reduce heat loss in winter and heat gain in summer through windows; current single glazing windows of the case buildings are assumed to be changed to double glazed windows in simulations. By this course, U value (thermal transmittance) of single glazing (6mm-clear) which is 5.778[53] W/m^{2}K is accepted to be improved to double glazing (Dbl LoE Spec Sel Clr 6mm/13mm Arg) that has 1.338[54] W/m^{2}K U-value and solar heat gain coefficient of 0.419. This double glazing system was selected from material data base of *DesignBuilder* software and specifically chosen for its low U value.

With the simulations utilizing glazing change, for Gürsel House, 7.3% enhancement in annual total primary energy consumption (Figure 104 and Table 36), 5.2% enhancement in annual total heating load (Figure 105 and Table 37) and 3.9% enhancement in annual total cooling load is observed (Figure 106 and Table 38).

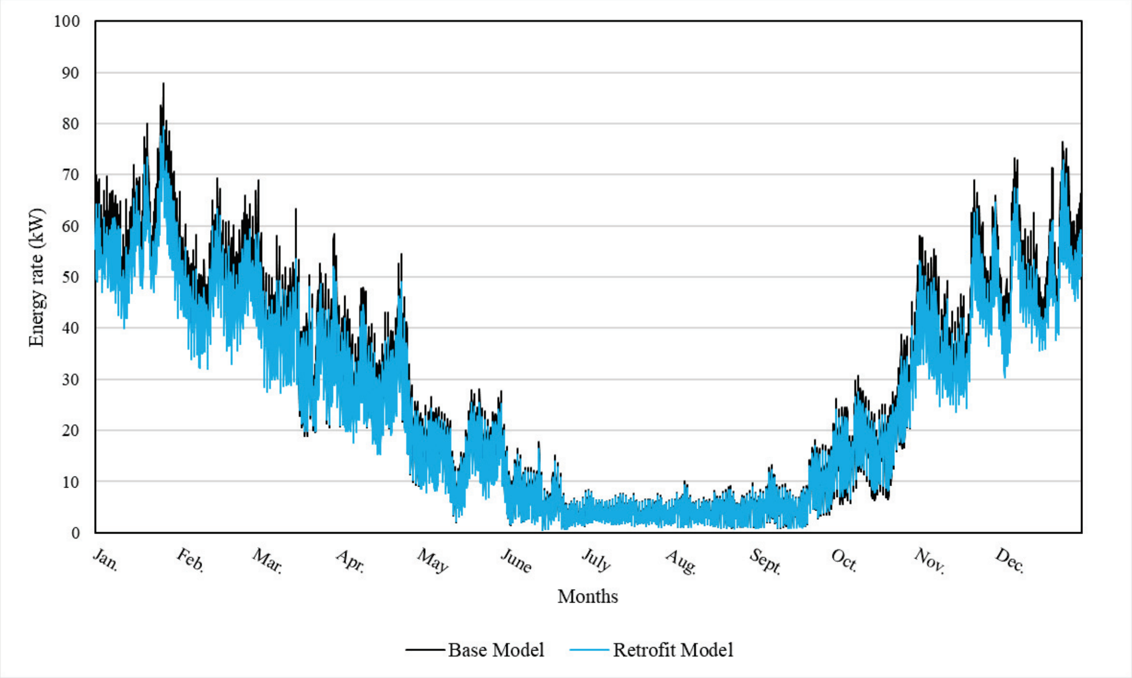

Figure 104. Comparison of base and retrofit models for primary energy consumption rates - Gürsel House / double glazing for windows

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[53] U value is specified in *DesignBuilder* software material data base.

[54] U value is specified in *DesignBuilder* software material data base.

Table 36. Comparison of base and retrofit models for primary energy consumption - Gürsel House / double glazing for windows

Double Glazing for Windows / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3172.30	**7.3%**

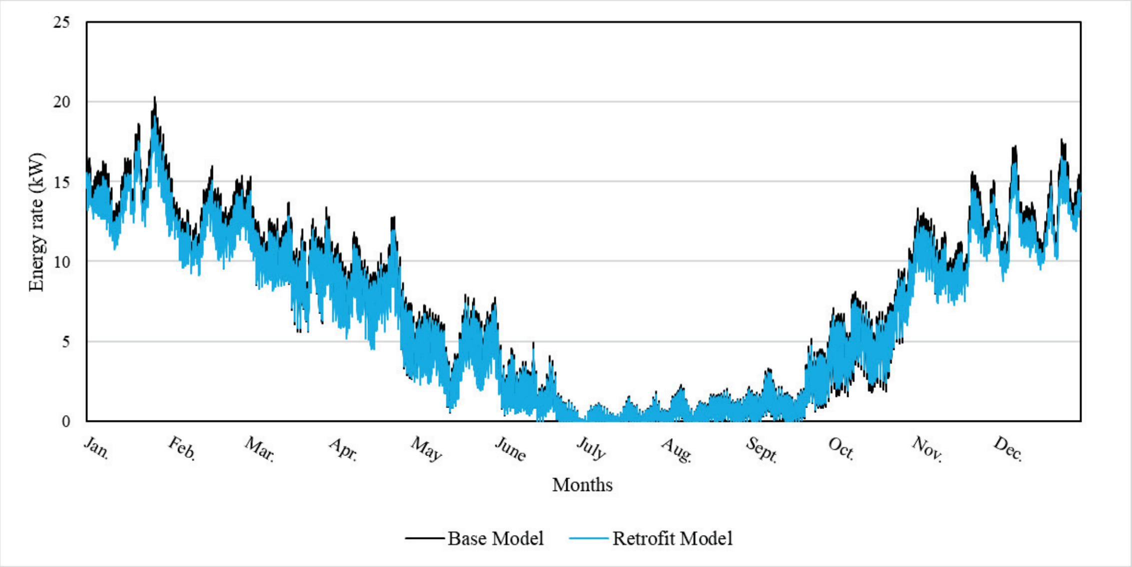

Figure 105. Comparison of base and retrofit models for heating load rates - Gürsel House / double glazing for windows

Table 37. Comparison of base and retrofit models for heating load - Gürsel House / double glazing for windows

Double Glazing for Windows / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	821.24	**5.2%**

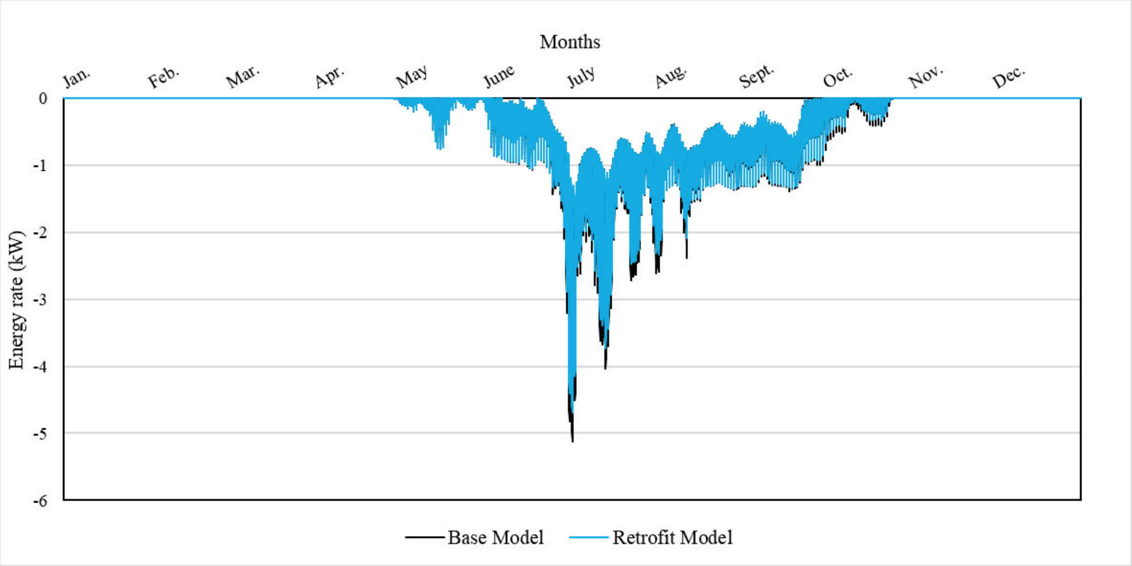

Figure 106. Comparison of base and retrofit models for cooling load rates - Gürsel House / double glazing for windows

Table 38. Comparison of base and retrofit models for cooling load - Gürsel House / double glazing for windows

Double Glazing for Windows / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-32.82	**3.9%**

For Sönmezer House, simulation results indicate 5.5% enhancement in annual total primary energy consumption (Figure 107 and Table 39), 4.0% enhancement in annual total heating load (Figure 108 and Table 40) and 4.6% enhancement in annual total cooling load (Figure 109 and Table 41).

With the results, it can be seen that for both case building, adding double glazing to the windows establishes evident improvement for both heating and cooling seasons.

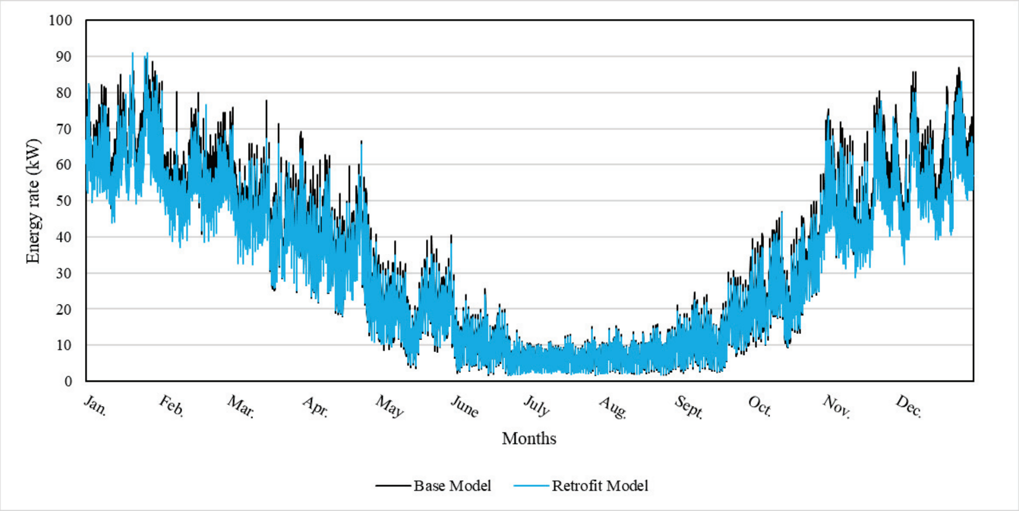

Figure 107. Comparison of base and retrofit models for primary energy consumption rates - Sönmezer House / double glazing for windows

Table 39. Comparison of base and retrofit models for primary energy consumption - Sönmezer House / double glazing for windows

Double Glazing for Windows / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3760.04	**5.5%**

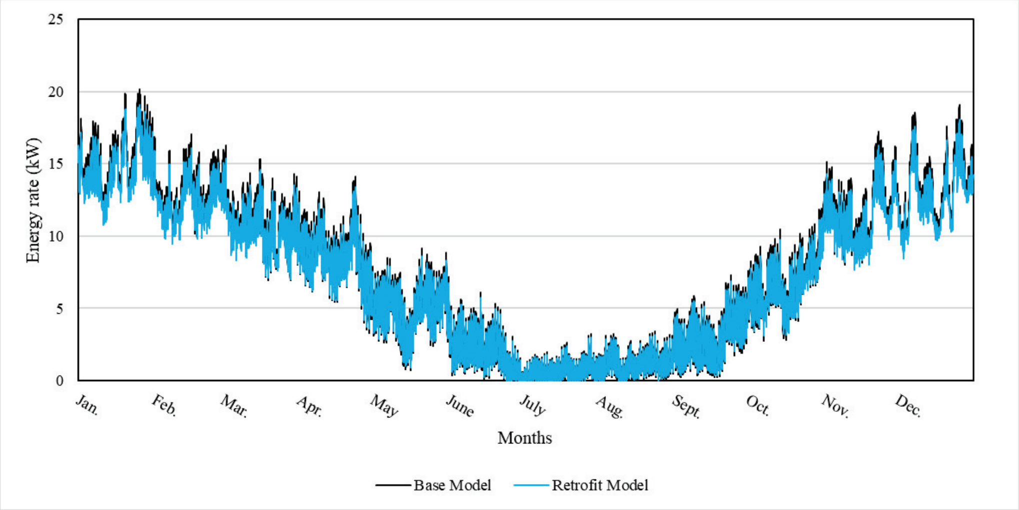

Figure 108. Comparison of base and retrofit models for heating load rates - Sönmezer House / double glazing for windows

Table 40. Comparison of base and retrofit models for heating load - Sönmezer House / double glazing for windows

Double Glazing for Windows / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	876.61	**4.0%**

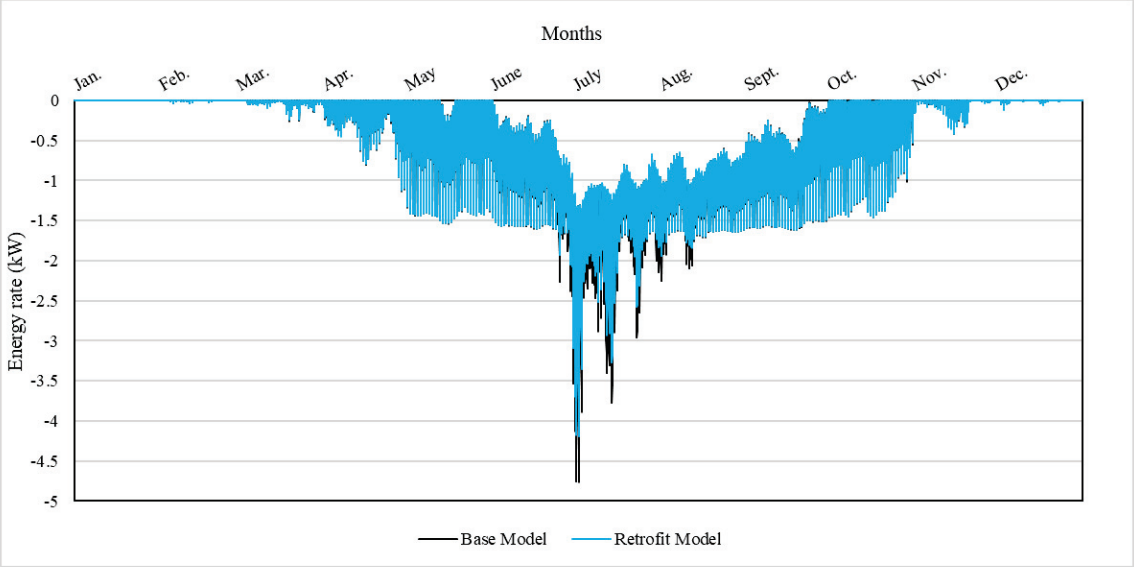

Figure 109. Comparison of base and retrofit models for cooling load rates - Sönmezer House / double glazing for windows

Table 41. Comparison of base and retrofit models for cooling load - Sönmezer House / double glazing for windows

Double Glazing for Windows / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-42.33	**4.6%**

5.2.5. Application of Thermal Insulation Material

Thermal insulation applications reduce energy transfer rate through building constructional sections (e.g. roofs, walls, floors) by the addition of new layer of insulation materials which have very low thermal conductivity properties. By these implementations, overall U-values of the construction sections are decreased which provides cut backs in the energy requirements of the buildings. Generally, the insulation work takes place on ground floors, floors between storeys, walls and roofs. As the insulation works that are applied on the facades jeopardize the aesthetic integrity of historical buildings due to the visual loss of original wall planes (carrying architectural elements such as pilasters and moldings as well as being expressive with their unique color and texture), insulation measure on the outer faces of the walls is omitted from the thermal measure list of this study. In addition, Walker et al. (2015) indicates that interior wall insulation practices can also be harmful as they can require replacing traditional linings and moldings, disturb internal features such as joinery and distort the original room proportions as well as they may lead to accumulation of moisture within the wall and potential interstitial condensation, frost damage, timber decay and mold growth. Taking these threats into account, interior wall insulation was also removed from the thermal intervention list. Thus, simulated insulation works were limited to more concealed sections of the buildings such as ground floors, floors between storeys and roofs.

In order to sustain humidity balance and consequently safeguard traditional building fabric, breathability (moisture permeability) is a very crucial concern for the historical buildings. Accordingly, it is recommended to use permeable insulation materials to maintain natural moisture balance (Historic England, 2012b). The insulation materials in general can be categorized into three types according to their moisture absorption characteristics. These are hygroscopic, non-hygroscopic and permeable but non-hygroscopic types. Among these types, hygroscopic (breathable) insulation made from natural materials (e.g. sheep’s wool, hemp fiber, cellulose and wood fiber) can be considered to be more suitable to traditional buildings as they allow the natural transfer of moisture vapor (Rhee-Duverne et al., 2015). For this reason, foamed plastic insulation, such as closed cell polyisocyanurate, polyurethane or polystyrene are incompatible to be utilized in historical buildings as their inability to absorb and release moisture may increase the risk of condensation. In addition to that, permeable but non-hygroscopic materials such as fiberglass and mineral wool are not suitable either. Even though they are moisture permeable, because they cannot absorb moisture, any condensation forming within these materials will reduce insulation performance, increase the heat transfer, and may also cause mold and rot in adjacent traditional fabric. Moreover, with consistent moisture, these insulation materials themselves can begin to deteriorate (Historic England, 2012b). Considering the reasons explained, for thermal simulations of this study, batts made from cellulose fibers (recycled paper) which is suggested in the publications of Change works (2008), Historic England (2012b), Jenkins et al. (2014) and Zagorskas et al. (2014) were selected as the insulation material for floors between storeys and roofs. And for the ground floors, expanded clay bedding which is recommended by works of Energy Saving Trust (2005), Paul Arnold Architects (2010) and Jenkins et al. (2014) is utilized. For the sectional dimensioning of insulation layers, building geometry restrictions (such as floor thickness), guidance of published case studies and technical suggestions of manufacturers[55] were taken into account. For the sectional dimensioning of roof insulation material, an average of 24 cm thickness is accepted as published case studies suggest insulation thicknesses range from 18 cm (Snow, 2013) to 30 cm (Rhee-Duverne et al., 2015). In the case of insulation of floors between storeys, the height of the timber joists which varies from 8 to 12 cm has been the main factor that determines the thickness of the insulation layer. The insulation layer in these sections has been used in 5 cm according to the detail in Figure 110.

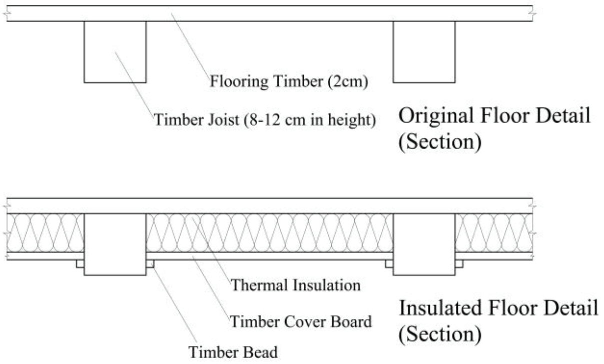

Figure 110. Insulated floor detail

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[55] http://www.techfil.co.uk/full-product-range/expanded-clay/ (accessed in August 2019) and https://www.ecocel.ie/wp-content/uploads/2017/10/Ecocel_tech.-data_Oct2017.pdf (accessed in August 2019) were referred for thermal properties of expanded clay and cellulose insulation respectively.

For ground floor insulation detail, the specifications suggested by manufacturers were followed (Figure 111).According to this specification, insulated ground floor detail is accepted to be formed by the layers of 50 cm expanded clay aggregate bedding, 20 cm lime mortar and 3 cm natural stone. This detail is only simulated added on the floors of wet cores (original storage spaces that were assumed to be converted to kitchen and toilets) which originally had compact soil flooring. Ground floor living rooms that have original timber flooring were assumed unchanged not to disturb the traditional building material.

Figure 111. Ground floor insulation detail[56]

Table 42 demonstrates the U-values of constructional assemblies in case study buildings before and after the application of insulation materials.

Table 42. Comparison of U-Values before and after insulation work

	Roofs		Floors Between Storeys		Ground Floors	
	Sönmezer H.	Gürsel H.	Sönmezer H.	Gürsel H.	Sönmezer H.	Gürsel H.
U-value before insulation (W/m^{2}K)	6.731	3.349	6.731	3.349	1.934	1.795
U-value after insulation (W/m^{2}K)	0.163	0.159	0.708	0.64	0.205	0.203

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[56] http://www.greenspec.co.uk/building-design/limecrete-floors-for-old-buildings/, access date: August 2019.

5.2.5.1. Roof Insulation

With the simulations utilizing roof insulation, for Gürsel House, 4.7% enhancement in annual total primary energy consumption (Figure 112 and Table 43) and 4.1% enhancement in annual total heating load is observed (Figure 113 and Table 44); however, cooling load is seen to be increased 15.9% (Figure 114 and Table 45) which demonstrates that roof insulation is only beneficial in heating seasons and causes overheating in summers.

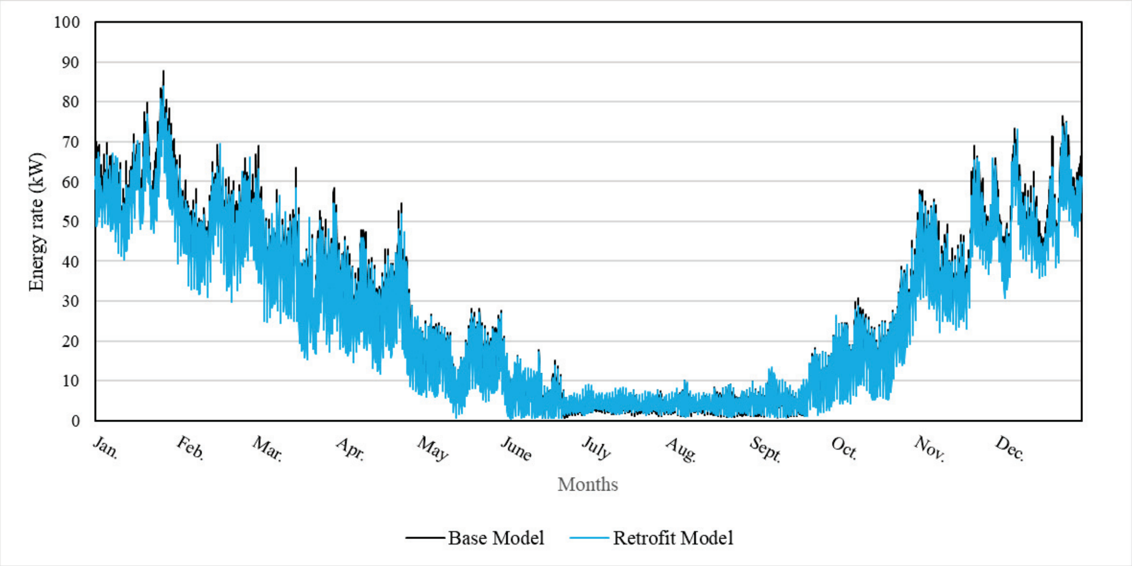

Figure 112. Comparison of base and retrofit models for primary energy consumption rates – Gürsel House / roof insulation

Table 43. Comparison of base and retrofit models for primary energy consumption – Gürsel House / roof insulation

Roof Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3263.74	**4.7%**

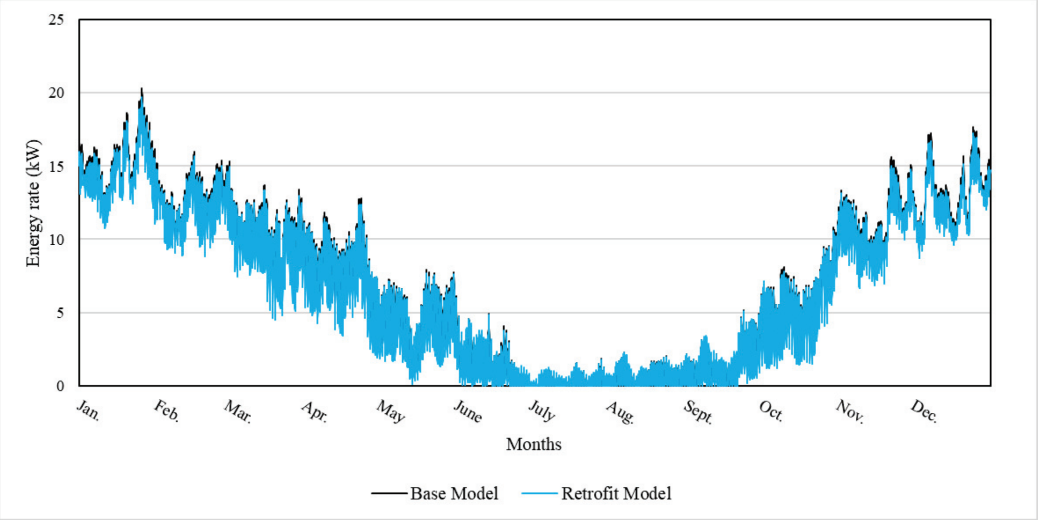

Figure 113. Comparison of base and retrofit models for heating load rates– Gürsel House / roof insulation

Table 44. Comparison of base and retrofit models for heating load – Gürsel House / roof insulation

Roof Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	830.82	**4.1%**

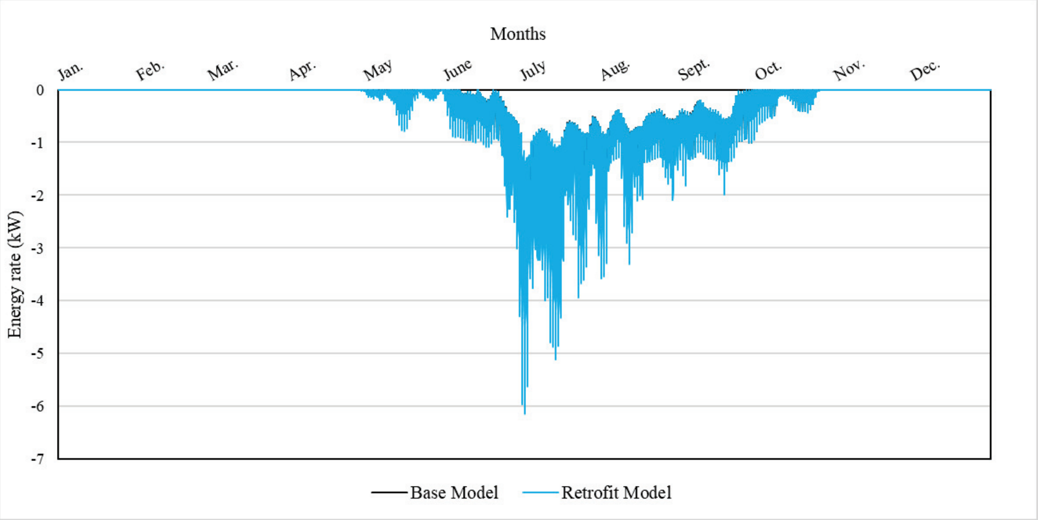

Figure 114. Comparison of base and retrofit models for cooling load rates– Gürsel House / roof insulation

Table 45. Comparison of base and retrofit models for cooling load – Gürsel House / roof insulation

Roof Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-39.58	**-15.9%**

For Sönmezer House, with the simulations utilizing roof insulation, 17.8% enhancement in annual total primary energy consumption (Figure 115 and Table 46), 13.3% enhancement in annual total heating load (Figure 116 and Table 47) and 5.0% enhancement in annual cooling load are observed (Figure 117 and Table 48).

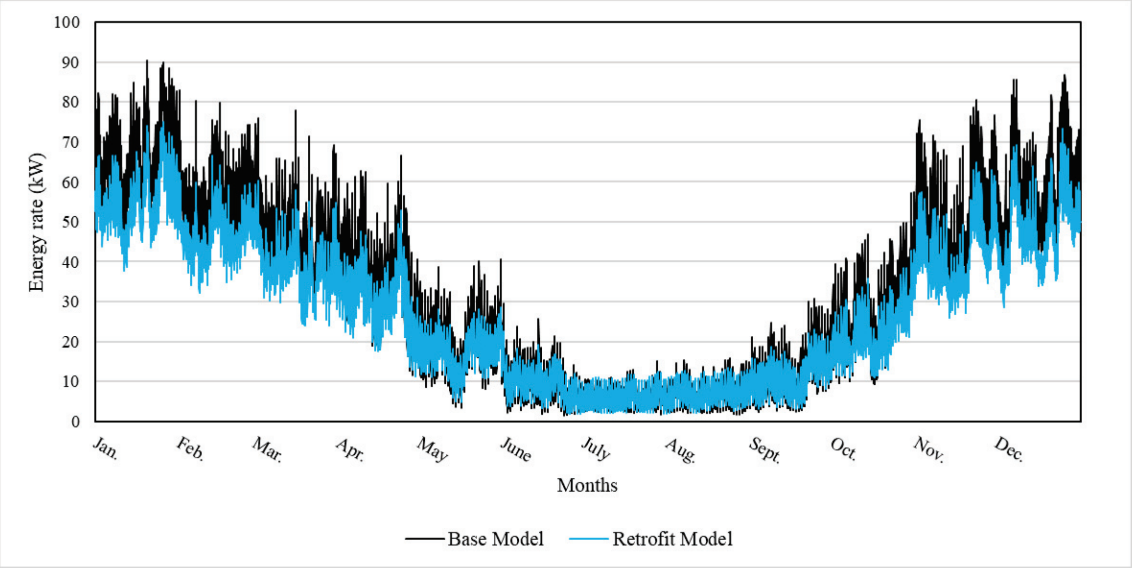

Figure 115. Comparison of base and retrofit models for primary energy consumption rates – Sönmezer House / roof insulation

Table 46. Comparison of base and retrofit models for primary energy consumption – Sönmezer House / roof insulation

Roof Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3271.08	**17.8%**

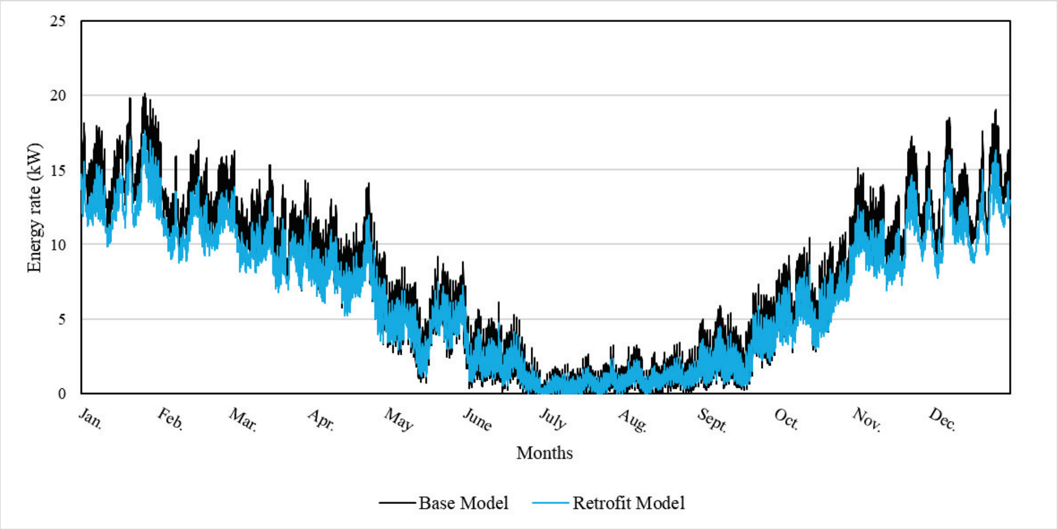

Figure 116. Comparison of base and retrofit models for heating load rates – Sönmezer House / roof insulation

Table 47. Comparison of base and retrofit models for heating load – Sönmezer House / roof insulation

Roof Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	791.72	**13.3%**

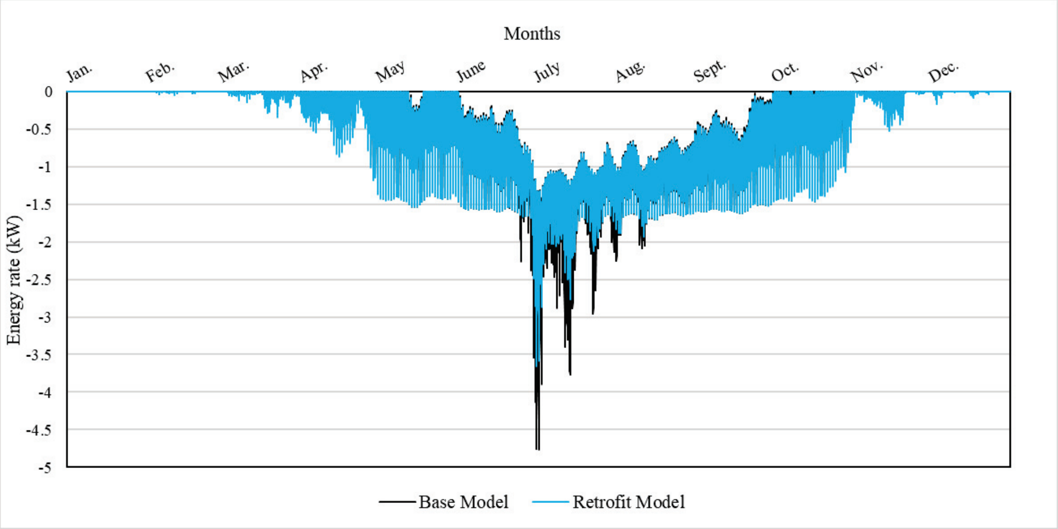

Figure 117. Comparison of base and retrofit models for cooling load rates – Sönmezer House / roof insulation

Table 48. Comparison of base and retrofit models for cooling load – Sönmezer House / roof insulation

Roof Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-42.14	**5.0%**

5.2.5.2. Insulation in Floors between Storeys

With the simulations utilizing floor insulation, for Gürsel House, 10.8% enhancement in annual total primary energy consumption (Figure 118 and Table 49), 4.8% enhancement in annual total heating load (Figure 119 and Table 50) and 19.3% enhancement in annual total cooling load is observed (Figure 120 and Table 51).

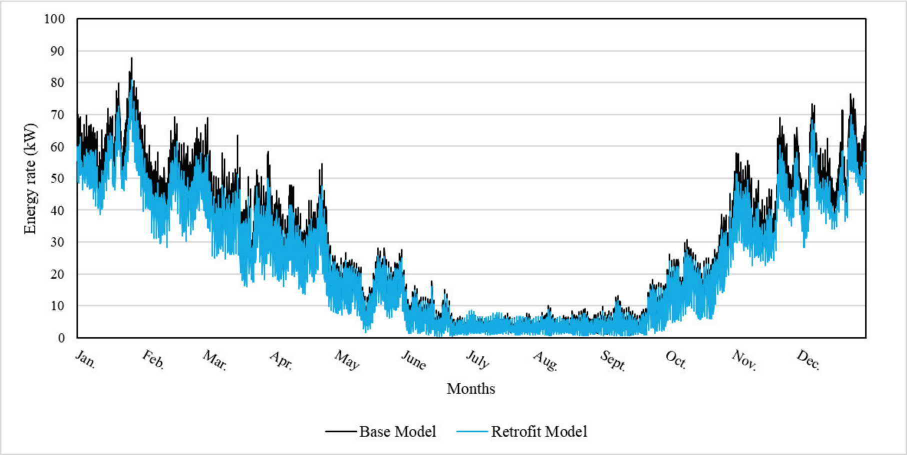

Figure 118. Comparison of base and retrofit models for primary energy consumption rates – Gürsel House / floor insulation

Table 49. Comparison of base and retrofit models for primary energy consumption – Gürsel House / floor insulation

Floor Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3054.61	**10.8%**

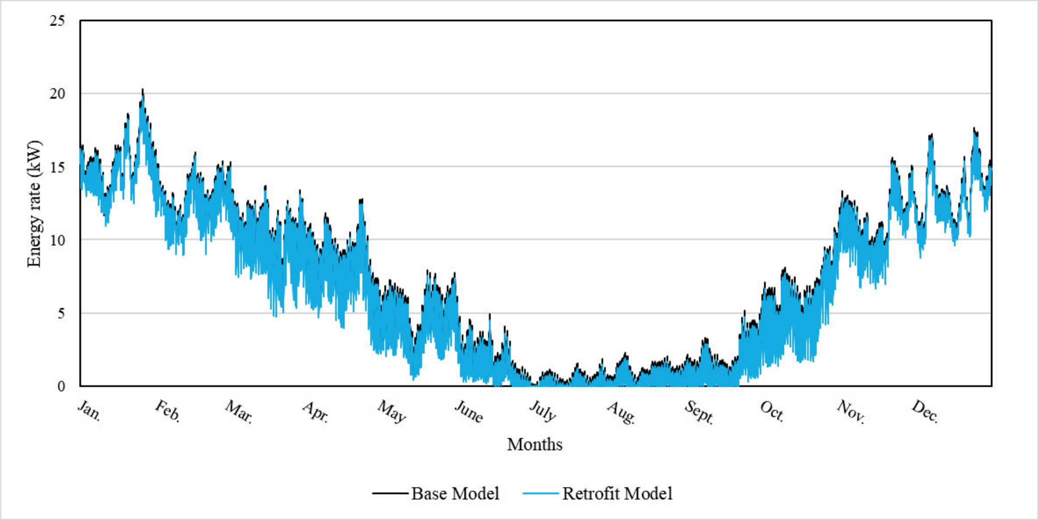

Figure 119. Comparison of base and retrofit models for heating load rates – Gürsel House / floor insulation

Table 50. Comparison of base and retrofit models for heating load – Gürsel House / floor insulation

Floor Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	825.17	**4.8%**

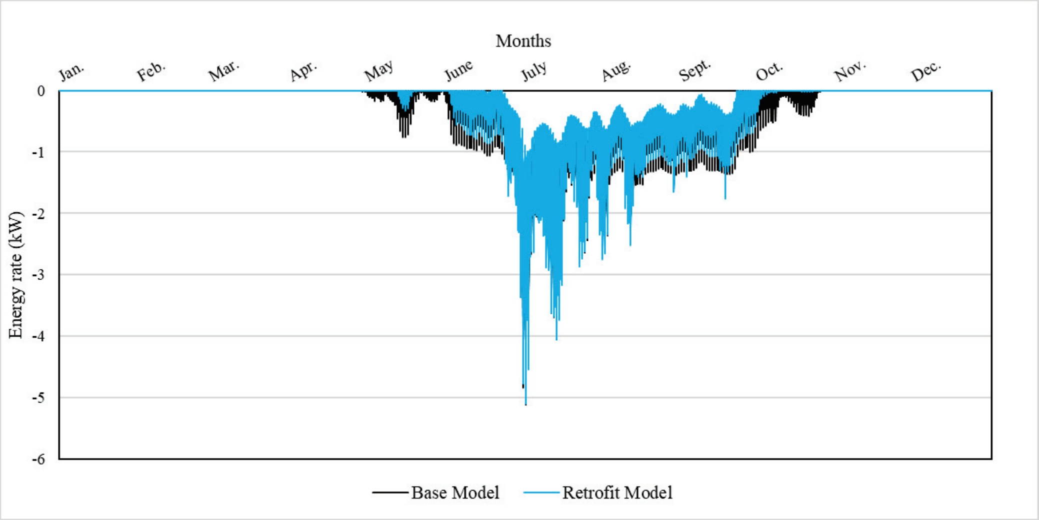

Figure 120. Comparison of base and retrofit models for cooling load rates– Gürsel House / floor insulation

Table 51. Comparison of base and retrofit models for cooling load – Gürsel House / floor insulation

Floor Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-27.55	**19.3%**

Likewise, for Sönmezer House, With the simulations utilizing floor insulation, 7.2% enhancement in annual total primary energy consumption (Figure 121 and Table 52), 2.0% enhancement in annual total heating load (Figure 122 and Table 53) and 21.0% enhancement in annual total cooling load is observed (Figure 123 and Table 54).

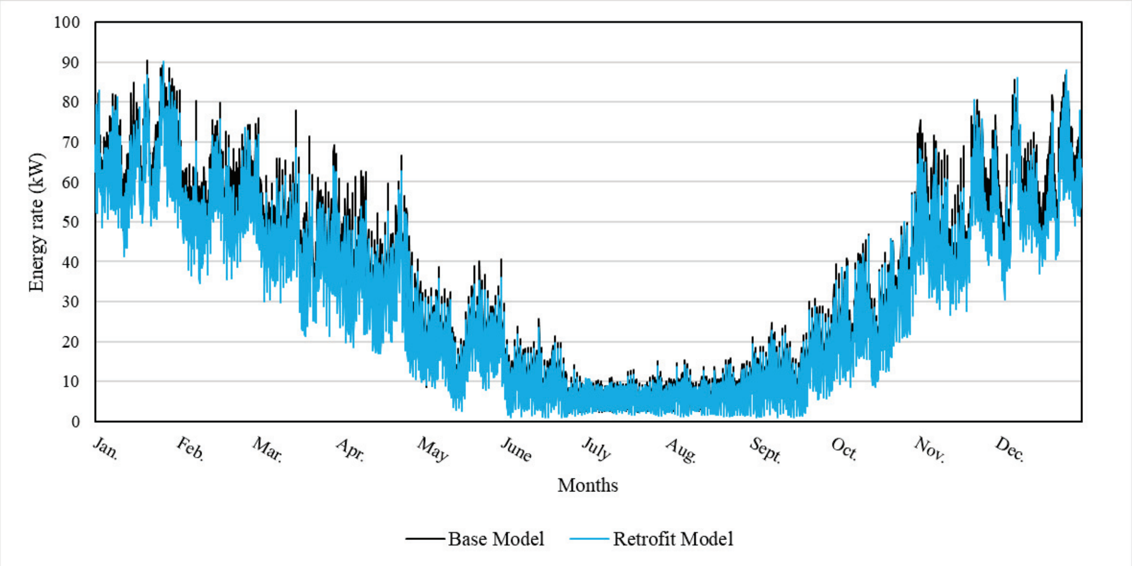

Figure 121. Comparison of base and retrofit models for primary energy consumption rates – Sönmezer House / floor insulation

Table 52. Comparison of base and retrofit models for primary energy consumption – Sönmezer House / floor insulation

Floor Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3695.18	**7.2%**

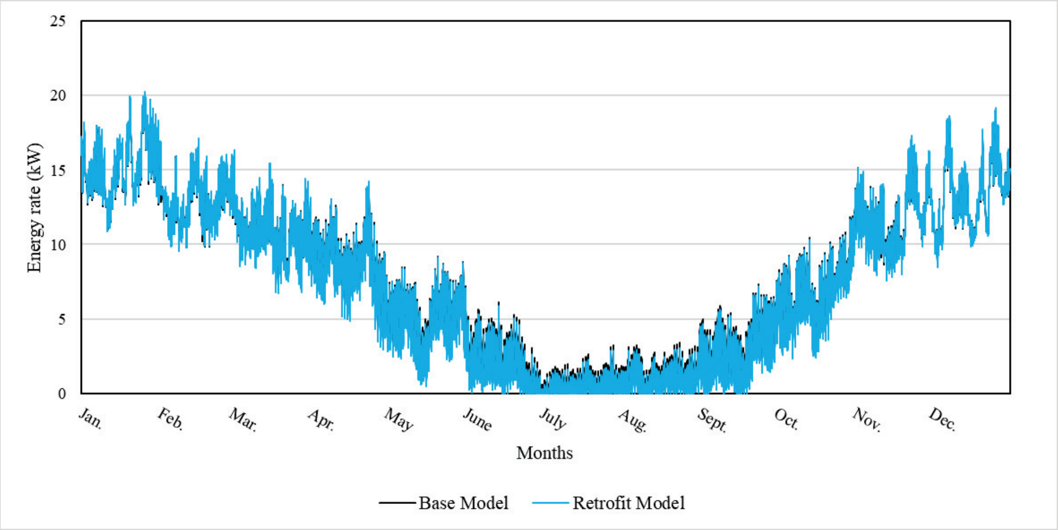

Figure 122. Comparison of base and retrofit models for heating load rates– Sönmezer House / floor insulation

Table 53. Comparison of base and retrofit models for heating load – Sönmezer House / floor insulation

Floor Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	895.18	**2.0%**

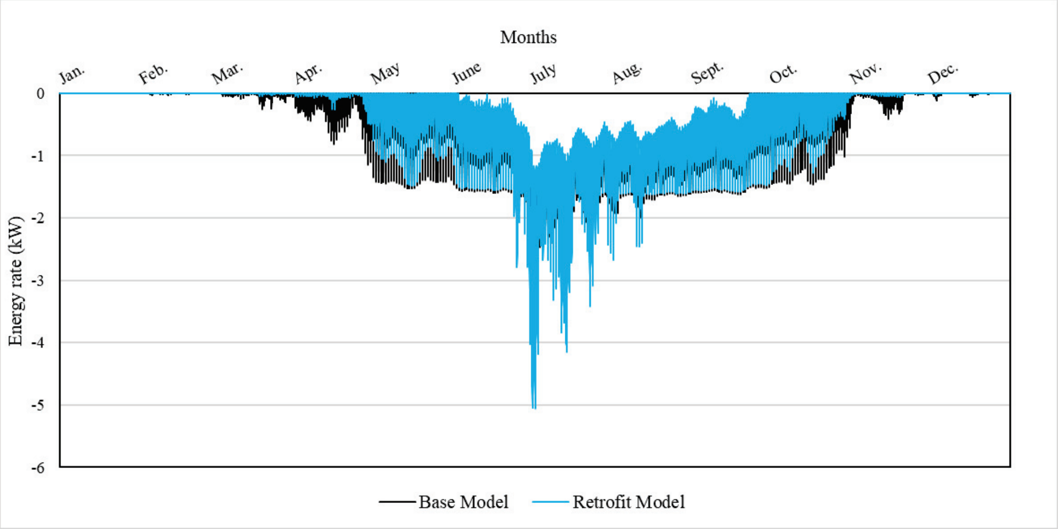

Figure 123. Comparison of base and retrofit models for cooling load rates– Sönmezer House / floor insulation

Table 54. Comparison of base and retrofit models for cooling load – Sönmezer House / floor insulation

Floor Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-35.05	**21.0%**

5.2.5.3. Insulation at Ground Floors

With the simulations utilizing ground floor insulation, for Gürsel House, 1.4% enhancement in annual total primary energy consumption (Figure 124 and Table 55) and 1.6% enhancement in annual total heating (Figure 125 and Table 56) load is observed; however, cooling load is seen to be increased 19.5% (Figure 126 and Table 57) which demonstrates that ground floor insulation is only beneficial in heating seasons and causes overheating in summers.

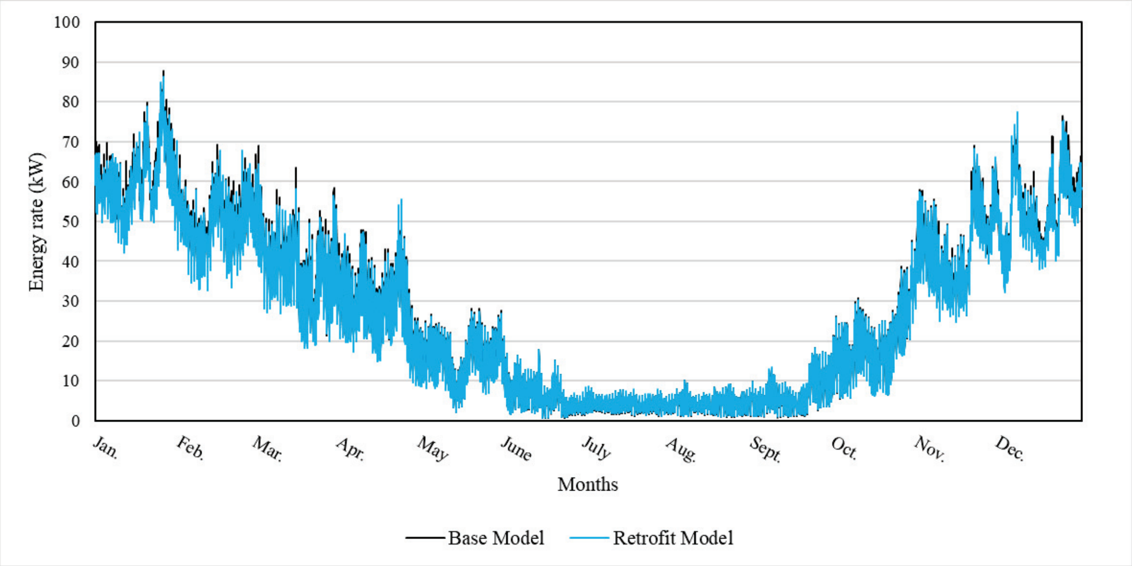

Figure 124. Comparison of base and retrofit models for primary energy consumption rates – Gürsel House / ground floor insulation

Table 55. Comparison of base and retrofit models for primary energy consumption – Gürsel House / ground floor insulation

Ground Floor Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	3375.97	**1.4%**

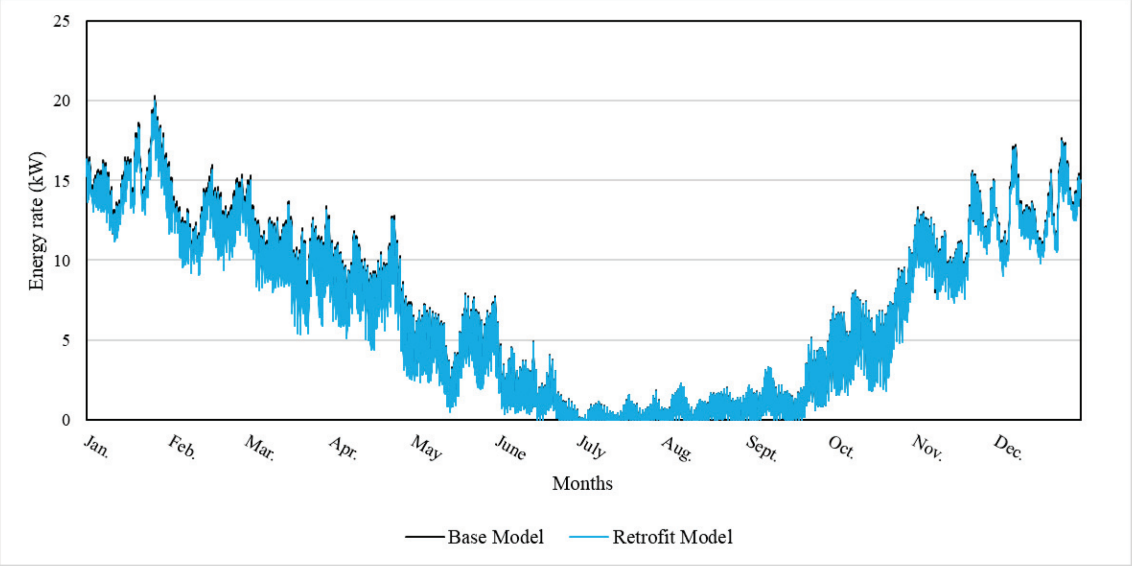

Figure 125. Comparison of base and retrofit models for heating load rates– Gürsel House / ground floor insulation

Table 56. Comparison of base and retrofit models for heating load – Gürsel House / ground floor insulation

Ground Floor Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	852.62	**1.6%**

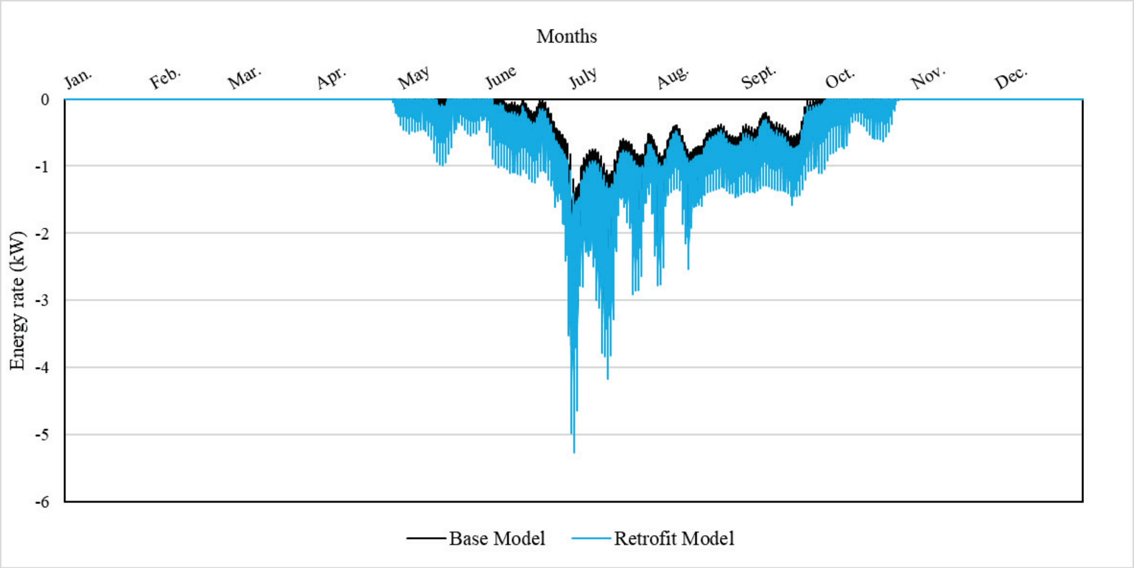

Figure 126. Comparison of base and retrofit models for cooling load rates– Gürsel House / ground floor insulation

Table 57. Comparison of base and retrofit models for cooling load – Gürsel House / ground floor insulation

Ground Floor Insulation / Gürsel house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-40.79	**-19.5%**

For the case of Sönmezer House, the simulations utilizing ground floor insulation result in 1.7% enhancement in annual total primary energy consumption (Figure 127 and Table 58) and 1.8% enhancement in annual total heating load (Figure 128 and Table 59); however, cooling load is seen to be increased 8.7% (Figure 129 and Table 60) which -like the case of Gürsel House- demonstrates that ground floor insulation is only beneficial in heating seasons and causes overheating in summers.

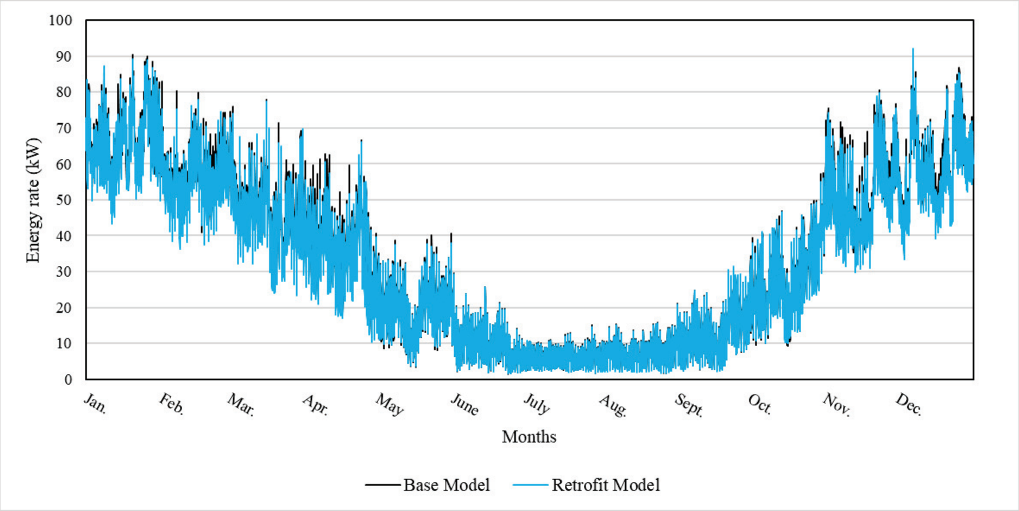

Figure 127. Comparison of base and retrofit models for primary energy consumption rates – Sönmezer House / ground floor insulation

Table 58. Comparison of base and retrofit models for primary energy consumption – Sönmezer House / ground floor insulation

Ground Floor Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	3913.26	**1.7%**

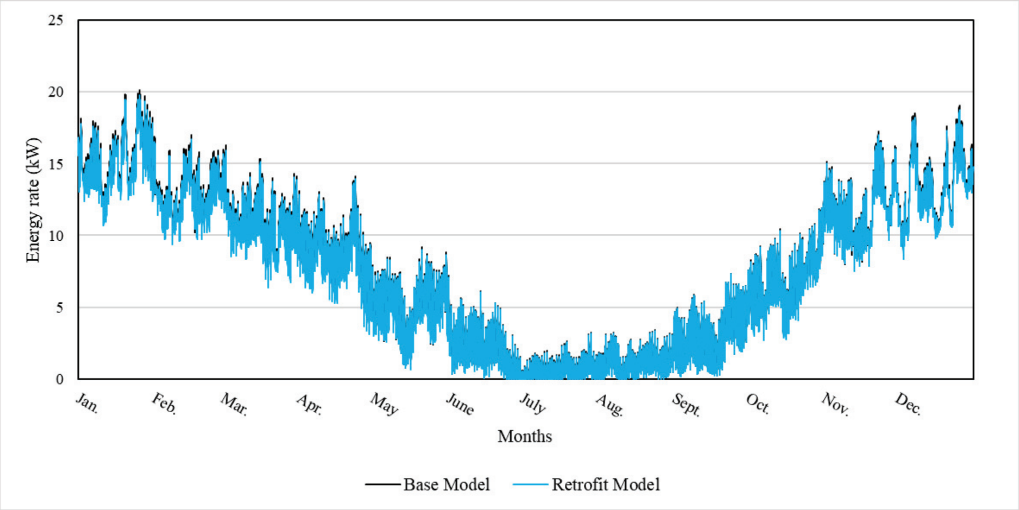

Figure 128. Comparison of base and retrofit models for heating load rates– Sönmezer House / ground floor insulation

Table 59. Comparison of base and retrofit models for heating load – Sönmezer House / ground floor insulation

Ground Floor Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	897.19	**1.8%**

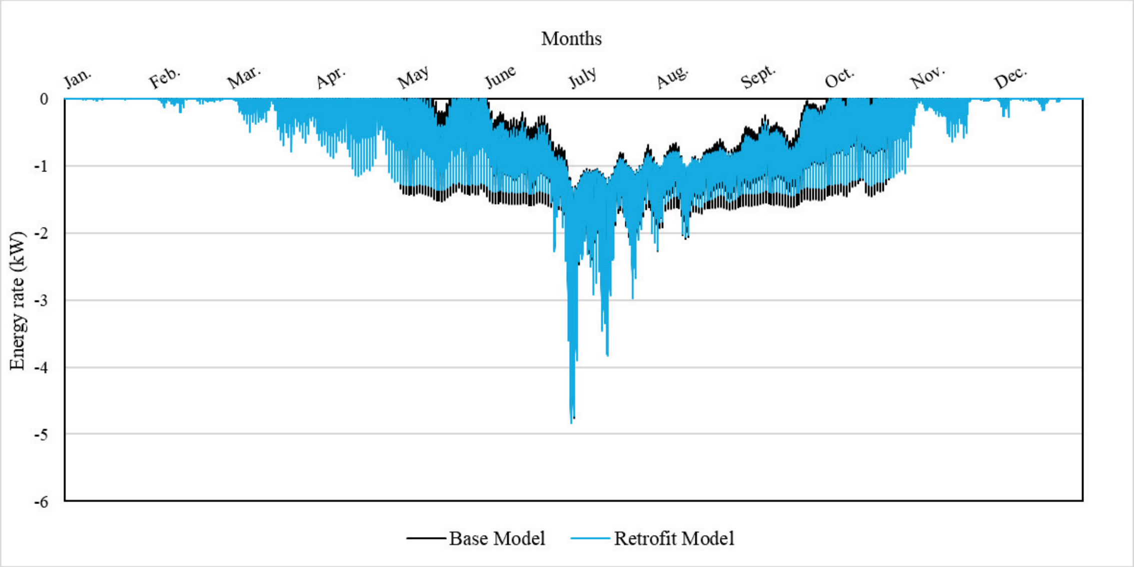

Figure 129. Comparison of base and retrofit models for cooling load rates – Sönmezer House / ground floor insulation

Table 60. Comparison of base and retrofit models for cooling load – Sönmezer House / ground floor insulation

Ground Floor Insulation / Sönmezer house	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-48.22	**-8.7%**

5.2.6. Addition of Closed, Glazed Corridors as Circulation Space

Traditional houses with exterior *sofa*s have been designed with closed rooms that open directly to outside weather conditions through semi open *sofa*s. This inherent architectural character has the potential deficiency[57] of heat loss / gain through the doors of rooms when they are open and also it causes thermal / functional discomfort for users when they circulate between rooms (e.g. circulating through semi-open *sofa*s when it is very cold in wintertime). In order to overcome this thermal imperfection, the solution of creating a thermally-conditioned, closed circulation space between rooms has been tested in simulations. These circulation spaces are assumed to be totally glazed as a partial enclosing of *sofa* spaces in order not to disturb visual integrity of the *sofa* facades. (Please see Figure 130 to Figure 133 for plan arrangements). They are simulated closed and thermally conditioned as being heated for 18 °C temperature set point (default set point of *DesignBuilder* software for domestic circulation spaces) throughout the wintertime (from October to May). And they are left totally open in summertime (from June to September) in order to prevent overheating as a possible consequence of greenhouse effect.

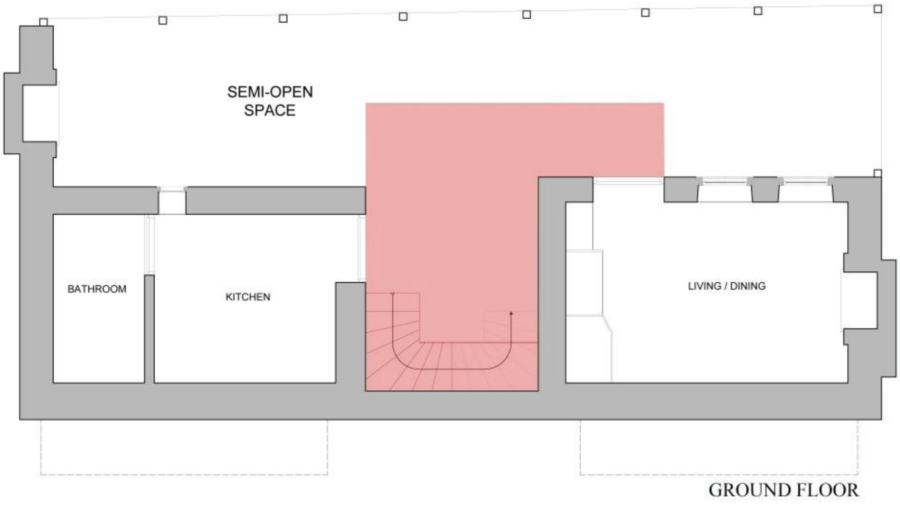

Figure 130. Gürsel House ground floor plan indicating glazed circulation proposal in red hatch

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[57] Here, the term deficiency is only used within the context of thermal behaviour of this architectural solution. The spatial arrangement of traditional buildings with exterior *sofa*s that has been established by rich dialogue between open, semi-open and closed spaces is a culturally unique architectural value. The thermal solution that is suggested in this section seeks to complement this value in a more thermal user-friendly manner.

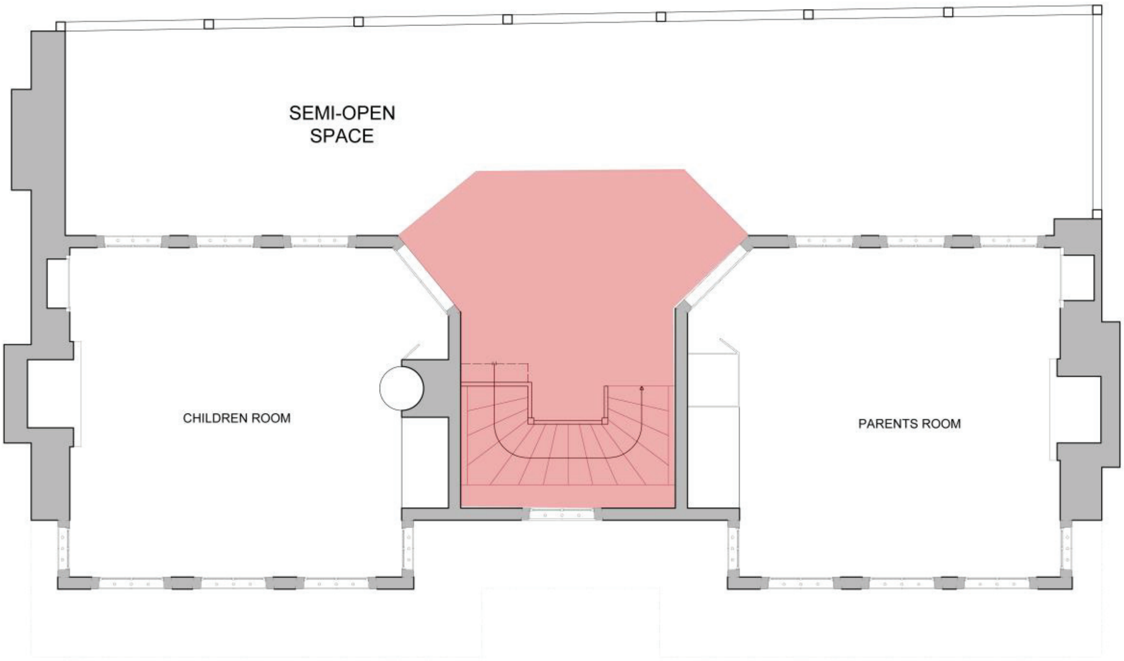

Figure 131. Gürsel House first floor plan indicating glazed circulation proposal in red hatch

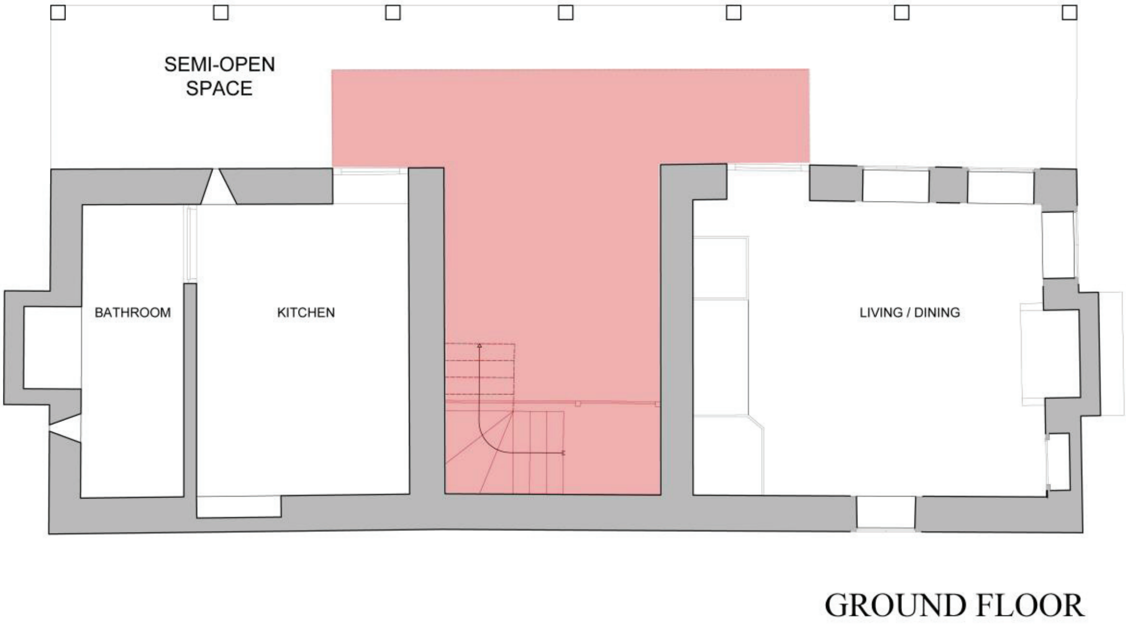

Figure 132. Sönmezer House ground floor plan indicating glazed circulation proposal in red hatch

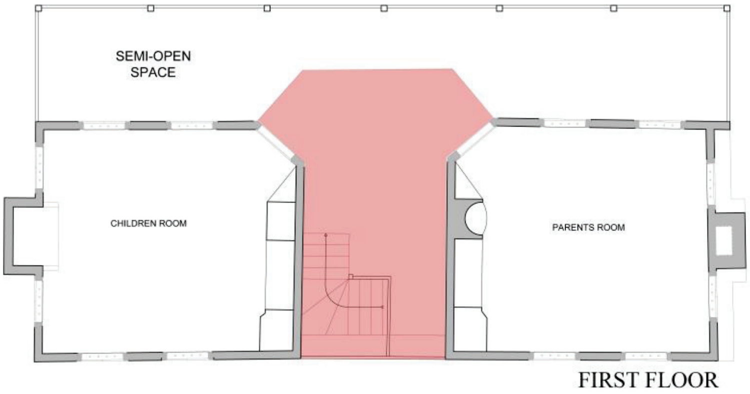

Figure 133. Sönmezer House first floor plan indicating glazed circulation proposal in red hatch

With the simulations utilizing glazed corridors, for Gürsel House, 7.9% enhancement in annual total primary energy consumption[58] (Figure 134 and Table 61) and 6.9% enhancement in annual total heating load (Figure 135 and Table 62) is observed; however, cooling load is seen to be increased 1.8% (Figure 136 and Table 63) which demonstrates that addition of glazed corridor is beneficial for heating loads while causing minor overheating problems even in heating season[59].

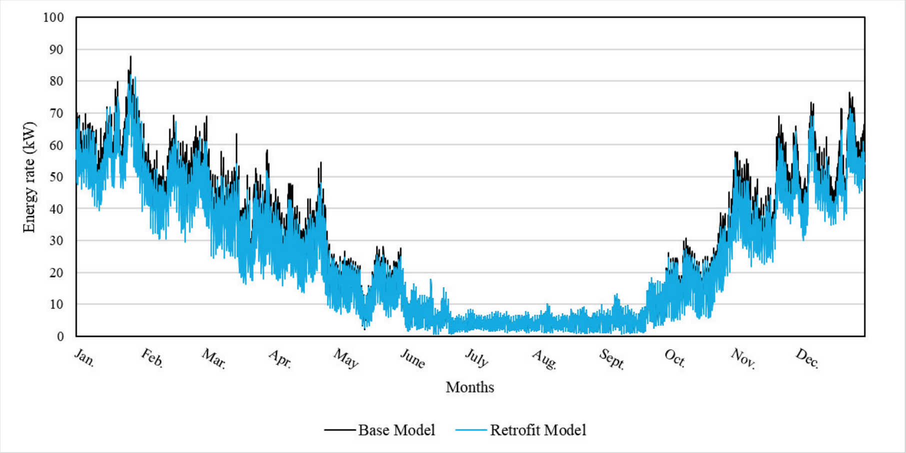

Figure 134. Comparison of base and retrofit models for primary energy consumption rates – Gürsel House / addition of glazed corridors

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[58] Please notice that for the comparisons of this intervention, primary energy consumption, heating load and cooling load values were given as building totals rather than building totals per unit areas. Because, with addition of glazed corridors, total area of the conditioned spaces increases (38% for Gürsel House and 42% for Sönmezer House) and consequently any analysis using building total per unit area values would cause misleading results.

[59] Probably due to hot days that may occur in late May and early October. In practice, the occupants could open these glazed spaces to overcome overheating.

Table 61. Comparison of base and retrofit models for primary energy consumption – Gürsel House / addition of glazed corridors

Addition of glazed corridors / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh	kWh	
Annual Primary Energy Consumption	241827.03	222782.26	**7.9%**

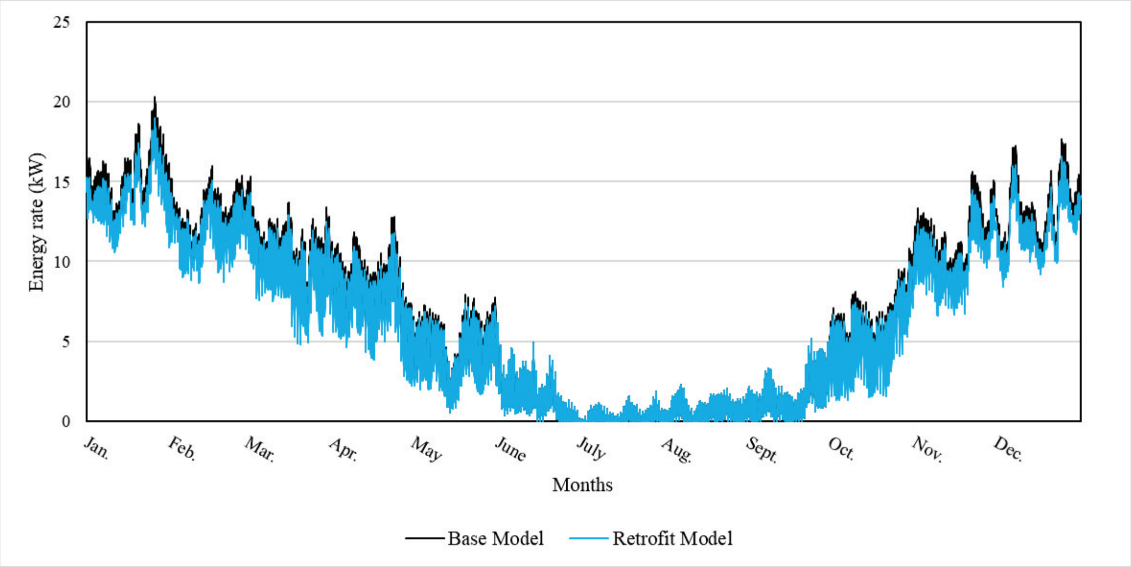

Figure 135. Comparison of base and retrofit models for heating load rates – Gürsel House / addition of glazed corridors

Table 62. Comparison of base and retrofit models for heating load – Gürsel House / addition of glazed corridors

Addition of glazed corridors / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh	kWh	
Annual Heating Load	61217.04	56985.58	**6.9%**

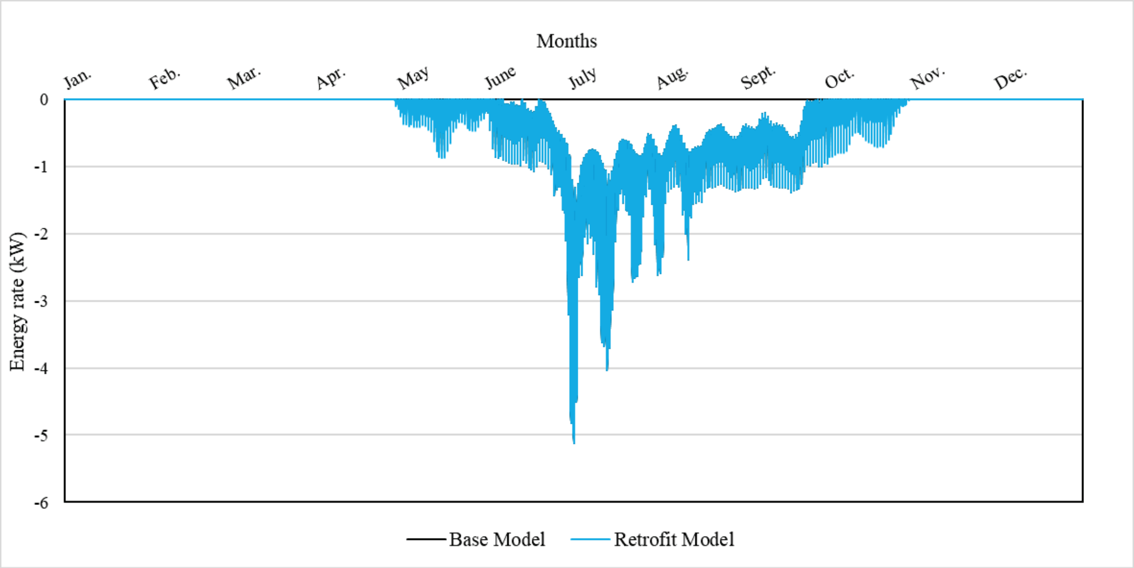

Figure 136. Comparison of base and retrofit models for cooling load rates – Gürsel House / addition of glazed corridors

Table 63. Comparison of base and retrofit models for cooling load – Gürsel House / addition of glazed corridors

Addition of glazed corridors / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh	kWh	
Annual Cooling Load	-2411.77	-2455.52	**-1.8%**

Similarly, for Sönmezer House, with the simulations utilizing glazed corridors, 9.5% enhancement in annual total primary energy consumption (Figure 137 and Table 64) and 8.2% enhancement in annual total heating load (Figure 138 and Table 65) is observed; however, cooling load is seen to be increased 14.4% (Figure 139 and Table 66) which demonstrates that addition of glazed corridor is beneficial for heating loads while causing considerable overheating problems even in heating season[60].

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[60] Probably due to hot days that may occur in late May and early October. In practice, the occupants could open these glazed spaces to overcome overheating.

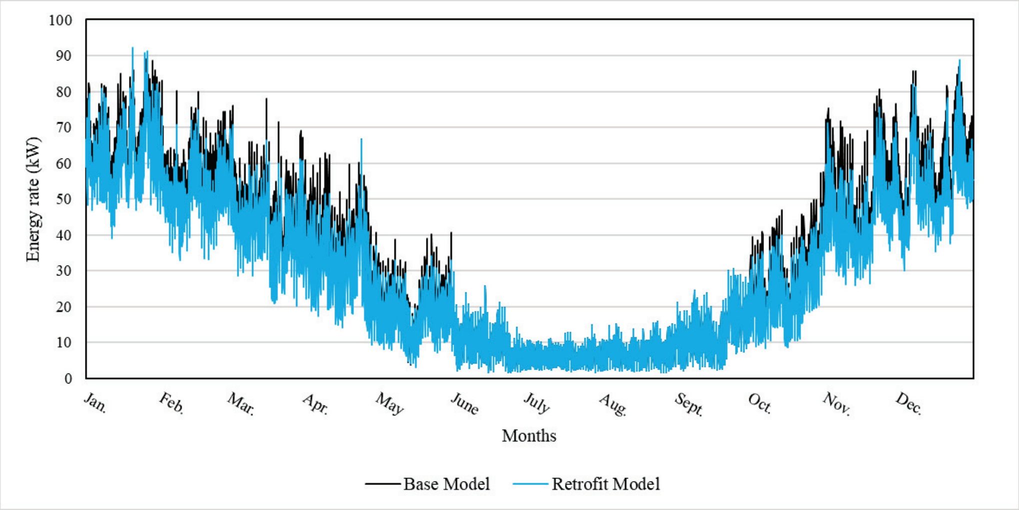

Figure 137. Comparison of base and retrofit models for primary energy consumption rates – Sönmezer House / addition of glazed corridors

Table 64. Comparison of base and retrofit models for primary energy consumption – Sönmezer House / addition of glazed corridors

Addition of glazed corridors / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh	kWh	
Annual Primary Energy Consumption	289950.36	262325.45	**9.5%**

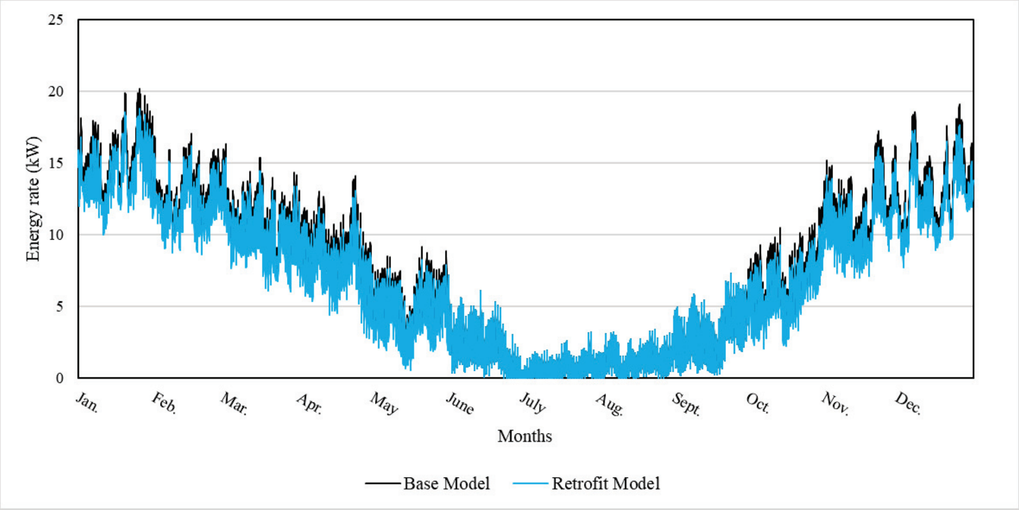

Figure 138. Comparison of base and retrofit models for heating load rates – Sönmezer House / addition of glazed corridors

Table 65. Comparison of base and retrofit models for heating load – Sönmezer House / addition of glazed corridors

Addition of glazed corridors / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh	kWh	
Annual Heating Load	66541.00	61062.13	**8.2%**

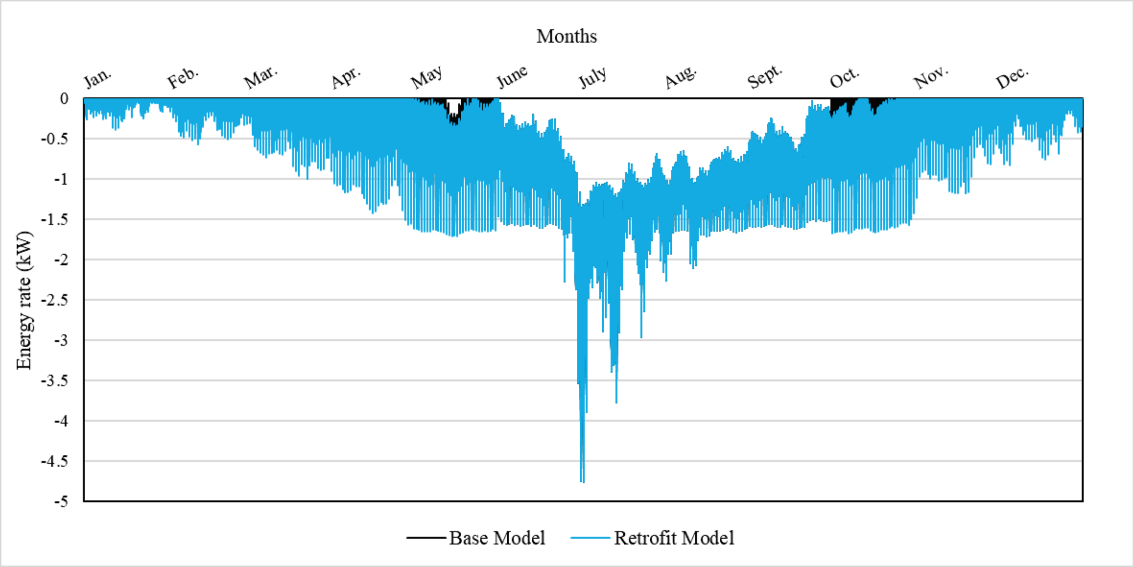

Figure 139. Comparison of base and retrofit models for cooling load rates – Sönmezer House / addition of glazed corridors

Table 66. Comparison of base and retrofit models for cooling load – Sönmezer House / addition of glazed corridors

Addition of glazed corridors / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh	kWh	
Annual Cooling Load	-3232.09	-3698.78	**-14.4%**

5.2.7. Effect of Whole Retrofitting Package / Set-1

In order to determine the cumulative effect of whole proposed retrofitting package (Set-1) applied together, models of the case buildings were simulated with the addition of all thermal measures excluding nighttime ventilation scheduling that resulted in increase for primary energy consumption. According to the results of these simulations, for Gürsel House, 38.0% enhancement in annual total primary energy consumption (Figure 140 and Table 67) and 33.6% enhancement in annual total heating load (Figure 141 and Table 68) were observed; however, cooling load was seen to be increased 5.8% (Figure 142 and Table 69) which can be interpreted as a significant cutback in the total thermal requirements of this case building with a minor increase in the cooling loads. The increase in the cooling load must be due to the thermal fabric enhancements (by proposed retrofitting measures) that diminishes heat transfer rate through building envelope and the shortage of cooling effects of natural wind that is obstructed by neighboring blocks. However, as described in *Energy Consumption of Base Models* section, since the dominant energy consumption parameter for the case study buildings are heating loads (e.g. the ratio of heating load to cooling load is roughly 25 to 1 for Gürsel House. Please see Figure 83); slight increase in cooling loads can be supposed acceptable when considering the significant reduction gained in the heating loads.

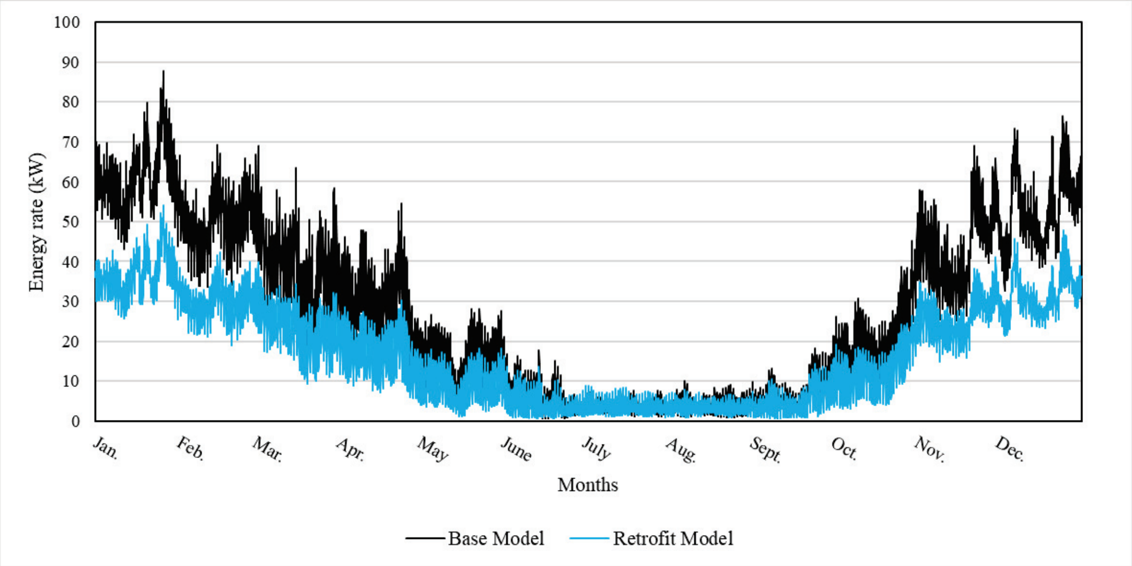

Figure 140. Comparison of base and retrofit models for primary energy consumption rates – Gürsel House / whole Retrofitting Package - Set-1

Table 67. Comparison of base and retrofit models for primary energy consumption – Gürsel House / whole Retrofitting Package - Set-1

Whole Retrofitting Package - Set-1 / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3423.86	2122.44	**38.0%**

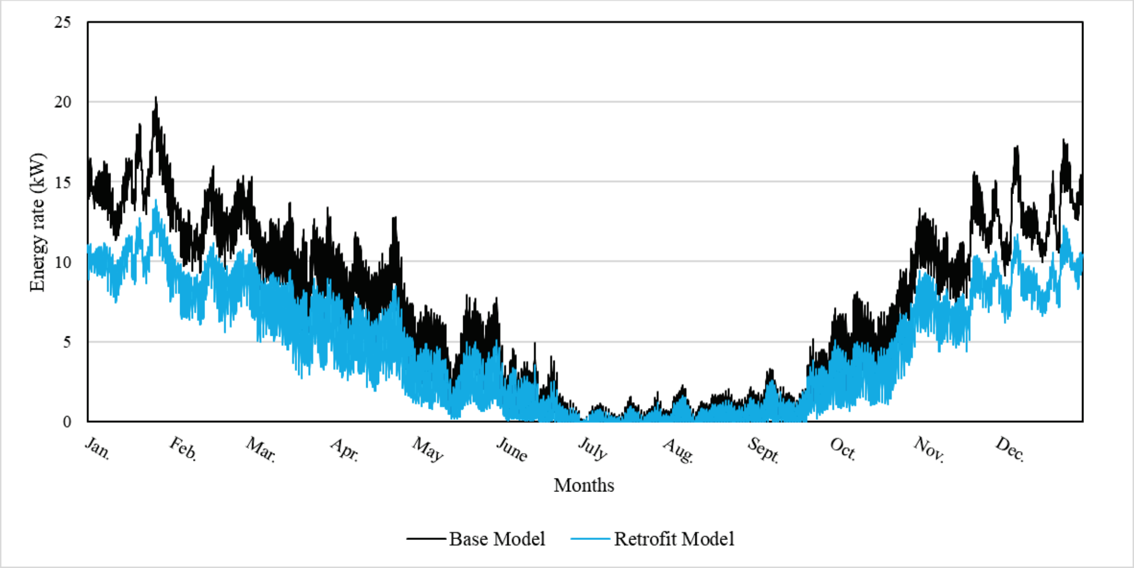

Figure 141. Comparison of base and retrofit models for heating load rates – Gürsel House / whole Retrofitting Package - Set-1

Table 68. Comparison of base and retrofit models for heating load – Gürsel House / whole Retrofitting Package - Set-1

Whole Retrofitting Package - Set-1 / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	866.73	575.88	**33.6%**

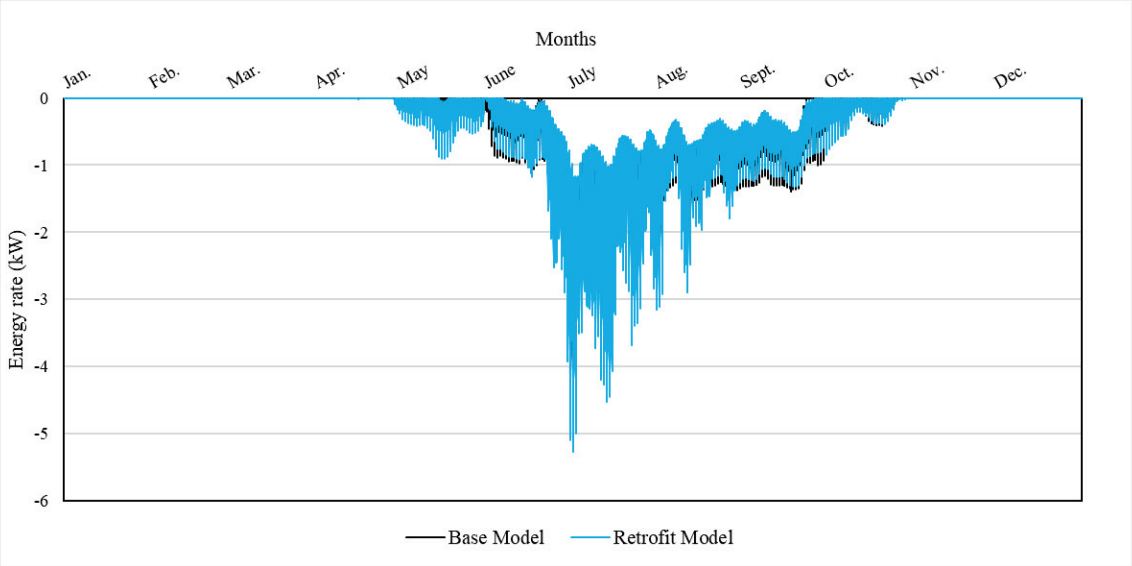

Figure 142. Comparison of base and retrofit models for cooling load rates – Gürsel House / whole Retrofitting Package - Set-1

Table 69. Comparison of base and retrofit models for cooling load – Gürsel House / whole Retrofitting Package - Set-1

Whole Retrofitting Package - Set-1 / Gürsel House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-34.15	-36.13	**-5.8%**

For Sönmezer House, the simulation results demonstrate even more pronounced improvement in thermal behavior. Moreover, slight increase of cooling load that was seen for Gürsel House was not observed for Sönmezer House. As Sönmezer House is located within loosely formed rural context away from neighboring blocks, this arrangement helps the building to cool down by the convective effect of wind in summer as opposed to the case of Gürsel House. By the simulation on Sönmezer House, 49.4% enhancement in annual total primary energy consumption (Figure 143 and Table 70), 43.6% enhancement in annual total heating load (Figure 144 and Table 71) and 9.3% enhancement in annual total cooling load was calculated (Figure 145 and Table 72).

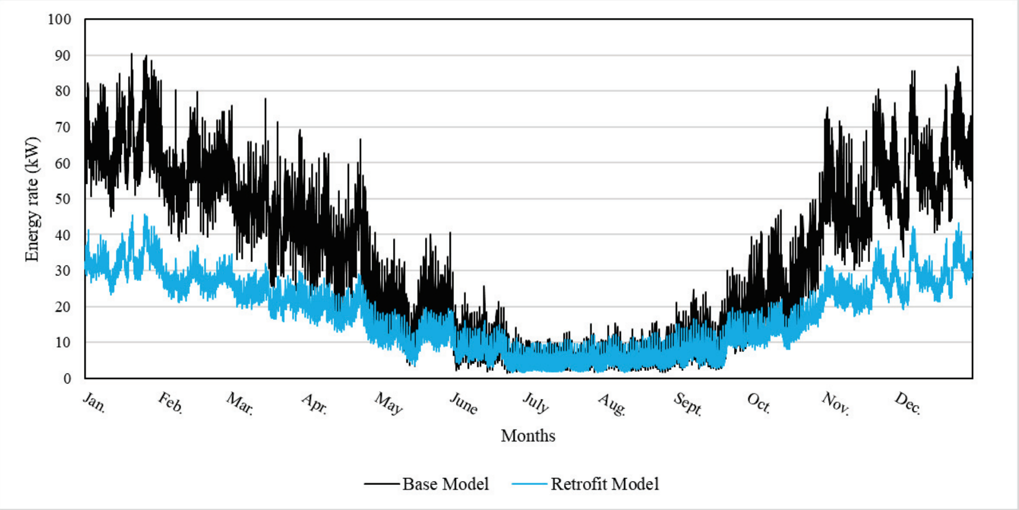

Figure 143. Comparison of base and retrofit models for primary energy consumption rates – Sönmezer House / whole Retrofitting Package - Set-1

Table 70. Comparison of base and retrofit models for primary energy consumption – Sönmezer House / whole Retrofitting Package - Set-1

Whole Retrofitting Package - Set-1 / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Primary Energy Consumption / Occupied Floor Area	3980.10	2014.79	**49.4%**

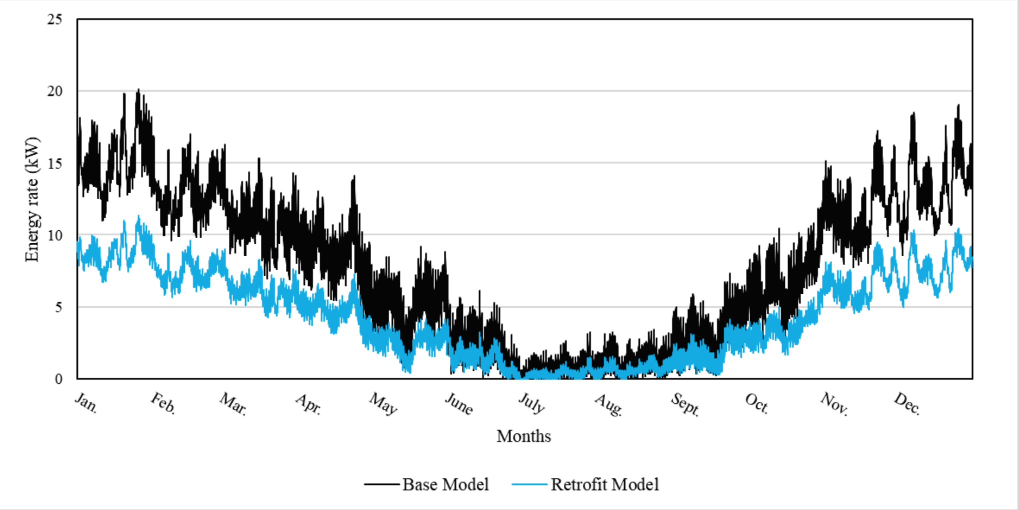

Figure 144. Comparison of base and retrofit models for heating load rates – Sönmezer House / whole Retrofitting Package - Set-1

Table 71. Comparison of base and retrofit models for heating load – Sönmezer House / whole Retrofitting Package - Set-1

Whole Retrofitting Package - Set-1 / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Heating Load / Occupied Floor Area	913.40	514.78	**43.6%**

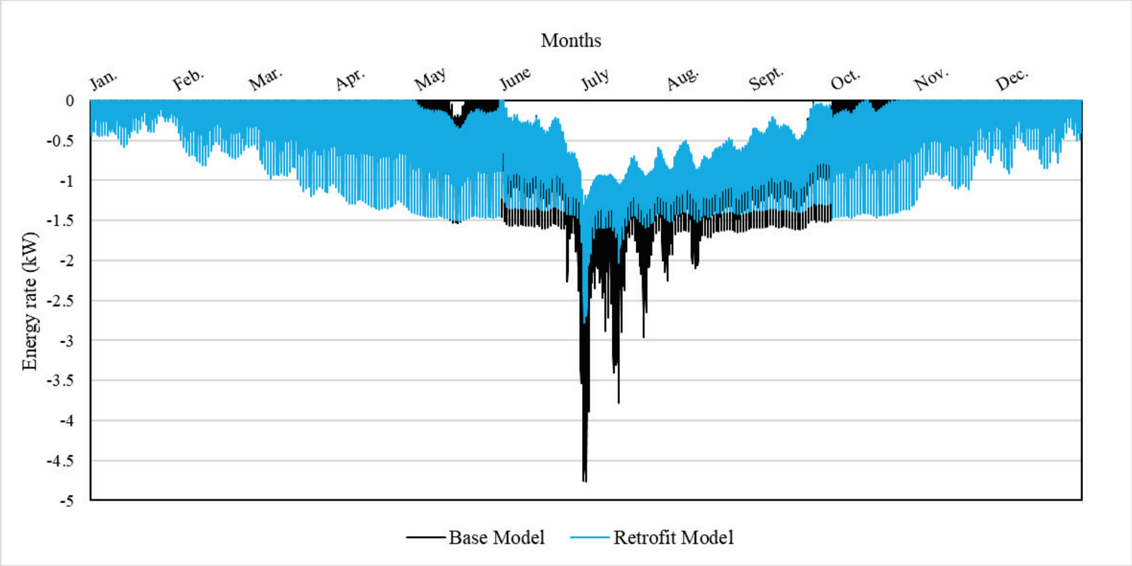

Figure 145. Comparison of base and retrofit models for cooling load rates – Sönmezer House / whole Retrofitting Package - Set-1

Table 72. Comparison of base and retrofit models for cooling load – Sönmezer House / whole Retrofitting Package - Set-1

Whole Retrofitting Package - Set-1 / Sönmezer House	Base Model	Retrofit Model	Enhancement Percentage
	kWh / m²	kWh / m²	
Annual Cooling Load / Occupied Floor Area	-44.37	-40.24	**9.3%**

5.2.8. Enhancement on HVAC Systems

As it was demonstrated in section *Models 2.1. Before-Retrofitting Models,* original HVAC system (traditional fireplaces) of the case study buildings was specified to be insufficient to sustain consistent thermal comfort. By the current occupants, this deficiency was sought to be overcome by the utilization of low-performance biomass stoves and air-conditioners. In this section, alternative HVAC systems were tested in simulations in order to determine their energy enhancement capacities as compared to the current HVAC preferences. As choosing suitable HVAC system for a building needs comprehensive research on many variables such as economical and practical feasibility, urban infrastructure, wiring / piping dimensioning, equipment sizing and architectural detailing which are out of the scope of this study; alternative systems were analyzed only for determining their energy benefit potentials to give a general insight on HVAC enhancements as comparative to Set-1 measures. For simulations, selected alternative systems are:

1. HVAC Alternative System-1-Replacing inefficient stoves with high-efficiency stoves while retaining air conditioners for cooling,
2. HVAC Alternative System-2-Utilizing Split-type Air conditioners for both heating and cooling,
3. HVAC Alternative System-3-Utilizing VRF (Variable refrigerant flow) air conditioners for both heating and cooling and
4. HVAC Alternative System-4-Utilizing Ground-Source Heat Pump for both heating and cooling.

These alternatives were chosen as they are commonly utilized (consequently easy to be accessed and installed) systems. For this section, some HVAC alternatives were omitted. For example, on-site solar panels were not tested as they require excessive equipment that were considered incompatible to the case studies and their urban context. Similarly, hot-water boilers were not examined as these systems need extra storage and equipment spaces that the case studies lack. Table 73 shows coefficient of performance values for tested HVAC alternatives. Figure 146 and Table 74 demonstrate the energy enhancement percentages provided by these alternatives.

Table 73. Coefficient of performance values for HVAC alternatives

	Base Case (Currently Utilized HVAC Systems)		**Upgraded Stove**		**Split Type Air-Conditioner**		**VRF System**		**Ground Source Heat Pump**	
			HVAC Alternative System-1		**HVAC Alternative System-2**		**HVAC Alternative System-3**		**HVAC Alternative System-4**	
	System	COP	System	COP	System	COP	System	COP	System	SCOP[61]
Heating	Low-efficiency Stove	0.30[62]	High-efficiency Stove	0.70	Split Type Air-Conditioner	3.61[63]	VRF System	4.40[64]	Ground Source Heat Pump	5.1
Cooling	Split Type Air-Conditioner	3.21	Split Type Air-Conditioner	3.21	Split Type Air-Conditioner	3.21	VRF System	4.33	Ground Source Heat Pump	5.1

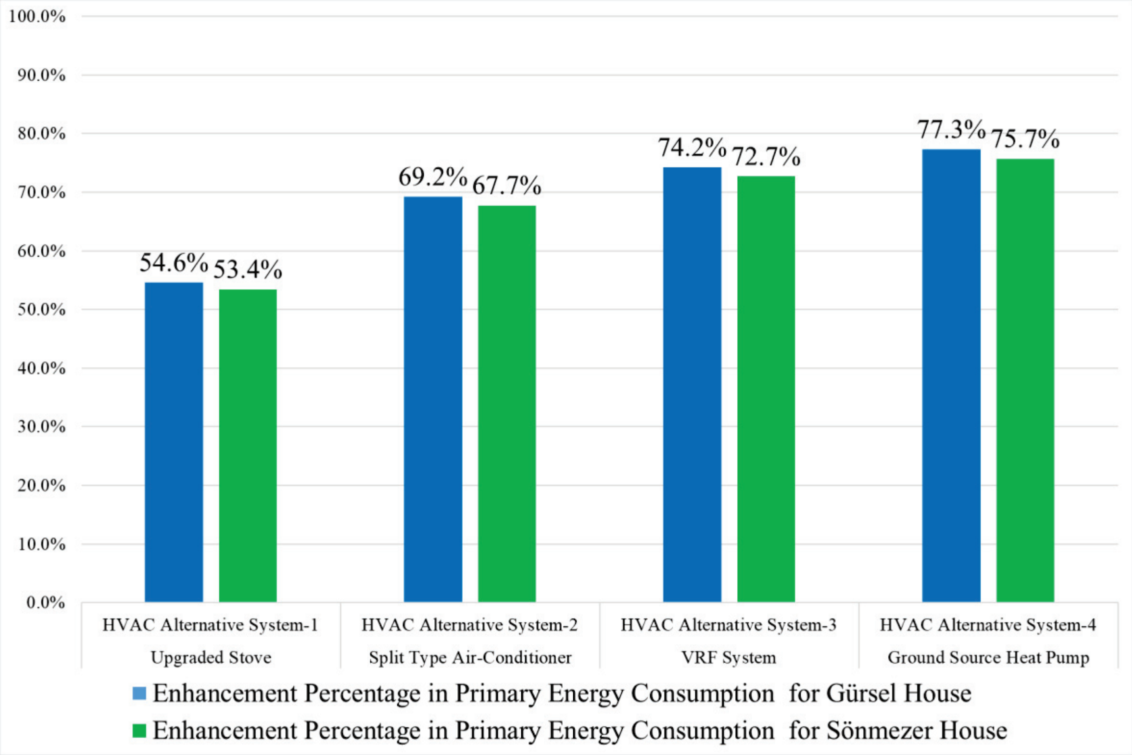

Figure 146. Comparison of HVAC alternatives for their enhancement percentages on primary energy consumption on case studies

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[61] Nibe Ground Source / A New Generation of Heat Pumps Brochure (2016) specifies average SCOP (Seasonal Coefficient of Performance) instead of separate efficiency rates for heating and cooling.

[62] According to ASHRAE (2016)

[63] According to Samsung Air Conditioner Catalog (2012)

[64] According to Toshiba VRF Solutions Catalogue (2017)

Table 74. Comparison of HVAC alternatives for their enhancement percentages on primary energy consumption of case studies

	Base Case (Currently Utilized HVAC Systems)		**Upgraded Stove**		**Split Type Air-Conditioner**		**VRF System**		**Ground Source Heat Pump**	
			HVAC Alternative System-1		**HVAC Alternative System-2**		**HVAC Alternative System-3**		**HVAC Alternative System-4**	
	Gürsel House	Sönmezer House	Gürsel House	Sönmezer House	Gürsel House	Sönmezer House	Gürsel House	Sönmezer House	Gürsel House	Sönmezer House
Annual Primary Energy Consumption / Occupied Floor Area (kWh / m²)	3423.9	3980.1	1555.6	1854.7	1053.7	1283.8	882.8	1087.8	777.4	967.3
Enhancement Percentage (%)	-	-	**54.6%**	**53.4%**	**69.2%**	**67.7%**	**74.2%**	**72.7%**	**77.3%**	**75.7%**

According to simulation results, in regards to primary energy consumptions, stove upgrading provides 54.6% and 53.4% improvements for Gürsel and Sönmezer Houses respectively; utilization of Split-type air conditioners reduces energy consumption by 69.2% and 67.6%; using VRF system yields in 74.2% and 72.7 reduction and use of ground source heat pump ensures 77.3% and 75.7% energy saving. Among these systems, installation of ground-source heat pump was specified to be the most beneficial HVAC alternative.

5.3. Comparison of Retrofitting Measures and Discussion

In this section, enhancement rates of the retrofitting measures are compared firstly within each case study building and secondly between different cases. And the last part of the section indicates the differences between enhancement rates of Set-1 (non-HVAC) and Set-2 (HVAC) retrofitting measures.

According to Figure 147, for Gürsel House, the most beneficial measure is the insulation work in floors between storeys and the least useful measure is the scheduling of window shutter operation followed by the ground floor insulation. It is also observed that night-time ventilation strategy causes even an increase in the overall primary energy consumption and therefore can be avoided. In addition, it is seen that interventions of roof insulation and ground floor insulation, while being beneficial in reducing heating loads, provoke evident rises in the cooling loads (Figure 148).

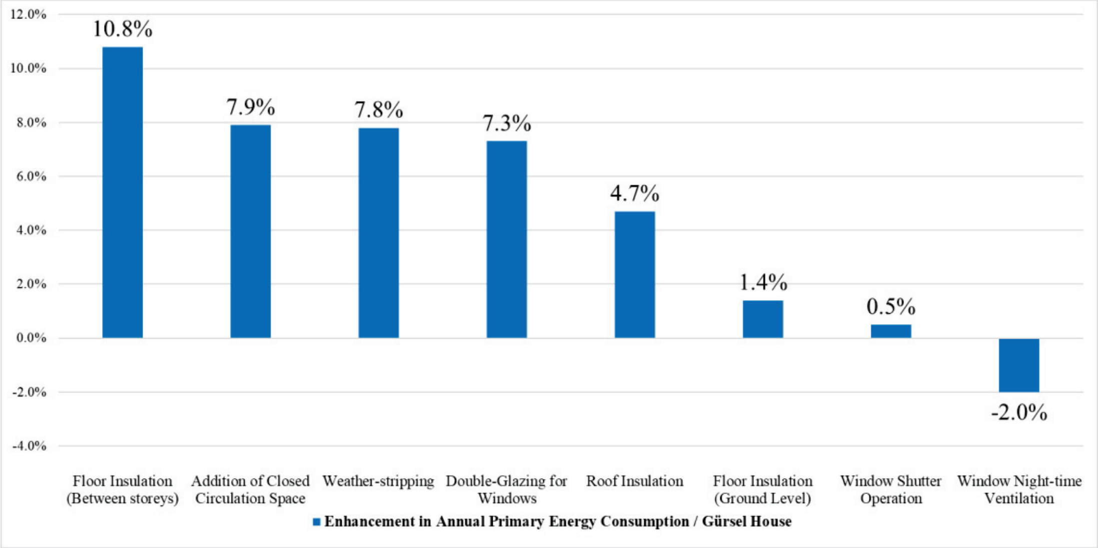

Figure 147. Ranking of enhancement rates for the retrofitting measures simulated in Gürsel House in regards to primary energy consumption

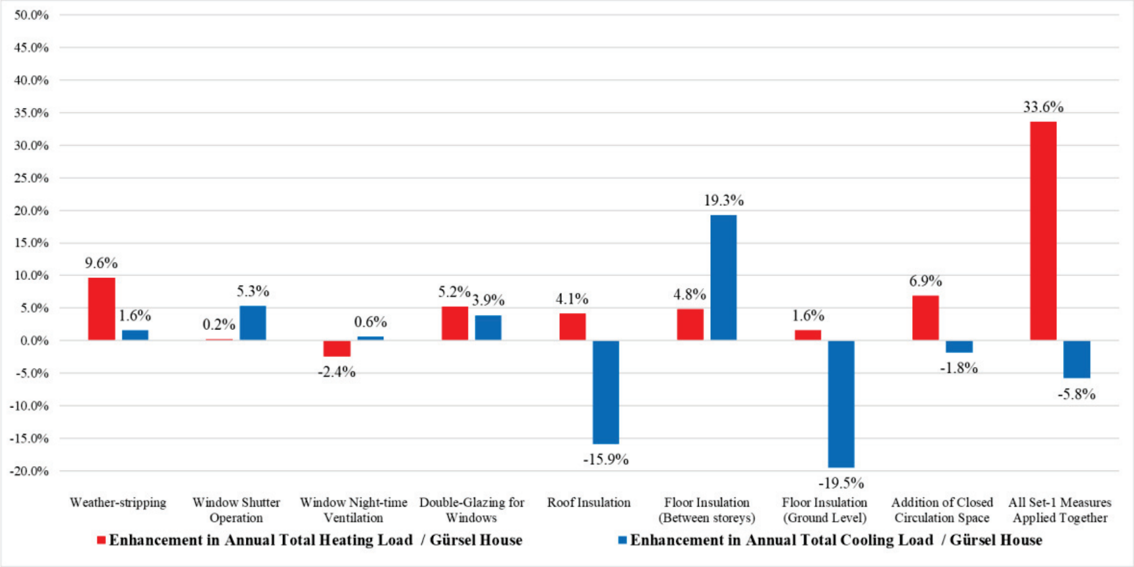

Figure 148. Comparison of retrofitting measures for Gürsel House in regards to heating and cooling loads

In the case of Sönmezer House, according to Figure 149, the most beneficial measure is the roof insulation and the least useful measures are the scheduling of night-time ventilation and window shutter operations followed by ground floor insulation. It is also observed that ground floor insulation and addition of glazed circulation space, while being beneficial in reducing heating loads, provoke evident rises in the cooling loads. However, as the dominant factor for the energy consumption of case studies is heating loads (Please refer to page 100), this rise in the cooling loads can be evaluated as negligible.

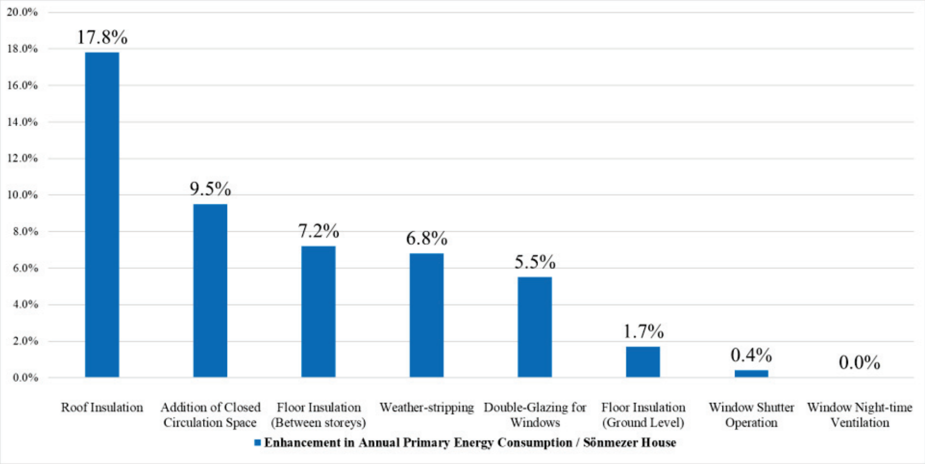

Figure 149. Ranking of enhancement rates for the retrofitting measures simulated in Sönmezer House in regards to primary energy consumption

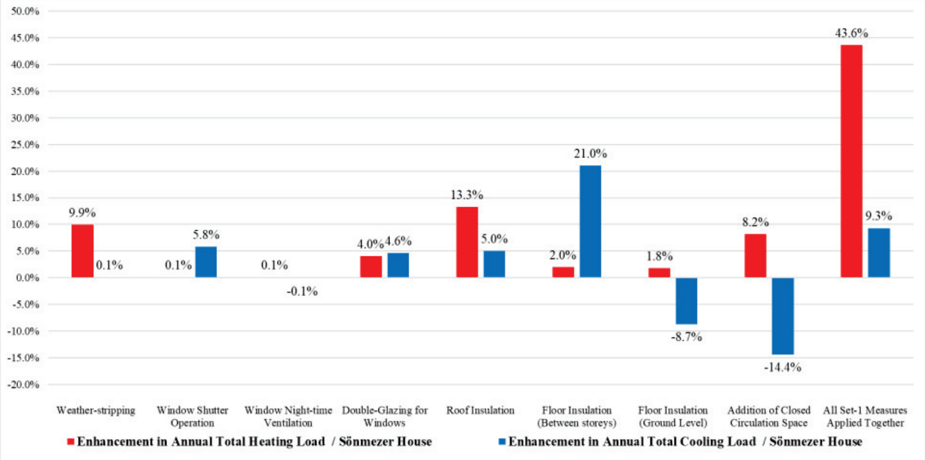

Figure 150. Comparison of retrofitting measures for Sönmezer House in regards to heating and cooling loads

Figure 151, Figure 152 and Figure 153 demonstrate the enhancement rates of retrofitting measures as compared between case studies for the variables of primary energy consumption, heating load and cooling load respectively. The charts show each measure result in enhancement rates with evident differences for each case study like the example of insulation in floors between storeys that result in 7.2 % enhancement for primary energy consumption of Sönmezer House while producing 10.8 % enhancement for Gürsel House. In addition to that, some measures even effect the thermal behavior of case studies inversely like the roof insulation that creates 5% reduction in the cooling loads of Sönmezer House while creating 15.9% increase for Gürsel House. As the case studies being selected from similar architectural type, scale, constructional features and even solar orientation, these differences are assumed to be originated from the influence of local microclimate and the neighborhood context. The difference is even more pronounced when all measures are applied together. In terms of annual primary energy consumption, 38.0% saving can be gained for Gürsel House while this saving rate can reach up to 49.4% for Sönmezer House.

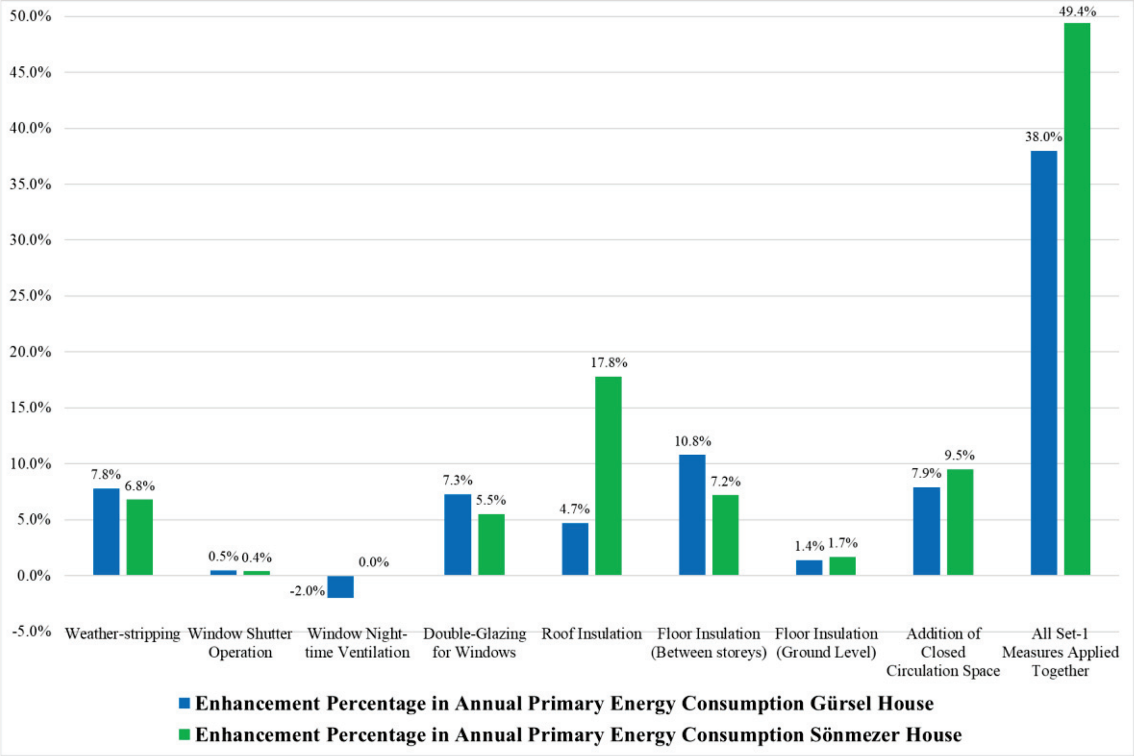

Figure 151. Comparison of retrofitting enhancement rates on primary energy consumption for both Gürsel and Sönmezer Houses

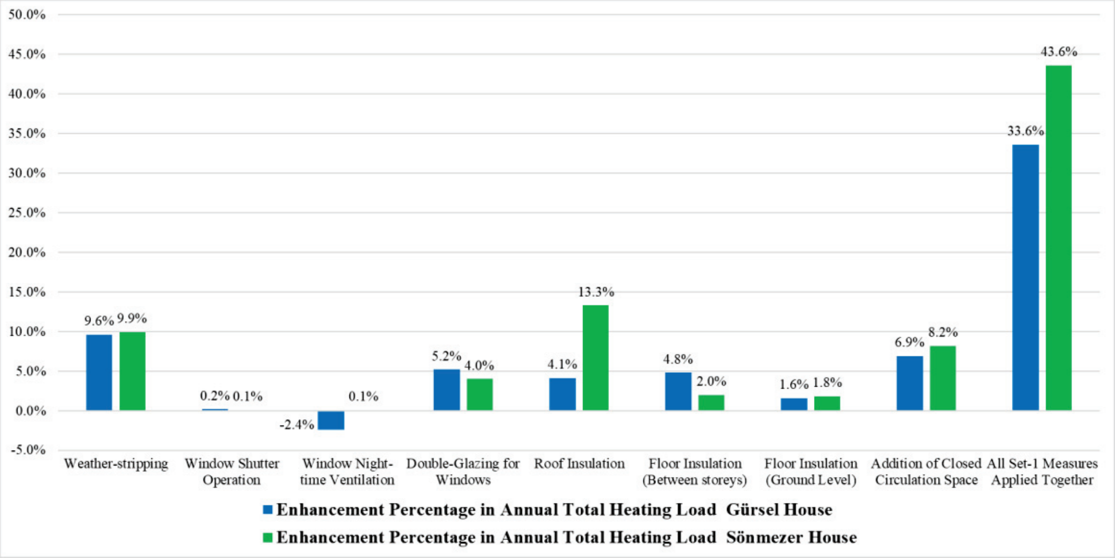

Figure 152. Comparison of retrofitting enhancement rates on heating loads for both Gürsel and Sönmezer Houses

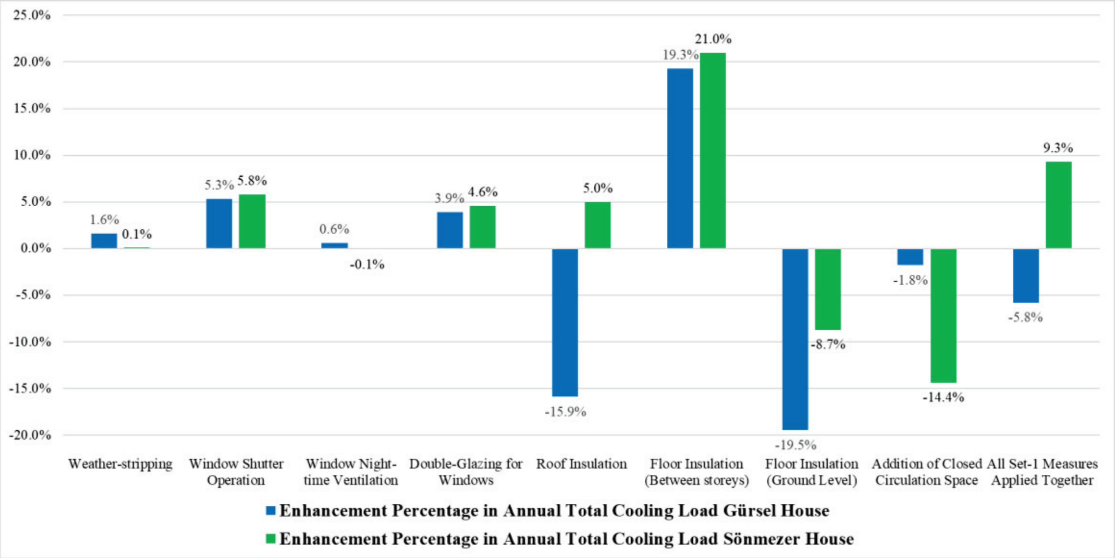

Figure 153. Comparison of retrofitting enhancement rates on cooling loads for both Gürsel and Sönmezer Houses

Figure 154 demonstrates the comparison of retrofitting enhancement rates of Set-1 (non-HVAC) and Set-2 (HVAC) measures. For Set-2, results of the most beneficial HVAC solution that is the installation of ground-source heat pump is presented. The chart is also complemented with the enhancement rates when all intervention sets are applied together.

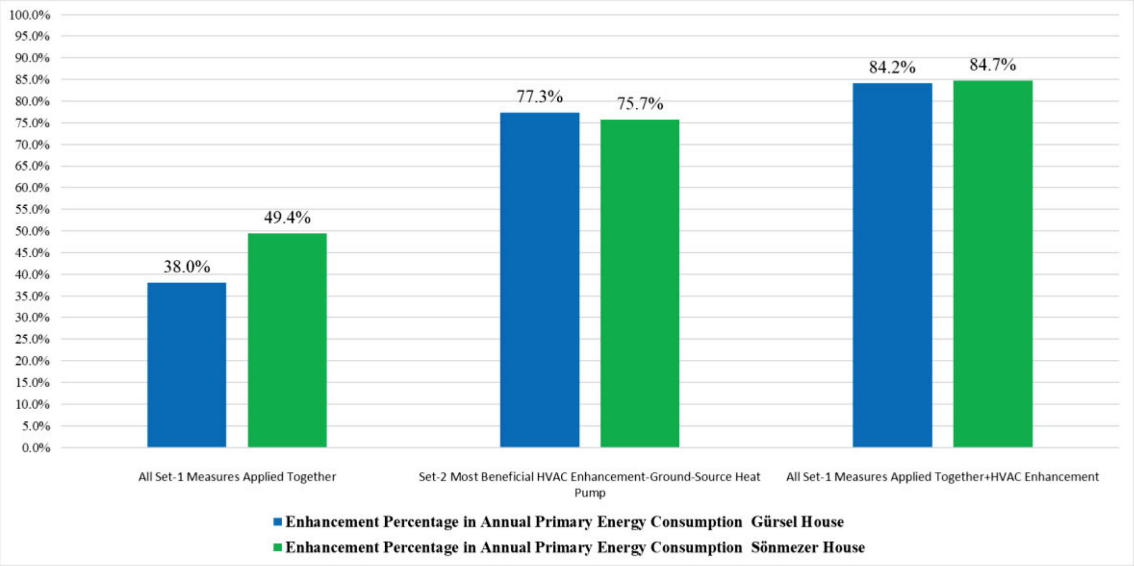

Figure 154. Comparison of retrofitting enhancement rates of Set-1 (non-HVAC) and Set-2 (HVAC) measures

According to this chart (Figure 154), introduction of new HVAC system seems significantly more beneficial than all non-HVAC interventions implemented together. However, it must be considered that the interventions on HVAC systems require an extensive set of potentially detrimental construction works (excavation, piping, wiring, equipment installation etc.) on the traditional building when the project is not carefully researched, designed, implemented and monitored. On the other hand, if all threats can be eliminated, it can be observed that more than 80% energy gain can be reached for both case studies when all retrofitting sets (HVAC + non-HVAC) are applied together which is not only important for the reduction of energy requirements but also for the reduction of ecological impacts of these traditional buildings considerably. Nevertheless, as seen by this quantitative study, traditional houses with exterior *sofa*s have evident potentials for energy upgrading even when not subjected to extensive interventions like the case of HVAC upgrading but retrofitted by simple fabric enhancements. The most beneficial of these enhancements can be specified as the insulation works on roofs and on floors between storeys, weather-stripping, addition of double glazing for windows and addition of glazed circulation corridors on *sofa*s. Conversely, ground floor insulation and rescheduling of window shutters seem to have very little effect while nighttime ventilation is not suggested.

In choosing of the thermal measures to be evaluated in this thesis study, some interventions, which have been commonly referred and suggested by the related literature (Table 76), such as the insulation works on walls[65] (Ascione et al., 2011; Berardinis et al., 2014; Deralla, 2014; Şahin et al., 2015; Ciulla et al., 2016; Cornaro et al., 2016; Ascione et al., 2017; Rodrigues. et al., 2017a; Rodrigues et al., 2017b; Ulu, 2018; Moschella. et al., 2018; Duarte et al., 2019) and the replacement of the original windows with high efficiency modern designs (Deralla, 2014; Şahin et al., 2015; Ciulla et al., 2016; Ascione et al., 2017; Duarte et al., 2019) were omitted from the tested retrofitting intervention list. By this course, it was sought to point out the possible detrimental effects that can be caused by the implementation of these interventions such as the loss of authentic features (e.g. original window design, workmanship, detailing and material) and the risk on the aesthetic integrity (mostly due to the visual alterations regarding the color, texture, ornamental elements, openings and the proportions of the interior and / or exterior facades) of the historical buildings. Moreover, with the simulation results of this thesis, it was demonstrated that even these interventions are not applied, significant energy saving rates can be reached by the combination of other types of thermal interventions (Figure 154). In contrast to this exclusion, there applied some special focus on some thermal intervention measures that have not been widely referred in earlier works. More specifically, thermal interventions such as the insulation works in floors between storeys and the addition of closed entrance / circulation corridors were tested and evaluated in this study in order to emphasize the possible thermal enhancement potentials of these solutions (Table 76). Furthermore, within the methodology of this study, thermal simulation analyses were complemented with PMV (thermal comfort) analyses in order to specify the optimum HVAC temperature set points separately for each room of the case studies rather than pre-assuming the same set points for all of them.

As seen in Table 75, there is a significant diversity between the energy saving percentages suggested by the researchers (Please see section 1.3.1 for the detailed descriptions of these works) evaluating the effects of thermal retrofitting measures applied on historical houses. This diversity mostly originates from the fact that the cases studied in these works demonstrate an extensive variety of building types such as single houses (urban and rural), apartment buildings and even palaces with distinct differences

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[65] Whether it is applied on the interior or exterior faces of the walls.

on their architectural and constructional characteristics as well as their urban contexts while being located on a large geography (Mediterranean countries).

Table 75. Comparison of the energy saving results of this thesis study to similar studies

Reference Study	**Scope of Retrofitting Measures**	**Overall Energy Saving Percentage**	**Location of Case Study**
Ascione et al., 2011	Building envelope, HVAC systems	22%	Benevento / Italy
Ulu, 2018	Building envelope	31%	İzmir / Turkey
Ascione et al., 2015	Building envelope, HVAC systems	38%	Benevento / Italy
Şahin et al., 2015	Building envelope, HVAC systems	35%-41%	İzmir / Turkey
This Thesis Study	Building envelope	**38%-49.4%**	Muğla / Turkey
Berardinis., 2014	Building envelope	53.4%	L'Aquila / Italy
Pisello et al., 2014	HVAC systems	57%	Perugia / Italy
Ascione et al., 2017	Building envelope, HVAC systems	59%	Naples / Italy
Ciulla et al., 2016	Building envelope	48.9%-69%	Palermo, Cagliari, Rome, Milano / Italy
This Thesis Study	Building envelope, HVAC systems	**84.2%-84.7%**	Muğla / Turkey
Duarte et al., 2019	Building envelope, HVAC systems	83.1%-140%	Lisbon / Portugal
* For saving percentages, best results that were suggested by the studies were presented in the table.			

However, variety of the different retrofitting measure sets that are proposed in these studies (Table 76) and the differences on their analysis and evaluation methods also enhance this diversity which consequently show that proposing thermal retrofitting measures as to be applied on historical buildings requires case-specific analyzes and evaluations as no generic solutions can be applied to all buildings. Notedly, this argument necessitates the active involvement of thermal analyses within the restoration processes of the historical buildings. This involvement must be established from the early building documentation stages as the specification of thermal features of the buildings regarding the constructional aspects, occupancy patterns, HVAC systems and the building services (e.g. artificial lighting, DHW). Similarly, in restitution stages, as complementary to the alteration analyses, historical buildings must also be re-evaluated for their original thermal behavior and its changing possibly occurred over time. And the final decision making stage of a restoration project, which conventionally establish the architectural, functional and constructional intervention sets, must also refer to the thermal needs of the occupants and the energy requirements of the historical buildings while seeking ways to reduce the energy use as assisting to sustain the functional continuity of these buildings.

Table 76. Thermal retrofitting measures that were evaluated in studies on historical houses

Retrofitting measure	**Study that evaluated the retrofitting measure**
Weather-stripping Works	Ascione et al., 2011; Şahin et al., 2015; Cornaro et al., 2016; Ulu, 2018; This Thesis Study
Night-time Ventilation	Ulu, 2018; Duarte et al., 2019; This Thesis Study
Rescheduling Window Shutter Operation	Ulu, 2018; Duarte et al., 2019; This Thesis Study
Replacement of Windows	Deralla, 2014; Şahin et al., 2015; Ciulla et al., 2016; Ascione et al., 2017; Duarte et al., 2019
Addition of Second Glazing to Windows	Ulu, 2018; Moschella. et al., 2018; This Thesis Study
Thermal Insulation on Walls	Ascione et al., 2011; Berardinis et al., 2014; Deralla, 2014; Şahin et al., 2015; Ciulla et al., 2016; Cornaro et al., 2016; Ascione et al., 2017; Rodrigues. et al., 2017a; Rodrigues et al., 2017b; Ulu, 2018; Moschella. et al., 2018; Duarte et al., 2019
Thermal Insulation on Roofs	Deralla, 2014; Şahin et al., 2015; Ciulla et al., 2016; Ascione et al., 2017; Rodrigues. et al., 2017a; Rodrigues et al., 2017b; Ulu, 2018; Moschella. et al., 2018; Duarte et al., 2019; This Thesis Study
Thermal Insulation in Floors Between Storeys	This Thesis Study
Thermal Insulation on Ground Floors	Şahin et al., 2015; Ulu, 2018; This Thesis Study
Addition of Closed Circulation / Entrance Space	This Thesis Study
Introduction of New HVAC System	Ascione et al., 2011; Pisello et al., 2014; Şahin et al., 2015; Ascione et al., 2017; Duarte et al., 2019; This Thesis Study
Altering Occupancy Patterns	Rodrigues. et al., 2017a

CHAPTER 6

CONCLUSION

The aim of this thesis is to examine thermal characteristics of traditional houses with exterior *sofa* which constitute a very common building type among the architectural heritage of Anatolia and based on this examination, to determine enhancement potentials of possible thermal retrofitting interventions in order to develop conservation decisions to sustain the functional continuity of these buildings. Within the scope of the thesis, evaluated thermal retrofitting interventions were chosen to focus more on the enhancements of building envelopes rather than HVAC solutions and rearrangement of occupant behaviors. And the analyses of the study were concentrated more on the energy saving rates of these enhancements rather than their financial feasibility and the architectural detailing for their implementations.

The method of the study consists of on-site thermal measurements and transient thermal analysis of case studies utilizing building thermal simulation software. In the application of this method and the selection of tools, specifying the building attributes such as building geometry, climate conditions, construction technique and material in detail and consequently establishing simulation results in precision were the main goal. In order to reach that goal, an extensive work of on-site architectural survey and thermal measurements, calibration of measurement instrument, laboratory analyses on construction materials, preparation of separate weather data for urban and rural sub-settlements, 3D virtual modeling, validation of the models with calibration assessments and transient simulations were conducted as complementary to one another. In parallel, for the determination of set point temperatures for HVAC systems that were processed in thermal simulations, no identical value was used for all rooms of case studies, but specific set points were determined utilizing room by room PMV analyses. As *DesignBuilder* software was used for modeling and simulation works, the results and analyses following these stages demonstrate the precision level within the capabilities and limitations of this software. These limitations especially affected the fine-tuning of PMV analyses.

Case study buildings were selected in Muğla City, which possesses a well-preserved stock of traditional houses. The cases were chosen from both urban and rural sub-settlements in order to detect possible effects of prevailing microclimates and dissimilar urban forms to the thermal behavior of the buildings. The results demonstrated that energy use of rural houses are much higher and they are significantly more responsive to thermal retrofitting measures. This situation is in parallel to the fact that thermal conditions of the rural sub-settlement tend to change more rapidly between daytime and nighttime hours in regards to the temperature and humidity values.

Using the results of thermal analyses, it was demonstrated that the most beneficial interventions are the insulation works on roofs and on floors between storeys, weather-stripping measures, addition of double glazing for windows and introduction of glazed circulation corridors that connect the rooms to one another which otherwise open directly to the outside weather conditions. Conversely, ground floor insulation and rescheduling of window shutter operation seem to have very little effect, while nighttime ventilation was noticed to be increasing the overall energy consumption and wall insulation was deemed to risk the heritage values by causing possible losses on texture, color and ornamentation regarding outer and inner facades of the buildings as well as jeopardizing room proportions and authentic detailing. Some alternatives of HVAC preferences such as use of high-efficiency stoves, split-type air-conditioners, VRF systems and ground-source heat pumps were also tested numerically as comparison to the building envelope enhancements. It was shown that retrofitting percentages of HVAC enhancements exceed the benefits of interventions on building envelopes by long margins. However, possible risks of these enhancements that may stem from their implementation extent and the necessity for further analyses were also pointed out. Nonetheless, the results of this study demonstrate that the traditional houses with exterior *sofa* have great potential for thermal enhancements which may be regarded as an available conservation strategy to safeguard the functional continuity of these buildings. More specifically, it was shown that without any HVAC alteration, thermal enhancement measures can provide energy saving rates more than one third of the current energy consumptions in the urban center and nearly half of the current consumptions in the rural area. These saving rates can reach more than 80% when complementary HVAC interventions are also implemented. These significant results call for the necessity to establish the thermal analyses as an active participant within the restoration processes that requires their involvement from the early architectural documentation phases to the final decision making stages.

As the traditional houses of Anatolia, which have been scattered through an extensive geography, demonstrate a great variety of building types in a diversity of different constructional features, dimensions, scales, geometry, spatial organizations, urban contexts and climatic conditions, this thesis study can be complemented by further researches focused on different architectural types in order to reach a general overview on the thermal behavior, requirements and retrofitting potentials of the traditional houses of Anatolia. This overview has the potential to support the decision-making processes regarding the conservation of these buildings.

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APPENDIX A

DATA LOGGER CALIBRATION READINGS & CORRECTION FORMULAS

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
9.8	10.0	10.0
19.9	20.0	20.0
30.0	30.0	30.0

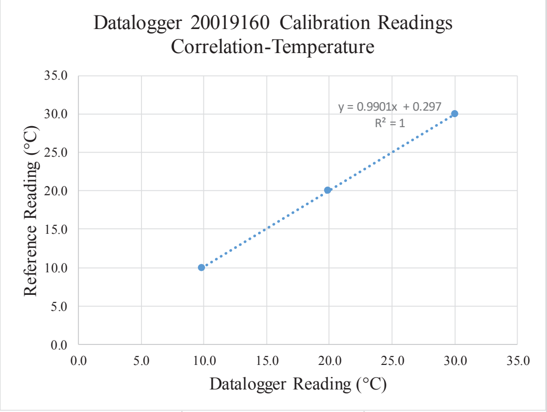

Figure 155. Temperature readings and calibration formula for data logger 20019160

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
20.2	14.9	14.9
53.5	52.4	52.5
81.3	79.9	80.2

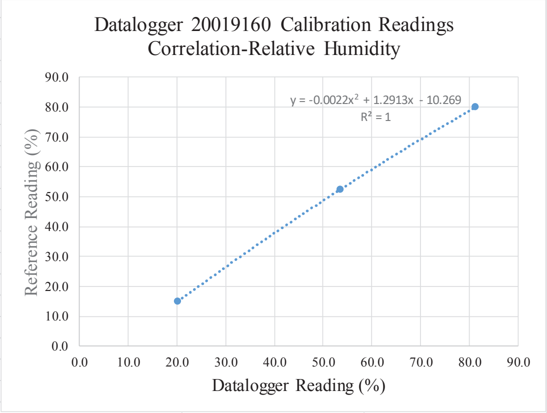

Figure 156. Relative humidity readings and calibration formula for data logger 20019160

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
10.0	10.0	10.0
20.0	20.0	20.0
30.0	30.0	30.0

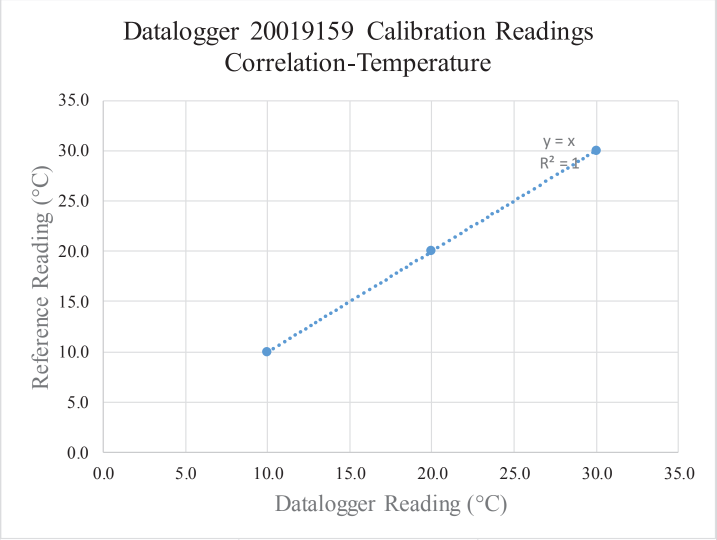

Figure 157. Temperature readings and calibration formula for data logger 20019159

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
19.2	14.9	14.9
51.4	52.4	52.4
80.3	79.9	79.8

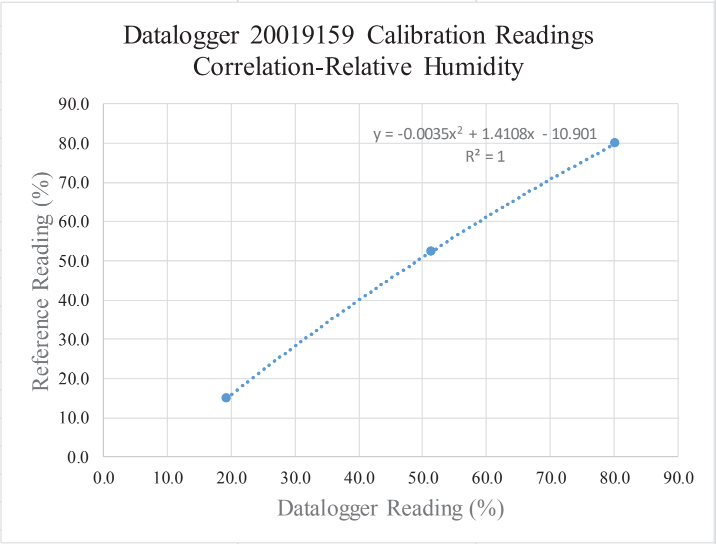

Figure 158. Relative humidity readings and calibration formula for data logger 20019159

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
10.1	10.0	10.0
20.0	20.0	20.0
30.2	30.0	30.0

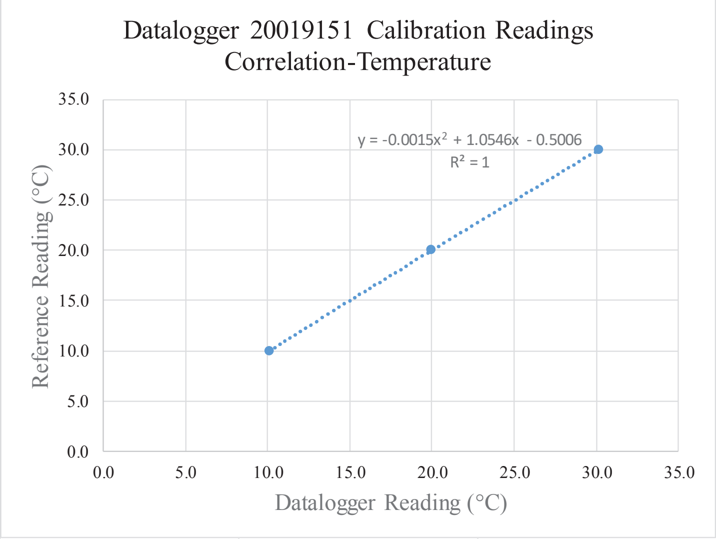

Figure 159. Temperature readings and calibration formula for data logger 20019151

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
20.5	14.9	14.9
53.6	52.4	52.5
81.0	79.9	80.1

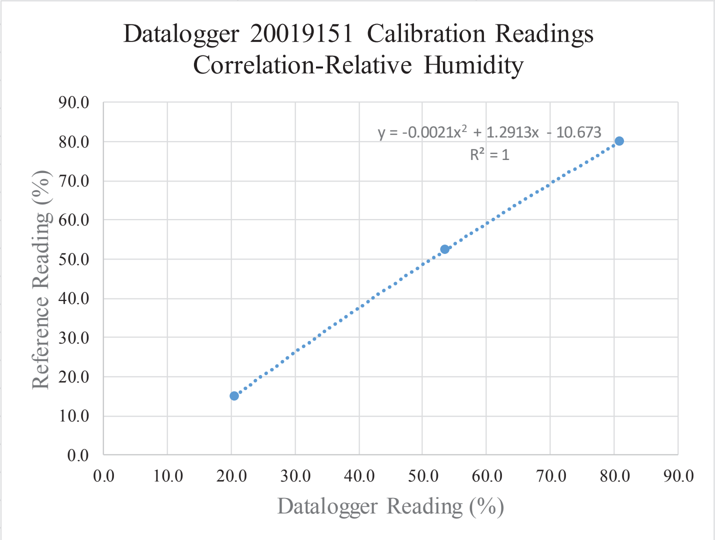

Figure 160. Relative humidity readings and calibration formula for data logger 20019151

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
10.0	10.0	10.0
20.0	20.0	20.0
29.9	30.0	30.0

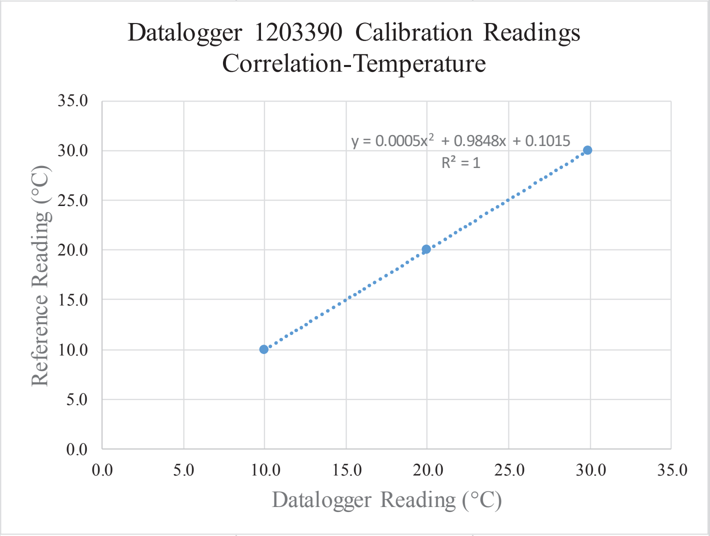

Figure 161. Temperature readings and calibration formula for data logger 1203390

Datalogger Reading	Reference Reading	Adjusted Reading with Correction Formula
23.0	14.9	14.9
56.0	52.4	52.5
80.5	79.9	80.2

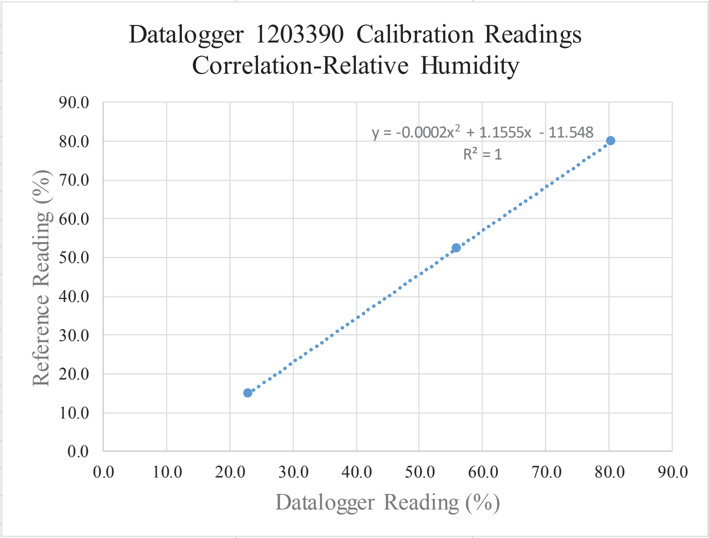

Figure 162. Relative humidity readings and calibration formula for data logger 1203390

APPENDIX B

COMPARISON OF DAILY TEMPERATURE MEASUREMENTS ON CASE STUDIES / HOURLY AVERAGES FOR EACH MONTH

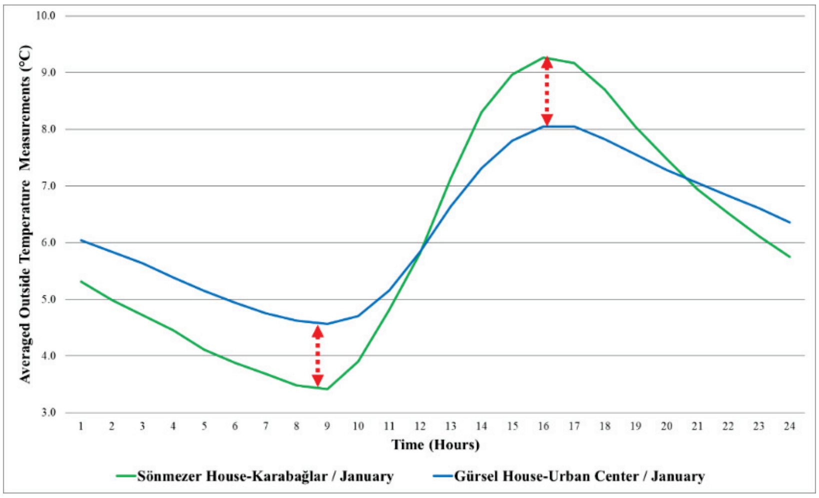

Figure 163. Comparison of monthly average daily temperature measurements on case studies / hourly averages for January. Red arrows indicate the hours with significant differences.

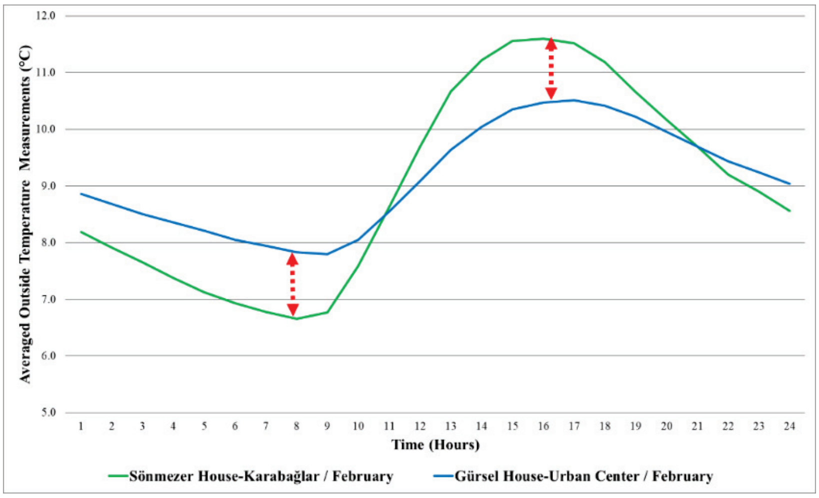

Figure 164. Comparison of monthly average daily temperature measurements on case studies / hourly averages for February. Red arrows indicate the hours with significant differences.

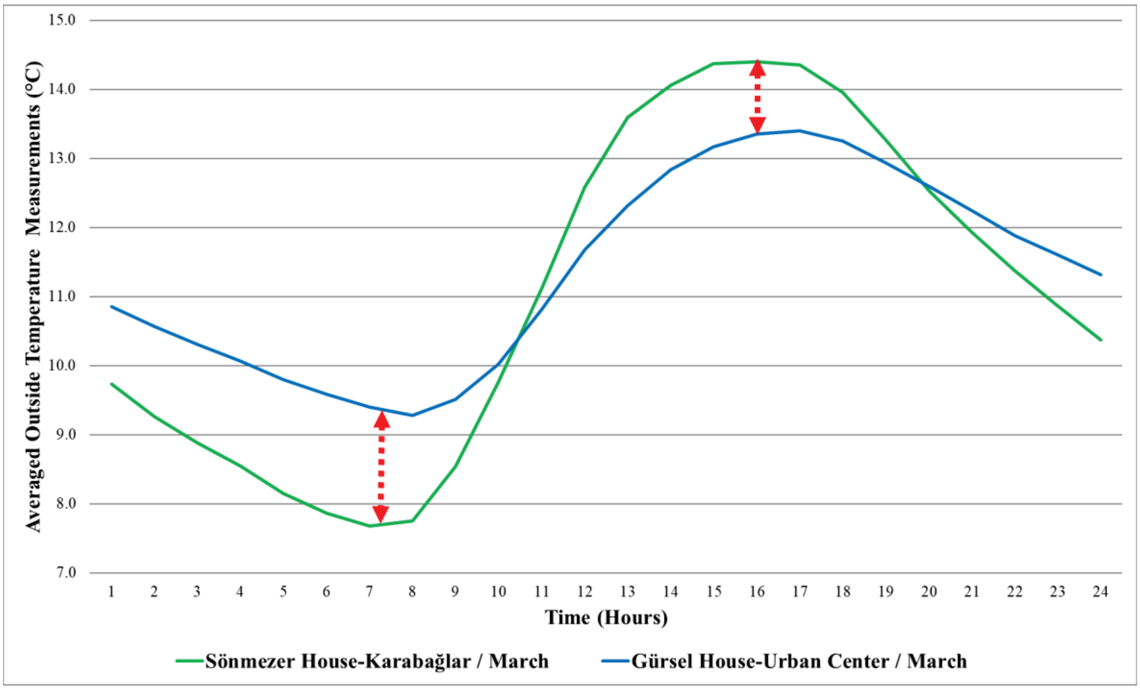

Figure 165. Comparison of monthly average daily temperature measurements on case studies / hourly averages for March. Red arrows indicate the hours with significant differences.

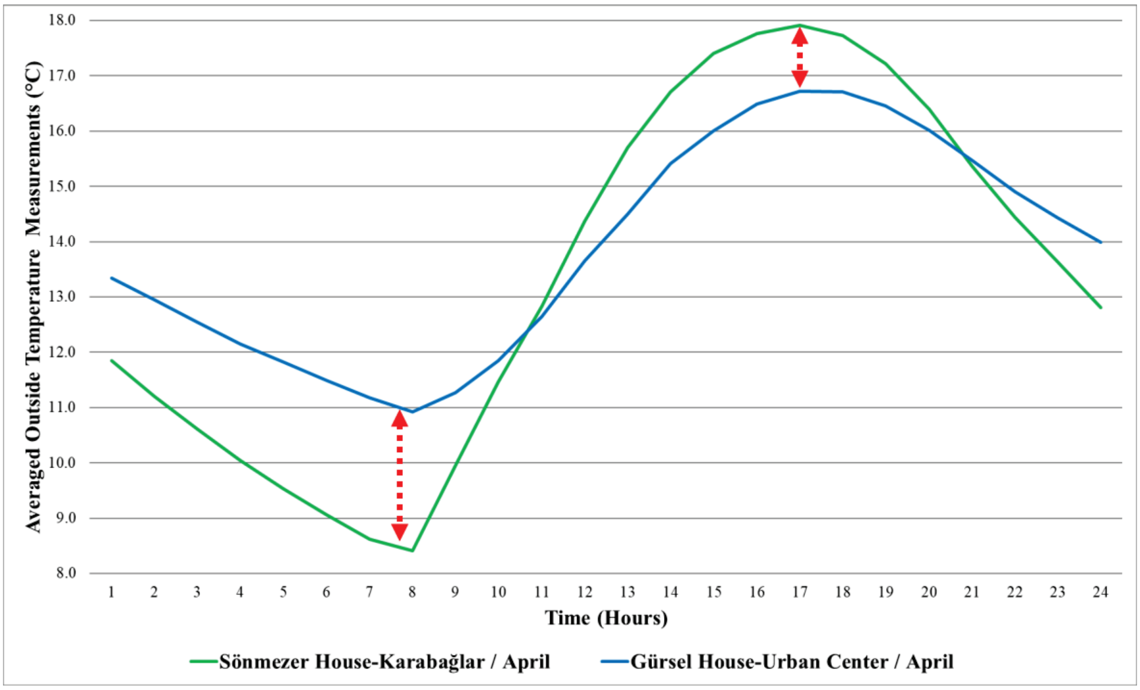

Figure 166. Comparison of monthly average daily temperature measurements on case studies / hourly averages for April. Red arrows indicate the hours with significant differences.

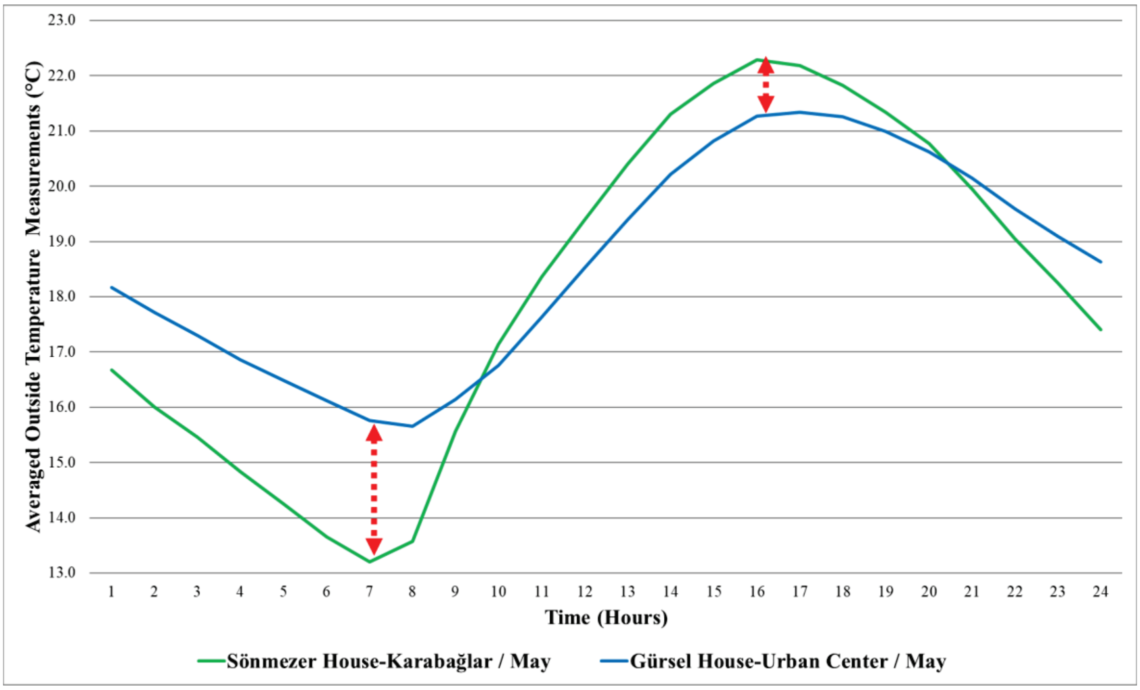

Figure 167. Comparison of monthly average daily temperature measurements on case studies / hourly averages for May. Red arrows indicate the hours with significant differences.

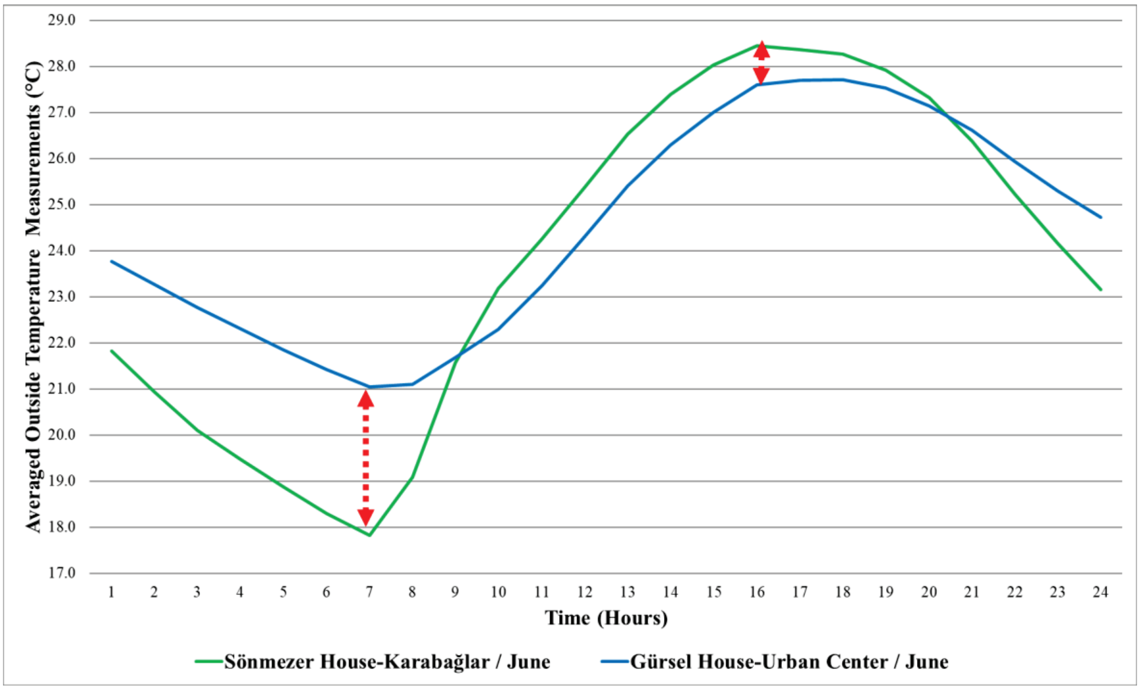

Figure 168. Comparison of monthly average daily temperature measurements on case studies / hourly averages for June. Red arrows indicate the hours with significant differences.

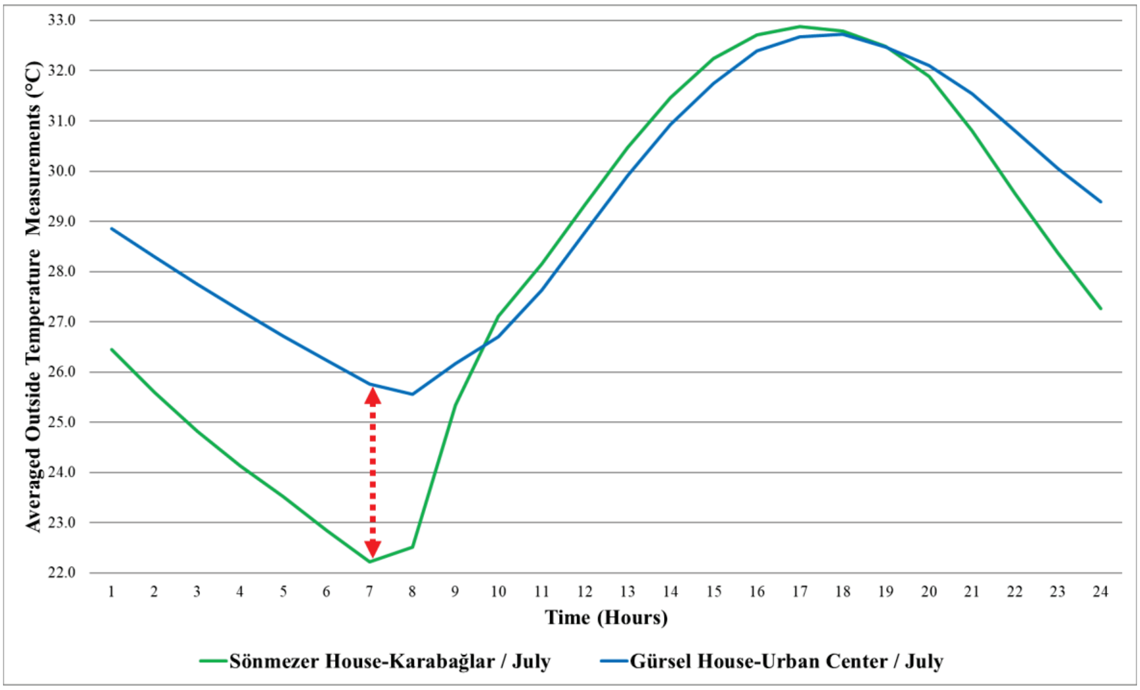

Figure 169. Comparison of monthly average daily temperature measurements on case studies / hourly averages for July. Red arrow indicates the hour with the most significant difference.

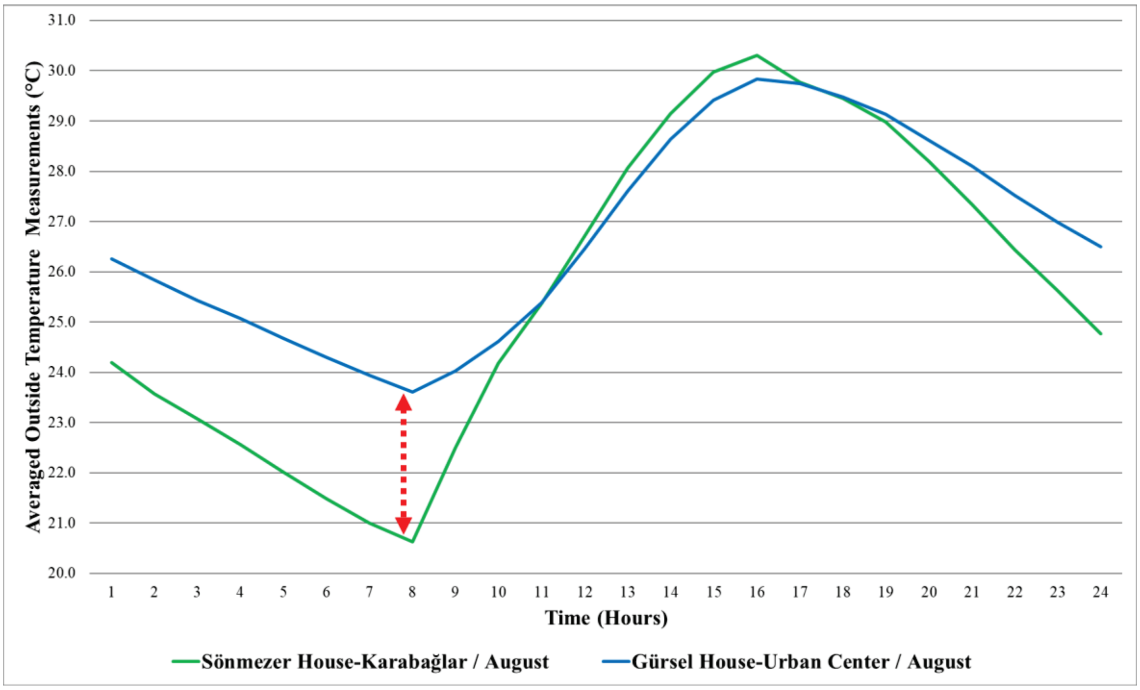

Figure 170. Comparison of monthly average daily temperature measurements on case studies / hourly averages for August. Red arrow indicates the hour with the most significant difference.

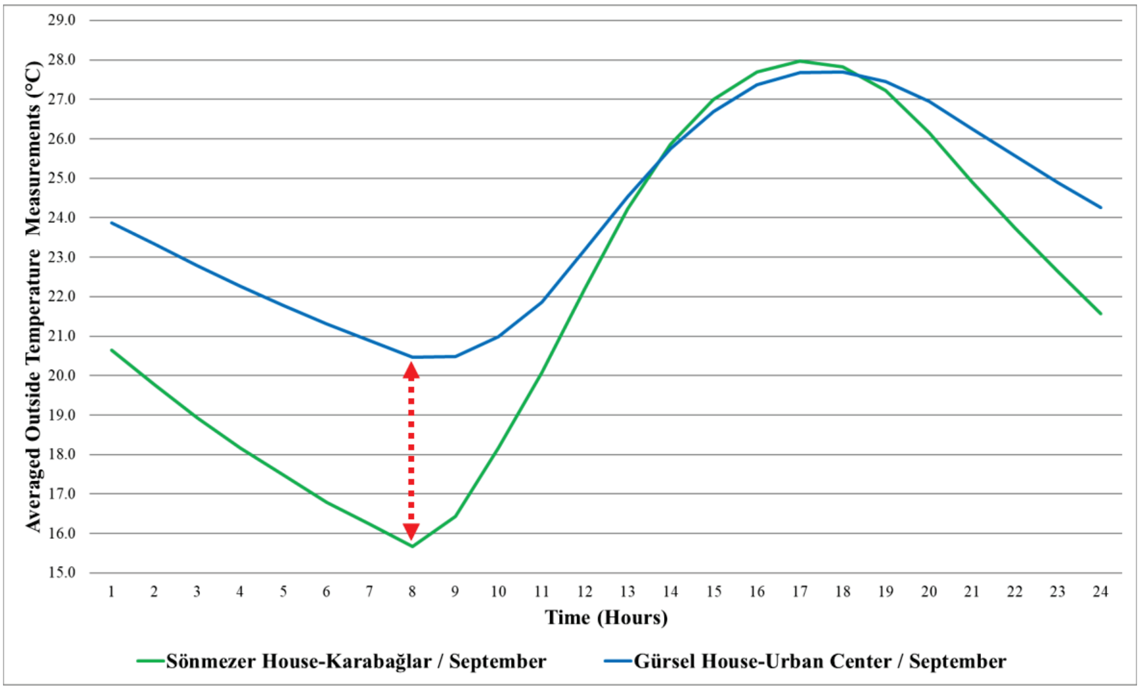

Figure 171. Comparison of monthly average daily temperature measurements on case studies / hourly averages for September. Red arrow indicates the hour with the most significant difference.

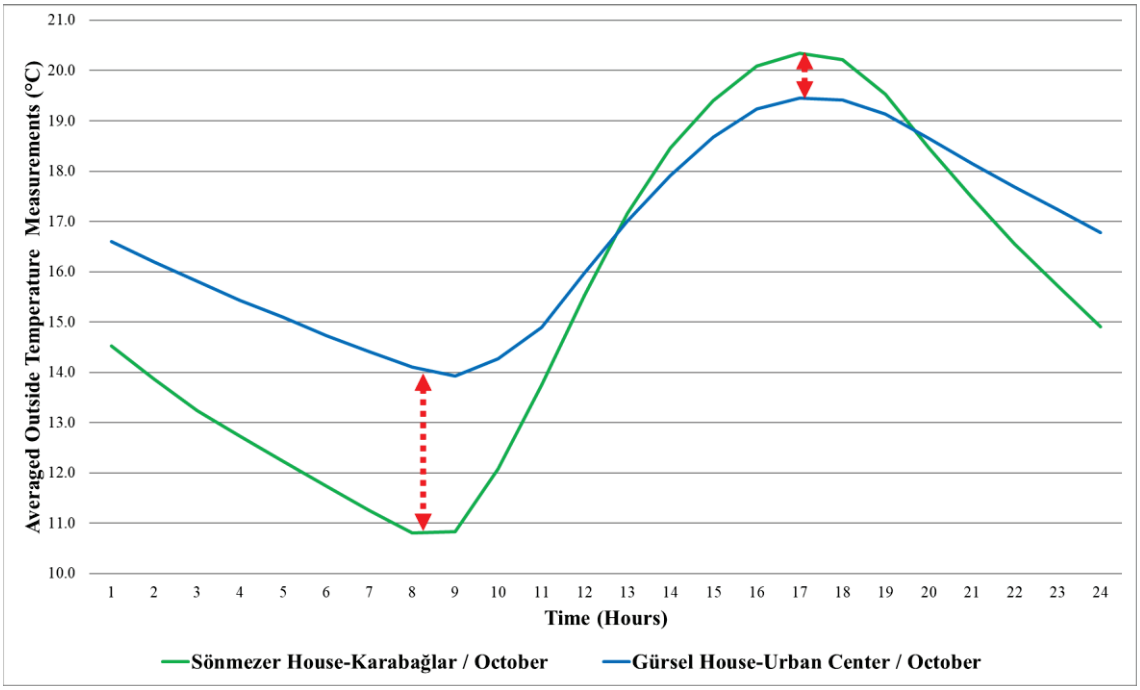

Figure 172. Comparison of monthly average daily temperature measurements on case studies / hourly averages for October. Red arrows indicate the hours with significant differences.

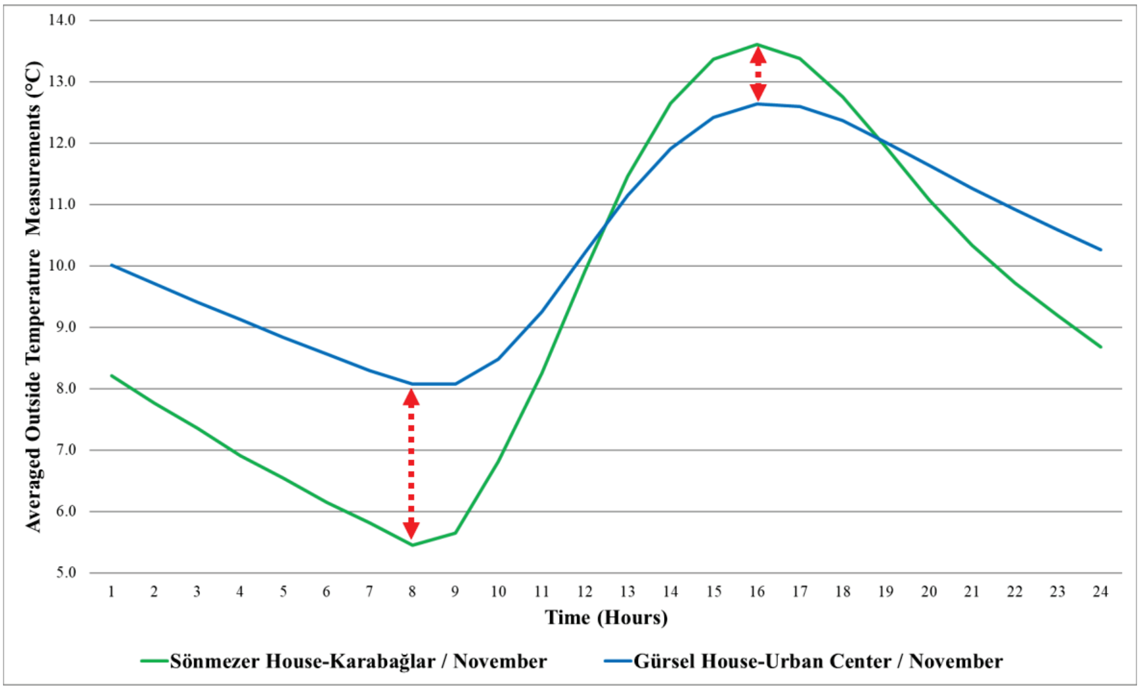

Figure 173. Comparison of monthly average daily temperature measurements on case studies / hourly averages for November. Red arrows indicate the hours with significant differences.

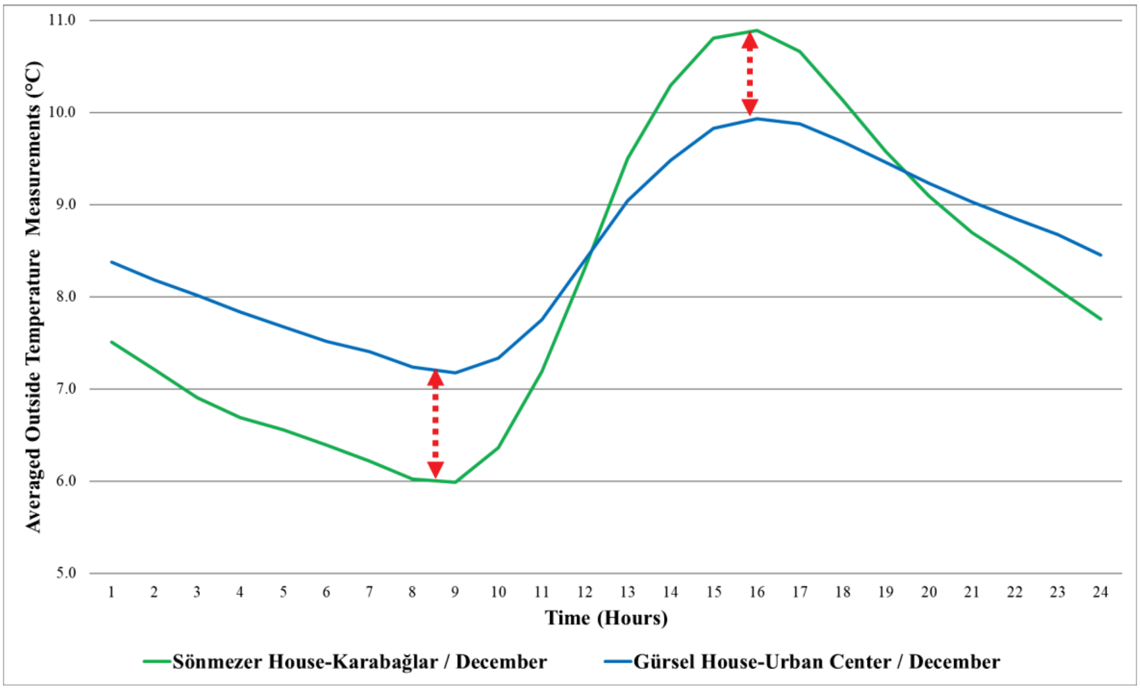

Figure 174. Comparison of monthly average daily temperature measurements on case studies / hourly averages for December. Red arrows indicate the hours with significant differences.

APPENDIX C

COMPARISON OF DAILY RELATIVE HUMIDITY MEASUREMENTS ON CASE STUDIES / HOURLY AVERAGES FOR EACH MONTH

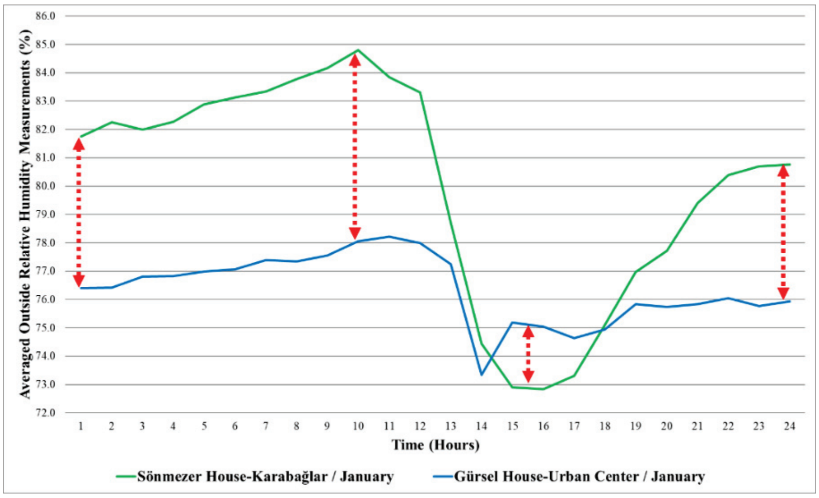

Figure 175. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for January. Red arrows indicate the hours with significant differences.

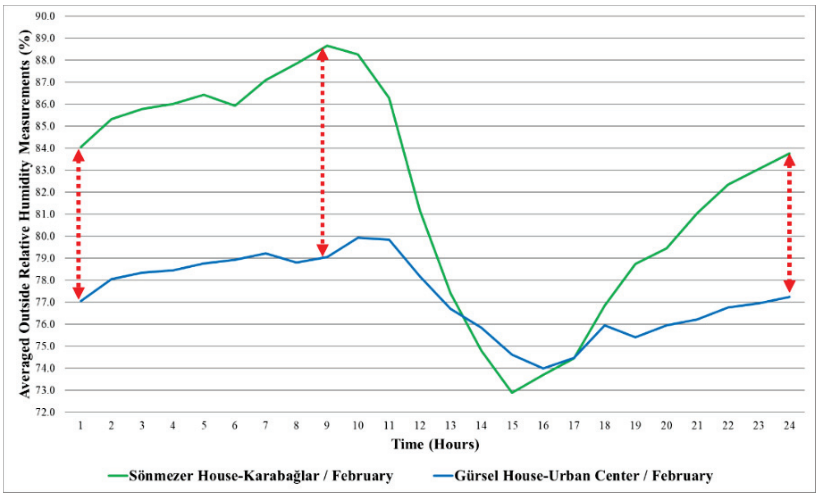

Figure 176. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for February. Red arrows indicate the hours with significant differences.

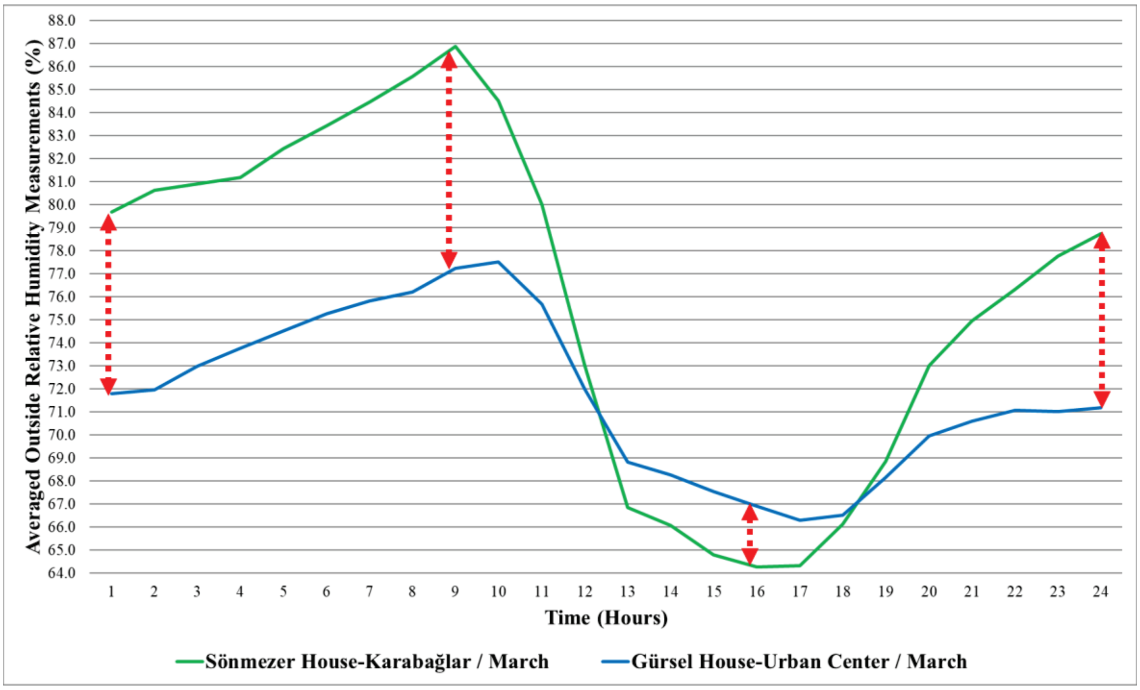

Figure 177. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for March. Red arrows indicate the hours with significant differences.

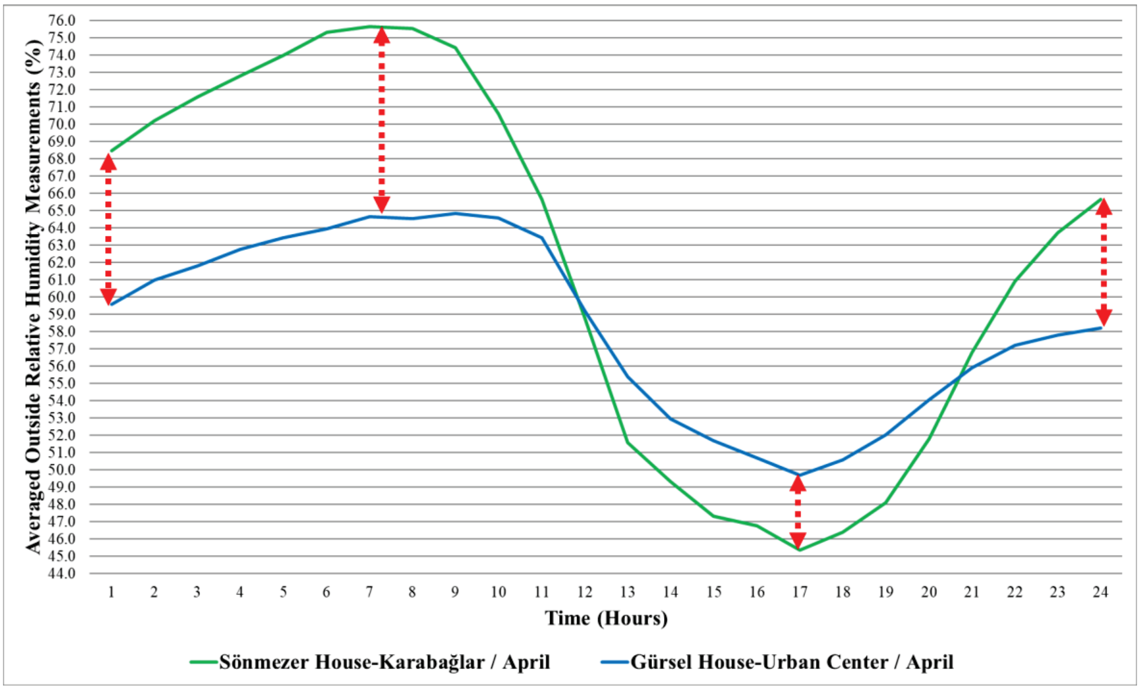

Figure 178. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for April. Red arrows indicate the hours with significant differences.

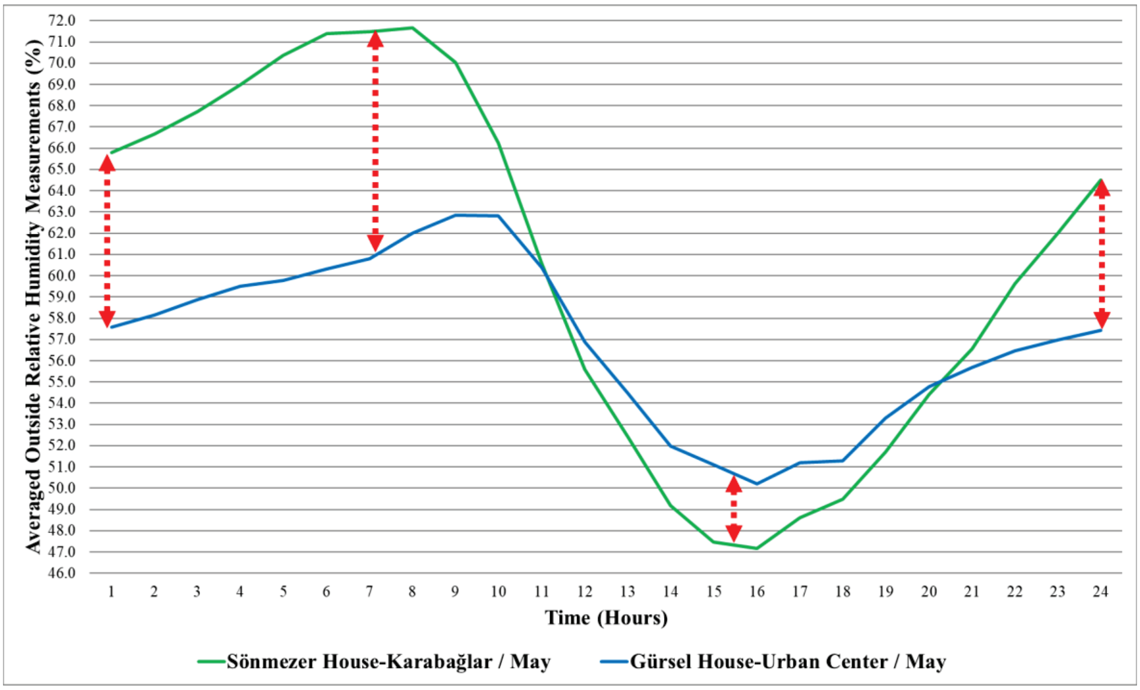

Figure 179. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for May. Red arrows indicate the hours with significant differences.

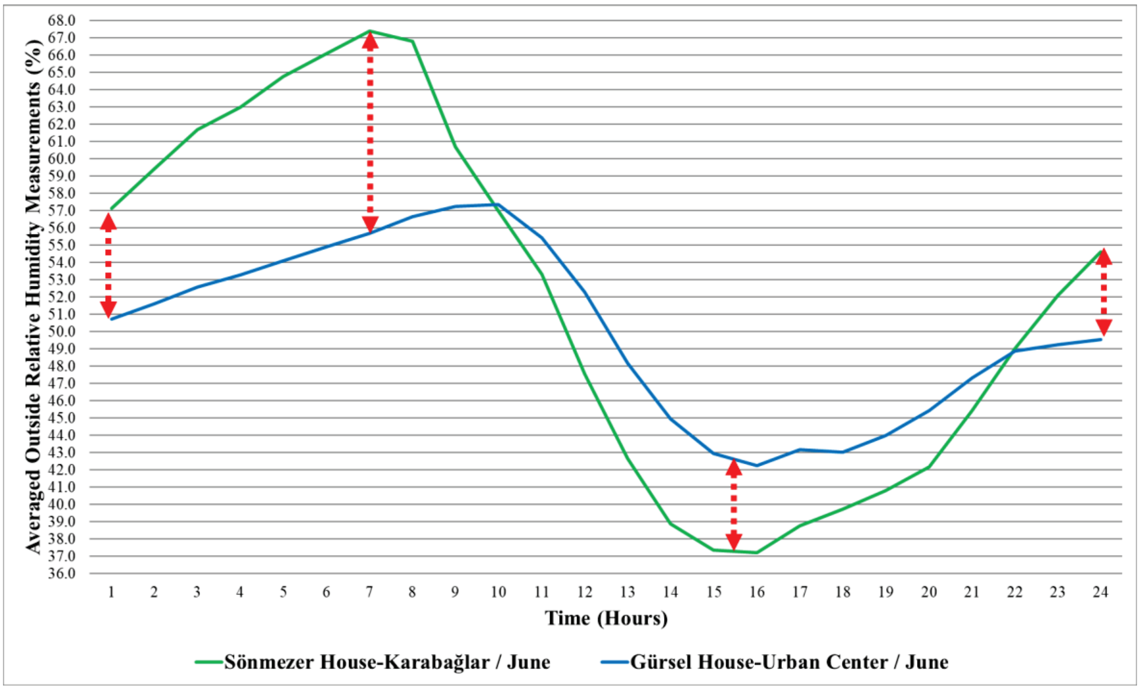

Figure 180. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for June. Red arrows indicate the hours with significant differences.

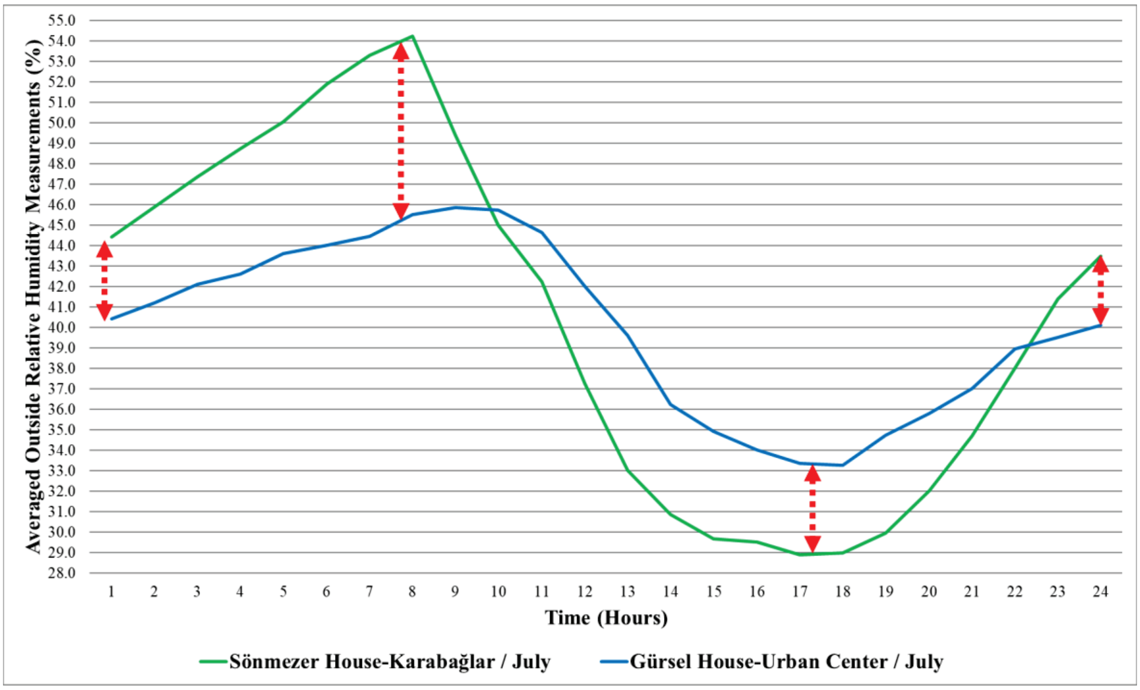

Figure 181. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for July. Red arrows indicate the hours with significant differences.

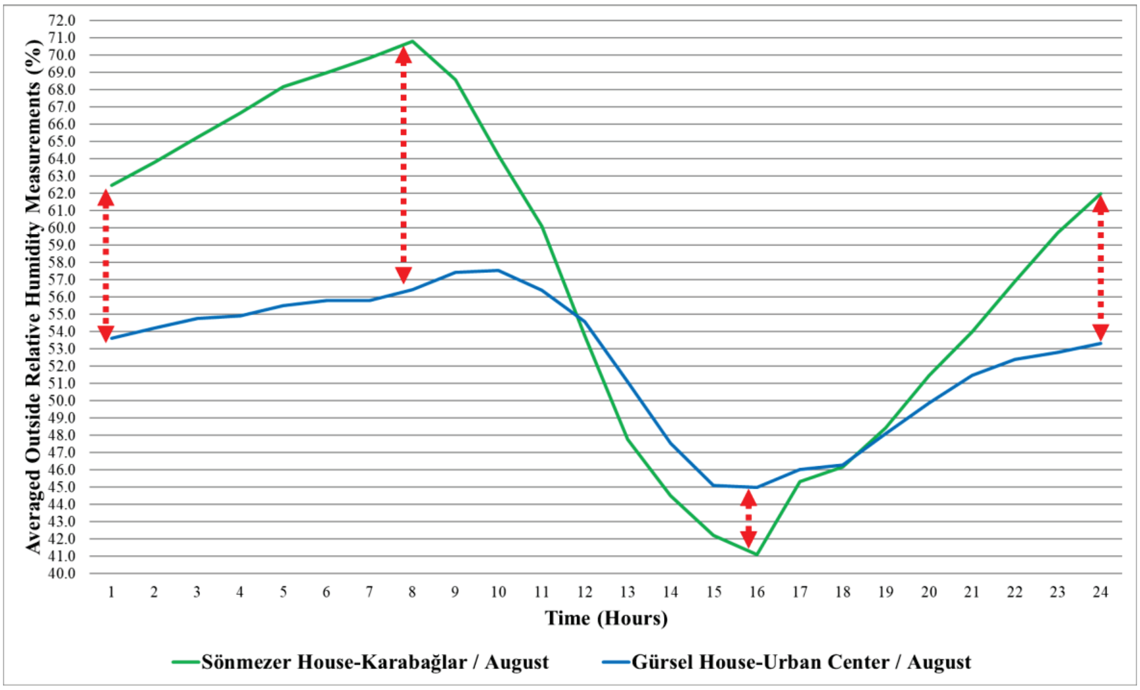

Figure 182. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for August. Red arrows indicate the hours with significant differences.

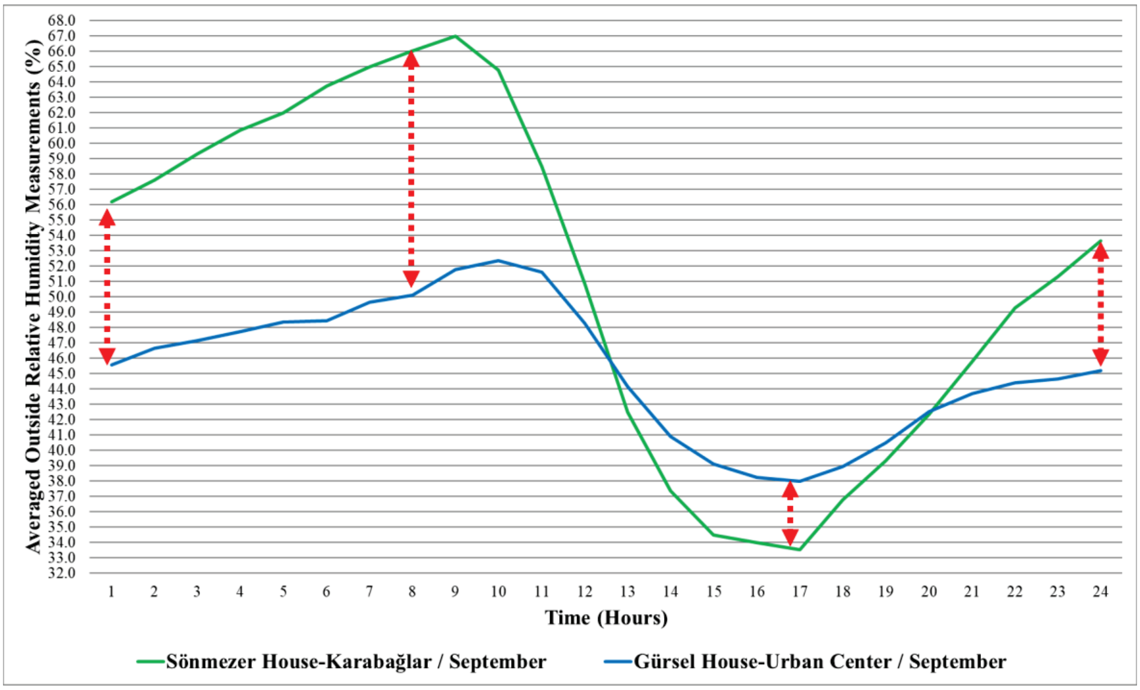

Figure 183. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for September. Red arrows indicate the hours with significant differences.

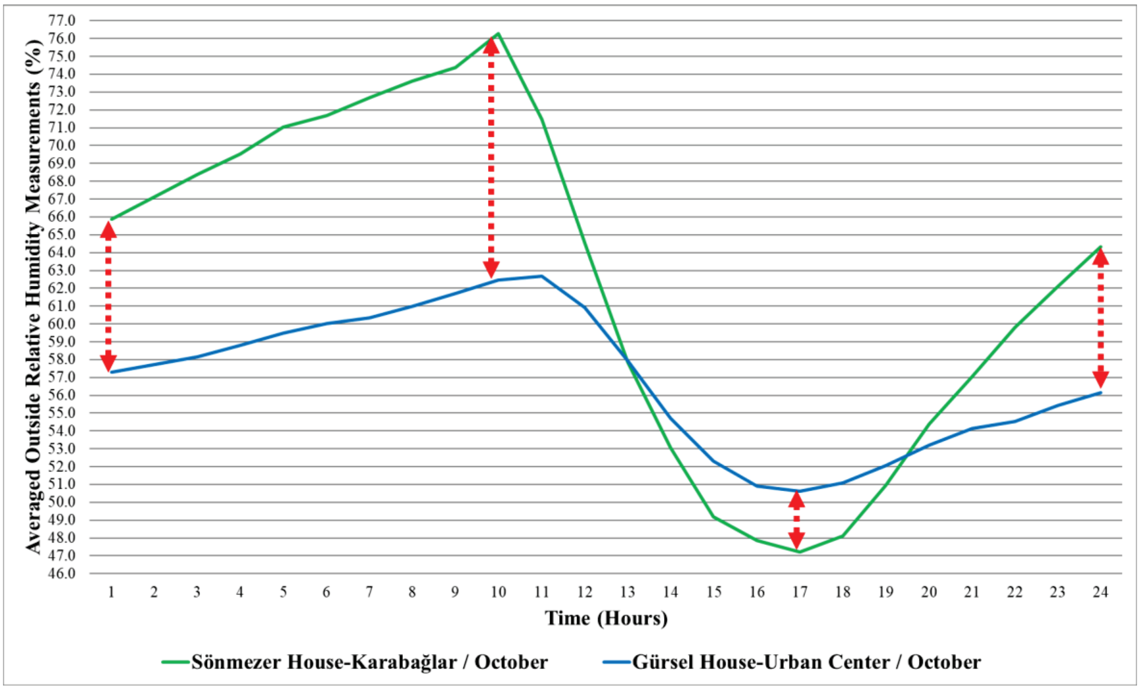

Figure 184. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for October. Red arrows indicate the hours with significant differences.

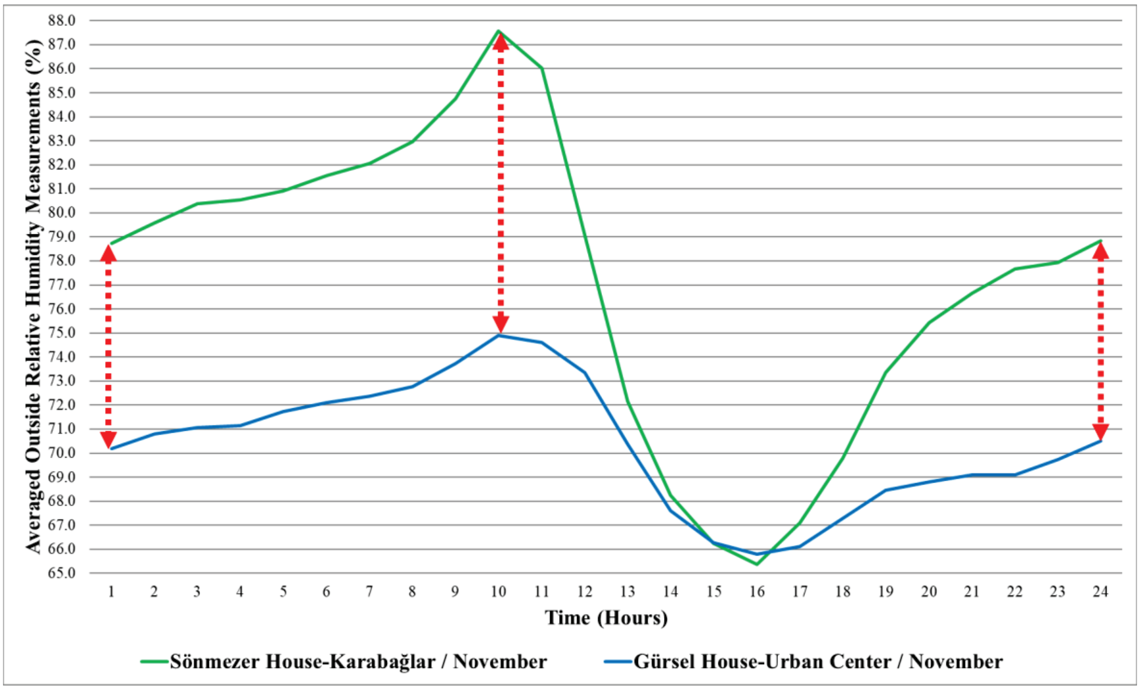

Figure 185. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for November. Red arrows indicate the hours with significant differences.

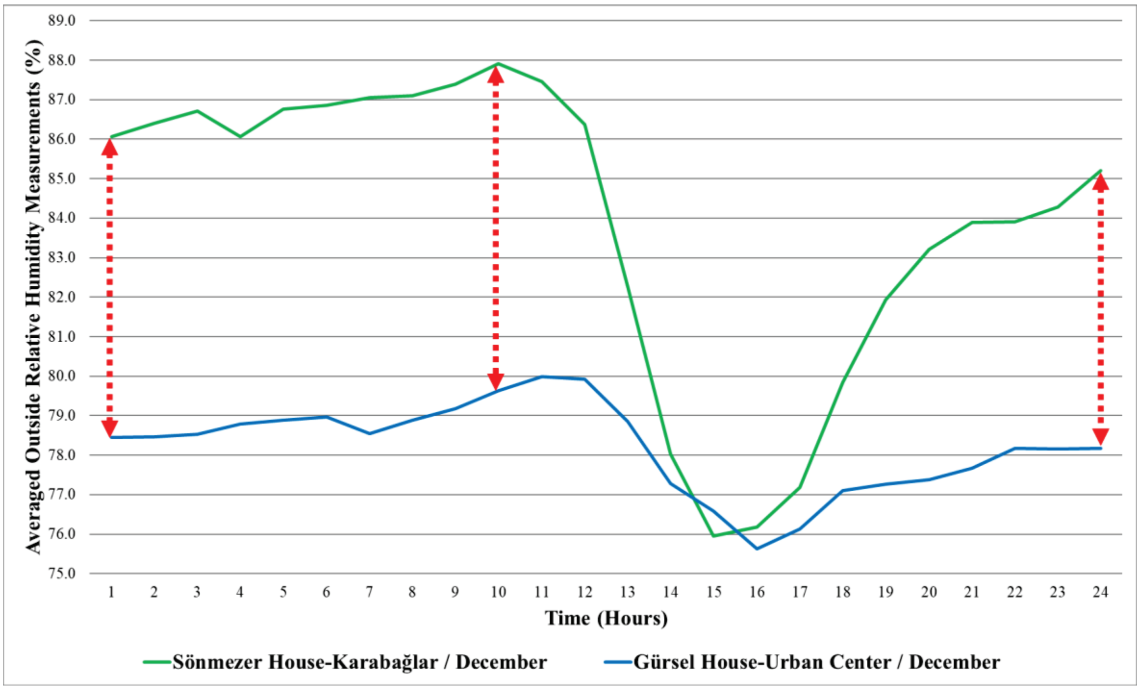

Figure 186. Comparison of monthly average daily relative humidity measurements on case studies / hourly averages for December. Red arrows indicate the hours with significant differences.

APPENDIX D

PHOTOGRAPHS OF SAMPLE CONSTRUCTION MATERIALS

Figure 187. Material sample *K-208-13-P-I-B* processed for thermophysical measurements

Figure 188. Material sample *K-208-13-P-O-R* processed for thermophysical measurements

Figure 189. Material sample *K-208-13-S-1-O* processed for thermophysical measurements

Figure 190. Material sample *K-208-13-T* processed for thermophysical measurements

Figure 191. Material sample *K-208-13-W-1-F* processed for thermophysical measurements

Figure 192. Material sample K-208-13-W-1-C processed for thermophysical measurements

APPENDIX E

LABORATORY MEASUREMENTS FOR SAMPLE TRADITIONAL BUILDING MATERIALS

Table 77. Thermal conductivity measurements for sample traditional building materials

Material Code	Measurement 1	Measurement 2	Measurement 3	Average λ (W/mK)
K-208-13-P-I-B	0.71	0.71	0.73	0.72
K-208-13-P-O-R	0.81	0.82	0.80	0.81
K-208-13-S-1-O	3.06	3.03	3.19	3.09
K-208-13-T	0.42	0.50	0.52	0.48
K-208-13-W-1-F	0.19	0.18	0.20	0.19
K-208-13-W-1-C	0.13	0.15	0.15	0.14

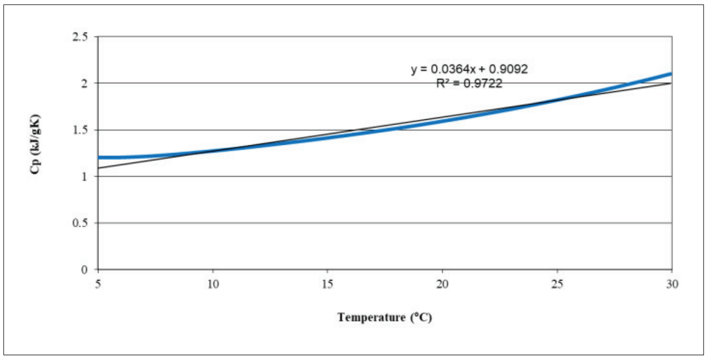

Figure 193. Specific heat measurement for K-208-13-P-I-B

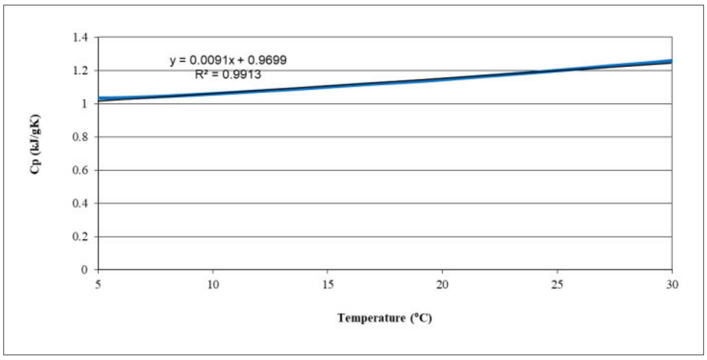

Figure 194. Specific heat measurement for K-208-13-P-O-R

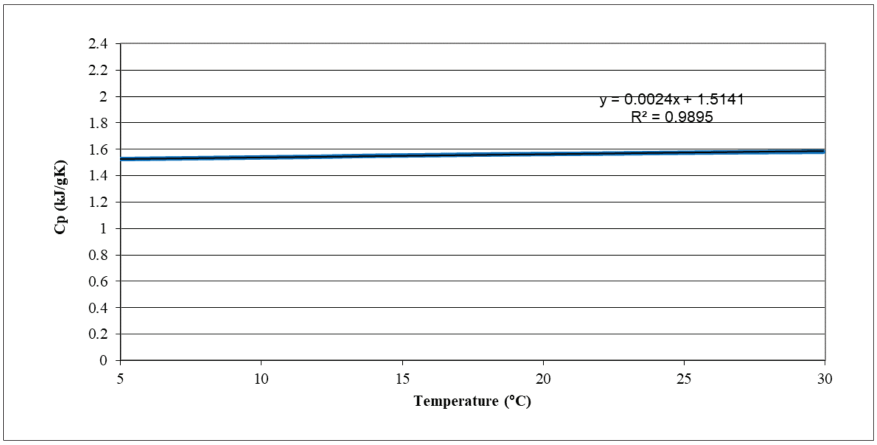

Figure 195. Specific heat measurement for K-208-13-S-1-O

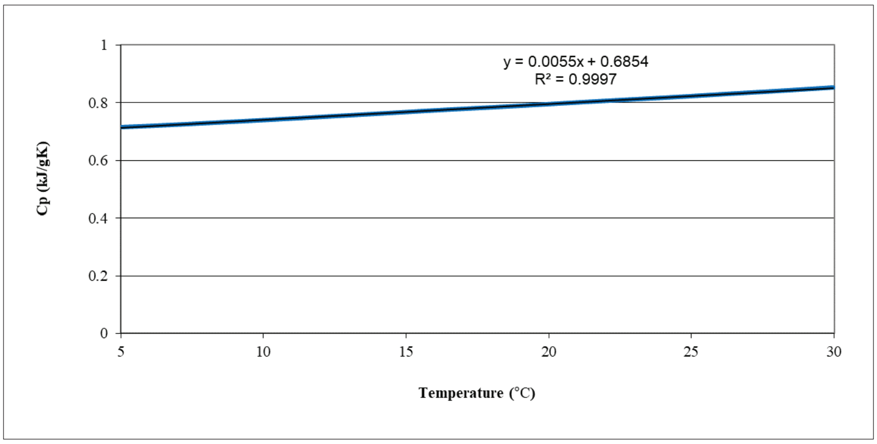

Figure 196. Specific heat measurement for K-208-13-T

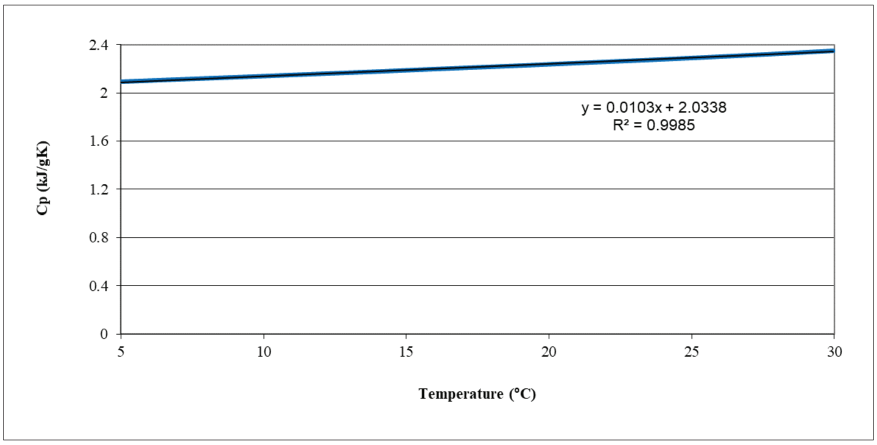

Figure 197. Specific heat measurement for K-208-13-W-1-F

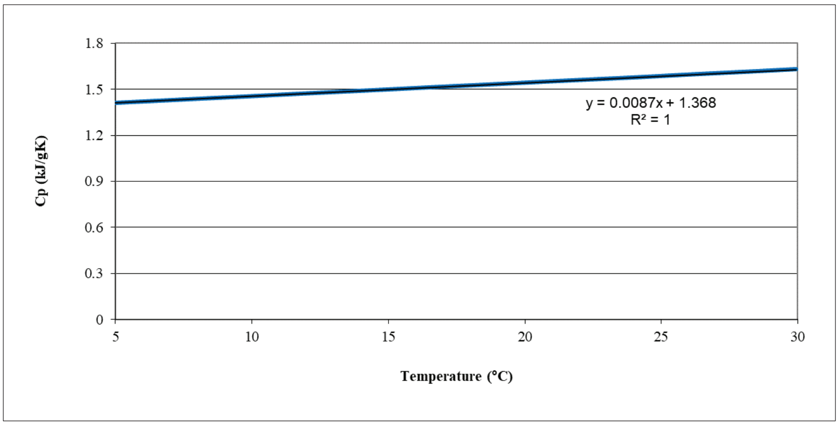

Figure 198. Specific heat measurement for K-208-13-W-1-C

Table 78. Density measurements for non-wooden materials

Material Code	Dry Weight (g)	Saturated Weight (g)	Archimedes Weight (g)	Density (g/cm³)-Two Parallel Measurements	Density (g/cm³)-Average
K-208-13-P-I-B-Sample 1	30.95	37.01	19	1.72	1.74
K-208-13-P-I-B-Sample 2	24.67	29.14	15.11	1.76	
K-208-13-P-O-R-Sample 1	25.86	30.73	15.82	1.73	1.78
K-208-13-P-O-R-Sample 2	23.54	27.31	14.4	1.82	
K-208-13-S-1-O-Sample 1	19.03	19.09	11.75	2.59	2.60
K-208-13-S-1-O-Sample 2	21.13	21.24	13.11	2.60	
K-208-13-T-Sample 1	22.7	27.69	12.98	1.54	1.53
K-208-13-T-Sample 2	22.48	27.67	12.89	1.52	

Table 79. Density measurements for wooden materials

Material Code	Air-dry Weight (g)	Air-dry Volume (cm³)	Oven-dry Weight (g)	Oven-dry Volume (cm³)	Density (g/cm³)
K-208-13-W-1-F	58.1	91.6	54.8	81.4	0.673
K-208-13-W-1-C	14.1	20.9	12.9	20.9	0.615

APPENDIX F

ON-SITE THERMAL READINGS ON CASE STUDY BUILDINGS

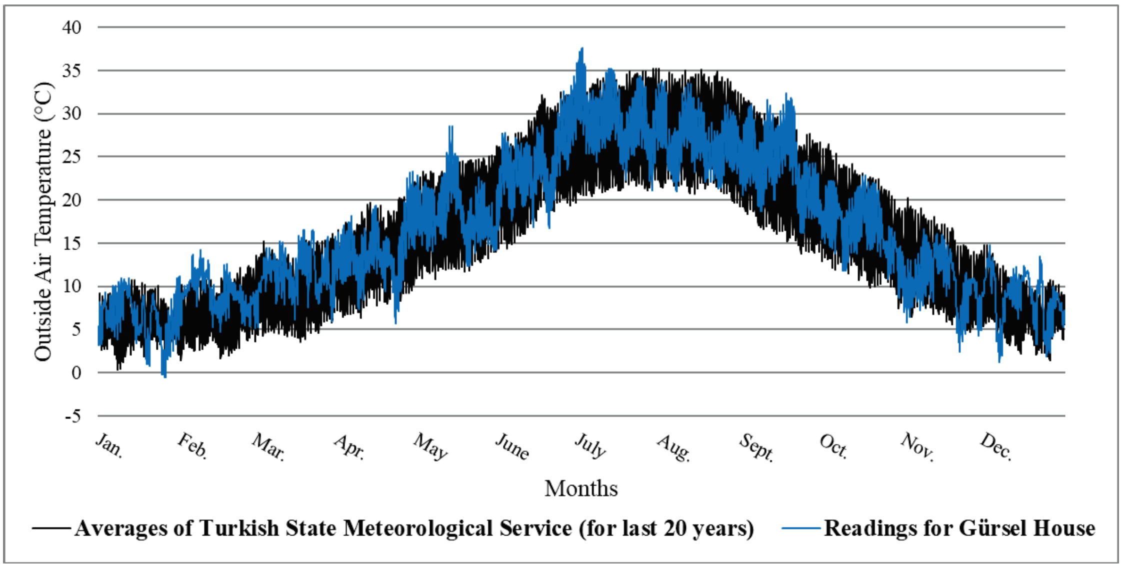

Figure 199. Outside temperature readings for Gürsel House in comparison to the averages of Turkish State Meteorological Service

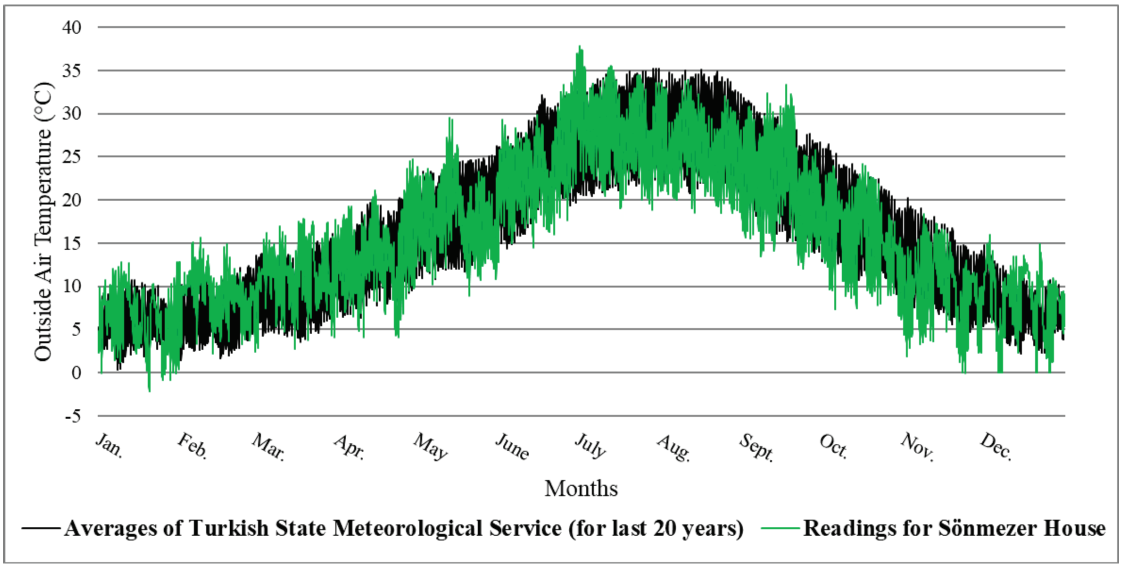

Figure 200. Outside temperature readings for Sönmezer House in comparison to the averages of Turkish State Meteorological Service

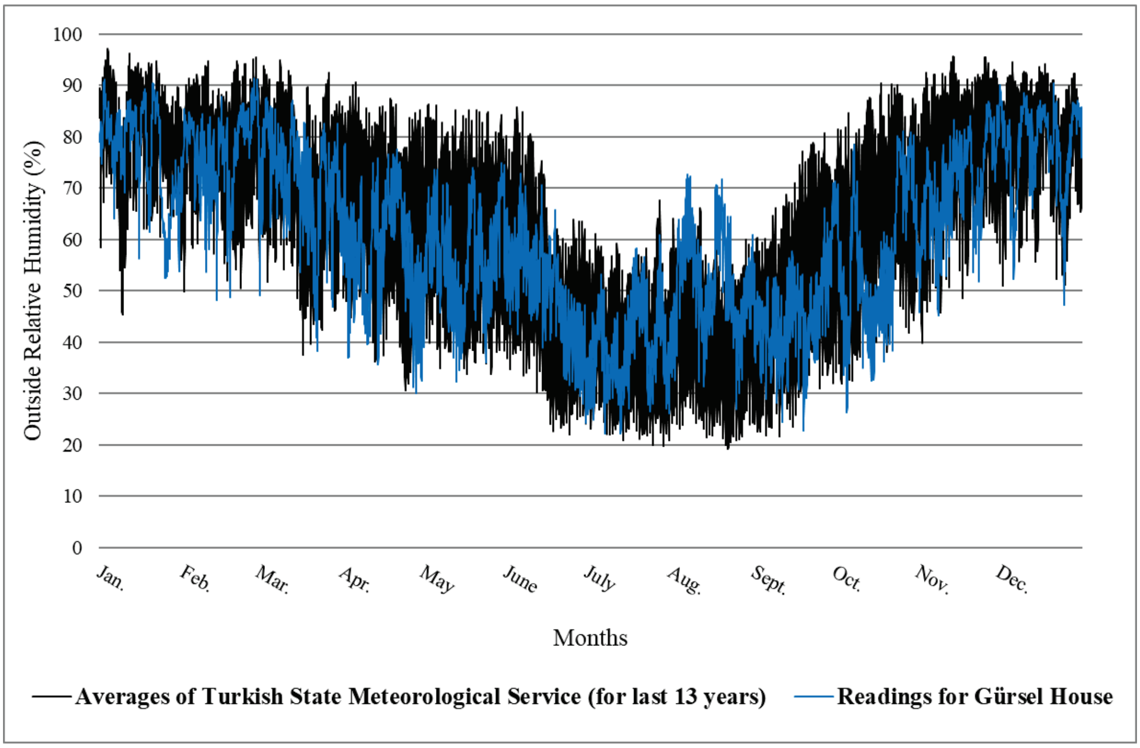

Figure 201. Outside relative humidity readings for Gürsel House in comparison to the averages of Turkish State Meteorological Service

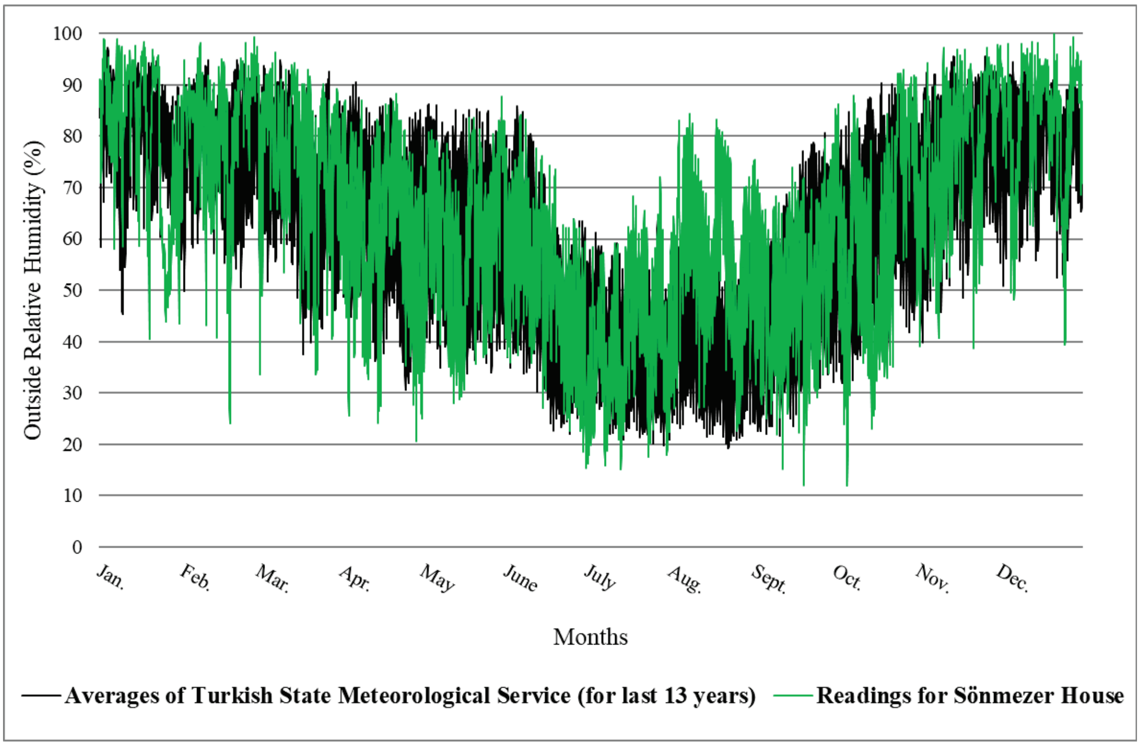

Figure 202. Outside relative humidity readings for Sönmezer House in comparison to the averages of Turkish State Meteorological Service

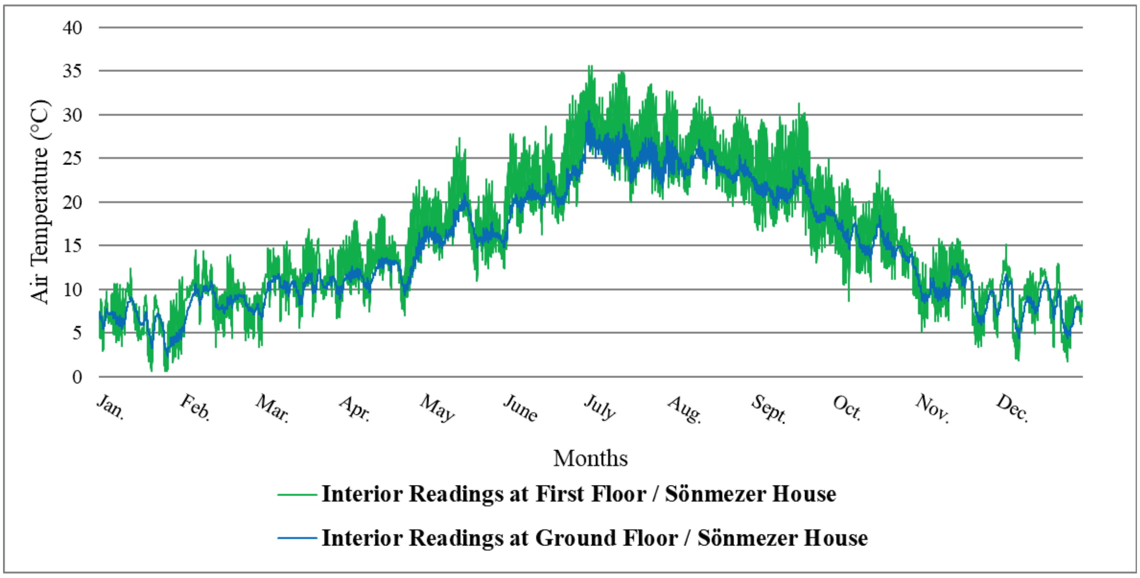

Figure 203. Comparison of interior temperature readings at ground and first floors for Sönmezer House

APPENDIX G

AVERAGES OF WEATHER STATISTICS RECEIVED FROM TURKISH STATE METEOROLOGICAL SERVICE

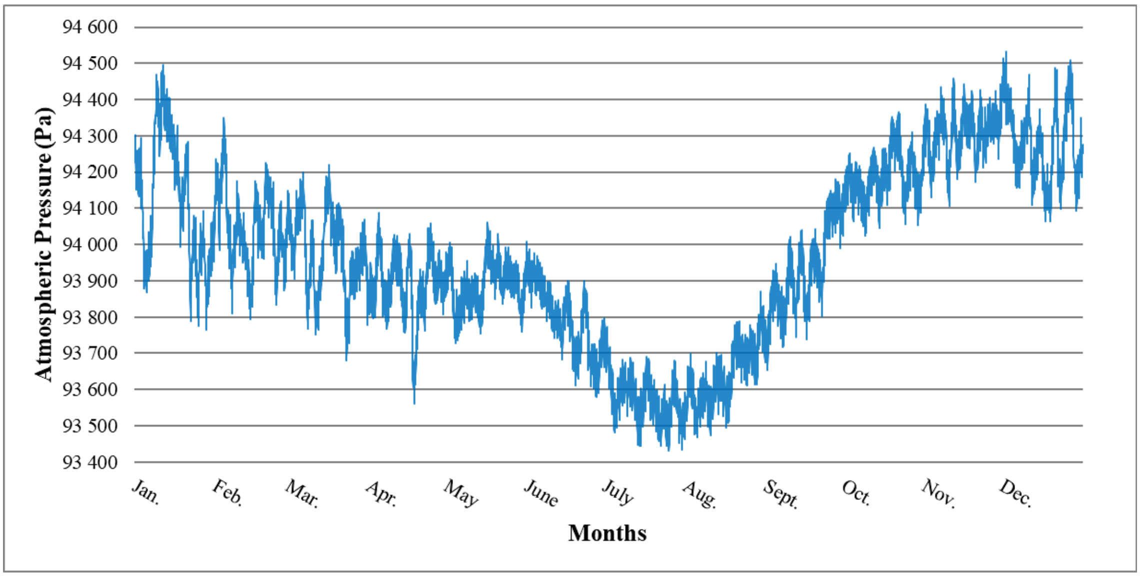

Figure 204. Whole year hourly averages of atmospheric pressure values for Muğla City (average of last 20 years)

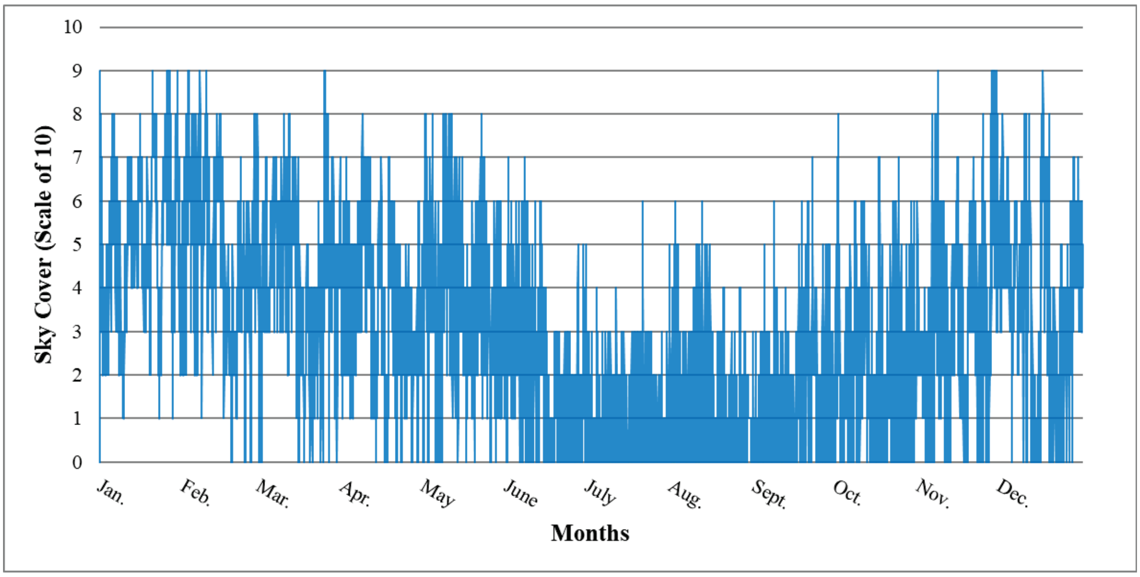

Figure 205. Whole year hourly averages of sky cover values for Muğla City (average of last 5 years)

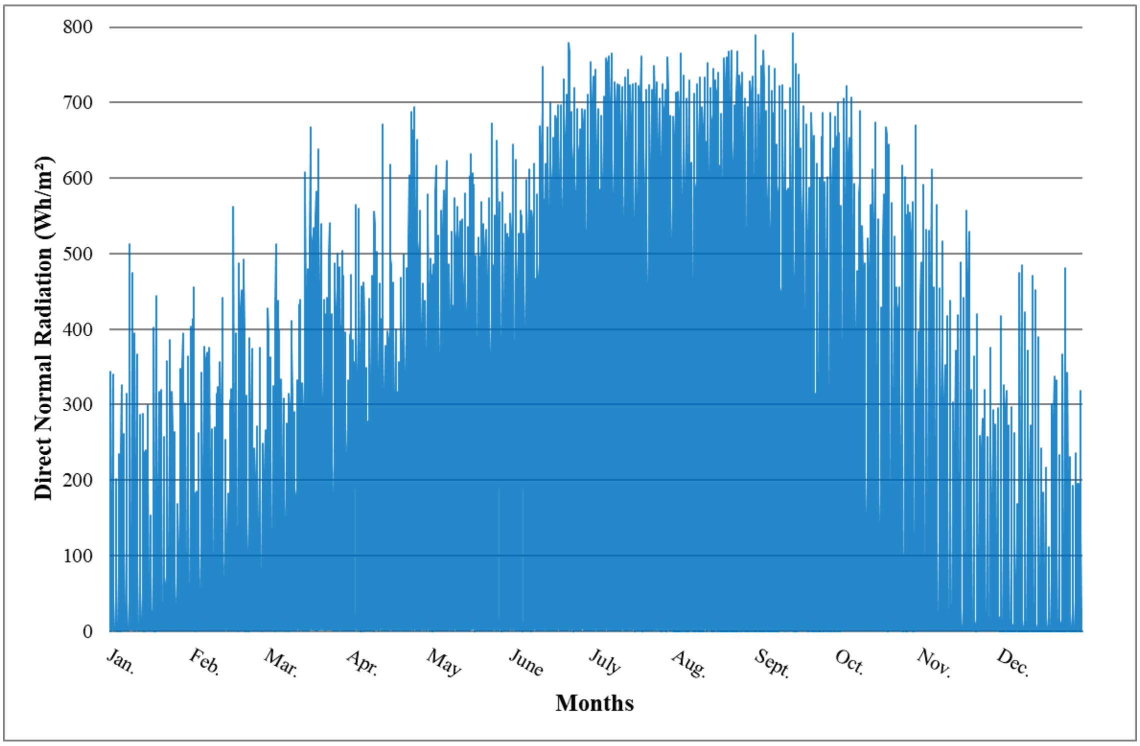

Figure 206. Whole year hourly averages of direct normal radiation values for Muğla City (average of last 13 years)

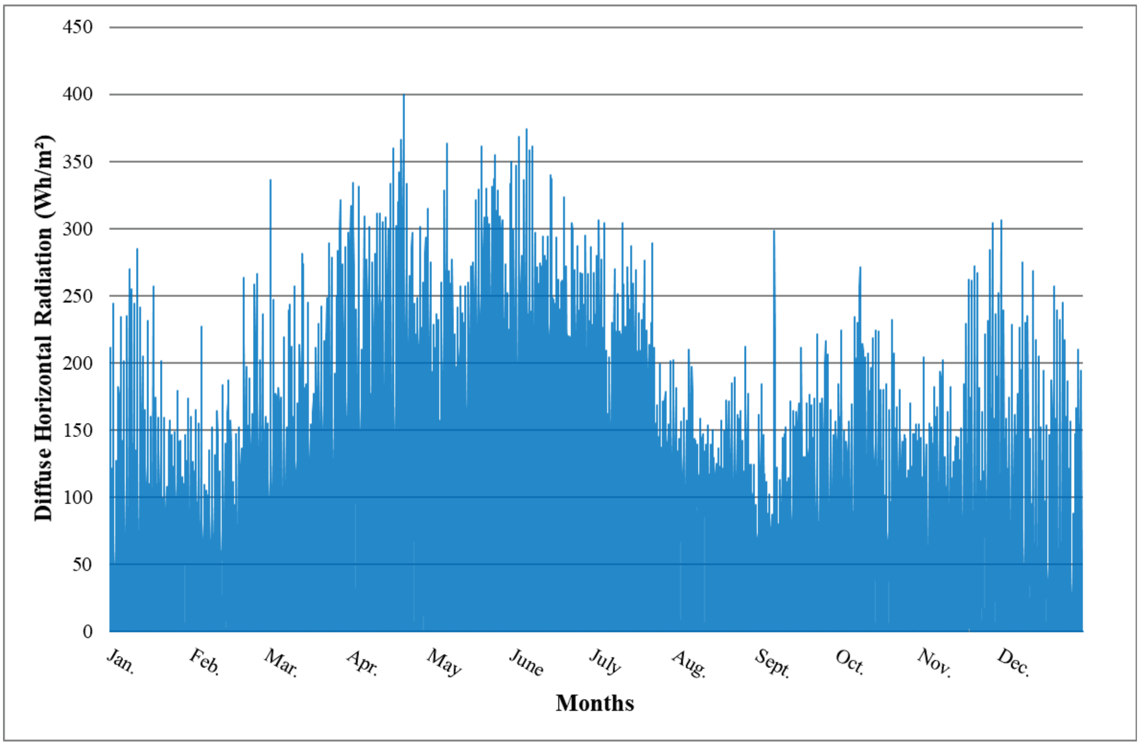

Figure 207. Whole year hourly averages of diffuse horizontal radiation values for Muğla City (average of last 6 years)

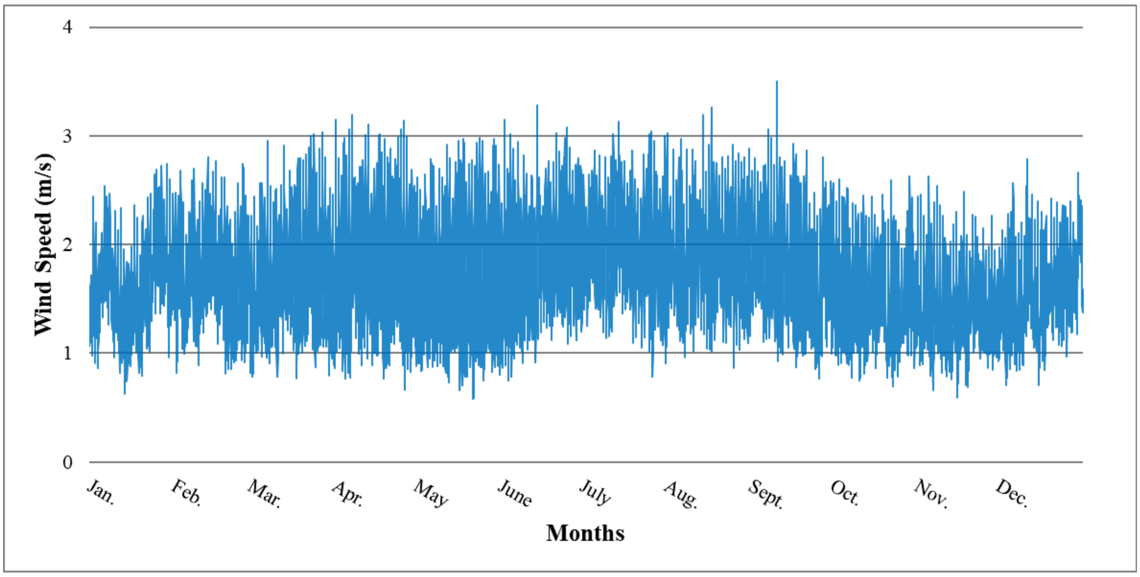

Figure 208. Whole year hourly averages of wind speed values for Muğla City (average of last 13 years)

APPENDIX H

SIMULATION RESULTS OF MODELS 2.1 FOR GÜRSEL HOUSE

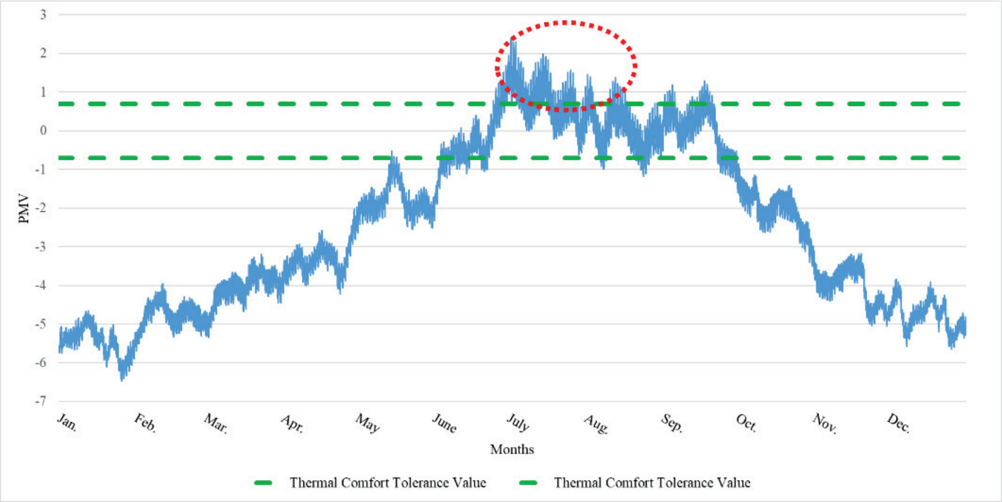

Figure 209. Simulation results demonstrating PMV values through whole year for the living room of Gürsel House when no fireplace is burnt. Chart shows that with no active cooling system in original design, PMV values can reach over thermal comfort tolerance value in summertime.

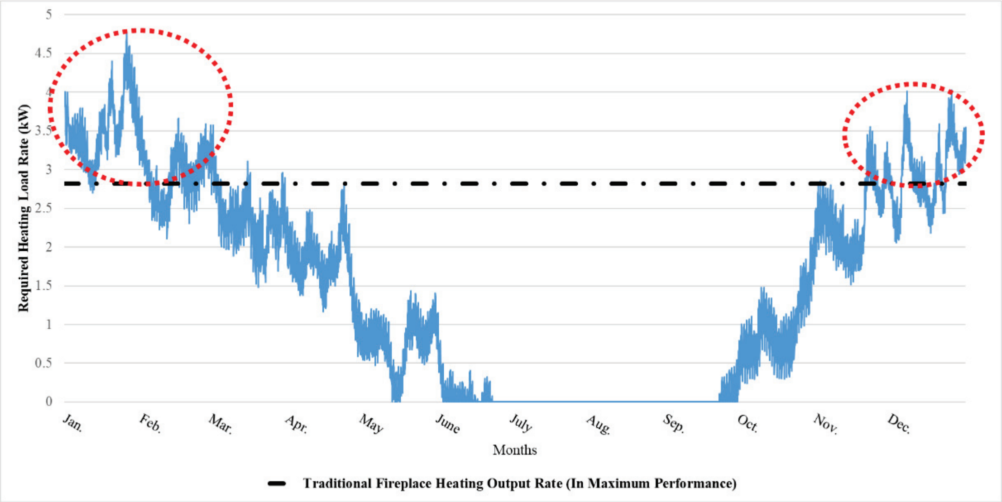

Figure 210. Simulation results demonstrating heating loads through whole year for the living room of Gürsel House. Chart shows that with heating output rate of 2.82 kW, traditional fireplace in this room lacks to be sufficient especially on the months of January, February and December.

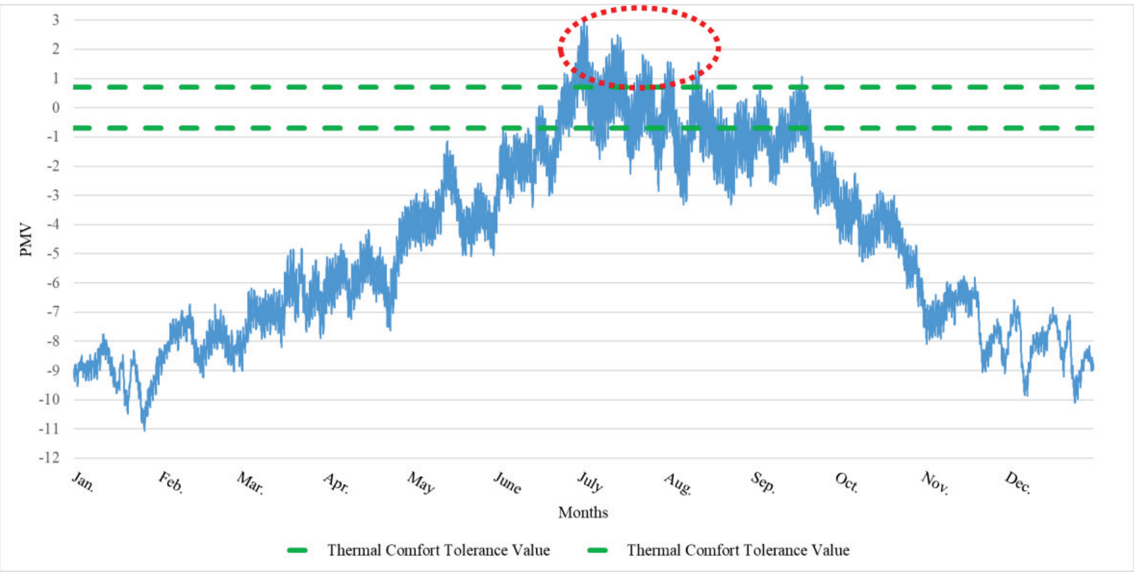

Figure 211. Simulation results demonstrating PMV values through whole year for the children room of Gürsel House when no fireplace is burnt. Chart shows that with no active cooling system in original design, PMV values can reach over thermal comfort tolerance value in summertime.

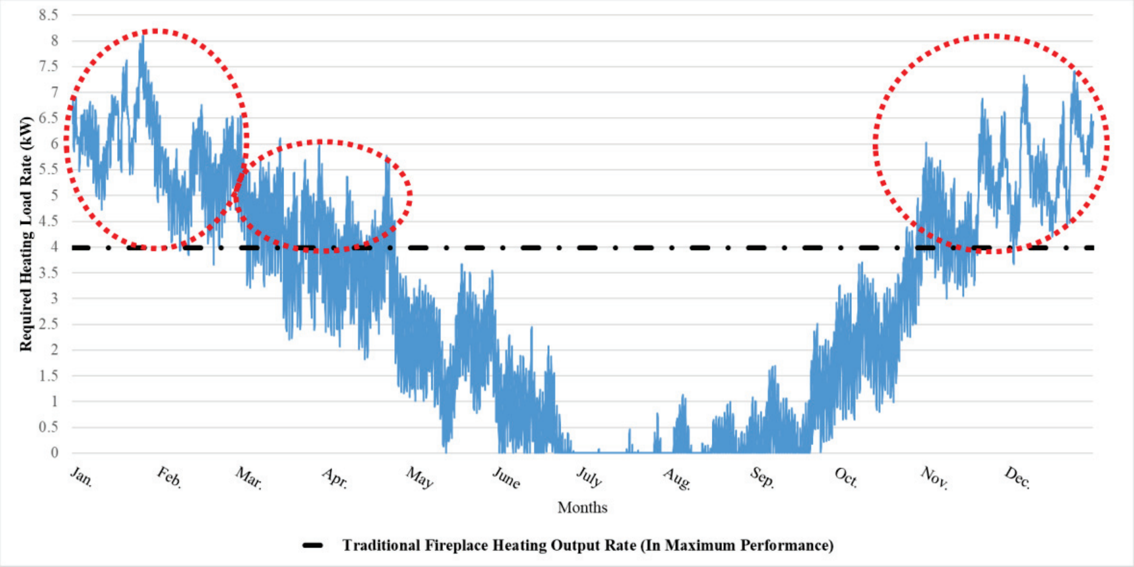

Figure 212. Simulation results demonstrating heating loads through whole year for the children room of Gürsel House. Chart shows that with heating output rate of 3.99 kW, traditional fireplace in this room lacks to be sufficient especially on the months from November until May.

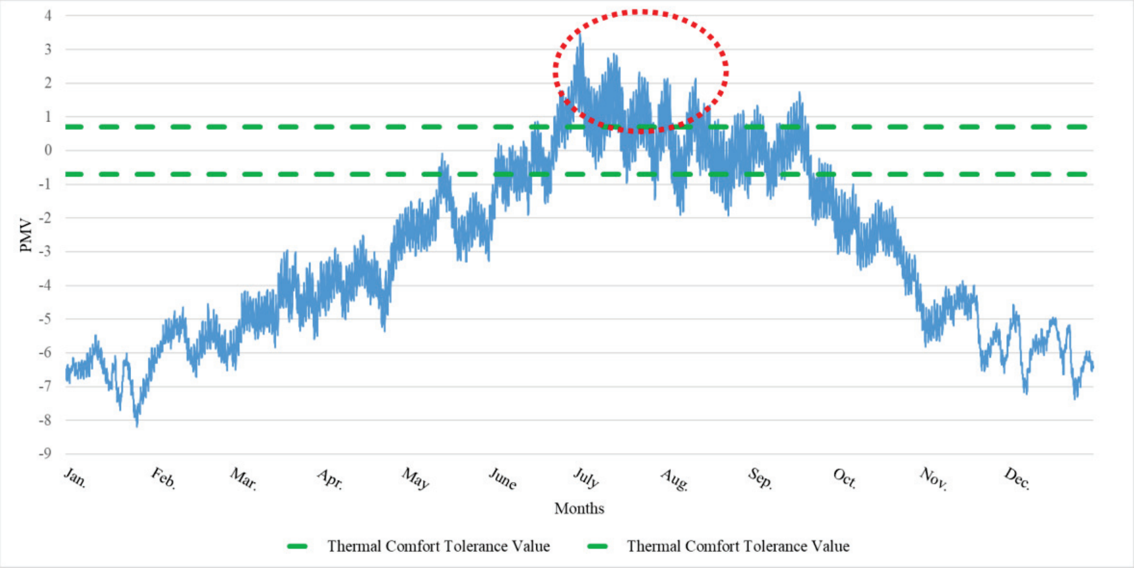

Figure 213. Simulation results demonstrating PMV values through whole year for the parent room of Gürsel House when no fireplace is burnt. Chart shows that with no active cooling system in original design, PMV values can reach over thermal comfort tolerance value in summertime.

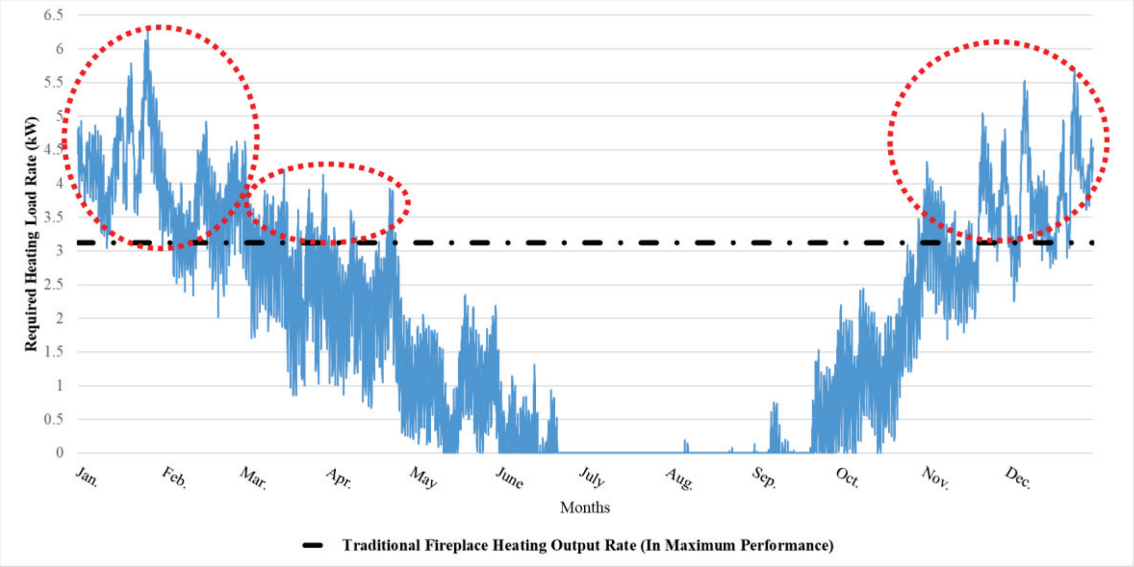

Figure 214. Simulation results demonstrating heating loads through whole year for the parent room of Gürsel House. Chart shows that with heating output rate of 3.12 kW, traditional fireplace in this room lacks to be sufficient especially on the months of January, February and December.

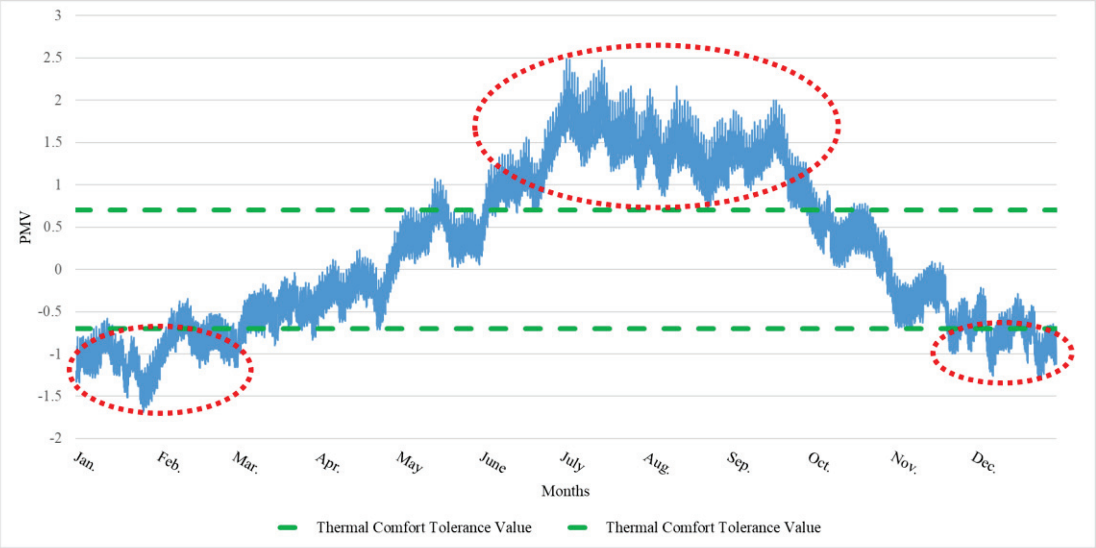

Figure 215. Simulation results demonstrating PMV values through whole year for the kitchen of Gürsel House. Chart shows that with no active heating and cooling system in original design, PMV values can reach over thermal comfort tolerance value for the whole summertime and can drop under the tolerance value on the months of January, February and December. No heating load analysis was conducted for this room as there is no active heating system in its original design.

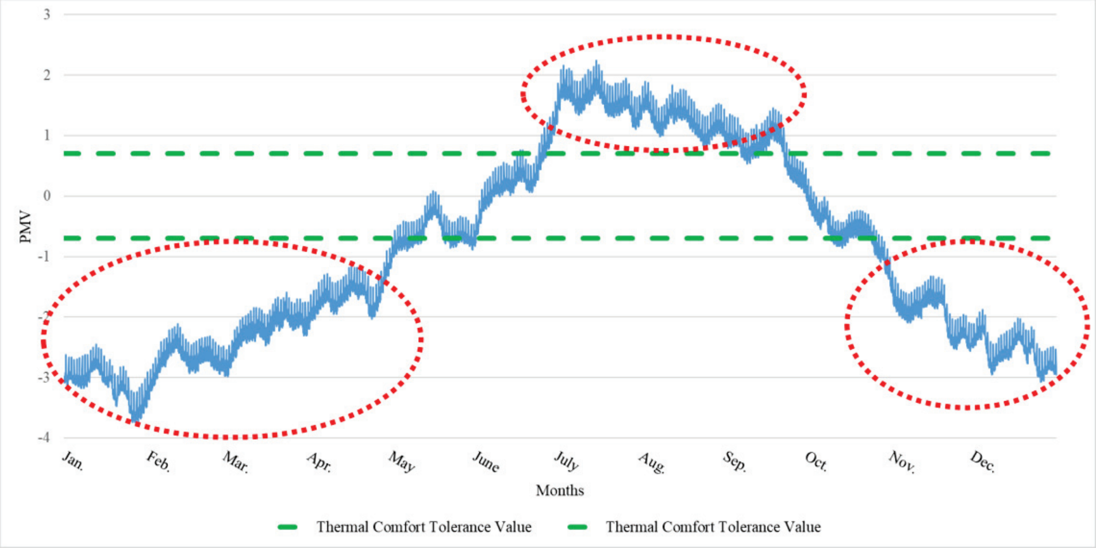

Figure 216. Simulation results demonstrating PMV values through whole year for the bathroom of Gürsel House. Chart shows that with no active heating and cooling system in original design, PMV values can reach over thermal comfort tolerance value for the whole summertime and can drop under the tolerance value on the months from November until April. No heating load analysis was conducted for this room as there is no active heating system in its original design.

APPENDIX I

SIMULATION RESULTS OF MODELS 2.1 FOR SÖNMEZER HOUSE

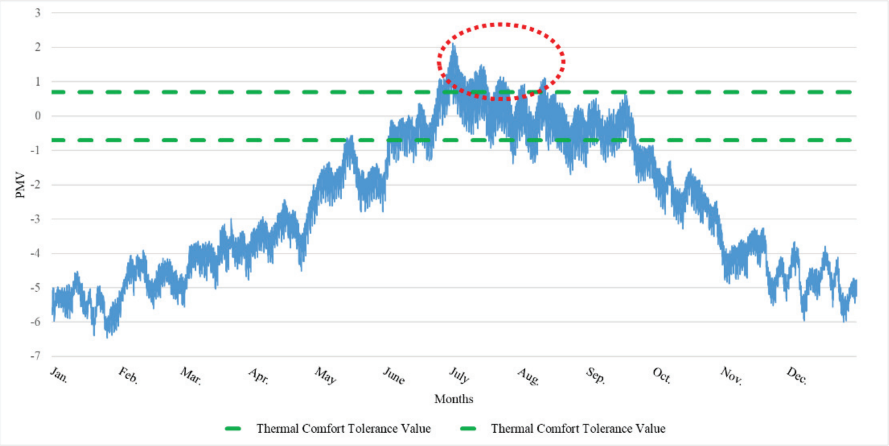

Figure 217. Simulation results demonstrating PMV values through whole year for the living room of Sönmezer House when no fireplace is burnt. Chart shows that with no active cooling system in original design, PMV values can reach over thermal comfort tolerance value in summertime.

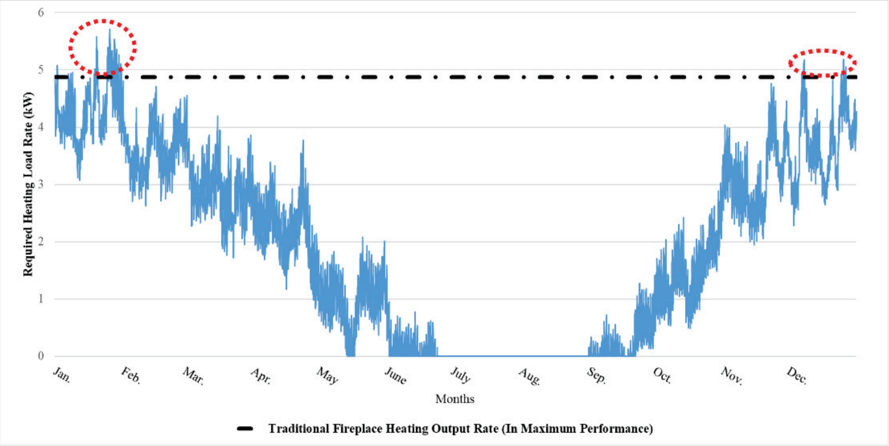

Figure 218. Simulation results demonstrating heating loads through whole year for the living room of Sönmezer House. Chart shows that with heating output rate of 4.87 kW, traditional fireplace in this room can maintain thermal comfort for most of the time in winters except for some coldest days at December and January which makes this room as the only room among the spaces of case studies that can sustain thermal comfort for the majority of wintertime in its original design.

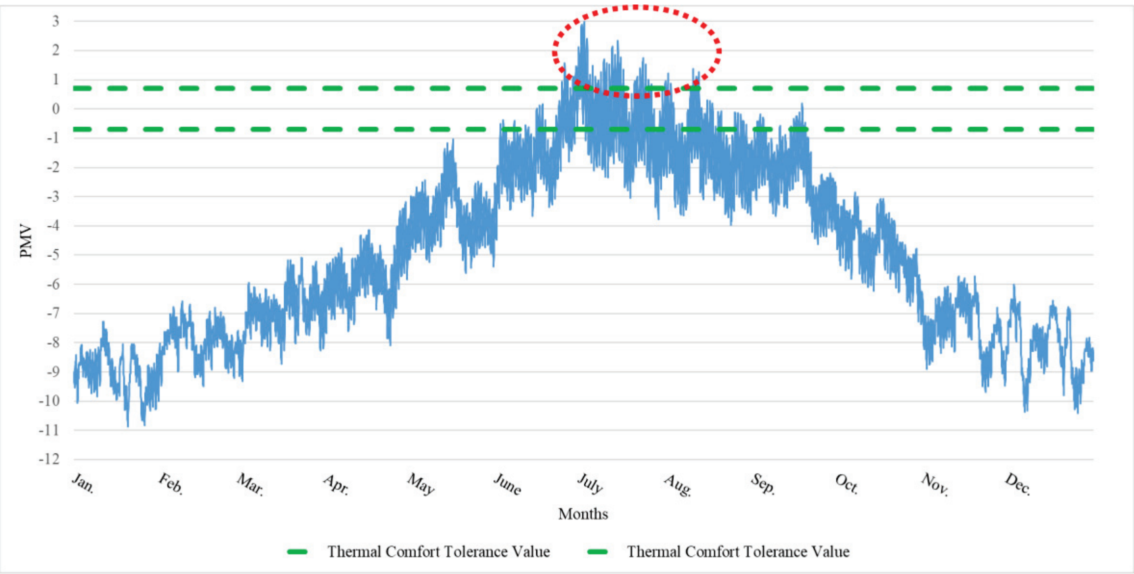

Figure 219. Simulation results demonstrating PMV values through whole year for the children room of Sönmezer House when no fireplace is burnt. Chart shows that with no active cooling system in original design, PMV values can reach over thermal comfort tolerance value in summertime.

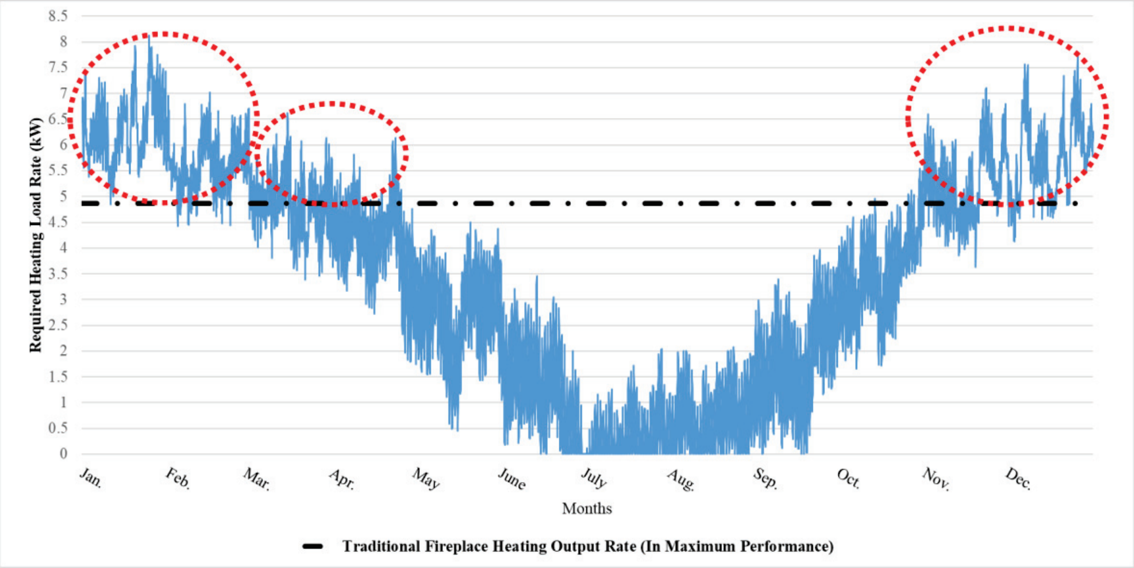

Figure 220. Simulation results demonstrating heating loads through whole year for the children room of Sönmezer House. Chart shows that with heating output rate of 4.87 kW, traditional fireplace in this room lacks to be sufficient especially on the months from November until May.

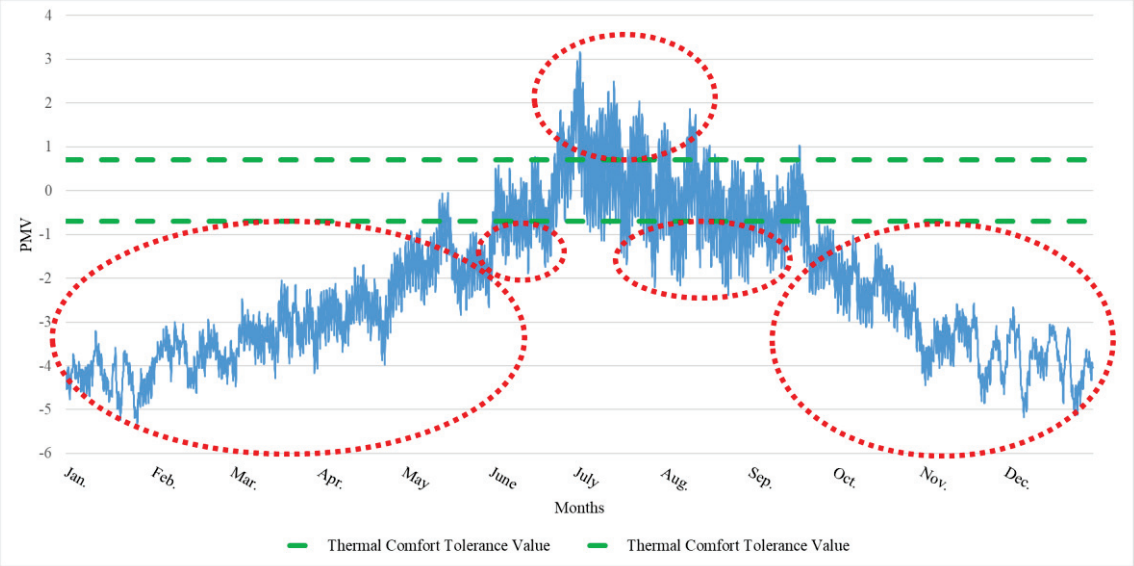

Figure 221. Simulation results demonstrating PMV values through whole year for the parent room of Sönmezer House. Chart shows that with no active heating and cooling system in original design, PMV values can reach over thermal comfort tolerance value on July and can drop under the tolerance value at nearly the whole portion of year. No heating load analysis was conducted for this room as there is no active heating system in its original design.

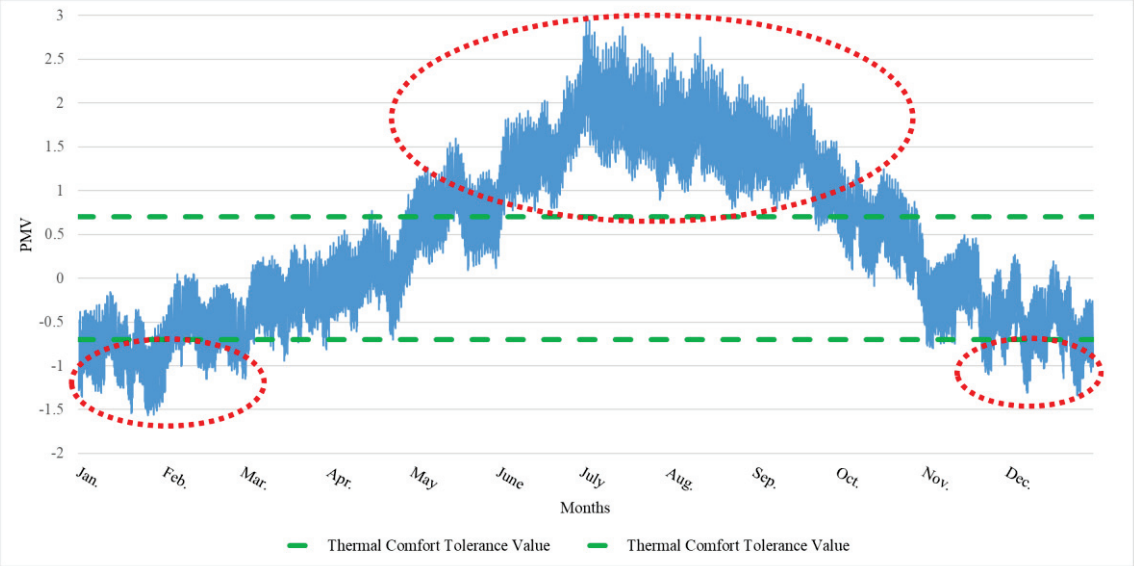

Figure 222. Simulation results demonstrating PMV values through whole year for the kitchen of Sönmezer House. Chart shows that with no active heating and cooling system in original design, PMV values can reach over thermal comfort tolerance value for the whole summertime and on the month of September and the values can drop under the tolerance value on the months of January, February and December. No heating load analysis was conducted for this room as there is no active heating system in its original design.

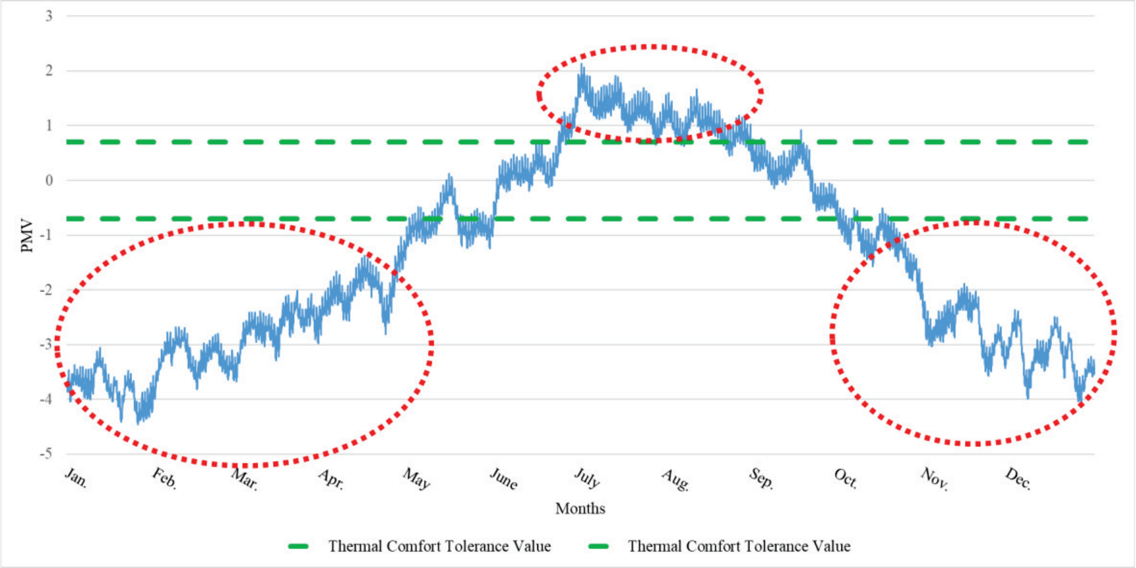

Figure 223. Simulation results demonstrating PMV values through whole year for the bathroom of Sönmezer House. Chart shows that with no active heating and cooling system in original design, PMV values can reach over thermal comfort tolerance value on the months of July and August and can drop under the tolerance value on the months from October until May. No heating load analysis was conducted for this room as there is no active heating system in its original.

APPENDIX J

RESULTS OF PMV ANALYSES FOR MODELS 2.2 TO ESTABLISH HVAC SET POINTS / GÜRSEL HOUSE

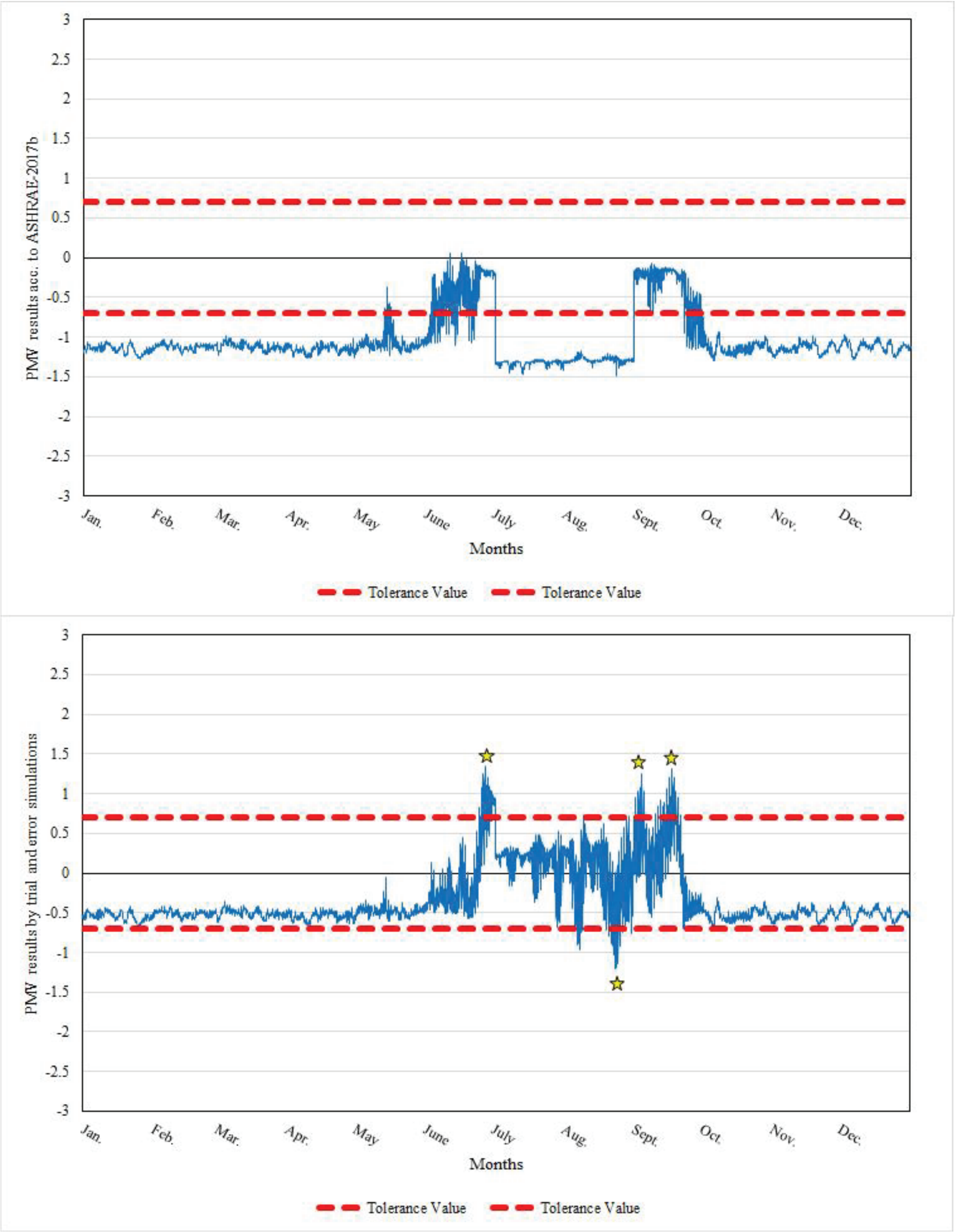

Figure 224. Comparison of thermal comfort status of the living room in Gürsel House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

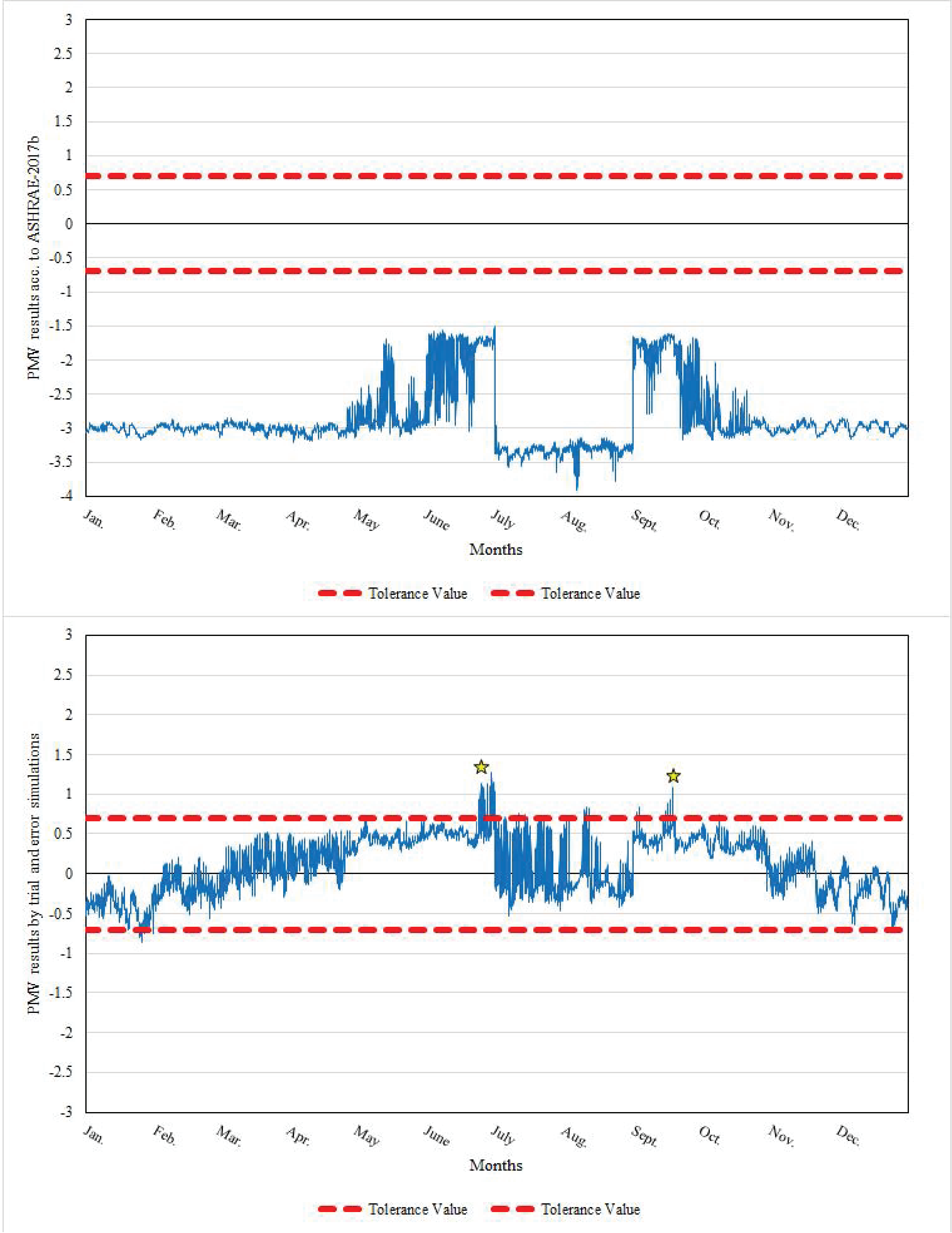

Figure 225. Comparison of thermal comfort status of the children room in Gürsel House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

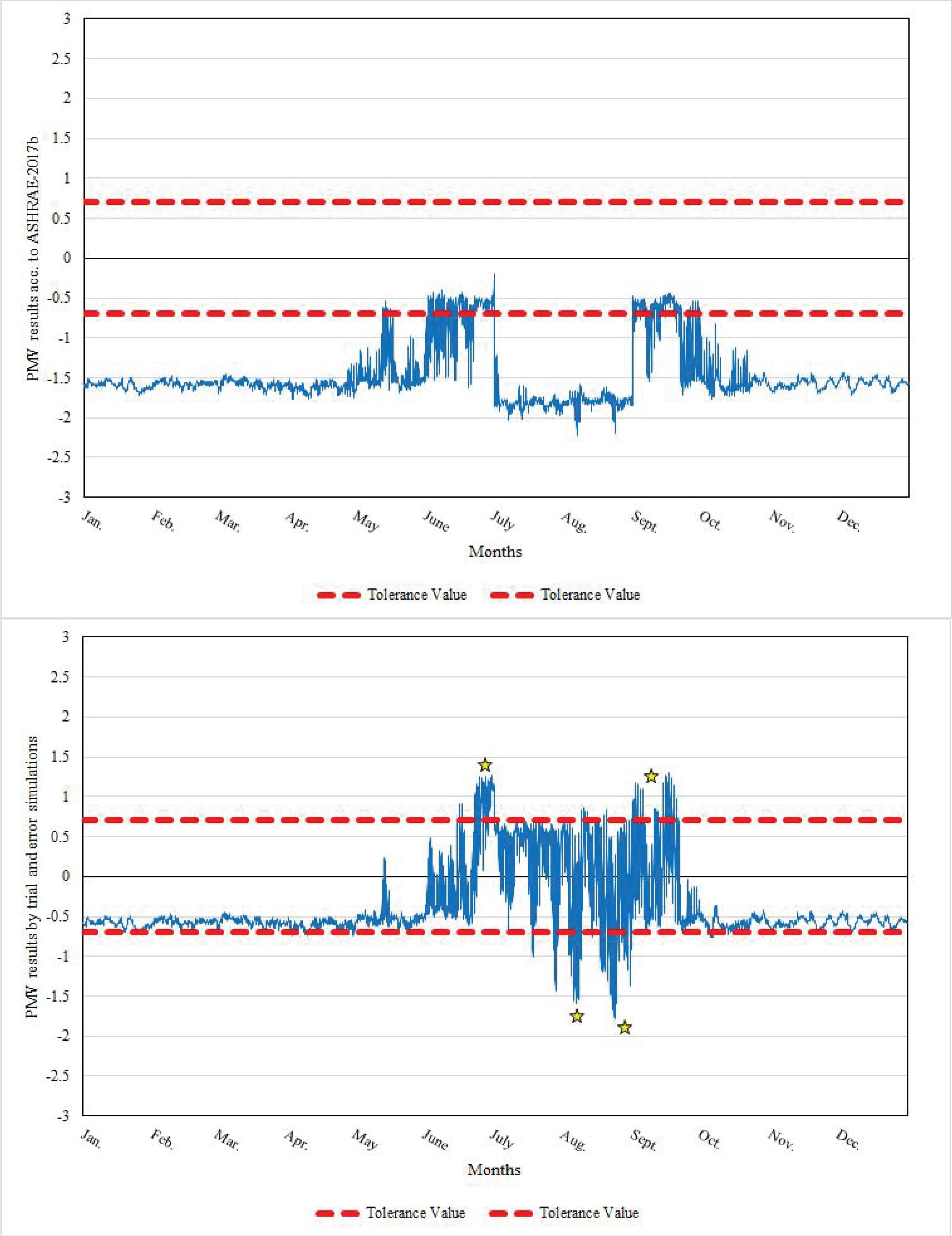

Figure 226. Comparison of thermal comfort status of the parent room in Gürsel House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

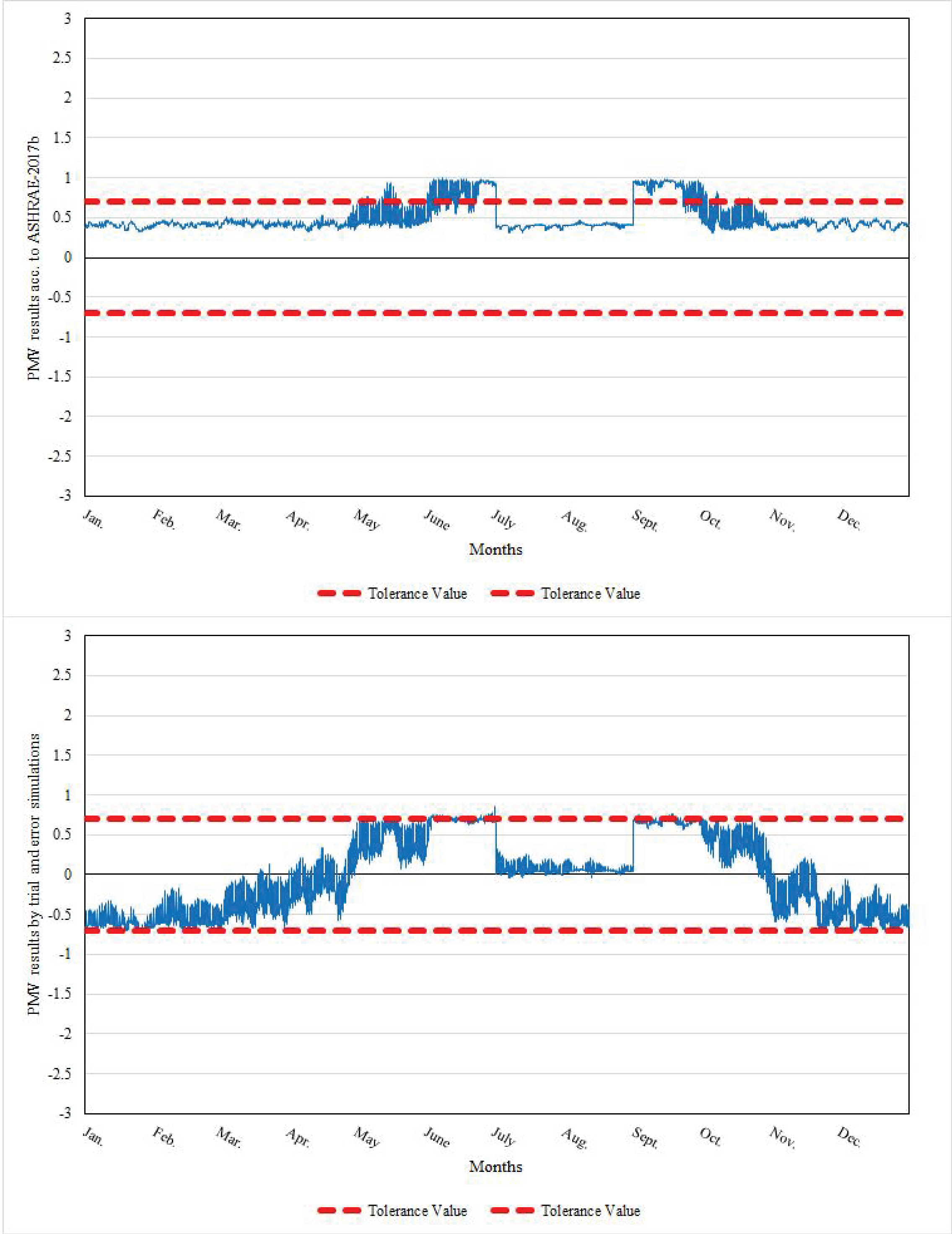

Figure 227. Comparison of thermal comfort status of the kitchen in Gürsel House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart).

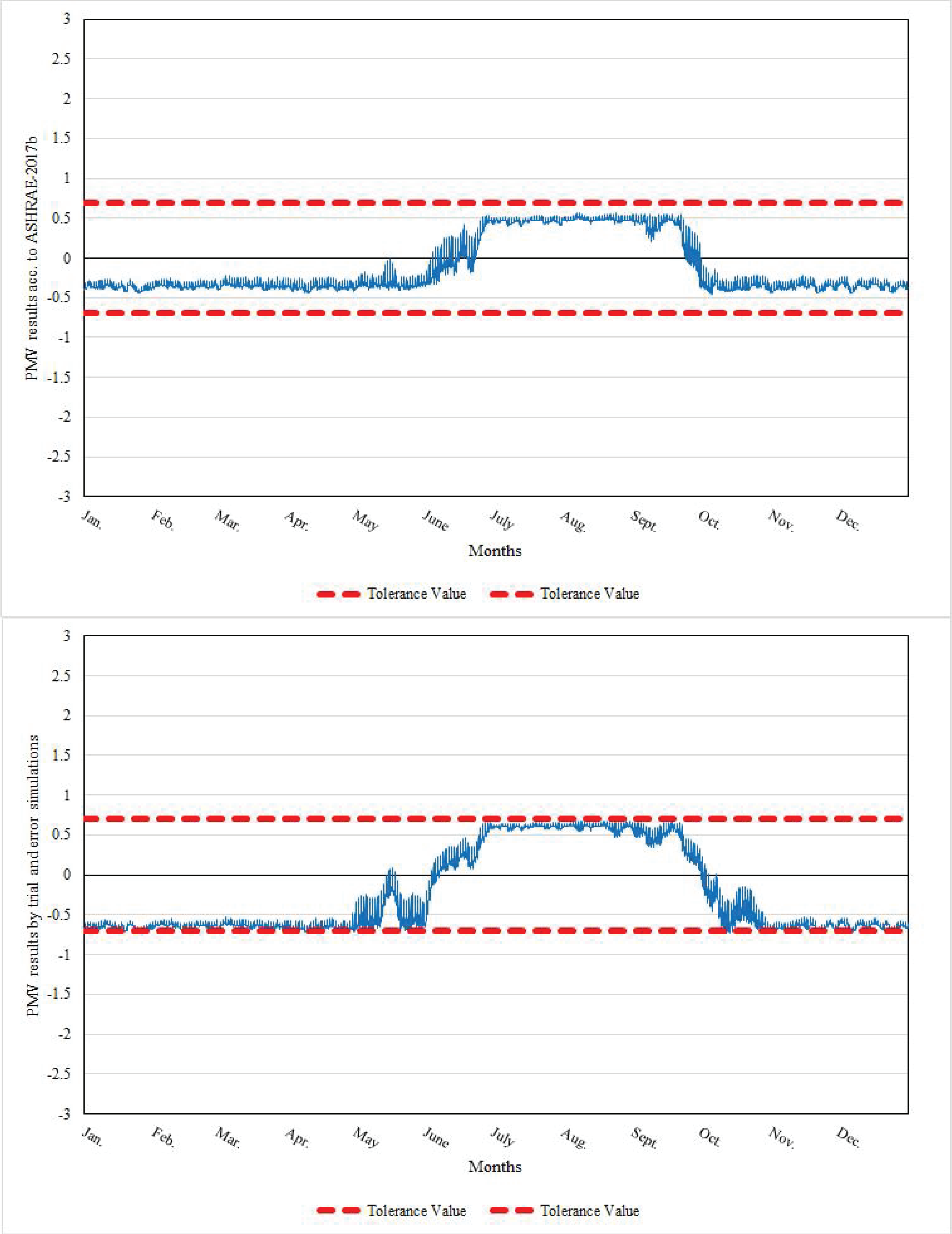

Figure 228. Comparison of thermal comfort status of the bathroom in Gürsel House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart).

APPENDIX K

ANNUAL OPERATIVE TEMPERATURE DISTRIBUTION OF THE ROOMS-MODELS 2.2 / GÜRSEL HOUSE

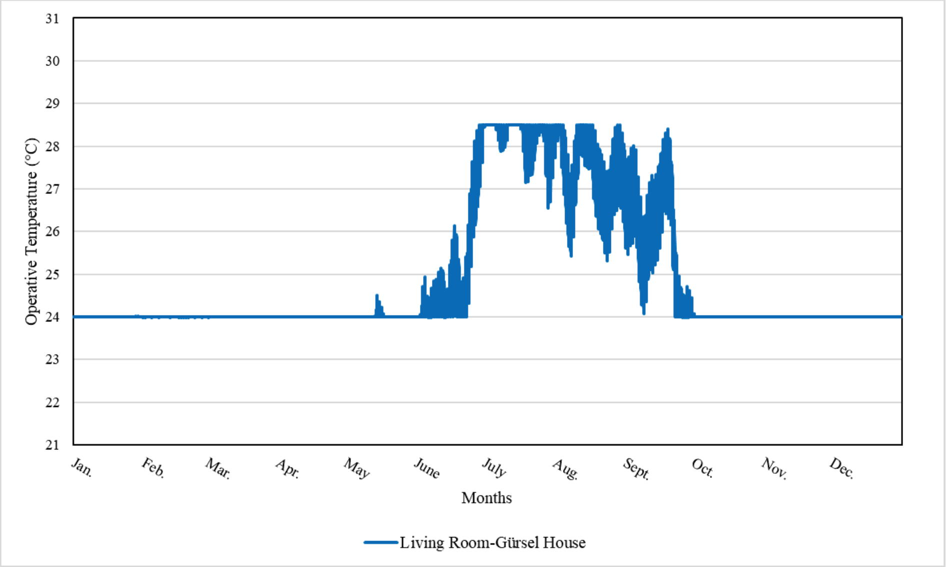

Figure 229. Annual operative temperature distribution of the living room - Model 2.2 / Gürsel house

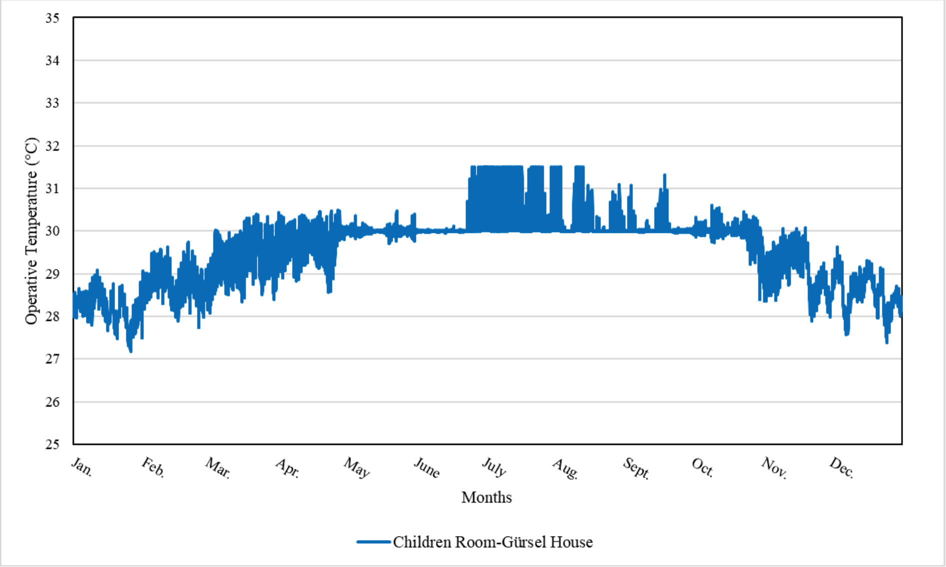

Figure 230. Annual operative temperature distribution of the children room - Model 2.2 / Gürsel house

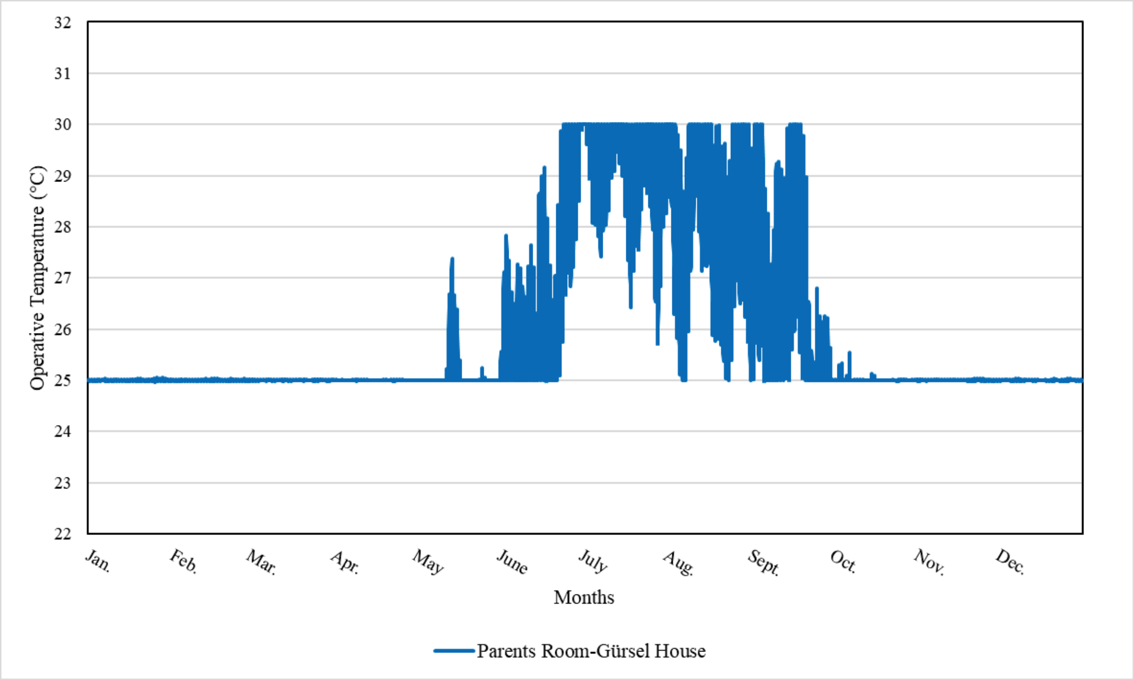

Figure 231. Annual operative temperature distribution of the parents' room - Model 2.2 / Gürsel house

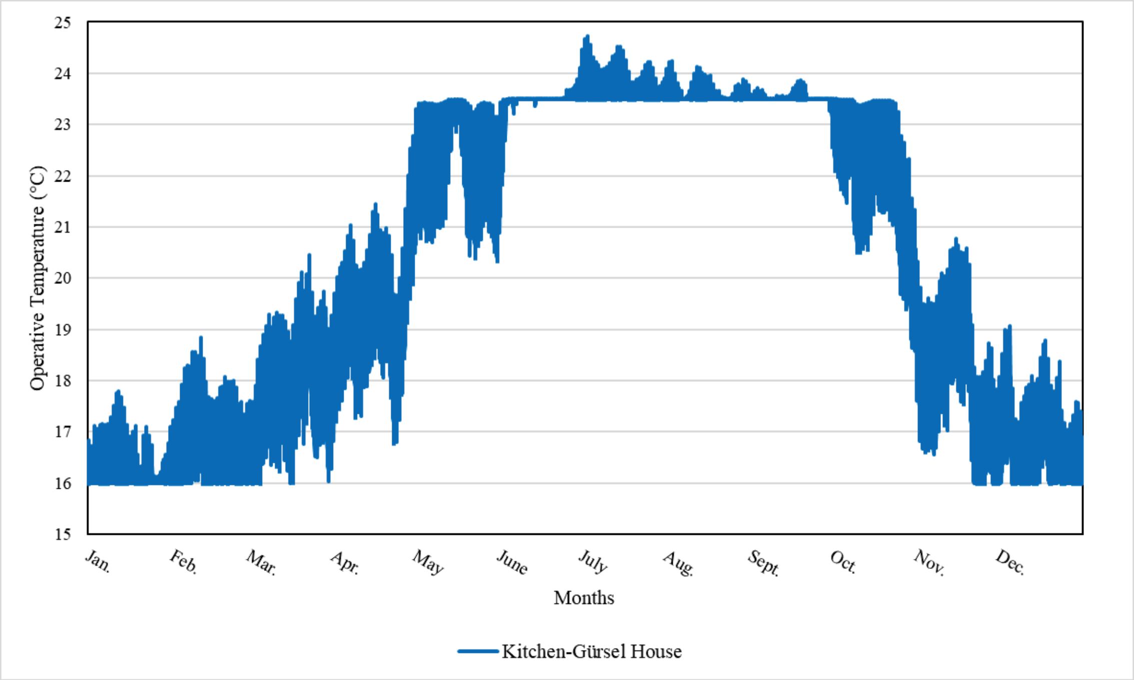

Figure 232. Annual operative temperature distribution of the kitchen - Model 2.2 / Gürsel house

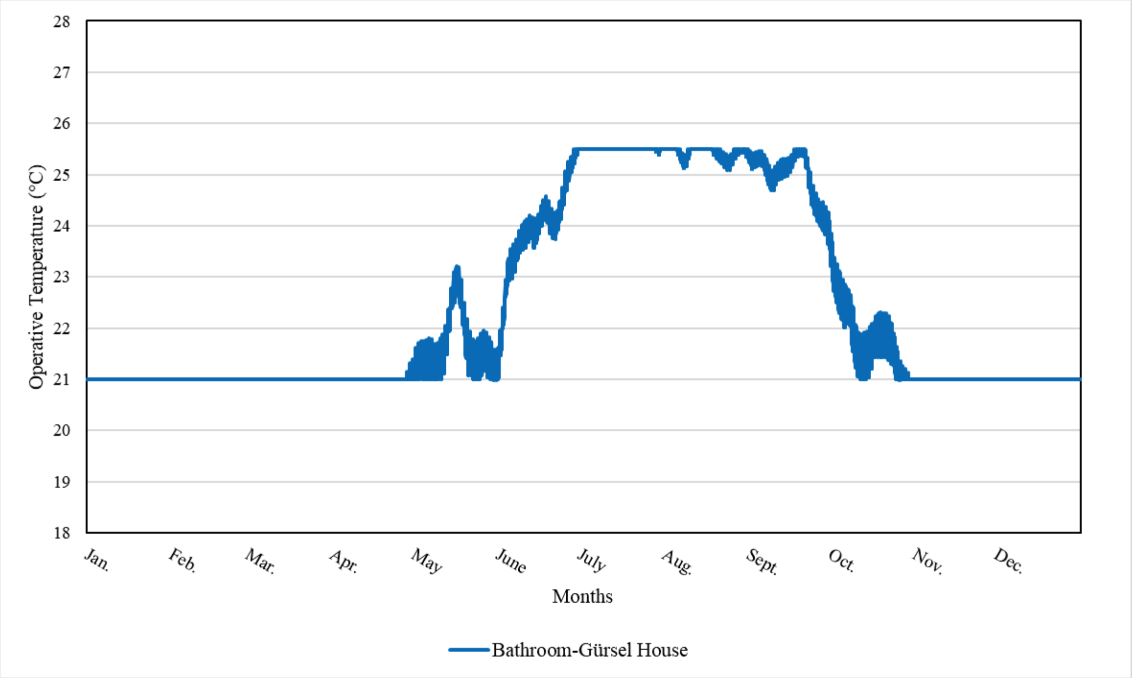

Figure 233. Annual operative temperature distribution of the bathroom - Model 2.2 / Gürsel house

APPENDIX L

RESULTS OF PMV ANALYSES FOR MODELS 2.2 TO ESTABLISH HVAC SET POINTS / SÖNMEZER HOUSE

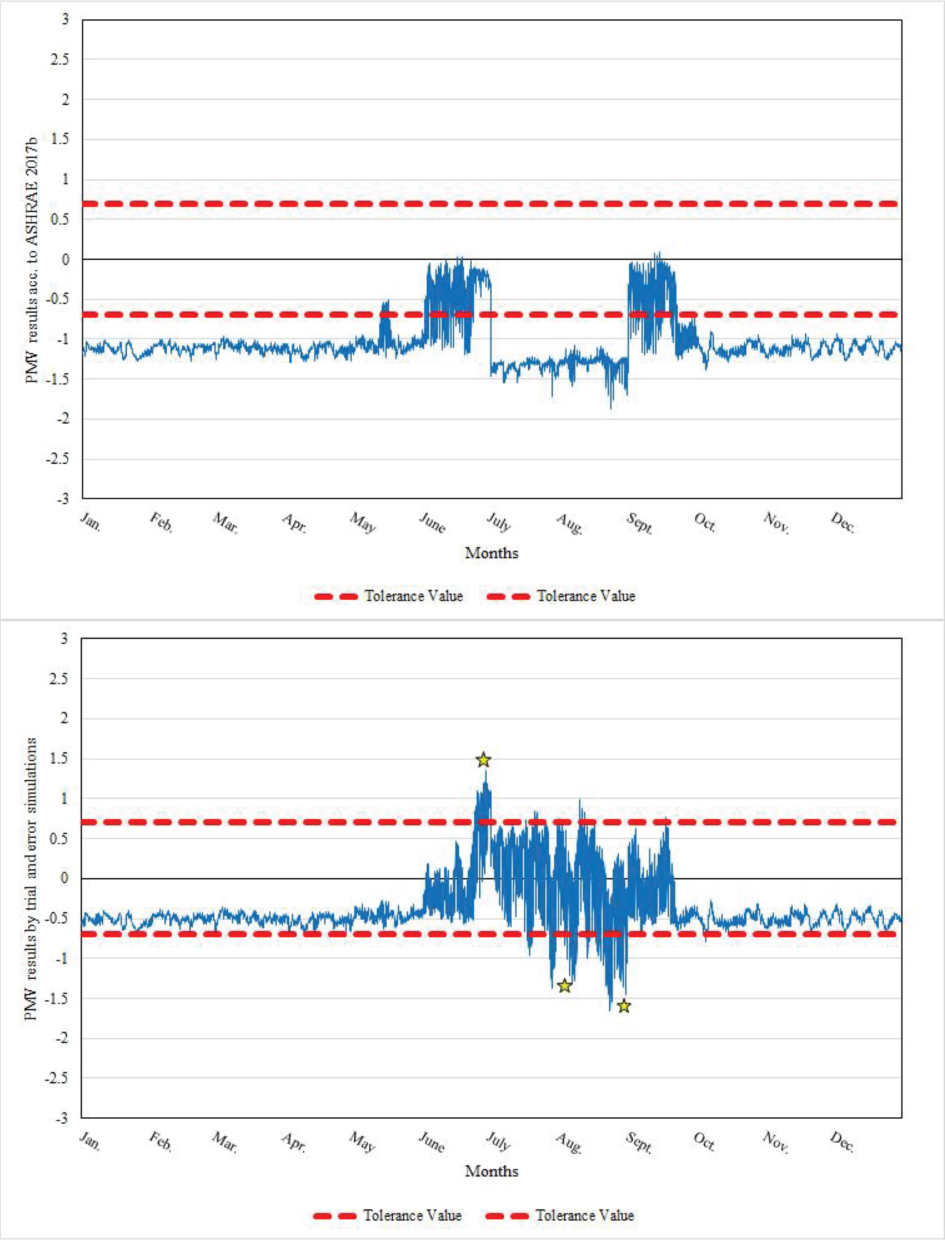

Figure 234. Comparison of thermal comfort status of the living room in Sönmezer House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

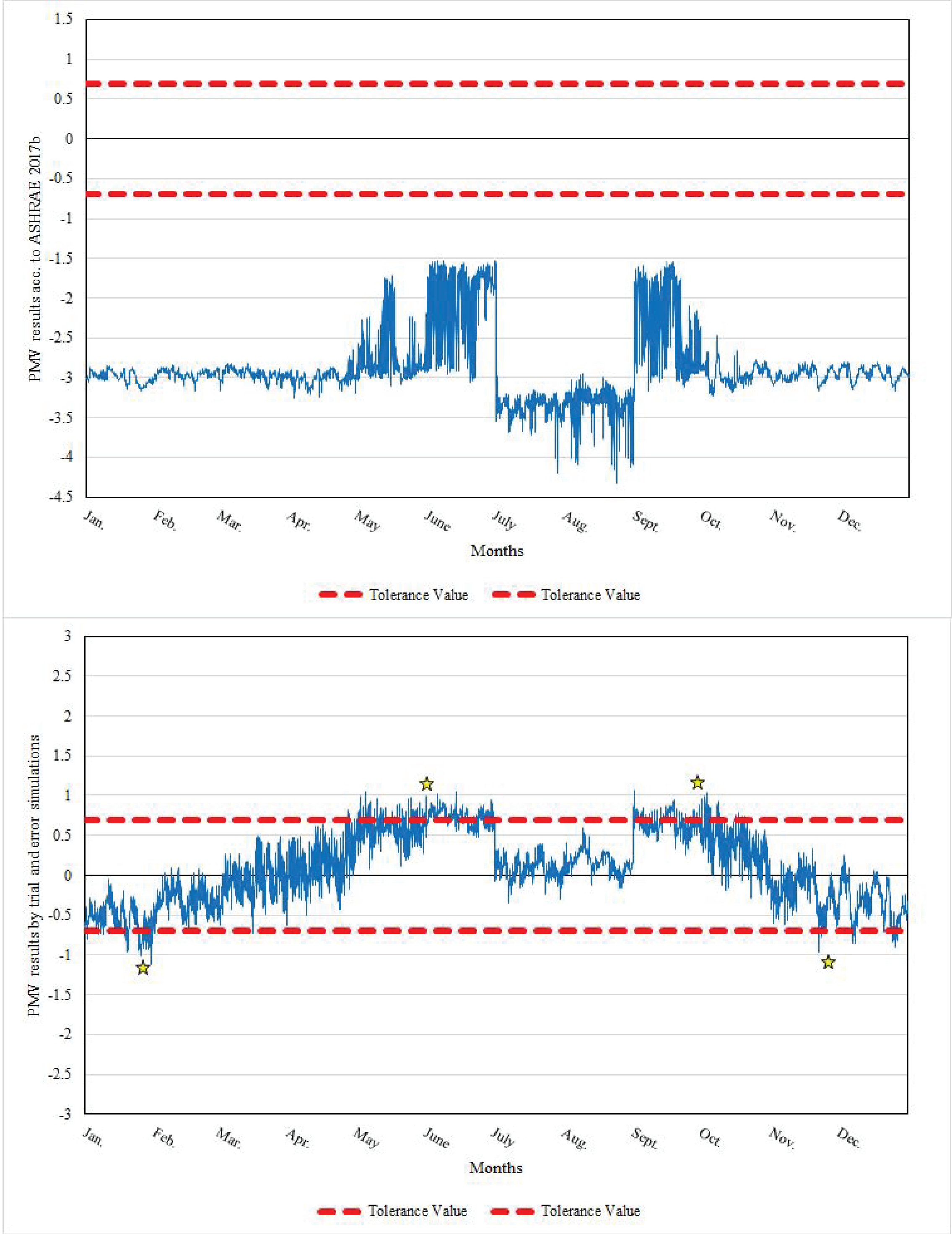

Figure 235. Comparison of thermal comfort status of the children room in Sönmezer House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

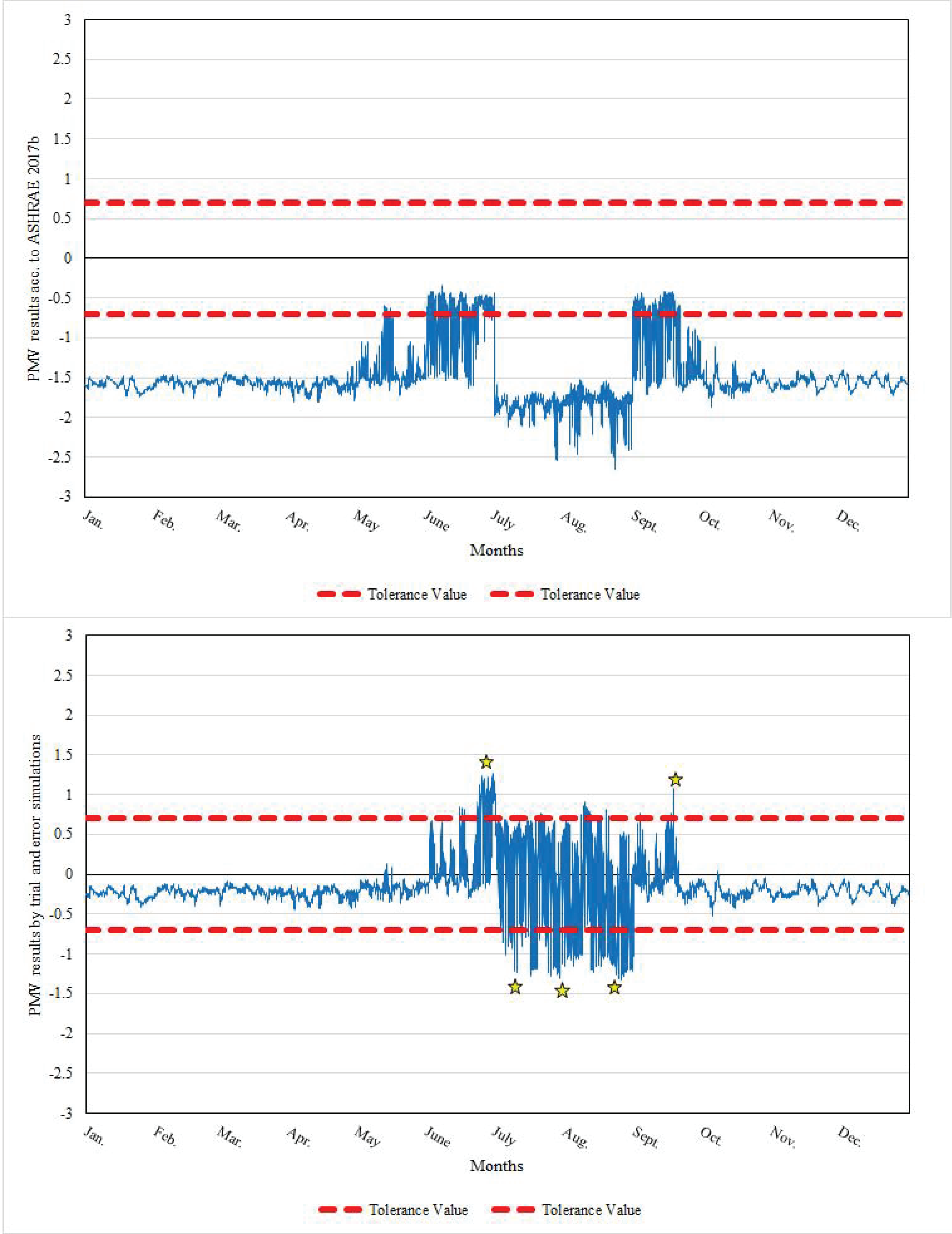

Figure 236. Comparison of thermal comfort status of the parent room in Sönmezer House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

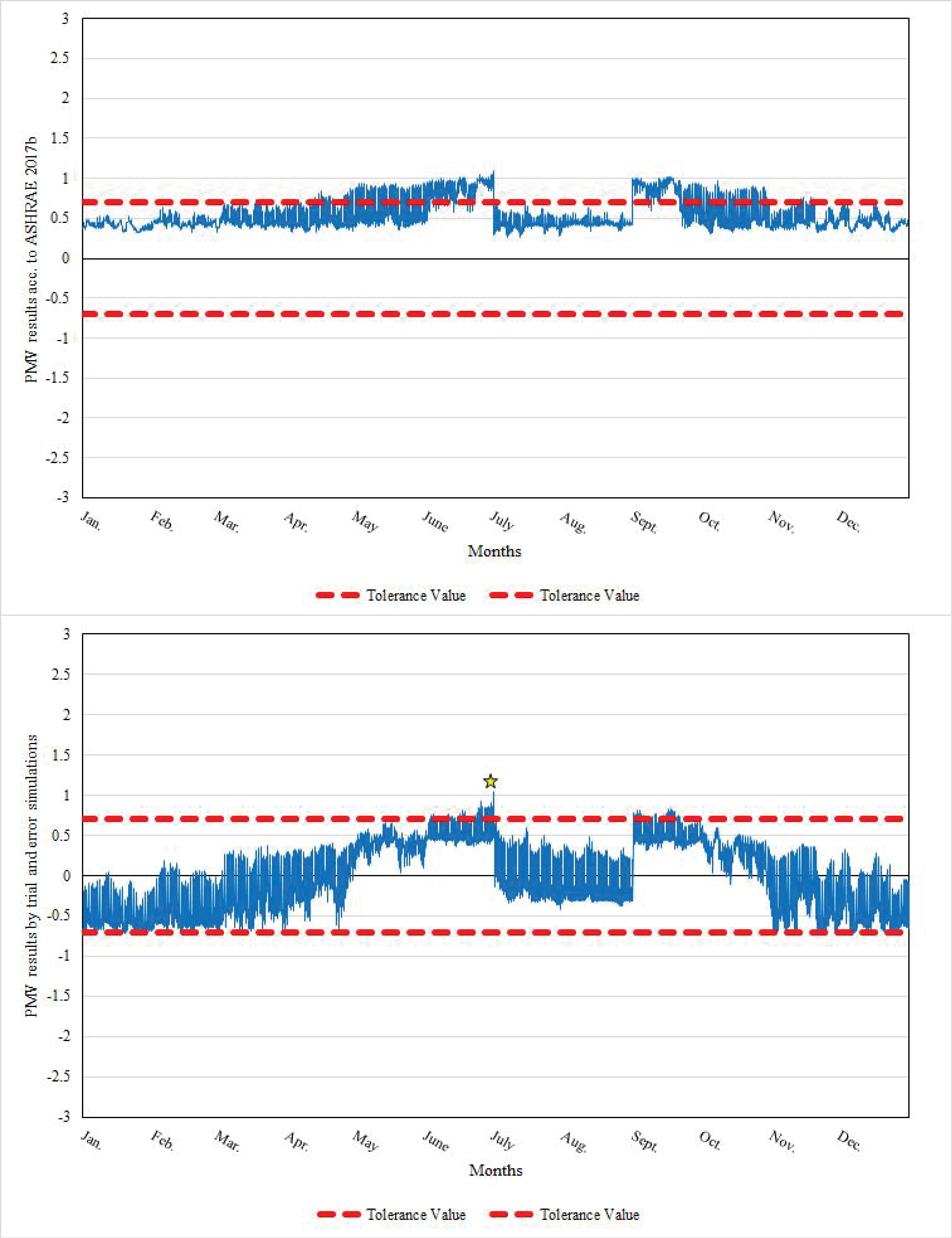

Figure 237. Comparison of thermal comfort status of the kitchen in Sönmezer House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart). The values on the lower chart that are out of the tolerance limits and marked by stars occurred due to the limitations of simulation software such as the inability to define varied occupant clothing values for day and nighttime.

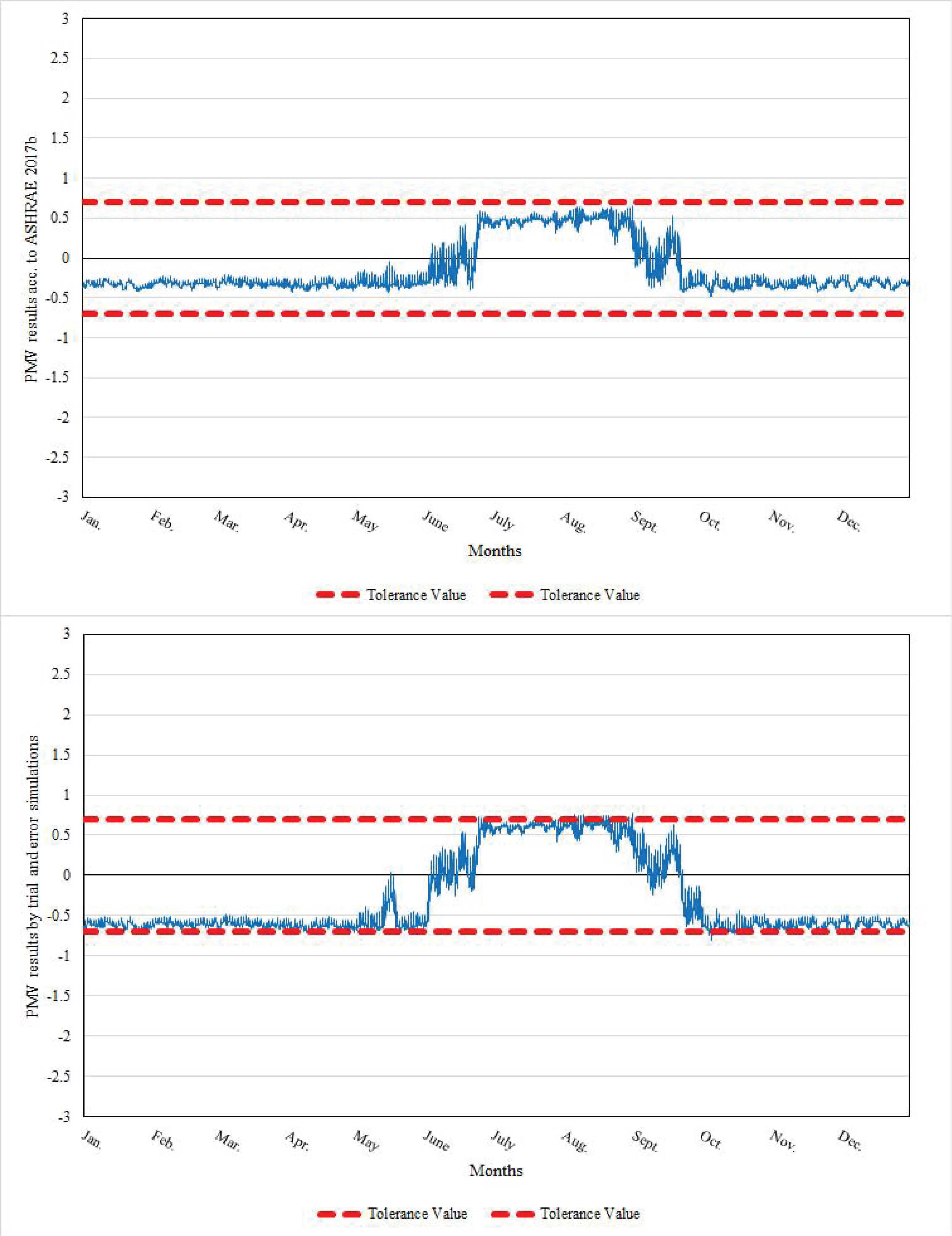

Figure 238. Comparison of thermal comfort status of the bathroom in Sönmezer House as HVAC set points are specified according to ASHRAE-2017b (Upper Chart) and through trial and error simulations (Lower Chart).

APPENDIX M

ANNUAL OPERATIVE TEMPERATURE DISTRIBUTION OF THE ROOMS-MODELS 2.2 / SÖNMEZER HOUSE

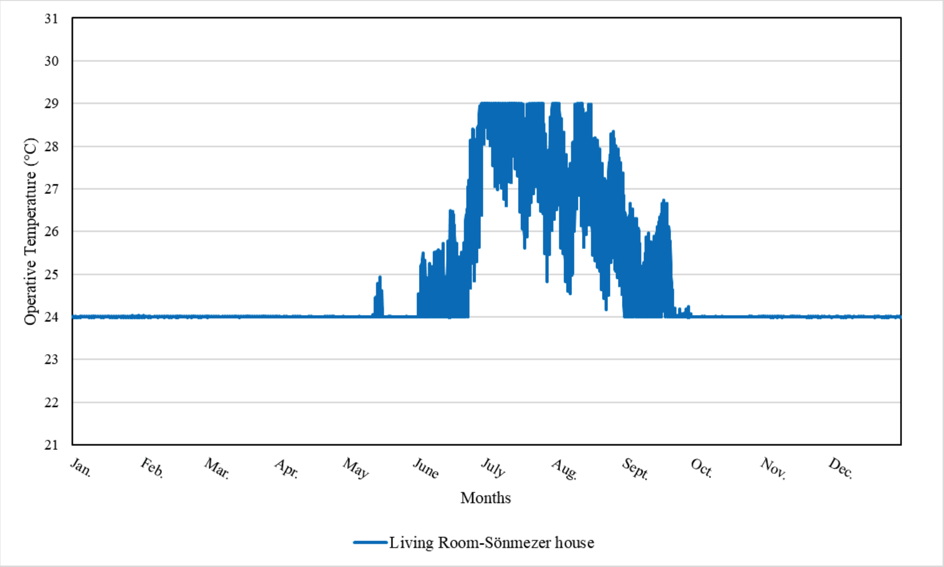

Figure 239. Annual operative temperature distribution of the living room - Model 2.2 / Sönmezer house

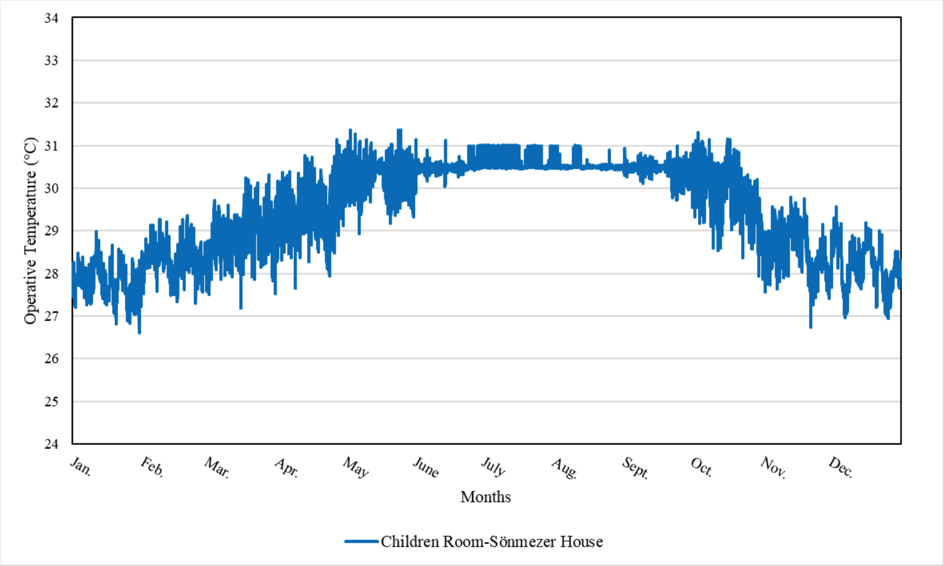

Figure 240. Annual operative temperature distribution of the children room - Model 2.2 / Sönmezer house

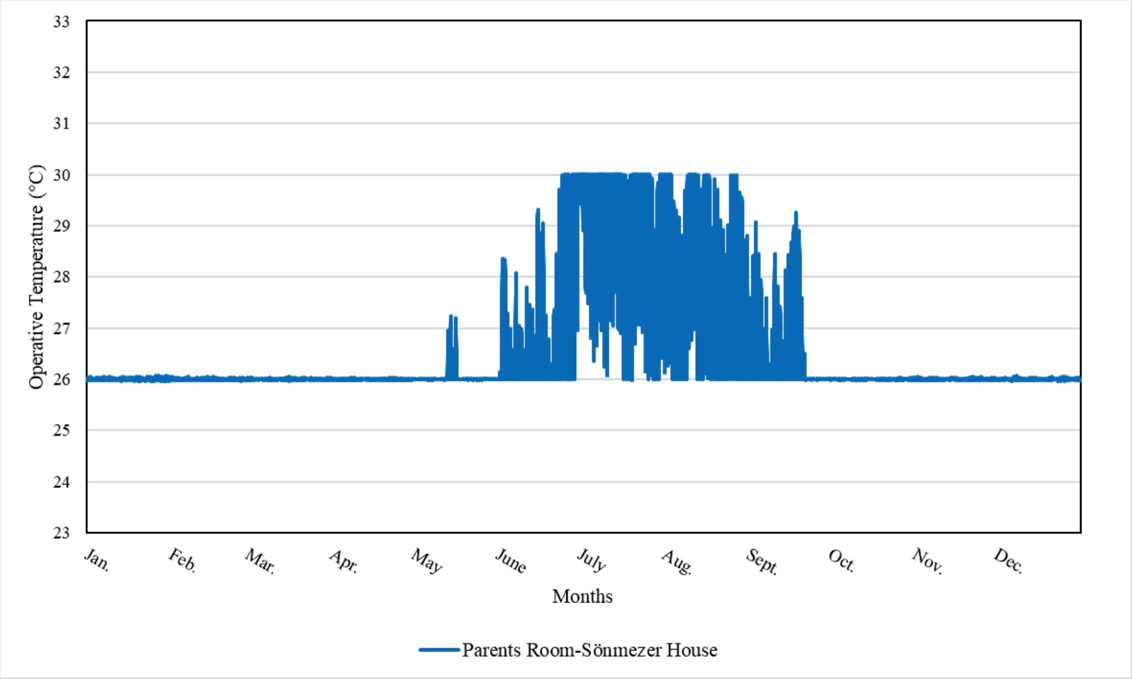

Figure 241. Annual operative temperature distribution of the parents' room - Model 2.2 / Sönmezer house

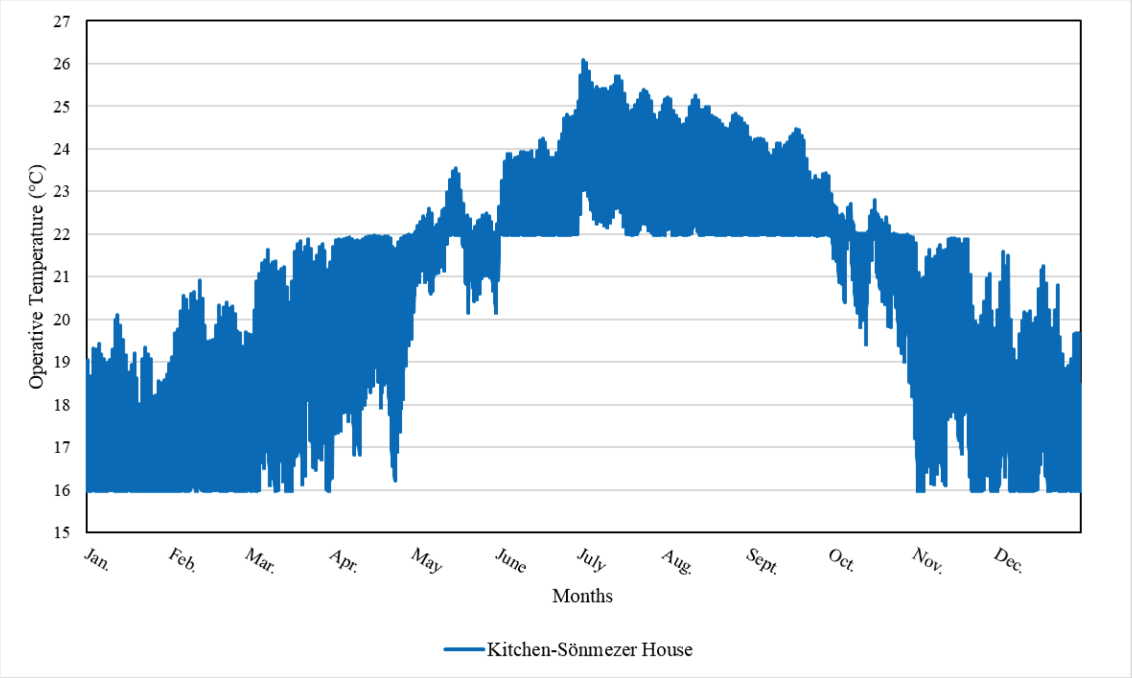

Figure 242. Annual operative temperature distribution of the kitchen - Model 2.2 / Sönmezer house

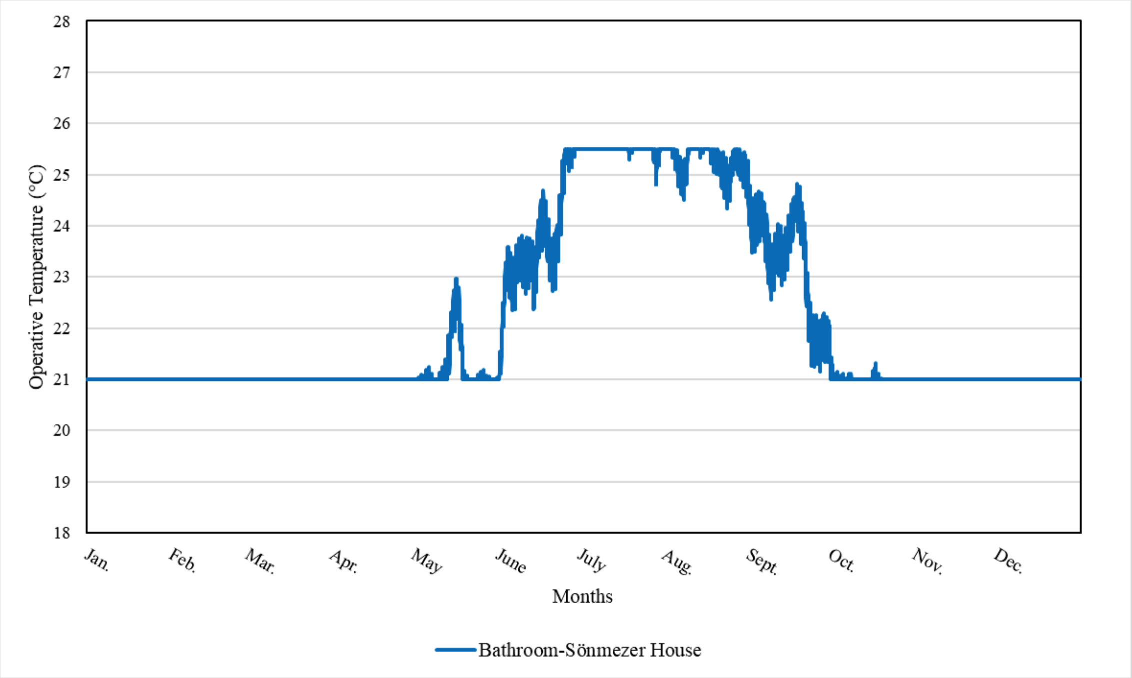

Figure 243. Annual operative temperature distribution of the bathroom - Model 2.2 / Sönmezer house

APPENDIX N

OPERATION SCHEDULES FOR WINDOWS AND SHUTTERS FOR RETROFITTING OF MODELS 2.2

Table 80. Operation schedule for window shutters

Through: January/31,	For: All Days,
	Until: 07:10, Closed,
	Until: 17:20, Open,
	Until: 24:00, Closed,
Through: February/28,	For: All Days,
	Until: 06:50, Closed,
	Until: 17:50, Open,
	Until: 24:00, Closed,
Through: March/31,	For: All Days,
	Until: 06:10, Closed,
	Until: 18:20, Open,
	Until: 24:00, Closed,
Through: April/30,	For: All Days,
	Until: 06:30, Closed,
	Until: 19:50, Open,
	Until: 24:00, Closed,
Through: May/31,	For: All Days,
	Until: 06:00, Closed,
	Until: 20:10, Open,
	Until: 24:00, Closed,
Through: June/30,	For: All Days,
	Until: 05:40, Open,
	Until: 20:30, Closed,
	Until: 24:00, Open,
Through: July/31,	For: All Days,
	Until: 06:00, Open,
	Until: 20:30, Closed,
	Until: 24:00, Open,
Through: August/31,	For: All Days,
	Until: 06:20, Open,
	Until: 20:00, Closed,
	Until: 24:00, Open,
Through: September/30,	For: All Days,
	Until: 06:50, Open,
	Until: 19:20, Closed,
	Until: 24:00, Open,
Through: October/31,	For: All Days,
	Until: 06:10, Closed,
	Until: 17:30, Open,
	Until: 24:00, Closed,
Through: November/30,	For: All Days,
	Until: 06:40, Closed,
	Until: 17:00, Open,
	Until: 24:00, Closed,
Through: December/31,	For: All Days,
	Until: 07:10, Closed,
	Until: 17:00, Open,
	Until: 24:00, Closed;

Table 81. Operation schedule for windows

Through: June/30,	For: All Days,
	Until: 24:00, Closed,
Through: August/31,	For: All Days,
	Until: 06:00, Open,
	Until: 20:00, Closed,
	Until: 24:00, Open,
Through: December/31,	For: All Days,
	Until: 24:00, Closed;

VITA

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Thesis: “Thermal Retrofitting on Traditional Buildings with Exterior Hall (*Sofa*): Urban and Rural Houses of Muğla”

M.Sc., Middle East Technical University, Graduate School of Natural and Applied Sciences, Department of Architecture / Ankara (2012)
Thesis: “A Study on Values, Problems and Potentials of the Traditional Dwellings in Karabağlar-Muğla”

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ACADEMIC EXPERIENCES

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