**ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE**

# THERMAL COMFORT OPTIMIZATION WITH OCCUPANT INTERACTION IN DYNAMIC HVAC CONTROL

**M.Sc. THESIS**

**Tuğçe AKER**

**Energy Science and Technology Division**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ**

# KULLANICI ETKİLEŞİMLİ DİNAMİK İKLİMLENDİRME SİSTEMİ KONTROLÜ İLE ISIL KONFOR OPTİMİZASYONU

**YÜKSEK LİSANS TEZİ**

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**HAZİRAN 2016**

Tuğçe AKER, a M.Sc. student of ITU Energy Institute student ID 301111025, successfully defended the thesis entitled “Thermal comfort optimization with occupant interaction in dynamic HVAC control”, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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**Date of Submission : 02 May 2016**
**Date of Defense : 09 June 2016**

***To my family,***

## FOREWORD

Firstly, I would like to express my gratitude to my advisor Prof. Dr. Nurdil ESKİN for the continuous support of my master study. Her guidance helped me throughout of research and writing of this thesis.

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May 2016

Tuğçe AKER
Mechanical Engineer

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## ABBREVIATIONS

**AMV** : Actual Mean Vote
**ASHRAE** : American Society of Heating, Refrigerating, and Air-Conditioning Engineers
**BMS** : Building Management System
**COP** : Coefficient of Performance
**CV(RMSE)** : Coefficient of Variation of the Root Mean Square Error
**DR** : Draughts rate
**HVAC** : Heating, Cooling, and Air Conditioning
**NMBE** : Normalized Mean Bias Error
**PD** : Percentage Dissatisfied
**PMV** : Predicted Mean Vote
**PPD** : Predicted Percentage of Dissatisfied
**RH** : Relative Humidity
**SBS** : Sick Building Syndrome

## SYMBOLS

$\mathbf{A_{eff}}$ : The effective radiation area of the clothed body ($m^2$)
$\mathbf{A_{Du}}$ : Body surface area (DuBois Area) ($m^2$)
$\mathbf{C}$ : The heat loss by convection from the outer surface of the clothed body (W)
$\mathbf{c_p}$ : The specific heat of dry air at constant pressure (kcal/kg°C)
$\mathbf{E_d}$ : The heat loss by water vapour diffusion through the skin (W)
$\mathbf{E_{sw}}$ : The heat loss by evaporation of sweat from the surface of the skin (W)
$\mathbf{E_{res}}$ : The latent respiration heat loss (W)
$\mathbf{f_{cl}}$ : The ratio of the surface area of the clothed body to the surface area of the nude body
$\mathbf{H}$ : The internal heat production in the human body (W)
$\mathbf{h}$ : Height (m)
$\mathbf{h_c}$ : Convective heat transfer coefficient ($W/m^2K$)
$\mathbf{I_{cl}}$ : Thermal resistance of the clothing (clo)
$\mathbf{K}$ : The heat transfer from the skin to the outer surface of the clothed body (W)
$\mathbf{L}$ : The dry respiration heat loss (W)
$\mathbf{m}$ : Permeance Coefficient of the skin (kg/h $m^2$mmHg)
$\mathbf{n}$ : Number of data points
$\mathbf{p}$ : Number of parameters
$\mathbf{P}$ : Sea level barometric pressure (mmHg)
$\mathbf{p_a}$ : Vapor pressure in ambient air (mmHg)
$\mathbf{p_s}$ : Saturated vapour pressure at skin temperature (mmHg)
$\mathbf{R}$ : The heat loss by radiation from the outer surface of the clothed body (W)
$\mathbf{R_{cl}}$ : The total heat transfer resistance from the skin to outer surface of the clothed body ($m^2$°C/W)
$\mathbf{S}$ : Stored energy (W)
$\mathbf{t_a}$ : Air temperature (°C)
$\mathbf{T_{accept}}$ : The limits of acceptable zones (°C)
$\mathbf{T_{cl}}$ : Temperature of clothing surface (°C)
$\mathbf{T_{ex}}$ : Expired air temperature (°C)
$\mathbf{T_f}$ : The floor temperature (°C)
$\mathbf{T_{mrt}}$ : The mean radiant temperature (°C)
$\mathbf{T_o}$ : Outdoor air temperature (°C)
$\mathbf{T_{lim}}$ : The range of acceptable temperature (°C)
$\mathbf{T_u}$ : The turbulence intensity (%)
$\mathbf{v}$ : Mean air velocity (m/s)
$\dot{\mathbf{V}}$ : Pulmonary ventilation (kg/h)
$\mathbf{w}$ : Weight (kg)
$\mathbf{W}$ : Mechanical work (W)

$\mathbf{W_a}$ : Humidity ratio of the inspiration air (kg water/kg dry air)
$\mathbf{W_{ex}}$ : Humidity ratio of the expiration air (kg water/kg dry air)
$\bar{y}$ : Arithmetic mean of sample of n observation
$y_i$ : Observed value
$\hat{y}_i$ : Predicted value of $y_i$
$\Delta T_{a,v}$ : The vertical air temperature differences between head and ankles
$\varepsilon$ : The emittance of the outer surface of the clothed body
$\eta$ : External mechanical efficiency
$\lambda$ : Heat vaporisation of water (kcal/kg, Wh/kg)
$\sigma$ : The Stefan-Boltzmann constant ($W/m^2K$)

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# THERMAL COMFORT OPTIMIZATION WITH OCCUPANT INTERACTION IN DYNAMIC HVAC CONTROL

## SUMMARY

According to the Environmental Protection Agency (EPA), people spend 90% of their time indoors. Consequently, a significant number of study is performed in order to determine the effect of thermal environment on occupant health and productivity. The findings of these studies show that thermal environment has a significant effect on occupant thermal sensation and well-being. With the development of HVAC and building management systems, total control of the indoor environment becomes possible, and comfort bears a higher level of importance in order to maintain healthy indoor conditions.

Thermal comfort is defined as "*the condition of mind that express satisfaction with the thermal environment*" and its depends on the different physical, physiological and psychological parameters. In order to assess thermal comfort, different models are proposed by a significant number of studies. The most widely accepted method is developed by Fanger, and it rests upon heat balance equations between indoor environment and the human body. This model is a function of six parameters, which split into environmental and personnel parameters; indoor air temperature, mean radiant temperature, relative humidity, air velocity, activity type and level, and clothing insulation of occupants.

The focus of this thesis is research and evaluation of dynamic thermal comfort optimization methods for a shared spaces. The reason of that in single occupant offices, a thermally comfortable environment can be created simply based on occupant requirement. However, it is difficult to find an optimal thermostat setting temperature for multiple occupants sharing the same office. Studies show that most of the occupants have to stay at uncomfortable environments during the day because of the lack of proper control in buildings. It causes a decrement in performance and well-being of occupant. To overcome this issue, HVAC system should be operated dynamically based on time-varying temperature requirement of space and occupant thermal comfort conditions. However, it is hard to determined optimum temperature setting based on thermal comfort in practice. Most of existing Building Management Systems (BMS) have the issue of the absence of adequate equipment to assess thermal comfort conditions. Even with the proper equipment, it would be near impossible to meet absolute satisfaction because of the subjectivity of the matter and optimum thermal comfort conditions vary from person to person.

In order to control HVAC system based on occupant requirement, The occupant participating approach has been developed. This method is bringing the humans in the loop by using their thermal perception feedback to improve mathematical models prediction, and it is started to utilize in a growing number of studies. In this study, thermal comfort optimization methods, which using the occupant participating approach, was examined to find simple and accurate optimization models. For this purpose, literature reviews and commercial products were reviewed, and three different optimization methods were chosen to evaluate. One of these methods uses PMV (Predicted Mean Vote), which is mainly used the method in studies and standards to assess thermal comfort, model to estimate initial thermal comfort conditions with temperature and humidity sensors outputs. In order to correct the PMV estimation, occupant participatory approach is used to collect real and continuous thermal sensation feedback of occupant via a smartphone application. Based on corrected PMV value, thermostat set point temperature is adjusted accurately. In the second method, only occupant feedbacks, which are collected in a similar way to the first method, are used to adjust the set point temperature of indoor HVAC system. The final method uses two-step model; the first step is calculation the optimal temperature for each occupant based on their energy expenditure level estimation and outdoor temperature and the last step is an adjustment the temperature based on occupant dynamic thermal sensation feedback via smart phone.

Performances of the selected optimization models were evaluated via Design Builder and EnergyPlus simulation tools. The analysis was conducted in a case study zone, which is an open plan office and located in ARI 6 Technopark building, Istanbul Technical University. Model performance was analyzed regarding energy consumption and thermal comfort conditions. Besides these analyses, effects of thermal comfort on occupants' productivity were examined. For this purpose, humidity and temperature data were monitored and recorded for a one-week period, also during this process, occupant real time feedbacks about their thermal sensations were collected via website application. Measured data were used to calibrate and validate the simulation model of case study building. The evaluations of optimization methods were performed by using calibrated model.

The findings of this thesis indicate that dynamic set point temperature control helped to optimize thermal comfort. In addition to this benefit of the control method, the productivity of workers increases under comfort conditions. On the other hand, the results proof the trade-off between thermal comfort and energy consumption of the building.

# KULLANICI ETKİLEŞİMLİ DİNAMİK İKLİMLENDİRME SİSTEMİ KONTROLÜ İLE ISIL KONFOR OPTİMİZASYONU

## ÖZET

İnsanlarda diğer canlılar gibi bulundukları ortam ile enerji dengesi sağlamaya çalışmaktadır. Isıl konfor, ısıl çevre ile kişi arasında sağlanan memnuniyet olarak tanımlanabilen, nesnel bir kavramdır. Çok farklı iklimlerde hayatta kalabilen insan için konforlu hissedilen sıcaklık aralığı çok dardır. Homeotermik bir canlı olan insanın yaşamsal fonksiyonlarının devam edebilmesi için vücudun neredeyse sabit bir sıcaklıkta tutulması gerekmekte ve bu amaçla fizyolojik denetim ve kontrol mekanizmaları kullanılmaktadır. Bunun yanında destek mekanizmalar olarak farklı metotların kullanımı ortaya çıkmıştır.

Çevre ile enerji dengesinin sağlanabilmesi için ilk olarak fizyolojik bir kontrol mekanizması olan termoregülasyon sistemi ile vücut içindeki ısı üretimi ile çevre ile olan ısı kayıpları arasında bir denge oluşturulmaya çalışmaktadır. Buna yardımcı olarak kıyafetler ve dış ortam etkilerini minimuma indiren binalar bu denge durumuna katkı sağlayan etkili birer mekanizma olarak insanlar tarafından kullanılmaktadır. İlk çağlardan bu yana binalarda kullanılan aktif ve pasif stratejiler ile dış ortamdan olabildiğince korunarak konforlu ortamlar oluşturulmaya çalışılmıştır. İklimlendirme sistemlerinin gelişmesi ile ısıl konfor konusu daha da önem kazanmaya başlamış ve 20. yüzyılın başlarında ASHRAE tarafından optimum konfor aralığı üzerinde çalışmalar yapılmaya başlanmıştır.

İç ortam koşullarının termal konfor şartları açısından uygunluğunu hesaplamak için birçok yöntem geliştirilmiştir. Bu metotların arasında en çok kullanılan ısıl konfor modeli Fanger tarafından oluşturulmuş olan ısıl konfor denklemidir. Isıl konforun tayini için ortama ait fiziksel parametreler (iç ortam hava sıcaklığı, ortalama yüzey sıcaklığı, bağıl nem ve hava hızı) ile kişisel faktörlerin (aktivite ve kıyafet yalıtım özellikleri) hesaba katıldığı PMV (Predicted Mean Vote – Tahmini Ortalama Oy) ve PPD (Percentage of Dissatisfied – Tahmini Konforsuzluk Yüzdesi) indeksleri bu model kapsamında geliştirilmiştir. Bu modelin iklimlendirme sistemler tarafından koşullandırılan binalarda geçerliliği birçok çalışma tarafında kanıtlanırken, doğal havalandırma ile çalışan binalarda ısıl konfor tayininde yetersiz kaldığı belirlenmiştir. Bu amaçla Adaptif kontrol modeli geliştirilmiştir.

İnsan vücudunun dış ortam ile ısıl dengesini ve dolayısıyla termal konforu etkileyen altı parametre bulunmaktadır. Bunlar, iç ortam sıcaklığı, bağıl nem, hava hızı, yüzey sıcaklığı, aktivite tipi ve seviyesi ve giysilerin yalıtım özelliği. Bu parametrelerin her birinin belirlenmesi ile PMV ve PPD değerleri kolaylıkla hesaplanabilmektedir. Fakat iç ortam sıcaklığı ve bağıl nem hariç dört parametrenin ölçülmesi ve takip edilmesi mevcut sensorlar ve bina kontrol sistemleri için mümkün olmamaktadır. Gün içinde dinamik ısıl konfor tayini gerçekleştirmek için birçok farklı çalışma gerçekleştirilmiştir.

Gelişen iklimlendirme ve kontrol sistemleri ile iç ortam koşullarını tam anlamıyla kontrol etmek mümkün hale gelmiş ve konfor, günün çok büyük bir bölümünü bina içerisinde geçiren kullanıcılar için daha da önem kazanmıştır. Ayrıca yapılan çalışmalarda görülmüştür ki konfor sadece kullanıcının memnuniyetini etkileyen bir parametre olmamakla birlikte aynı zamanda insan sağlığı, performansı, üretkenliği ve yaşam kalitesi açısından da önem teşkil etmektedir.

Isıl konfor aynı zamanda enerji tüketimi üzerinde de büyük bir etkiye ve öneme sahiptir. Bina sektörü toplam enerji tüketiminin üçte birini oluştururken bu tüketimin büyük bir bölümü binada yer alan ısıtma/soğutma ve havalandırma sistemleri tarafından tüketilmektedir. Çalışmalar göstermektedir ki yetersiz kontrol sistemleri nedeniyle birçok kullanıcı gün boyunca konforsuz koşullara maruz kalmaktadır. Bu durum ortamda kalan kullanıcıları farklı aksiyonlara yönlendirmektedir. Genel itibari ile insanlar rahatsız hissedilen bir ortamda kıyafet değişikliği, pozisyon değişikliği, rahatsız hissedilen hacimden ayrılmak ya da pasif veya aktif kontroller ile ortam koşullarını değiştirerek bu durumu düzeltmeye çalışmaktadır. Ofis gibi alanlarda kullanıcılar bu duruma çözüm olarak ek ısıtıcılar ya da soğutucu sistemleri kullanmaktadırlar. Fakat bu durum hem enerji tüketimini arttırmakta hem de ortamda ısıl dengesizliklere yol açmaktadır. Yapılan çalışmalar bu dengesizliklerin önüne geçmek için gerçek zamanlı ve dinamik kontrol sistemlerinin kullanımı bir çözüm olabileceğini göstermektedir. Bu kontrol metotları ile kullanıcıların ihtiyaçlarına anında cevap verilerek, bina kullanıcılarının çoğunluğu için optimum iç ortam koşulları sağlanılması amaçlanmaktadır.

Dinamik termostat sıcaklık kontrolü ile gün boyunca değişen dış hava sıcaklığı, güneş ışınımları, kullanıcı yoğunluğu ve ekipman operasyonları gibi birçok parametre nedeniyle değişen iç ortam parametreleri takip edilerek sıcaklığın sürekli olarak optimumda tutulması sağlanabilir ve kullanıcıların konfor ihtiyaçları karşılanabilmektedir.

Bu çalışmanın amacı, termostat set sıcaklıklarını kullanıcıların ısıl konforunu optimumda tutacak şekilde gün içinde dinamik olarak kontrolünü sağlayacak metotların incelenmesi ve gerçek uygulamalarda kullanıma en uygun ve doğruluğu en iyi olan metodun belirlenmesidir. Bu amaçla literatür taraması yapılırken, bir taraftan da markette yer alan ürünler ve uygulamalar incelenmiştir. Yapılan çalışmalar sonucunda üç farklı optimizasyon modeli belirlenmiştir. Seçim yapılırken dikkat edilen husus, mevcut bina kontrol ve izleme sistemlerine rahatlıkla adapte edilebilecek, kolay ve güvenilir bir yöntem olmasıdır.

Tez kapsamında incelenecek ilk yöntem binada yer alan sensorlardan gerçek zamanlı sıcaklık ve nem değeri ölçümü yapılmakta ve bu değerler ile belirli aralıklarla ortamın PMV değeri hesaplanmaktadır. Fakat PMV hesabında yer alan diğer parametreler (radyant sıcaklık, hava hızı, aktivite ve kıyafet yalıtımı) sabit kabul edildiğinden dolayı hesaplamalarda hata oluşmakta ve bu durumu çözmek için ise diğer yöneteme benzer şekilde kullanıcılardan anlık konfor durumlarını oylamaları istenmektedir. Kullanıcılardan gelen oylar PMV skalasındaki değerlere karşılık gelen çok sıcak (+3), sıcak (+2), biraz sıcak (+1), normal (0), biraz soğuk (-1), soğuk (-2) ve çok soğuk (-3) olarak yedi kademeden oluşmaktadır. Böylelikle gelen olaylar yardımıyla hesaplanan PMV değer düzeltilmekte. Yeni çıkan PMV değerini 0'a getirecek termostat değeri hesaplanmaktadır.

Diğer yöntemde ise, kullanıcılardan konfor koşulları ile ilgili gelen öznel geri bildirimlerden yararlanarak termostat sıcaklığını ayarlan bir sistemdir. Bu yöntemde binada herhangi bir ölçüme gerek duyulmamakta sadece kullanıcılardan gelen sıcak (+1), soğuk (-) ya da normal (0) olmak üzere üç kademeden oluşan bir skala üzerinden gerçekleştirilen oylama sonuçlarına göre kontrol sağlanmaktadır.

Son olarak incelenen teknik, her bir kullanıcı için optimum sıcaklığı değerini hesaplayabilen bir model oluşturulmuştur. Bu kapsamda, ilk olarak her bir kullanıcı için PMV endeksi hesaplanmasını sağlayan matematiksel bir model oluşturulmuştur. Bu model kişinin yaş, boy, kilo, cinsiyet, faaliyet durumu ve dış ortam sıcaklıklarını değişken olarak hesaba katmakta ve kişiye özgü optimum sıcaklık değerini hesaplamaktadır.

Tez kapsamında seçilmiş olan hacim için mevcut ısıl konfor durumunun belirlenmesi amacıyla farklı metotlar uygulanmıştır. İlk olarak kullanıcılara ASHRAE 55 standardında yer alan ısıl konfor anketi uygulanmıştır. Bu anket ile yıl boyunca kullanıcıların bulundukları hacim ile ilgili ısıl konfor durumlarını değerlendirmeleri istenmiş konforsuzluğa neden olan problemlerin belirlenmesi amaçlanmıştır. Anket sırasında kullanıcıların kıyafetleri ile yaş, boy ve kilo bilgileri de toplanmıştır.

İkinci olarak iki haftalık saha ölçümleri gerçekleştirilmiştir. İlk hafta iklimlendirme sisteminin devrede olmadığı durum incelemiş ve 10 dakikalık aralıklarla iç ortam sıcaklığı ve nem değerleri yerleştirilen sensor ile ölçülmüştür. Sonraki hafta termostat değeri 24°C’de sabit tutularak kullanıcıların ofiste olduğu zaman aralıkları incelenmiştir. Bu zaman diliminde de sensor 10 dakika aralıkla sıcaklık ve nem ölçümü almaya devam etmiştir.

Son olarak kullanıcı ile değişen iç ortam koşulları arasındaki ilişkinin incelenebilmesi için oylama işlemi gerçekleştirilmiştir. Bu kapsamda kullanıcıların istedikleri süre içerisinde ortamın ısıl konfor durumu ile ilgili histekilerini oylayabilecekleri bir internet sitesi hazırlanmıştır. Oylama ASHRAE’nin 7 noktalı skalası ile yapılmıştır.

Değerlendirmek üzere seçilen optimizasyon metotları bina enerji modeli ile incelenmiştir. Modelleme ile farklı dinamik set sıcaklıklarının enerji tüketimine ve ısıl konfora olan etkileri incelenebilmiştir. Modelin doğruluğu ve geçerliliğinin sağlanabilmesi için sensor ile yapılan ölçüm sonuçları ile karşılaştırma yapılmış ve modelin hata payının belirlenen limit değerlerinin altında ya da aralığında kalması yapılan kalibrasyon işlemi ile sağlanmıştır.

Değerlendirmek üzere seçilen optimizasyon modelinin enerji tüketimi ve ısıl konfor üzerindeki etkisi binanın bilgisayar modeli üzerinden incelenmiştir. Bu kapsamda binanın mimari, mekanik, elektrik ve malzeme bilgileri toplanmış ve bunlara uygun olarak model oluşturulmuştur. Modelin geçerliliğini belirlemek için oylama sırasında yapılan sıcaklık ve nem ölçümleri, binada yer alan kartlı giriş sisteminden alınan kullanıcı giriş-çıkış bilgiler, dış ortam iklim verileri modele entegre edilerek gerçek koşulların bilgisayar ortamında modellenmesi sağlanmıştır. Bu analizlerin yanında optimizasyon modellerinin kullanıcıların yazma ve düşünme performanslarına olan etkileri de incelenmiştir.

Analiz sonuçlarına göre, dinamik termostat kontrolü ile kullanıcılar için daha konforlu ve sağlıklı bir ortam oluşturulabileceği belirlenmiş olup aynı zamanda iş performanslarında da artış yaşanabileceği tespit edilmiştir. Bunun yanında enerji tüketimi ile konfor arasındaki ilişki incelenmiş olup, konforu sağlarken enerji tasarrufunda da artış yaşandığı tespit edilmiştir. Daha sonra yapılacak çalışmalarda bu sorunu ortadan kaldıracak optimizayon modelleri geliştirilip ısıl konfordan ödün vermeden enerji tasarrufu sağlayacak modeller üzerinde çalışmalıdır.

# 1. INTRODUCTION

Humans are homoeothermic which means that the body regulates the internal body temperature nearly constant by thermoregulation system [1]. The human body is under almost constant thermal stress in outdoor conditions, and it has great difficulty remaining in balance. In order to preserve constant temperature, buildings have been used since the early ages in addition to clothing and physicological mechanism. To create acceptable thermal environments for life, passive design strategies and basic conditioning systems, such as stove and fireplace, have been used in early buildings. Due to the development of HVAC system, total control is possible in indoor conditions and people can create a thermally comfortable artificial environment. However, HVAC system cannot meet thermal comfort requirement and occupants have to stay in uncomfortable indoor environments in most cases because of the inappropriate control methods [2].

Due to the fact that people spend most of their time in these artificial environments, indoor environmental quality and accordingly, thermal comfort become important subjects for occupants, in terms of health, comfort and performance. Studies proof that poor indoor thermal conditions may cause Sick Building Syndrome (SBS). People show indications of this problem as nose irritation, stuffed nose, rainy nose, eye irritations, cough, tightness in the chest, fatigue, headache, and rash. SBS is triggered by imbalanced in relative humidity ratio. Relative humidity also affects the energy balance in the body and consequently thermal comfort of occupant [3].

Thermal comfort is not only important term for health, but it also has significant effects on task performance of occupant. Several mechanisms have an impact on productivity and work performance of the occupant, such as rapid or slow temperature swing and vertical thermal gradients. A considerable number of study has conducted in order to determine the relation between thermal environment and performance. The findings of these studies indicate the effects of indoor conditions on productivity [4].

HVAC systems are designed to provide comfortable environment with heating/cooling function, filtered outdoor air, and proper humidity level. HVAC system and thermal comfort has effects on not only occupant health, performance, and quality of life but also has a significant impact on building energy consumption. When sectoral energy consumption is analyzed, it can be seen that the building sector is the largest energy consumer with one-third of final energy consumption share globally and also it is important source of $CO_2$ emissions [5]. In Turkey, 35% of total energy is consumed by residential and commercial buildings [6].

In Figure 1.1, worldwide end-use of building sector data is given. HVAC system consumption is equal to %34 of total energy consumption in the residential building. This ratio increase to 40% in commercial building [7].

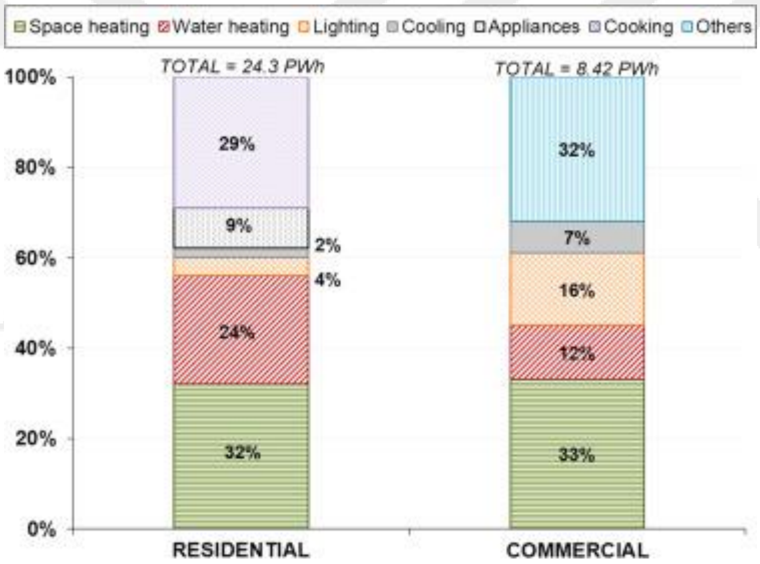


**Figure 1.1 :** Energy consumption by end uses in building sector.

Climate change and the urgency of minimizing the carbon footprint of the built environment are driving people to seek energy efficient building solutions. Due to the high energy intensity of HVAC system, a part of energy efficiency studies concentrate on this system. In order to reduce the energy consumption of HVAC system, there are several methods such as enhancing building envelope thermo-physical properties, retrofitting HVAC system, etc. [5]. Though energy efficient HVAC system alone is not enough, also real-time monitoring and control systems help to minimize energy and cost. According to the one of the market survey results, building control systems have a great impact on consumption reduction. The traditional energy management system can save between 5% and 10% energy. The lighting system, which is controlled based on occupancy presence sensors, decrease energy consumption by 20-28%. Demand controlled ventilation can reduce energy consumption by 10-15% [8]. As it is seen, real-time control and optimization can help building owner to reduce energy consumption and cost. In spite of saving potential of these control mechanism, control system does not design to include these strategies in many case.

Discomfort, which is the main result of the inapproprate control, may lead people to use additional heating and cooling sources, such as electrical heaters and fans. These local sources can cause a thermal imbalance and reduce satisfaction in a zone. Moreover, energy consumption and cost increase [9]. In order to overcome this problem, proper control methods should be used in the building. Especially, dynamic controls become important for multiple occupants to share the same office, and it is possible by using real-time monitoring and control systems.

Outdoor air temperature and solar radiation value, occupancy density, equipment operation can cause fluctuation in indoor air temperature and consequently, a thermal sensation of occupant change in time. The focus of this thesis is research and evaluation of dynamic thermal comfort optimization methods for a shared space, offices, schools, etc. The reason of that in single occupant offices, a thermally comfortable environment can be created simply based on occupant requirement. However, it is difficult to find an optimal thermostat setting temperature for multiple occupants sharing the same office. Studies show that most of the occupants have to stay at uncomfortable environments during the day because of the lack of proper control in buildings. It causes a decrement in performance and well-being of occupant. To overcome this problem, HVAC system should be operated dynamically based on thermal comfort time-varying temperature requirement of space. However, it is hard to assess thermal comfort conditions in practice. Most of existing Building Management Systems (BMS) have the issue of the absence of adequate equipment. Even with the proper equipment, it would be near impossible to meet absolute satisfaction because of the subjectivity of the matter and optimum thermal comfort conditions vary from person to person.

For this purpose, three different set point optimization methods were selected and examined. Performances of the selected optimization models were evaluated via Design Builder and EnergyPlus simulation tools. The measurements and analyses were conducted in a case study building, which is an open plan office and located in ARI 6

Technopark building, Istanbul Technical University. Model performance was analyzed regarding energy consumption and thermal comfort conditions. Besides these analyses, effects of thermal comfort on occupants’ productivity were examined.

# 2. LITERATURE REVIEW

## 2.1 Thermal Comfort Assessment

In order to assess of thermal comfort, a large number of studies have been conducted, and models have been developed. One of these methods uses mathematical representation of the thermal relationship between the human body and environment with integrating the heat transfer, heat balance, thermoregulation and thermal physiology into a mathematical model. Over the years, various mathematical models have been developed. Nowadays, two main mathematical models, which are the rational or heat balance approach and the adaptive approach. While heat balance approach is based on climate chamber experiment result, the adaptive approach uses statistical model with field studies data [10]. Based on these model, thermal comfort indices have been generated to express comfort conditions of the environment. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied Index (PPD) are commonly used in studies and standards as an thermal comfort indicator. In addition to these models, questionnaires also used to evaluate thermal comfort of occupant [11].

In practice, indoor environments change continuously due to dynamic weather, occupant and operation conditions. Therefore, above mentioned models are steady-state and consequently, they are not suitable to implement to real-time control system. For this type situation, dynamic models are required in order to assess occupant thermal comfort in real time. To do this, personal and environmental parameters, which affect thermal sensation of human, should be monitored and recorded continuously. For the existing building management system (BMS), it is hard to measured these variables. The main reason of this, the most of parameters cannot measured by standard BMS. Generally, air temperature and humidity data can be collected via sensors [12]. In order to overcome this issue, one method is installation sensors that measure air velocity, the mean radiant temperature in addition to the existing temperature and humidity sensors. On the other hand, two personal parameters which are clothing insulation and metabolic rate, are hard to determine. However, different methods have been developed and examined in order to predict clothing insulation level. An example study of this, is carried out by Lee et al. (2016) [13]. In this study, real-time measurement of the face and clothing temperature is used to determine clothing level and estimate thermal comfort [13].

Besides the conventional thermal comfort assessment methods, which are cannot assess thermal comfort continuously, different approaches have been proposed to evaluate people thermal sensation. For this purpose, Sim et al. (2016) carried out a study which evaluates the feasibility of wrist skin temperature in order to predict thermal sensation of the occupant [14]. Similarly, Takada et al. (2013) built an equation as a function of mean skin temperature to predict thermal sensation based on an experimental dataset of the thermal sensation vote and mean skin temperature of subjects [15]. By using these methods, thermal comfort can be determined accurately. Despite this, it is not feasible in terms of economy, building operation and maintenance. In order to simplify this phase, the required data, except temperature and humidity, can be assumed as fixed value to use in mathematical models. In that case, model accuracy decreases because of these assumptions. In order to solve accuracy issue, a new approach, which is called occupant participatory approach, was proposed which brings the humans in the control loop by using their thermal perception feedback.

Occupancy participatory approach have been used in significant number of studies and commercial applications. Erickson and Cerpa (2012) proposed a model with using this approach to increase PMV calculation accuracy in order to maximize thermal comfort of people in shared same zone [12]. For this purpose, a smartphone application and website are developed to collect occupancy thermal sensation feedback. Aggregated occupancy feedback and sensor measurement data are used to calculate optimum thermostat set temperature to maximize occupant thermal comfort [12].

In this method, PMV is calculated based on measurement data from temperature and humidity sensors except these variables, the rest of the required data is considered as a fixed value.  Occupant thermal sensation vote are collected for the same time period. Based on these two dataset, optimum thermostat temperature is determined. In order to calculate optimum value, two different control method is developed based on BMS system existence. If the building has BMS control, real-time control, which is shown in Figure 2.1, is used. If not, the learned-based control system is applied to the building. For this method, during the learning period, HVAC indoor unit is operated with fixed set point temperature and occupant feedbacks are collected. Based on historical temperature and feedback data, hourly temperature schedule is created. Workflow of learned-based approach is given in Figure 2.2.

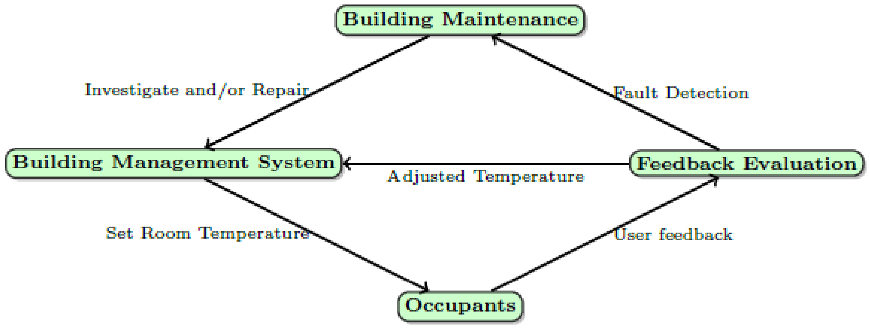


**Figure 2.1 :** Real-time control architecture of Thermovote system.

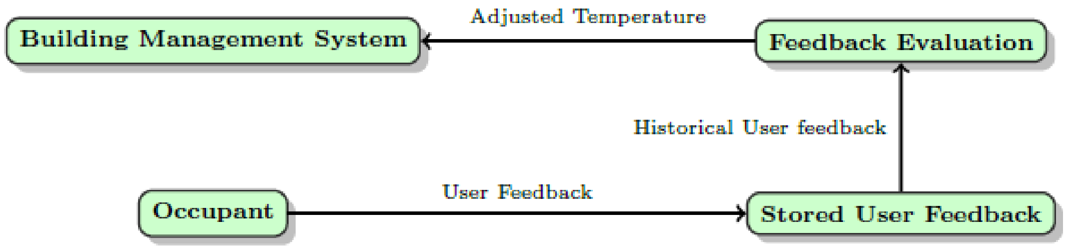


**Figure 2.2 :** Learned-based control architecture of Thermovote system.

The experiment was conducted in different offices with 39 participants over five weeks; one week of measurement, one-week of learning and three weeks of implementation, to evaluate method validity. The results show that real-time control strategy improves thermal comfort and satisfaction of occupants [12].

Murakami et al. (2007) developed an occupant controlled air conditioning system. This method does not require sensors to measure temperature, humidity or air velocity [16]. Figure 2.3 gives the structure of this control strategy.

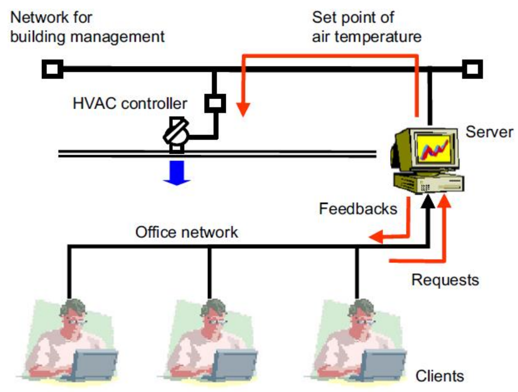
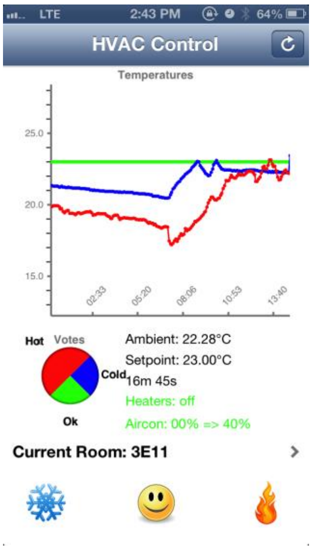


**Figure 2.3 :** Structure of HVAC control method.

Occupants can vote their thermal sensation with ASHRAE seven-point scale at any time. The server gathers these votes (requests) and calculated optimum set point values for every minute. This adjusted set point temperature is sent to HVAC controller via building management network.

In this study, besides thermal comfort, energy saving is taken into consideration. In order to evaluate effects of this approach on thermal comfort and energy consumption, the experiment was carried out in an open-plan office with 50 occupants during summer periods (from August to September). The results shows that, when comparing operation of fixed thermostat temperature, occupant participant approach ensures 20% energy saving while thermal comfort condition is provided to a majority of the occupants [16].

Purdon et al. (2013) proposed model, in a similar way to the study of Murakami et al., which is a sensor-free approach that uses occupant feedback directly, to change thermostat setting regarding their thermal sensation [17]. A smartphone application is developed to collect occupant feedback. As it can be seen in Figure 2.4, the application has a three-point scale thermal comfort index; hot (+1), neutral (0) and cold (-1) different from the other studies.



Ambient: 22.28°C
Setpoint: 23.00°C
16m 45s
Heaters: off
Aircon: 00% => 40%
Current Room: 3E11

**Figure 2.4 :** The user interface of the smartphone application.

According to aggregated occupant feedback, set point temperature is increased or decreased by a fixed value, which is called *Step* by authors until thermal neutrality is provided. In addition to the maximize thermal comfort, model tries to maximize energy saving in HVAC system. To achieve this goal, Drift strategy is proposed. With this strategy, adjusted set point temperature is increased or decreased by *Drift Step.* In this way, indoor temperature can drift as long as it does not impact the thermal comfort of occupants. In an office, this control method was applied, and impact on the energy and thermal comfort of occupants were examined. The experiment's findings shows that, 50% energy reduction can be achieved with this strategy [17].

Different from the thermal comfort assessment with PMV, several methods have been developed. Chen et al. (2015) designed a model predictive control and investigated the effects of this model on thermal comfort and energy consumption [18]. In the first phase of the study, the experimental study was carried out in climate chamber. In the experiment, HVAC set point temperature changes from 21°C to 30°C and during this alteration, the skin temperature of subjects was measured, and thermal sensation votes were collected. Based on participant’s gender, age, weight, and height; the basal metabolic rates were estimated and also clothing level and activity type data were recorded. Based on the climate chamber experiments, a data-driven dynamic thermal sensation model was derived to describe occupant’s thermal sensation rest upon the changes of indoor air temperature. Data driven model is used to determine optimum set temperature to provide comfortable environment for majority of occupant. In the second phase of the study, model was used to create dynamic control model and occupant feedbacks were integrated into model to correct optimum value based on their requirement [18].

In a different study, Lam and Wang (2014) developed a temperature comfort correlation (TCC) method to determine thermal comfort profile of each occupant instead of using PMV model [19]. This model consists of two phases which are heat generation and heat loss model. First, heat production of each occupant is calculated based on occupant’s age, gender, height, weight and activity level. Then heat loss model takes the difference between outdoor and indoor temperature into consideration in order to evaluate heat losses based on ASHRAE seven-point scale. In final step, optimum thermostat setting is determined based on heat loss and generation calculations. The set point temperature, which satisfies thermal comfort requirement of each occupant, is calculated with TCC model, and the optimized set point is calculated iteratively. The temperature is adjusted based on the occupant feedbacks. In order to evaluate this model, two different experiments were conducted in a classroom and an office. Experiment’s results show that TCC model was able to achieve to provide 70% of comfort requirement of occupants while maintaining thermal comfort, energy consumption of HVAC system was reduced by 18% [19].

## 2.2 Thermal Comfort and Human Performance

The indoor temperature does not only affect thermal comfort but also have a significant effect on indoor air quality, SBS, and productivity in work [20]. When thermal discomfort occurs, occupants are distracted, and they concentrate on the thermal environment rather than a work task, it cause productivity loss. Published studies proof that there is a direct linkage between occupants' performance and indoor air temperatures. Studies indicate that small differences in temperature can affect the worker's task performance, such as typing, learning, reading, calculation speed and memory, by 2% to 20%. Besides the effects on task performance, indoor environmental conditions influence the economy. Due to the SBS syndrome, the estimated productivity loss is equal to 2% and annual costs of this decrements is $60 billion [21]. Studies show that the improvement of indoor environment reduces the medical care cost of workers by reduction of SBS and also building maintaining cost, which occurs because of the complaints of occupant about indoor conditions and HVAC system [22]. There is a potential monetary gain due to improved workers' productivity. Skaret (2004) published a study, which corroborates this idea, and shows that improvement of productivity by indoor climate is least 10 to 100 times greater than the operational and maintenance costs [23].

In order to represent the relationship between indoor thermal conditions and productivity, a significant number of study has been conducted. In a study undertaken by Seppänen and Fisk (2005), in order to shows the relationship between temperature and performance, published studies were examined and the results show that productivity is unaffected by the temperature at 21°C to 25°C as it can be seen in Figure 2.6 [20].

Based on the findings from the studies, they established a model to estimate productivity decrement (P) for different indoor air temperature ($T_{air}$) range as it is given in following equation [20].

$$\begin{array}{ll} 25°\mathrm{C} < \mathrm{T_{air}} < 33°\mathrm{C} & \mathrm{P}(\%) = 2(\mathrm{T})\text{-}50 \\ 21°\mathrm{C} < \mathrm{T_{air}} < 25°\mathrm{C} & \mathrm{P}(\%) = 0 \end{array} \quad (2.1)$$

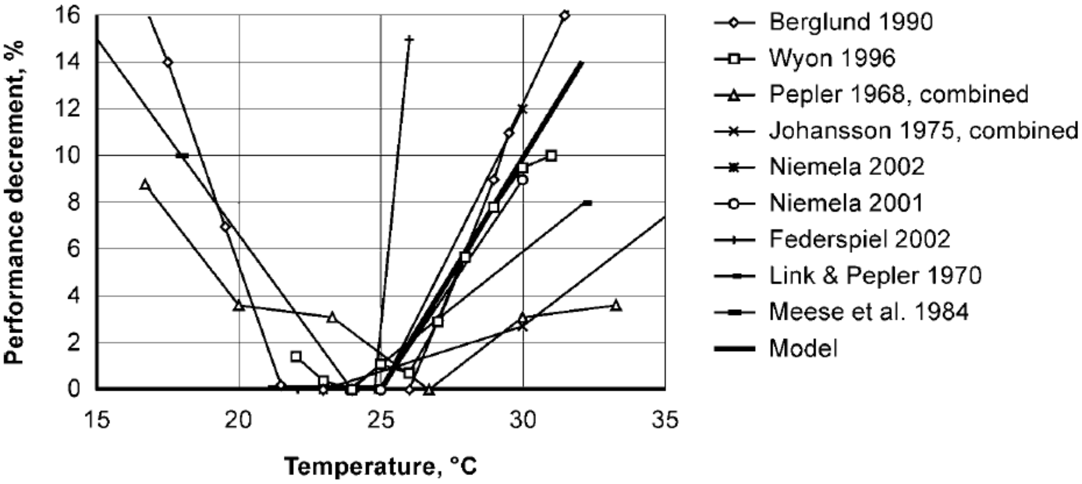


**Figure 2.5 :** The effect of room temperature on decrement of performance and productivity.

Also based on the literature review, Seppänen et al. (2006) carried out another study to investigated the relationship between indoor air temperature and performance at a call-center [24]. The performance of occupants at office work such as typing, simple calculation, the length of telephone customer service time and handling time were examined under different temperature. According to results of this study, task performance increases with temperature up to 21-22°C, and when temperature reach to 23-24°C, performance starts to decrease. At 30°C, temperature decrement is equal to 8,9% [24].

Similar to Seppänen, Tanabe et al. (2009) conducted several studies in order to examine the relationship between thermal satisfaction and performance of occupants at a call-center [25]. The impact of the seasonal and yearly thermal environment on workers' call response rate was observed. Temperature, relative humidity, $CO_2$ concentration and desktop illuminance values were monitored and recorded over the 134 days. In addition to the environmental variables, the call responses rate, which is calculated based on an average number of calls handled per hour by each operator, were calculated automatically for each operator each day to determine task performance of workers. With these collected data, a linear regression model was established to predict the performance of worker under specific indoor air temperature values. According to the regression model, the worker performance decrease by 1,9% and the call responses decrement is equal to 0,26calls/h when indoor air temperature increase 1°C [25].

In a different study of Tanabe et al. (2007), a climate chamber experiments were conducted in order to determine the impact of the moderately high temperature on occupant task performance [26]. For this purpose, participants' typing and cognitive performance were tested under three different temperature conditions; 25,5°C, 28°C and 33°C. Results show that mental performance decrement occurs at higher indoor temperature [26].

Wyon has published a report that summarized the several thermal effects on productivity. In the laboratory, the effect of temperature on thinking and writing tasks were researched. The main finding of this study shows that thinking task performance reduced 30% at 27°C, and 70% performance reduction was observed at 25°C for writing tasks. Based on the findings of experimental study, productivity reaches the peak level when PMV value is equal to -0,21 and PPD level is 6,3%. In order to assess productivity under different thermal comfort conditions, Kosonen and Tan conducted a study with using Wyon's review. In this study, the relationship between PMV and typing, thinking task were examined [23]. The result shows that the between PMV and productivity loss, linear correlation occurs and following equations represents this correlation for typing and thinking respectively [23].

$$\begin{aligned} y &= -60{,}543PMV^6 + 198{,}41PMV^5 - 183{,}75PMV^3 + 50{,}24PMV^2 \\ &+ 32{,}123PMV + 4{,}8988 \end{aligned} \tag{2.2}$$

$$\begin{aligned} y &= 1{,}5928PMV^5 - 1{,}5526PMV^4 - 10{,}401PMV^3 + 19{,}226PMV^2 \\ &+ 13{,}389PMV + 1{,}8763 \end{aligned} \tag{2.3}$$

With using this curve fitting equations, productivity losses can predict as a function of PMV and PPD for typing and thinking tasks [23].

## 2.3 Thermal Comfort Standards

### 2.3.1 ASHRAE 55-2010

ASHRAE has developed "*ASHRAE 55: Thermal Environmental Conditions for Human Occupancy*" in order to specify a thermal environmental condition for the comfort of the occupant. This standard is used to analyze thermal environment in building design, commissioning stage, and existing buildings.

In ASHRAE 55, provide a model to determined thermal sensation of occupant based on environmental and personal factors, which are air temperature, relative humidity, air speed, mean radiant temperature clothing insulation and metabolic rate. Two type methods can be used to predict thermal sensation of occupancy. If the occupants' activity levels are between 1-1,3 and clothing insulation level differ from 0,5 to 1clo (clo is the unit for clothing insulation level) the graphical method can be used to assess thermal conditions. For this approach, the range of acceptable operative temperatures, which is described as the average of the mean radiant and air temperatures, weighted by the convective heat transfer coefficient for the occupant, can be determined by using psychometric chart as given in Figure 2.7 [27, 28].

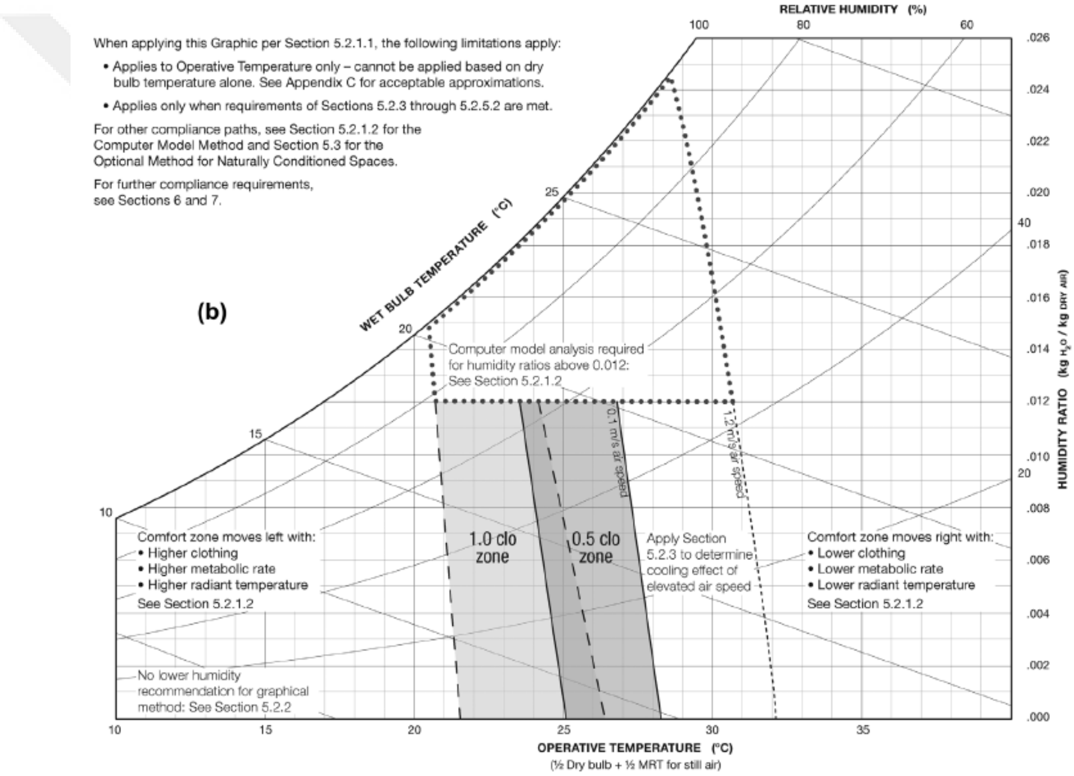


**Figure 2.6 :** Acceptable range of operative temperature and humidity for spaces under conditions for graphical method.

Figure 2.6 gives the thermal comfort zone based on two different clothing values; 1,0clo for winter conditions and 0,5clo for summer conditions.

Computer-based methods can be applied to a wider range of activity and clothing insulation levels to compare with the graphical method. This method is based on PMV and PPD indices. The acceptable range of PPD and PMV level is given in Table 2.1 [27].

**Table 2.1 :** An acceptable thermal environment for general comfort.

| PPD | PMV |
|---|---|
| <10 | -0,5<PMV<+0,5 |

Above mentioned methods are used in building with HVAC system. For naturally ventilated building, the adaptive model, which is the suggested method by standards, is used to defined occupant thermal sensation. In this method, comfortable temperature is calculated based on outdoor temperature. In Figure 2.7, acceptable operative temperates rest upon different outdoor temperature. For 80% acceptability, the operative temperature cannot exceed ±3,5°C from comfortable temperature. The allowable operative temperature limit range is ±2,5°C to provide a comfortable environment for 90% of the occupant [27, 29].

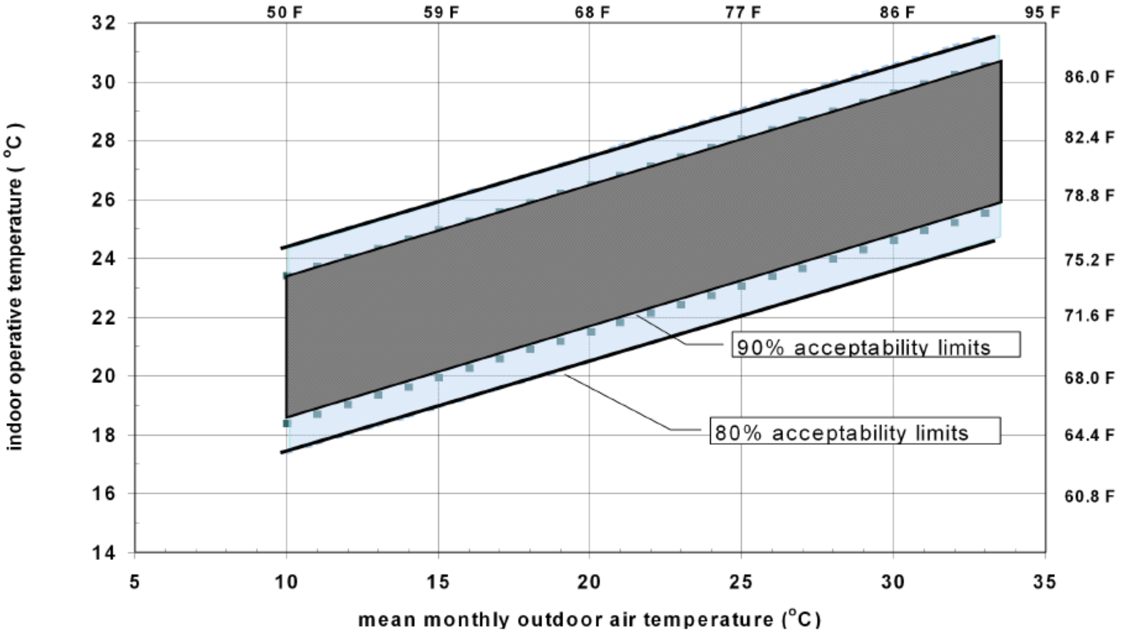


**Figure 2.7 :** Acceptable operative temperature ranges for naturally ventilated buildings.

### 2.3.2 EN 15251:2007

"*EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*" has been established to make calculations to dimensioning of systems and predict energy use of the building. The scope of EN 15251 is wide, and it provides design criteria for air quality, lighting, acoustic and thermal environment. Regarding thermal comfort, this standard does not provide assessment methods only gives acceptable PMV and PPD range, which is given Table 2.2, for different indoor environment categories [32].

**Table 2.2 :** Recommended categories for the design of mechanical heated and cooled buildings.

| Class/Category | Thermal state of the body as a whole | |
|---|---|---|
| | PPD (%) | PMV |
| I | <6 | -0,2< PMV <+0,2 |
| II | <10 | -0,5< PMV <+0,5 |
| III | <15 | -0,7< PMV <+0,7 |
| IV | >15 | PMV < -0,7 or +0,7 < PMV |

The level of comfort is affected by building systems, which are determined based on the decision of system designers and it depends on technical possibilities, economy, energy usage, environmental pollution and performance of systems. Therefore, EN 15251 specified different levels of building categories based on building indoor air quality level. These categories and their descriptions are given in Figure 2.3 [32].

**Table 2.3 :** Different building categories and their description category description.

| Class/Category | Description |
|---|---|
| I | High level of expectation and is recommended for space occupied by very sensitive and fragile persons occupied by very special requirements such as physically challenged, sick, very young children and elderly persons |
| II | Normal level of expectation and should be used for new buildings and renovations |
| III | An acceptable, moderate level of expectation and may be used for existing buildings |
| IV | Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year |

In EN 15251, similar with ASHRAE 55, the allowable operative temperatures limits are defined based on adaptive approach for naturally ventilated buildings. Graphical representation of these limits based on outdoor temperature (y axis) and operative temperature (x axis) are given in Figure 2.8 [32].

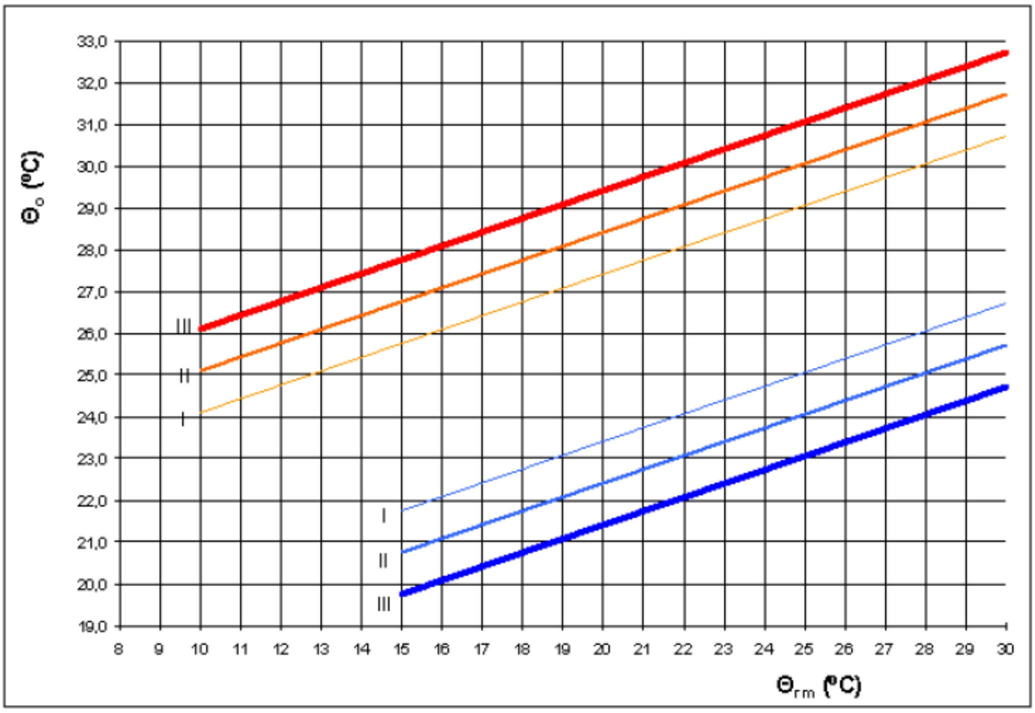


**Figure 2.8 :** Design values for the indoor operative temperature for building without the mechanical cooling system.

### 2.3.3 ISO 7730:2005

"*ISO 7730: Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*" provides an analytical method to predict the general thermal comfort and degree of discomfort of people for the moderate thermal environment. ISO 7423, ISO 7933 and ISO 11079 are used to evaluate occupants' thermal comfort under extreme conditions [30].

ISO 7730 assess thermal comfort relies on heat-balanced approach and using PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) indices. This standard also provides methods to assess local discomfort that caused by draft, asymmetric radiation and temperature gradients. ISO 7730 can be used for the determination of thermal comfort for the new design phase of new buildings and existing buildings [31].

The criteria for acceptable thermal environment ranges are given in Table 2.4. For each categories, which are explained in EN 15251, the maximum percentage of dissatisfied for the body (PPD) and a Percentage dissatisfied (PD) for different types of local discomforts are defined in this standard to provide comfortable indoor environment.

**Table 2.4 :** Categories of thermal environment based on ISO 7730.

| | Thermal state of the body as a whole | | | Local Discomfort Percentage Dissatisfied (%) | | |
|---|---|---|---|---|---|---|
| Category | PPD (%) | PMV | Draught Rate (%) | Vertical air temperature difference | Caused by warm or cool floor | Radiant asymmetry |
| A | <6 | -0,2< PMV <+0,2 | <10 | <3 | <10 | <5 |
| B | <10 | -0,5< PMV <+0,5 | <20 | <5 | <10 | <5 |
| C | <15 | -0,7< PMV <+0,7 | <30 | <10 | <15 | <10 |

# 3. THERMAL COMFORT ASSESSMENT

## 3.1 Description of Thermal Comfort

ASHRAE defines the thermal comfort as *the condition of mind that express satisfaction with the thermal environment* [27]. Most people can agree on this definition, but it is complex and not easily converted into physical parameters. It depends on the different physical, physiological and psychological parameters.

Thermal comfort is achieved when the heat balance is maintained between the body and environment. Although people can survive in various climatic conditions, the comfort range is narrow. In the beginning 20th century, ASHRAE attempted to define the “comfort zone”. Over the years, a large number of study have been conducted and made a significant contribution to defining and determine thermal comfort and the parameters that effect the thermal sensation of people. In this section, parameters that affect the comfort and assessment methods are explained.

### 3.1.1 Thermal comfort parameters

Thermal comfort is mainly related to the heat balance of human body with the environment. This balance is affected by six primary indoor thermal environmental and human-related factors;

- Air temperature
- Humidity
- Air speed
- Mean radiant temperature (MRT)
- Metabolic rate
- Clothing insulation

#### 3.1.1.1 Metabolic rate

According to the first law of thermodynamic, energy can be neither created nor destroyed, but can be converted from one to another. The human body works based on this thermodynamic law in order to balance between energy intake and expenditure [33].

The body releases energy from foods, which are consist of carbohydrates, proteins, fats, and alcohol, by oxidation and this energy is used in order to sustain metabolism, nerve transmission, respiration, circulation and physical work. In addition to the energy production, during this process, the heat is released [3]. 40 percent of this energy is used for work, and the rest of it turns into heat.

Work can be divided into two categories; external and internal work. External work can be described that useful work energy spent in overcoming external mechanical forces on the body, for most activities it can be neglected. As for internal work, it is considered as the whole remaining work, including skeletal muscle activity, which is not used for moving external objects. As a result, the total produced energy (M) may be transformed into body heat (H), may appear as external work (W), or be stored (S) in the body in the form of organic molecules. The equation (3.1) gives the total energy expenditure of the body [34].

$$\mathrm{M} = \mathrm{H} + \mathrm{W} + \mathrm{S} \tag{3.1}$$

The metabolic rate is described as the energy rate which is expanded by the body during both external and internal work. Metabolic rate and, consequently, the rate of heat production vary depending on several factors, such as exercise, anxiety, shivering and food intake [35]. Table 3.1 shows some activity and their metabolic rate values [27].

**Table 3.1 :** Metabolic rate for typical activities.

| Activity | Metabolic Rate ($W/m^2$) |
|---|---|
| Resting | |
| Reclining | 45 |
| Sleeping | 40 |
| Seated, quite | 60 |
| Standing, relaxed | 70 |

**Table 3.1 (continued) :** Metabolic rate for typical activities.

| Activity | Metabolic Rate ($W/m^2$) |
|---|---|
| Walking | |
| 0.9m/s (3.2km/h) | 115 |
| 1.2m/s (4.3km/h) | 150 |
| 1.8m/s (6.8km/h) | 220 |
| Office Activities | |
| Reading, seated | 55 |
| Writing | 60 |
| Typing | 65 |
| Filing, seated | 70 |
| Filing, standing | 80 |
| Walking about | 100 |
| Miscellaneous Occupational Activities | |
| Cooking | 95-115 |
| House cleaning | 115-200 |

#### 3.1.1.2 Clothing insulation

The clothes are the main factor in climate adaptation of man to the environment. Metabolic heat production, and thermoregulatory system regulates how much is transferred to the skin and it is directly affected by clothing layer. Clothing creates a resistance to heat and moisture transfer between skin and environment and also protects the body against extreme heat and cold [36]. Typical clothing and their thermal insulation values are given in Table 3.2 [27].

**Table 3.2 :** Typical clothing and thermal insulation values.

| Clothing Description | $I_{clo}$ (clo) |
|---|---|
| Trousers, short-sleeve shirt | 0.57 |
| Trousers, long-sleeve shirt | 0.61 |
| Trousers, long-sleeve shirt, suit jacket | 0.96 |
| Trousers, long-sleeve shirt, suit jacket, vest, T-shirt | 1.14 |
| Trousers, long-sleeve shirt, long-sleeve sweater, T-shirt | 1.01 |
| Trousers, long-sleeve shirt, long-sleeve sweater, T-shirt suit jacket and short-sleeve shirt | 1,30 |
| Knee-length skirt, short-sleeve shirt (Sandals) | 0,54 |

**Table 3.2 (continued) :** Typical clothing and thermal insulation values.

| Clothing Description | $I_{clo}$ (clo) |
|---|---|
| Knee-length skirt, long-sleeve shirt, full slip | 0,67 |
| Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater | 1,10 |
| Knee-length skirt, long-sleeve shirt, half slip, suit jacket | 0,36 |
| Walking shorts, short-sleeve shirt | 0,72 |
| Long-sleeve coveralls, T-shirt | 0,89 |
| Insulated coveralls, long-sleeve thermal underwear tops, and bottoms | 1,37 |
| Sweat pants, long-sleeve sweatshirt | 0,74 |
| Long-sleeve pajamas tops, long pajama trousers, short ¾ length robe (slippers, no socks) | 0,96 |

As shown in above table, the thermal insulation of clothes expresses with “clo” unit that is proposed by Gagge. “clo” represents the thermal insulation required to keep a sedentary person comfortable at 21°C and 1clo is equal to $0{,}155 m^2K/W$ [23, 24]. The value of $I_{cl}$ is calculated by equation 3.2.

$$I_{cl} = \frac{R_{cl}}{0.18} \tag{3.2}$$

$R_{cl}$ is the total heat transfer resistance from skin to the other surface of the clothed body and depends on the material type of clothing, characteristic of fiber, etc. [11].

#### 3.1.1.3 Air temperature

Air temperature is the most important environmental variable for indoor thermal comfort. Heat flow rate, between surrounding air and the body, is determined according to the air temperature. Table 3.3 gives recommended temperature range for the different type of building and space based on activity and clothing range (for cooling session clothing insulation is assumed as 1,0clo and for heating, this value decreases to 0,5clo) [30].

**Table 3.3 :** Recommended temperature ranges for different type and space of buildings.

| **Type of Building/Space** | **Activity ($W/m^2$)** | **Category** | **Temperature range for cooling (°C)** | **Temperature range for heating (°C)** |
|---|---|---|---|---|
| Single Office<br>Landscape Office<br>Conference Room | 70 | A | 24,5±1,0 | 23,0±1,0 |
| | | B | 24,5±1,5 | 22,0±2,0 |

**Table 3.3 (continued) :** Recommended temperature ranges for different type and space of buildings.

| Type of Building/Space | Activity ($W/m^2$) | Category | Temperature range for cooling (°C) | Temperature range for heating (°C) |
|---|---|---|---|---|
| Auditorium | 70 | B | 24,5±1,5 | 22,0±2,0 |
| Cafeteria/Restaurant<br>Classroom | | C | 24,5±2,5 | 22,0±3,0 |
| Kindergarten | 81 | A | 23,5±1,0 | 22,0±1,0 |
| | | B | 17,5-22,5 | 22,0±3,5 |
| | | C | 16,5-23,5 | 22,0±3,5 |
| Department Store | 93 | A | 23,0±1,0 | 19,0±1,5 |
| | | B | 23,0±2,0 | 19,0±3,0 |
| | | C | 23,0±3,0 | 19,0±4,0 |

### 3.1.1.4 Radiant temperature

In addition to the air temperature, radiant temperature, is described that mean temperature of the surrounding surfaces weighted by the solid angle subtended by each surface has an impact on the human body in terms of heat losses and gains. Different from the air temperature, the exposure angle of all objects that are in view of the body determines the rate of radiant heat loss and gains.

### 3.1.1.5 Air speed

The magnitude of air movement affects both convective heat losses and the skin and clothing surface heat transfer coefficients, as well as increasing evaporation from the skin, thus producing a physiological cooling effect [38].

The movement of the ambient air results from;

- Free buoyant motion caused by warm body in cool air medium
- Forced ventilation of the environment itself
- Bodily motion caused by activity

Effect of air velocity on thermal comfort and thermal sensations of occupants is given in Table 3.4 [39].

**Table 3.4 :** Effect of air velocity on indoor thermal comfort.

| Air velocity (m/s) | Equivalent Temperature Reduction (°C) | Effect on Comfort |
|---|---|---|
| 0,05 | 0 | Stagnant air, slightly uncomfortable |
| 0,2 | 1,1 | Barely noticeable but comfortable |
| 0,25 | 1,3 | Design velocity for air outlets that are near occupants |
| 0,4 | 1,9 | Noticeable and comfort |
| 0,8 | 2,8 | Very noticeable but acceptable |
| 1,0 | 3,3 | Upper limit for air-conditioned spaces |
| 2,0 | 3,9 | Good air velocity for comfort ventilation in hot and humid climates |
| 4,5 | 5,0 | Considered a gentle breeze when felt outdoors |

Table 3.5 gives recommended values are changes based different parameter based on ISO 7730 to provide heatlhy and comfortable indoor condition. Maximum mean air velocity for a different type of building and space based on activity and clothing range (for cooling session clothing insulation is assumed as 1,0clo and 0,5clo for the heating session) [30].

**Table 3.5 :** Maximum mean air velocity recommendation for different type of building and space.

| Type of Building/Space | Activity ($W/m^2$) | Category | Maximum mean air velocity for cooling (m/s) | Maximum mean air velocity for heating (m/s) |
|---|---|---|---|---|
| Single Office<br>Landscape Office | 70 | A | 0,12 | 0,10 |
| Conference room<br>Auditorium | | B | 0,19 | 0,16 |
| Cafeteria/Restaurant<br>Classroom | | C | 0,24 | 0,21 |
| Kindergarten | 81 | A | 0,11 | 0,10 |
| | | B | 0,18 | 0,15 |
| | | C | 0,23 | 0,19 |
| Department Store | 93 | A | 0,16 | 0,13 |
| | | B | 0,20 | 0,15 |
| | | C | 0,23 | 0,18 |

### 3.1.1.6 Humidity

Relative humidity, which is defined in ASHRAE 55 as *the ratio of the partial pressure of the water vapor in the air to the saturation pressure of water vapor at the same* *temperature and the same total pressure* [27], plays a major role in evaporative heat loss. When the moisture is absorbed by dry air, the body cools rapidly. When it reachs the maximum humidity, cooling stops because of the water already carried by air.

Besides the cooling effect, it causes sweating on the body and mildew growth on buildings, while dry air lead to Sick Building Syndrome (SBS) which causes nose irritation, stuffed nose, rainy nose, eye irritations, cough, tightness in the chest, fatigue, headache and rash [3, 28]. Acceptable humidity range for the comfortable indoor environment is between 40% and 60% [30].

## 3.2 Thermal Comfort Assessment

The relation between physical parameters of the indoor environment and the human thermal perception has been studied by many authors, and a large number of thermal models and indices have been proposed over the years.

Thermal models are a mathematical representation of interactions of the human body with surrounding and thermoregulatory system. In order to develop models, thermodynamic (heat transfer, heat balance) and physiological (thermoregulation along with the anthropometry and anatomy) principles should be taken into consideration [31]. Nowadays, two main models, which are the rational or heat balance approach and the adaptive approach, are used in order to determine indoor thermal comfort. While heat balance approach is based on climate chamber experiment result, the adaptive approach rest upon field studies data and questionnaries [10].

In the seventies of the twentieth century, the Danish physiologist Povl Ole Fanger developed thermal comfort model and defined thermal comfort index by conducting series of experiments and tests. Fanger focused on the relationship between the physical parameters of an environment and the physiological parameters of people and the perception of wellbeing expressed by people themselves [11]. In order to describe the mean thermal sensation for a large group of occupants as a function of environmental parameters, activities and clothing insulation predicted mean vote (PMV) model is developed based on energy balance equation. Predicted percentage of people dissatisfied (PPD) can be determined with using PMV value. This model is applied to many applications by engineers, building designers and researchers and practice has shown values of the model in the area of air-conditioned buildings where thermal comfort and neutral, slightly cool or warm thermal conditions are maintained well.

For naturally ventilated buildings, studies pointed out that there is a discrepancy between survey votes and PMV calculations [40]. As a result, adaptive model, which is based on the idea that *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort* was proposed by de Dear and Brager. This model is established based on field surveys conducted in a wide range of environments [41]. The underlying assumption of this concept is that people can act as “meter” of their surroundings, and when discomfort occurs, this situation is triggered people behavioural response to the environment [42]. In order to develop adaptive comfort model, the RP-884 project is conducted, and the database was established with using 22,000 sets of raw data from 160 different office building from various countries and climate zone. This database consists of a full range of thermal questionnaire responses, clothing and metabolic estimates, concurrent indoor climate measurements, a variety of calculated thermal indices and outdoor meteorological observation. Based on this database, the relationship between outdoor and indoor comfort temperature is derived for naturally conditioned buildings [43].

### 3.2.1 Fanger method

The steady-state thermal comfort model, which is developed by Fanger in 1970, is based on heat balance equation and operation of human thermoregulation system, which tries to conserve human body at a constant temperature with the balance between heat generation in the body and heat dissipation between body and environment [44]. Thermal interaction between human body and environment can be seen in Figure 3.1 [28].

The heat production in the human body is used to increase the body temperature or lost to the environment through the skin surface and respiratory tract. Therefore, the heat balance for a human body is given in equation (3.3); [10]

$$\mathrm{H}\text{-}\mathrm{E_d}\text{-}\mathrm{E_{sw}}\text{-}\mathrm{E_{re}}\text{-}\mathrm{L} = \mathrm{K} = \mathrm{R} + \mathrm{C} \tag{3.3}$$

The equation shows that the internal heat production and heat losses from the skin (Ed+Esw) and by respiration (Ere+L) are equal to the heat conducted through the clothing (K) and dissipated at the outer surface of the clothing by radiation ad convection(R+C) [45].

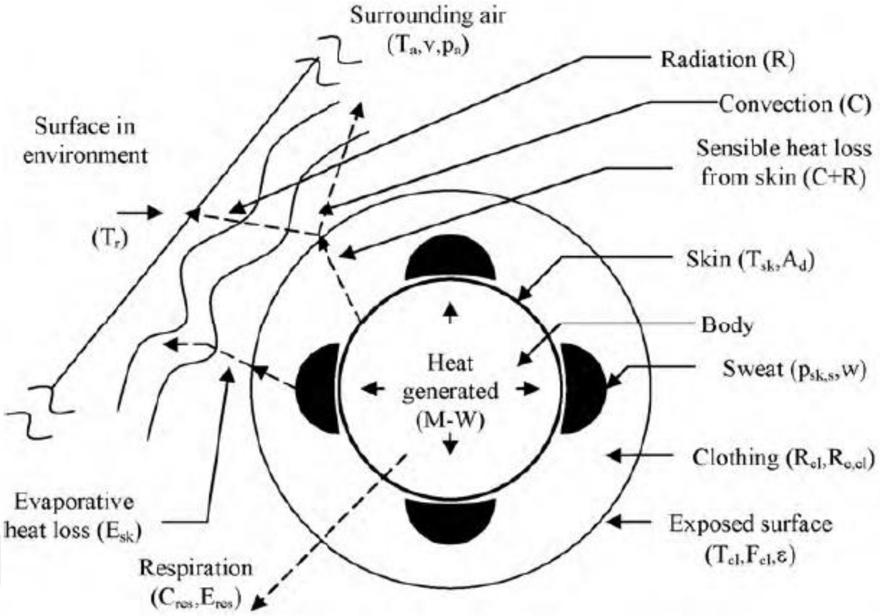


**Figure 3.1 :** Thermal interaction between a human body and environment.

In the following sections, each term of the heat balance equation and their calculation methods are explained.

### 3.2.1.1 Internal heat production

As aforementioned in section 3.1.1.1, the human body provide the energy for basic functions e.g. respiration, heart functions by the oxidation process. Almost 60% of the released energy turns into heat (H), and 40% is used for external work (W). Equation (3.4) shows the relation between energy production (M) and expenditure (H+W).

$$M=H+W \tag{3.4}$$

The ratio between this external work and the energy production is called the “mechanical efficiency (η)” with which the body performs the work. The value of η is equal to zero for most activity. It is used only for intense physical activity such as uphill races, carpentry works and heavy activity.

$$\eta=\frac{W}{M} \tag{3.5}$$

According to the equation (3.5), equation (3.6) can be written as;

$$H=M(1-\eta) \tag{3.6}$$

Per unit body surface are, internal heat production can be expressed as;

$$\frac{H}{A_{Du}}=\frac{M}{A_{Du}}(1-\eta) \tag{3.7}$$

$A_{Du}$ is the area of the Dubois is used to determine the body surface based on weight (w) and height (h) data of person;

$$A_{Du}=0.202\times w^{0.425}\times h^{0.725} \tag{3.8}$$

#### 3.2.1.2 Heat loss by skin diffusion

Most of the body's heat flow is through the skin. The heat loss by skin diffusion is defined that the amount of energy exchanged depends on the amount of water vapour dispersed through sweat.

$$E_d=\lambda m A_{Du}(p_s-p_a) \tag{3.9}$$

As it can be seen in equation (3.9), the amount of energy exchanged depends on the pressure difference between vapor pressure at skin temperature ($p_s$-$p_a$) and ambient air temperature, presence coefficient of the skin (m) and latent heat of vaporization (λ) which is the quantity of heat absorbed by a fluid per unit mass under isobaric and isothermal equilibrium conditions. At 35°C, the latent heat of vaporization (λ) is equal to the 575kcal/kg.

If skin temperature ($T_s$) is between 27°C and 37°C, saturated vapour pressure ($p_s$) can be expressed as in equation (3.10).

$$p_s=1.92T_s-25.3 \tag{3.10}$$

If equation (3.10) integrate to the equation (3.9), the heat loss by skin diffusion can be expressed by equation (3.11).

$$E_d=0.35A_{Du}(1.92T_s-25.3-p_a) \tag{3.11}$$

#### 3.2.1.3 Heat loss by evaporation of sweat production

When skin diffusion is not enough to maintain body temperature, sweat is produced, and the evaporative cooling mechanism is brought into action [46].

#### 3.2.1.4 Heat loss by respiration

The primary task of the respiratory system provides oxygen for the metabolic process to release energy from food by oxidation. The second mission of the respiratory system is dissipating metabolic byproducts which are carbon dioxide, water, and heat.

During the respiration, the body losses sensible and latent heat, and these losses are caused by evaporation and convection of heat from the respiratory tract to the inhaled air. In a normal situation, about 10% of the total heat loss of the body, whether at rest or work, occurs in the respiratory tract and this percentage increases to about 25% at outside temperature of -30°C [33]. The heat losses by respiration are examined under two categories; latent and sensible.

**Latent Respiration Heat Loss**

The specific task of breathing is to move air into, through and out of the lungs. This process includes conditioning the inspired air, adjusting the temperature of the incoming flowing air, moistening or drying it. Latent heat loss occurs when the lungs moisten inhaled air. The rate of heat loss depends on volume and humidity of air as shown in equation (3.12).

$$E_{res}=\dot{V}(W_{ex}-W_a)\lambda \tag{3.12}$$

The latent heat loss is a function of the pulmonary ventilation ($\dot{V}$), differences in water content between expired and inspired air ($W_{ex}$-$W_a$) and heat of vaporisation of water at 35°C ($\lambda$).

**Dry Respiration Heat Loss**

Cool inhaled air is heated by convective heat transfer with the core temperature in the lungs. The heat loss from the body due to the difference in temperature between expired and inspired ($T_{ex}$-$T_a$) air can be expressed by equation (3.13).

$$L=\dot{V}c_p(T_{ex}-T_a)=0.0014M(T_{ex}-T_a) \tag{3.13}$$

In this equation, $\dot{V}$ represents the pulmonary ventilation, $c_p$ is the specific heat of dry air at constant pressure and it is equal to the 0.24kcal/kg°C.

The temperature of the expired air can be written as a function of the condition of the inspired air and expired air temperature, which can be assumed as a constant value (34°C). With this assumptions, dry respiration heat loss can be written;

$$L=0.0014M(34-T_a) \tag{3.14}$$

### 3.2.1.5 Heat conduction through the clothing

As mentioned hereinbefore, clothing insulation is a property of the clothing and represents the resistance to heat transfer between the skin and the clothing surface.

$$K=A_{Du}\frac{T_s-T_{cl}}{0.18I_{cl}} \tag{3.15}$$

The dry heat transfer rate through the clothing (K) is by conduction, depends on the surface area (ADu), the temperature gradient between skin and clothing surface (Ts-Tcl) and the thermal conductivity of the clothing (Icl) as shown in equation (3.15) [45].

### 3.2.1.6 Heat loss by radiation

Heat exchange through radiation depends on temperature differences between two opposing surfaces. Expression of "Stefan-Boltzmann Law of Radiative Heat Transfer" allows calculating the amount of radiating energy (R) gained or lost by the human body can be seen in equation (3.16).

$$R=A_{eff}\varepsilon\sigma[(T_{cl}+273)^4+(T_{mrt}+273)^4] \tag{3.16}$$

In the equation $A_{eff}$ represents the effective radiation area of the clothed body, ε is the emittance of the outer surface of the clothed body, σ is the Stefan-Boltzmann constant, and it is equal to $5.67x10^{-8}W/m^2K^4$, and the mean radiant temperature is shown as $T_{mrt}$.

$$R=3.4\times10^{-8}A_{Du}f_{cl}[(T_{cl}+273)^4+(T_{mrt}+273)^4] \tag{3.17}$$

In this equation, $f_{cl}$ is the ratio of the surface area of the clothed body to the surface area of the nude body.

### 3.2.1.7 Heat Losses by Convection

Convection is the process of heat exchange between the clothing surface and surrounded air. The rate of heat exchange depends on the temperature of the clothing surface, the ratio of the surface area of the clothed body to the surface area of the nude body, and characteristics (speed) of the air around the body.

$$\mathrm{C}=\mathrm{A}_{\mathrm{Du}}\mathrm{f}_{\mathrm{cl}}\mathrm{h}_{\mathrm{c}}(\mathrm{T}_{\mathrm{cl}}\text{-}\mathrm{T}_{\mathrm{a}}) \tag{3.18}$$

Where $h_c$ is the convective heat transfer coefficient, and it depends on the convection process. For low air velocities, the heat transfer method is called free convection, and it changes based on the difference between clothing surface and air temperature. For high air velocity, heat transfers by forced convection and magnitude of transfer rate changes according to the speed of air.

$$\mathrm{h}_{\mathrm{c}}=\begin{cases} 2.05(\mathrm{T}_{\mathrm{cl}}\text{-}\mathrm{T}_{\mathrm{a}})^{0.25} & \text{for} \quad 2.05(\mathrm{T}_{\mathrm{cl}}\text{-}\mathrm{T}_{\mathrm{a}})^{0.25}>10.4\sqrt{\mathrm{v}} \\ 10.4\sqrt{\mathrm{v}} & \text{for} \quad 2.05(\mathrm{T}_{\mathrm{cl}}\text{-}\mathrm{T}_{\mathrm{a}})^{0.25}<10.4\sqrt{\mathrm{v}} \end{cases} \tag{3.19}$$

### 3.2.1.8 Heat balanced formula

Consequently, thermal comfort is function of variables which define heat generation and losses and this equation can be represented as the following form;

$$\begin{aligned} &\frac{M}{A_{Du}}(1-\eta).0,35\left[43-0,061\frac{M}{A_{Du}}(1-\eta)-p_a\right]-0,42\left[\frac{M}{A_{Du}}(1-\eta)-50\right]- \\ &0,0023\frac{M}{A_{Du}}(44-p_a)-0,0014\frac{M}{A_{Du}}(34-T_a) \\ &=3,4.10^{-8}f_{cl}\left[(T_{cl}+273)^4-(T_{mrt}+273)^4\right]+f_{cl}h_c(T_{cl}-T_a) \end{aligned} \tag{3.20}$$

In this equation, M is the metabolic heat generation rate, W is the external work (equal to zero for most activities), $p_a$ is the partial water vapor pressure, $f_{cl}$ is the clothing area factor (ratio of clothed/nude surface area), $T_a$ is the ambient air temperature, $T_{mrt}$ is the mean radiant temperature, $h_c$ is the convective heat transfer coefficient, and $T_{cl}$ is the surface temperature of clothing. The clothing area factor ($f_{cl}$) is calculated based on clothing insulation ($I_{cl}$) as;

$$\mathrm{f}_{\mathrm{cl}}=\begin{cases} 1{,}00+1{,}290\mathrm{I}_{\mathrm{cl}} & \text{for} \quad \mathrm{f}_{\mathrm{cl}}\leq 0{,}078\mathrm{m}^2\mathrm{K/W} \\ 1{,}05+0{,}645\mathrm{I}_{\mathrm{cl}} & \text{for} \quad \mathrm{f}_{\mathrm{cl}}>0{,}078\mathrm{m}^2\mathrm{K/W} \end{cases} \tag{3.21}$$

Similar to the clothing area factor, clothing surface temperature (Tcl) are calculated based on clothing insulation with using equation 3.20.

$$\begin{aligned} T_{cl} &= 35{,}7 - 0{,}028.(M - W) \\ &- I_{cl}\left\{3{,}96.10^{-8} f_{cl}\left[(T_{cl}+273)^4 + (T_{mrt}+273)^4\right] + f_{cl} h_c (T_{cl} - T_a)\right\} \end{aligned} \tag{3.20}$$

### 3.2.2 Adaptive comfort model

Adaptive comfort model is based on the idea that *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.* This model is established based on field surveys that was conducted in a wide range of environments rather than climate chamber experiments and heat balance equation as previously described [41].

In order to develop adaptive comfort model, ASHRAE started funding field survey studies of thermal comfort in an office building in four different climate zones. In this context, the RP-884 project was conducted and began collected raw field data from projects around the world. The RP-884 database consists of 22,000 sets of raw data from 160 different office buildings located in various continents and climate zones. The data covers a full range of thermal questionnaire responses, clothing and metabolic estimates, concurrent indoor climate measurements, a variety of calculated thermal indices and outdoor meteorological observation.

Two regression models have been developed from the database; one for buildings with centralized HVAC systems and one for buildings with natural ventilation. In Figure 3.2 and Figure 3.3 shows observed and predicted indoor comfort temperature by using PMV and adaptive model [47].

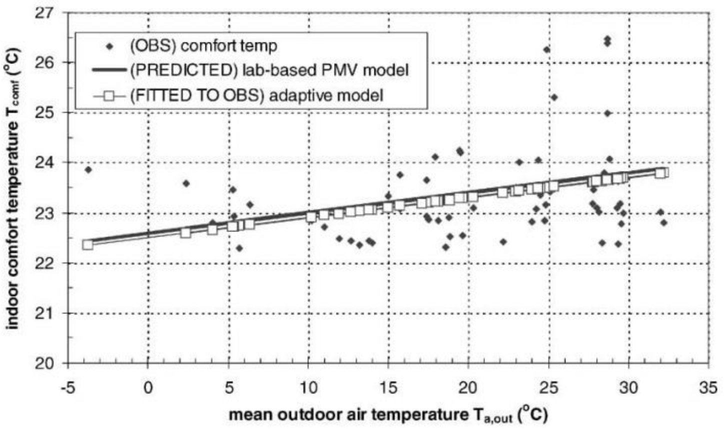


**Figure 3.2 :** Observed and predicted comfort temperatures for HVAC buildings.

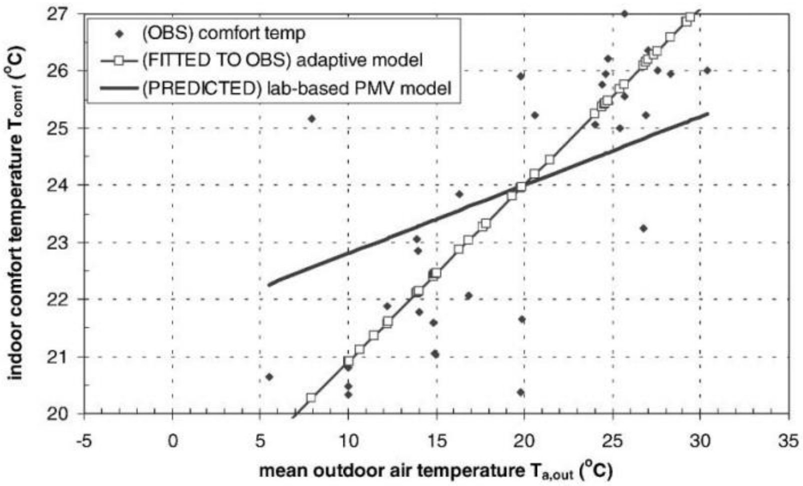


**Figure 3.3 :** Observed and predicted comfort temperatures for naturally ventilated building.

As it can be seen figures above, for buildings with centralized HVAC system, indoor air temperature does not affect from the outdoor conditions and PMV index can make accurate predictions. On the other hand, indoor temperature strongly depends on outdoor temperature for naturally ventilated building and PMV model predicts people would be warmer or cooler than they are [47].

Adaptive model, different from the PMV model, which is based on heat-balance thermal comfort model, the only outdoor temperature is required to predict the temperature that people will find comfortable, and this model does not predict occupant responses. Indoor comfort temperature is predicted by using equation 3.23 which show the relation between outdoor and indoor comfort temperature is established with using RP-884 database and equation (2.15) is obtained for naturally ventilated building [29].

$$T_c(T_o)=17.8+0.31T_o \tag{3.23}$$

Where $T_c(T_o)$ is the optimal temperature for comfort and $T_o$ is the mean outside temperature. From equation 3.23, the optimum indoor temperature can be calculated as a function of outdoor temperature [29].

$$T_{accept}=0.31T_o+0.31\pm T_{lim} \tag{3.24}$$

In equation 3.24, $T_{accept}$ represents the limits of acceptable temperatures for comfortable environment, and $T_{lim}$ is the range of acceptable temperature for 80% of occupants being satisfied is defined as ±3,5°C and for 90% is given as ±2,5°C [37]. A mean comfort zone band, which is derived by using adaptive model, can be seen in Figure 3.4 [27].

According to the ASHRAE 55, in order to apply this method, the building must be equipped with operable windows that open to the outdoor and controlled by occupants. There must be no mechanical cooling system for space. If the building or space meet these requirements, the temperature can be used to predict thermal comfort with using Figure 3.4. PMV model is more accurate in conditioned building than in naturally ventilated buildings, and it is applicable for all type of buildings with HVAC [27].

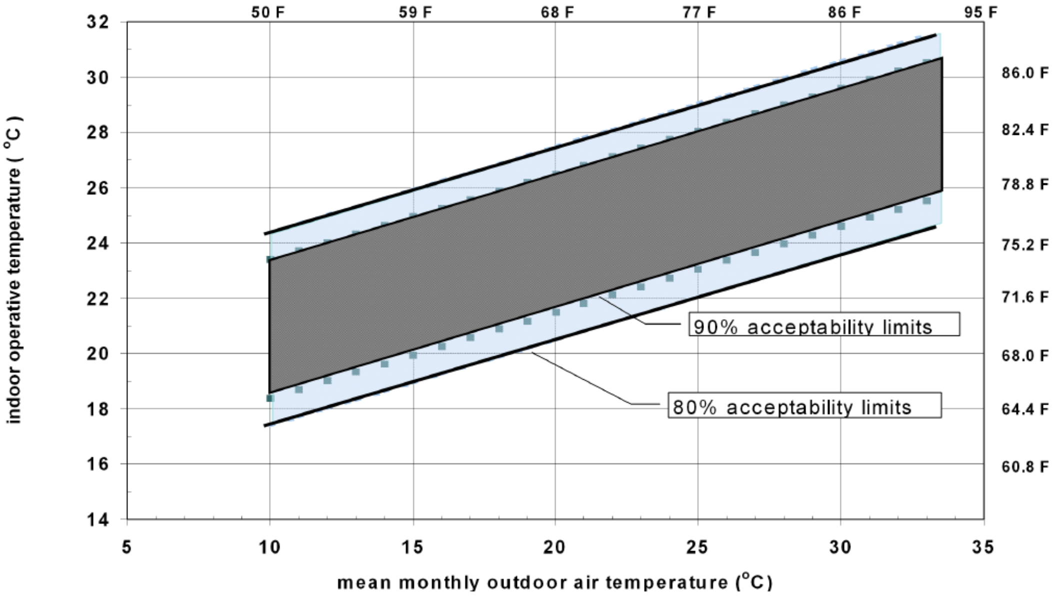


**Figure 3.4 :** Acceptable operative temperature range for naturally conditioned space.

### 3.3 Comfort Indexes

Thermal sensation is related to how occupant feel and it is not possible to define in physical or physiological terms [31]. In order to define and predict thermal sensation a group of occupant or individuals, significant number of studies have been conducted. Consequently, comfort ındexes, which are values and shows the relation between human and environment, are developed. These indicators allow people to express an opinion about the comfort in the environment.

In 1970, Fanger proposed the indices, Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) by adopting a statistical approach to defined feeling about the comfort conditions. The indices of comfort summarize the complexity of the reactions that occur between human body, activity, clothing insulation and the variability of physical quantities relating to the environment.

### 3.3.1 Predicted mean vote (PMV)

The PMV index predicts the mean response regarding thermal sensation of a large group of people exposed to certain thermal conditions for a long time. Table 3.6 shows the value of PMV index is a seven point psychophysical scale [27].

**Table 3.6 :** Thermal sensation scale.

| Thermal Sensation | PMV Index | Thermal Sensation | PMV Index |
|---|---|---|---|
| Cold | -3 | Slightly warm | 1 |
| Cool | -2 | Warm | 2 |
| Slightly cool | -1 | Hot | 3 |
| Neutral | 0 | | |

Thermal sensation and PMV index is a function of the thermal load (L) of the body which is defined as “the difference between the internal heat production and heat loss to actual environment for a man hypothetically kept at comfort values of the mean skin temperature and the sweat secretion at the activity level” [45]. In following equations shows that the relation between thermal load and PMV index.

$$\mathrm{PMV} = (0.303\mathrm{e}^{-0.036\mathrm{M}} + 0.028)\mathrm{L} \tag{3.25}$$

$$\begin{aligned} L = {} & (M - W) - 0{,}0014M(34 - T_a) \\ & - 3{,}05.10^{-3}\left[5733 - 6{,}99(M - W) - p_a\right] \\ & - 0{,}42(M - W - 58{,}15) - (1{,}72.10^{-5}M(5867 - p_a) \\ & - 39{,}6.10^{-9} f_{cl}\left[(T_{cl} + 273)^4 + (T_{mrt} + 273)^4\right] - f_{cl}h_c(T_{cl} - T_a) \end{aligned} \tag{3.26}$$

If the person is in an ideal comfort condition, which occurs when the body and environment in balance, PMV index is equal to 0. Accroding to the ISO 7730, the acceptable range of PMV for optimal indoor thermal comfort conditions is given in Table 3.7 [30]. As described in section 2, ASHRAE 55 is defined the comfortable range of PMV as that is between -0,5 and +0,5 [27].

### 3.3.2 Predicted percentage of dissatisfied (PPD)

The PMV expresses the thermal sensation opinions of the people, but it does not assess what is the acceptability of the conditions of comfort. Following this consideration, the predicted percentage of dissatisfied (PPD) index was proposed by Fanger.

PPD provides practical information concerning the number of potential complainers. Examination of a large volume of data shows 5% of the occupants would be dissatisfied even under the “best” conditions, when PMV equals to 0 [45].

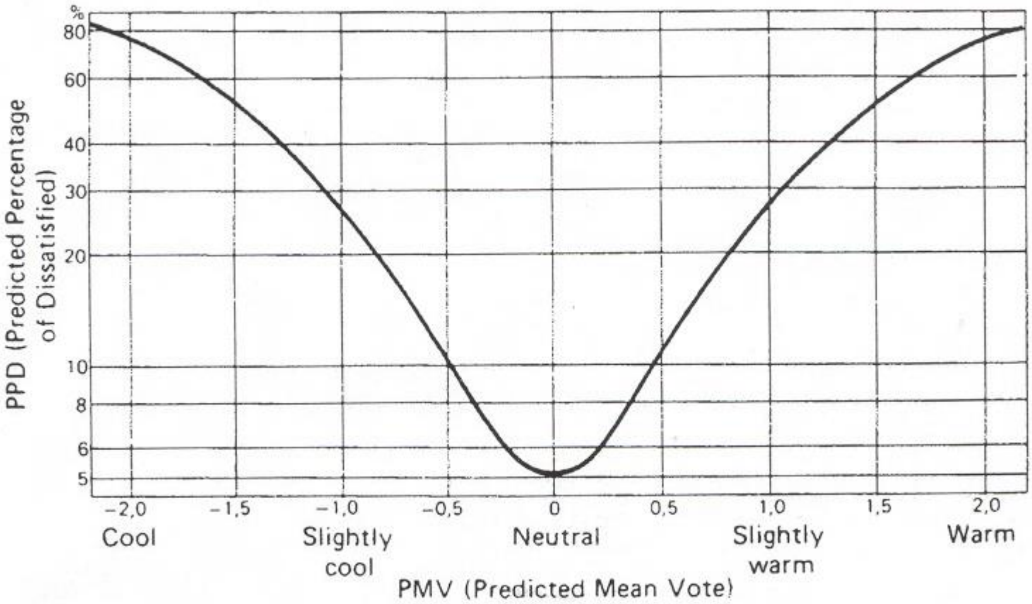


**Figure 3.5 :** Relation between PPD and PMV.

The empirical curve, which is shown in Figure 3.5, shows the PPD as a function of PMV.  Equation (3.27) shows calculation method of PPD with using PMV value.

$$\text{PPD}=100\text{-}95\exp(\text{-}0.03353\text{PMV}^4\text{-}0.2179\text{PMV}^2) \quad (3.27)$$

As mentioned previously, ASHRAE defines the maximum limit value as 10% for the pleasant environment [27]. For ISO 7730, the acceptable value is change based on indoor environment quality categories and is shown in  Table 2.4 [30].

### 3.3.3 Local thermal discomfort

The PMV and PPD express the discomfort for the body as a whole. However, thermal discomfort can occur when part of the body. This issue is known as local discomfort. Local discomfort can be the result of the drafts, high vertical temperature differences between head and ankles, too warm or too cold surface, or too high a radiant temperature asymmetry [11, 30]. The allowable limit values for local discomfort is given in Table 2.4 for ISO 7730 and Table 3.7 based on ASHRAE 55 [27, 30].

**Table 3.7 :** Local thermal discomfort limits based on ASHRAE 55.

| Draught Rate (%) | Vertical air temperature difference | Caused by warm or cool floor | Radiant asymmetry |
|---|---|---|---|
| <20 | <5 | <10 | <5 |

#### 3.3.3.1 Draughts

The most common source of local discomfort is drafts. ISO 7730 defines drafts as an *unwanted local rating cooling of the body caused by air movement.* The ASHRAE defines the draft as *the most annoying factors in offices.* There are several source of the drafts. The leakage of exterior or interior windows, the presence of fan coil or air vent can be shown as a cause of drafts [11, 28, 30].

Draft rate depends on the air temperature ($T_a$), velocity (v) and turbulence intensity ($T_u$) and the percentage of dissatisfied people because of the draft can be determined by using equation 3.28 [30, 31].

$$\mathrm{DR}=(34\text{-}\mathrm{T_a})(\mathrm{v}\text{-}0{,}05)^{0{,}62}(0{,}37\mathrm{vT_u}+3{,}14) \tag{3.28}$$

Where DR is the percentage dissatisfied due to the draughts and $T_u$ is the turbulence intensity in % defined by the following equation.

$$\mathrm{T_u}=100\frac{\mathrm{v_{sd}}}{\mathrm{v}} \tag{3.29}$$

$v_{sd}$ is the standard deviation of the velocity measured with an omnidirectional anemometer. Turbulence intensity can be taken 40% when this variable is not known [28, 31].

#### 3.3.3.2 Vertical air temperature difference

In space, temperature differences between head and ankle because warm air rises and temperature vary through space. However, if the temperature differences between head and ankle are high, thermal comfort occurs although the body as a whole is thermally neutral. Figure 3.6 shows the effect of the temperature differences on local discomfort [30, 31].

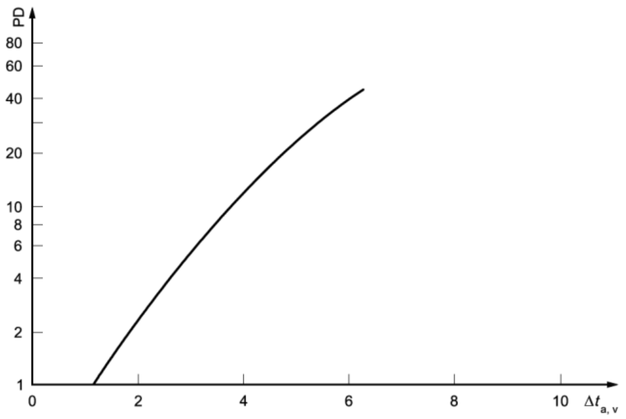


**Figure 3.6 :** Local discomfort caused by vertical air temperature difference.

The percentage dissatisfied can predict by using Equation 3.30 as a function of the vertical air temperature differences between head and ankles ($\Delta T_{a,v}$) [30].

$$\mathrm{PD} = \frac{100}{1 + (\exp(5{,}76\text{-}0{,}856\Delta T_{a,v})} \tag{3.30}$$

ISO 7730 and ASHRAE 55 recommended that the temperature differences between head and ankle (1,1m and 0,1m above the floor) should be less than 3°C [27, 30].

### 3.3.3.3 Warm and cool floors

The direct skin contact with solid surface affects the thermal comfort of occupants. Too high or too low floor temperature can cause a local discomfort because of the direct contact between feet and floor. The relationship between floor temperature ($T_f$) and percentage dissatisfied can be seen in Figure 3.7 [28, 30].

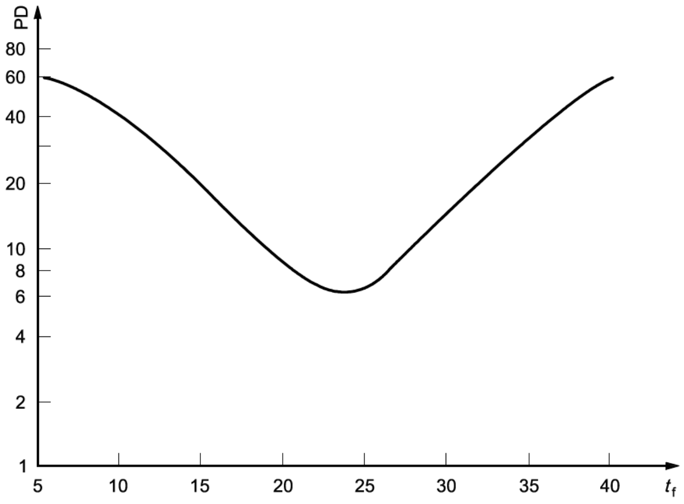


**Figure 3.7 :** Local thermal discomfort caused by warm or cold floors.

The percentage dissatisfied due to the warm or cool floor can predict by using Equation 3.31 as a function of the floor temperature ($T_f$) [30].

$$\mathrm{PD} = 100\text{-}94\exp(\text{-}1{,}387 + 0{,}118\mathrm{T_f}\text{-}0{,}0025\mathrm{T_f}^2) \tag{3.31}$$

### 3.3.3.4 Radiant asymmetry

Hot and cold surfaces and direct sunlight caused to non-uniform thermal radiation field about the body. The asymmetry occurs in all practical environment although it can cause discomfort when the asymmetry is sufficiently large. Cold windows, uninsulated walls, cold products, cold or warm machinery or improperly sized heating panels on the wall or ceiling can be the source of the asymmetric thermal radiation. The relation between asymmetric radiation and percentage of people expressing discomfort can be seen in Figure 3.8 [28, 31].

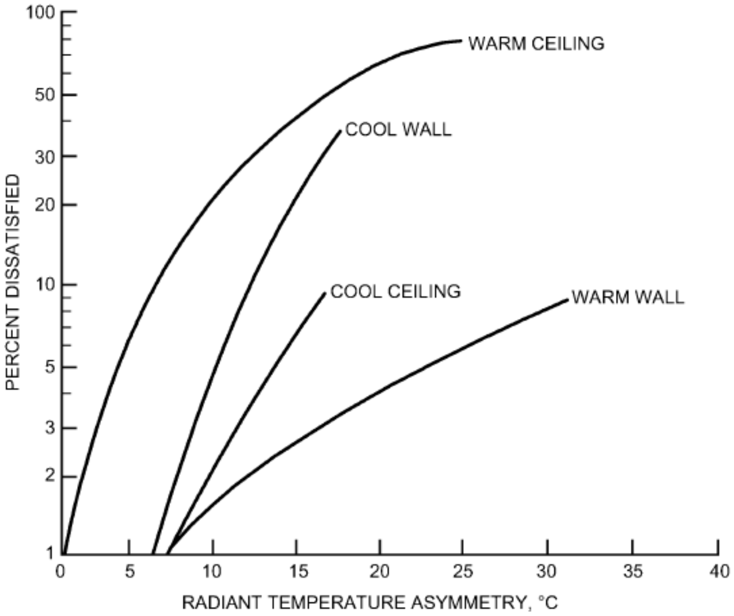


**Figure 3.8 :** Percentage of people expressing discomfort.

# 4. SIMULATION OF NON-RESIDENTIAL BUILDING

## 4.1 Energy and Thermal Comfort Simulation Tool

In order to improve building design for realizing energy efficient building with comfortable indoor conditions, energy transfer between a building and surroundings should be evaluated. For conditioned building, it helps to calculate energy consumption and correspondingly, optimum HVAC equipment size can be selected. On the other hand, for non-conditioned building, it calculates temperature variation in the building over a specified period and helps to detect the uncomfortable periods.

Various heat exchange processes are possible between a building and the external environment. Heat losses and gains occur through the building envelope (walls, roof, ceiling, windows, etc.) by conduction, convection, and radiation. Heat is also added to space via equipment, occupants, and lighting system. Environmental parameters, such as outdoor air temperature, humidity, neighbor objects' shading, also affects the energy transfer between building and surroundings.

Calculation of energy consumption and thermal comfort of a given building is complicated. To overcome this problem building simulation tools have been developed. These tools can estimate the performance of different design of the building for a given environmental condition and it helps to the designers and engineers to create energy efficient and comfortable indoor environments.

In order to calculate model outputs accurately, building model should be input data, which mainly consist of detailed information about the building and its operations; e.g. building geometry, internal loads, HVAC systems and components technical details, operating strategies and schedules, and also weather data as given in Figure 4.1. According to these inputs, energy simulation tools perform a calculation based on thermodynamic equations, principles, and assumptions [48].

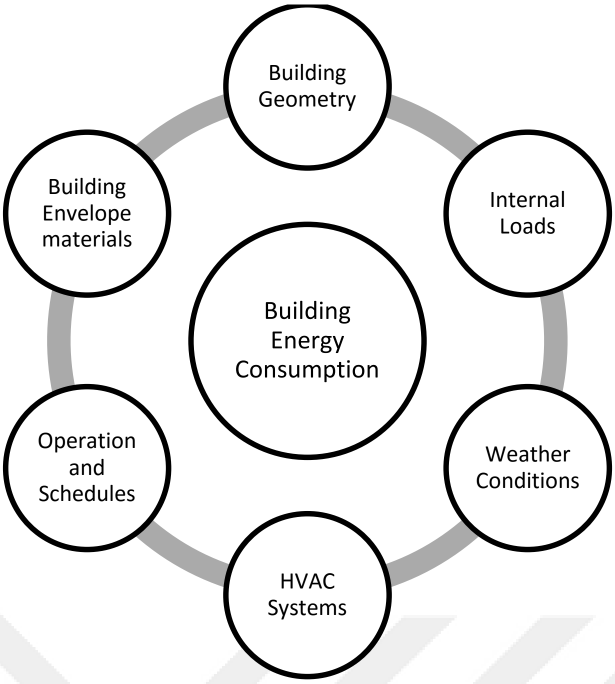


**Figure 4.1 :** General input data for building energy simulation tools.

A large number of tools are available to simulate the energy consumption and thermal comfort of a given building with different capabilities. Crawley et al. (2005) conducted a study to compare building simulation tools in the following categories; general modeling features; buildings envelope, daylighting and solar calculation capabilities; infiltration, ventilation, and multizone airflow control nd calculations; HVAC systems and components, renewable energy systems; thermal comfort calculation competence [49]. Table 4.1, Table 4.2, Table 4.3 and Table 4.4, gives the comparison of different softwares and their capabilities based on above list.

**Table 4.1 :** General modeling features comparisons.

| General Modelling Features | BLAST | DOE-2.1E | ECOTECT | EnergyPlus | eQUEST | ESP-r | HAP | IES-VE | TRNSYS |
|---|---|---|---|---|---|---|---|---|---|
| Full Geometric Description | | | | | | | | | |
| • Walls, roofs floors | X | X | X | X | X | X | X | X | X |
| • Windows, skylights, doors and external shadings | X | X | X | X | X | X | X | X | X |
| Import building geometry from CAD programs | | | X | X | X | X | | X | X |
| Export building geometry to CAD programs | | | X | X | | X | | X | |

**Table 4.2 :** Building envelope, daylighting and solar calculation capabilities comparison.

| Building Envelope, Daylighting, and Solar | BLAST | DOE-2.1E | ECOTECT | EnergyPlus | eQUEST | ESP-r | HAP | IES-VE | TRNSYS |
|---|---|---|---|---|---|---|---|---|---|
| Inside radiation view factors | | | | X | | X | X | | |
| Radiation-to-air component separate from detailed convection | | | | X | X | X | X | X | X |
| Solar gain and daylighting calculations account for interreflections from external building components and other buildings | | | X | X | | X | | X | X |

**Table 4.3 :** Infiltration, ventilation, room air and multizone airflow control and calculation comparisons.

| Infiltration, Ventilation Room Air, and Multizone Airflow | BLAST | DOE-2.1E | ECOTECT | EnergyPlus | eQUEST | ESP-r | HAP | IES-VE | TRNSYS |
|---|---|---|---|---|---|---|---|---|---|
| Single zone infiltration | X | X | X | X | X | X | X | X | X |
| Natural ventilation (pressure, buoyancy driven) | | | | X | | X | | X | |
| Multizone airflow | | | | X | | X | | X | |
| Hybrid natural and mechanical ventilation | | | | | | | | X | |
| Control window opening based on zone or external conditions | | | | X | | X | | X | |

**Table 4.4 :** Thermal comfort calculation capabilities comparisons.

| Thermal Comfort | BLAST | DOE-2.1E | ECOTECT | EnergyPlus | eQUEST | ESP-r | HAP | IES-VE | TRNSYS |
|---|---|---|---|---|---|---|---|---|---|
| Fanger | X | | X | X | | X | | X | X |
| Kansas State University | X | | | X | | | | X | |
| Pierce two-node | X | | X | X | | | | | X |
| MRT (Mean radiant temperature) | X | | | X | | X | | X | |
| Radiant discomfort | | | | | | X | | X | |
| Simultaneous CFD solution | | | | | | | | | |

**Table 4.5 :** HVAC System and component, renewable energy system modeling capabilities comparisons.

| HVAC Systems/Components & Renewable Energy Systems | BLAST | DOE-2.1E | ECOTECT | EnergyPlus | eQUEST | ESP-r | HAP | IES-VE | TRNSYS |
|---|---|---|---|---|---|---|---|---|---|
| Renewable Energy Systems | | | | | | | | | |
| Trombe wall | X | X | X | X | X | X | | X | X |
| Rock bin thermal storage | | | | | | X | | | X |
| Solar thermal collectors | | | | | | | | | |
| • Glazed flat plate | | | X | X | | X | | X | X |
| • Unglazed flat plate (heating and cooling) | | | X | | | X | | | X |
| • Evacuated tube collector | | | | | | | | | X |
| • Unglazed transpired solar collector | | | | X | | | | | X |
| • High temperature concentrating collectors | | | | | | | | | X |
| User-configured solar systems | | | | | | | | | X |
| Integral collector storage systems | | | | | | | | | X |
| Photovoltaic power | | | X | X | X | X | | X | X |
| Hydrogen systems | | | | | | X | | | X |
| Wind power | | | | | | X | | | X |

In this study, to evaluate thermal comfort and energy consumption of case study building, EnergyPlus, and Design Builder software were used because of the thermal comfort calculation capabilities of this software.

### 4.1.1 EnergyPlus

EnergyPlus, has been developed by US Department of Energy (DOE), is one of the most known energy simulation program. This software developed from two existing programs, BLAST, and DOE-2 to create more capabile simulation tool. The load calculation is based on ASHRAE heat-balance approach, and it makes the calculations more precise than the DOE-2 [48].

EnergyPlus is a code based program and does not exist a visual interface that allows users to see and concept the building. Because of the lack of user interface, third party software tools have been developed to simplify modeling, e.g., DesignBuilder, which is explained following section.

EnergyPlus is a thermal simulation software that allows users to see the effects of building’s design on energy and comfort. Based on input parameters like construction material, HVAC system, equipment, and lighting system details, schedules, etc., heating and cooling loads to maintain the building at the required set point. In addition to the load analysis, system sizing, retrofit analysis, detail energy consumption calculation can be performed by using EnergyPlus. To perform these analyses, different modules are used, as it can be seen in Figure 4.2 [50].

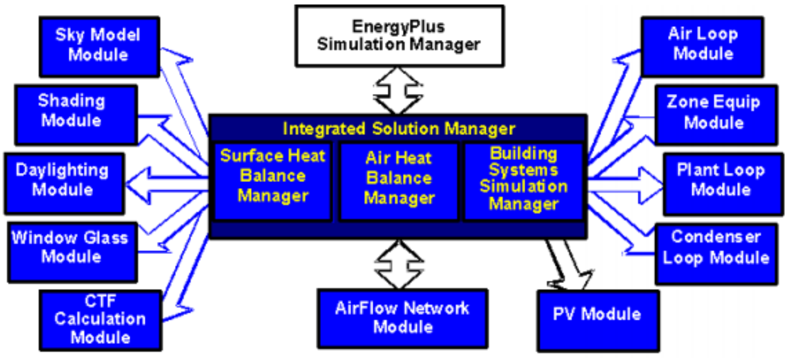


**Figure 4.2 :** EnergyPlus program schematic.

Besides the energy modeling, EnergyPlus can be performed thermal comfort analysis with using different thermal comfort models;

- Fanger comfort model
- Pierce two-node model
- KSU two-node model
- Adaptive comfort model based on ASHRAE 55-2010
- Adaptive comfort model based on EN 15251-2007

In order to evaluate thermal comfort, indoor environmental parameters, which are indoor air temperature, mean radiant temperature, humidity, air velocity, are calculated. Other parameters, activity, and clothing are determined based on user input and schedules. These parameters are calculated based on user inputs about buliding thermo-physical properties, HVAC system details, and building control and operation data [50].

### 4.1.2 Design Builder

EnergyPlus engine relies on input from text files, which increase the effort to define all input data compared to engines with graphical user interface. Several user interfaces are developed over the years. Design builder is the most advanced user interface to EnergyPlus engine. The program provides performance parameters of building such as energy consumption, carbon emissions, comfort conditions, daylight illuminance and HVAC component size.

The typical usage of Design Builder includes;

- Energy consumption calculation
- Evaluation of façade options
- Daylight control
- Daylight analysis with Radiance program
- Visualization of site layouts and solar shading
- thermal simulation of natural ventilation
- Heating/cooling load calculation
- Detail simulation and analysis of HVAC system and components
- Economic analysis based on construction cost, utility cost and life cycle costs
- Optimization analysis [51].

## 4.2 Building Model

### 4.2.1 Description of building

In order to evaluate set point optimization models' performance, an open office is selected as a case study. This office is located in ARI 6 on the campus of the Istanbul Technical University as given in Figure 4.4. The building was built as the first Energy Technopark of Turkey in 2014. Figure 4.3 shows the exterior photos of ARI 6 building.

**Figure 4.3 :** Exterior photos of Arı 6 building.

**Figure 4.4 :** Location of Arı 6 building on the campus of Istanbul Technical University.

Total building area is 4.000m$^2$ and is consisting of 36 offices areas, one conference room, one kitchen, cafeteria area and technical and management areas. In following figures, building floor plans and usage purpose of building zones can be found.

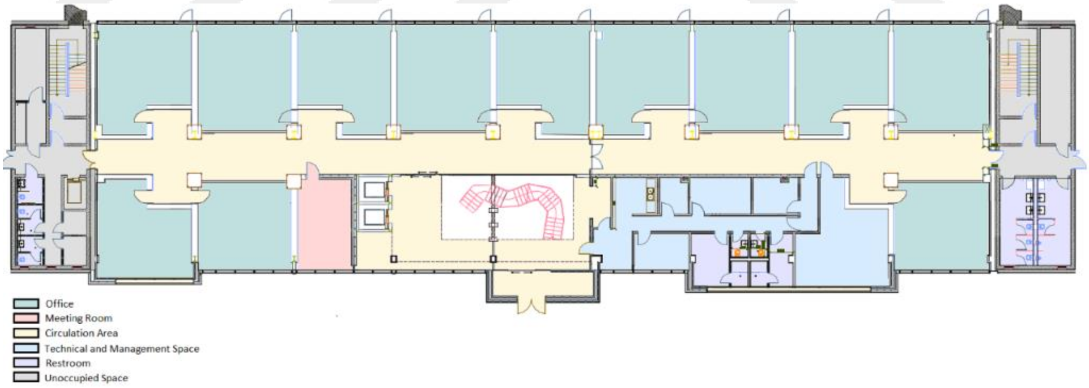


**Figure 4.5 :** Ground floor plan.

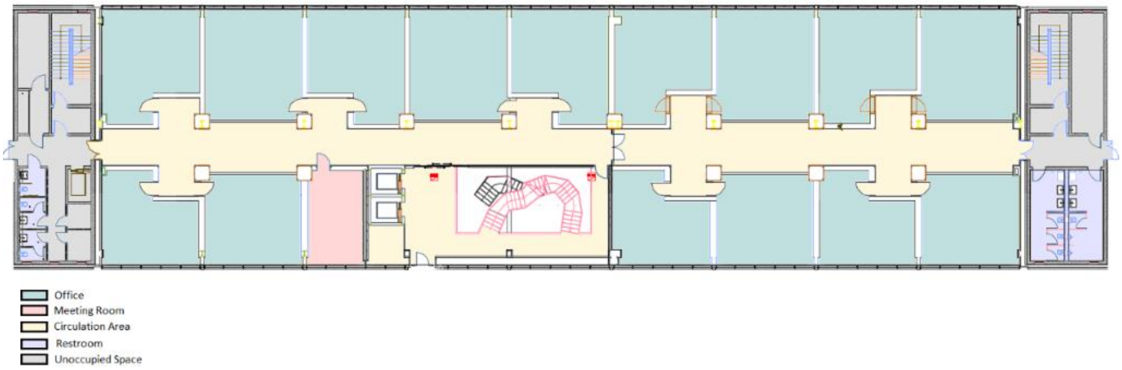


**Figure 4.6 :** First-floor plan.

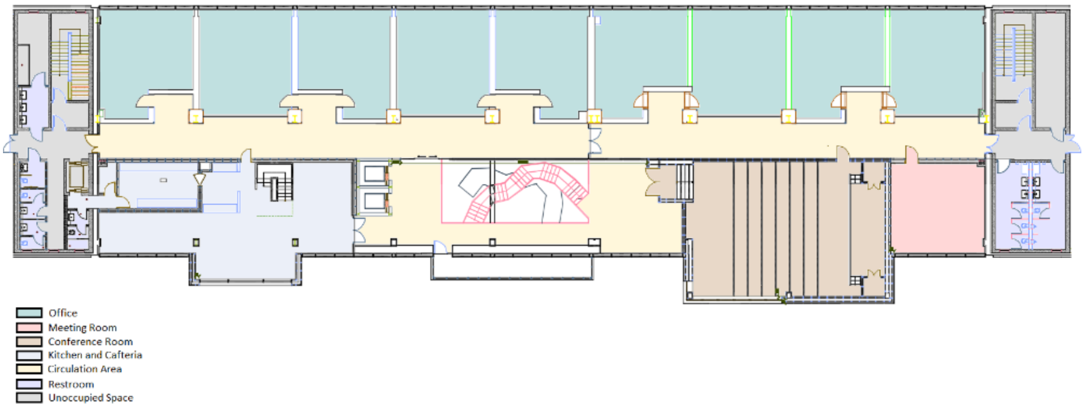
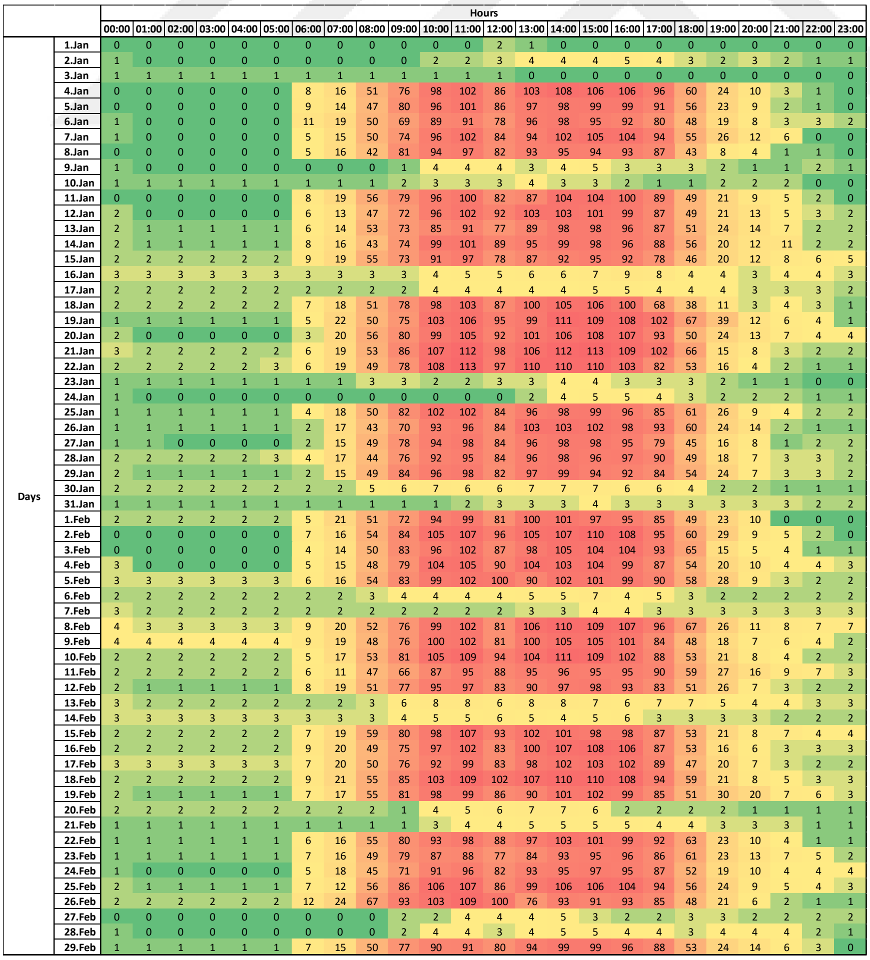


**Figure 4.7 :** Second-floor plan.

Building has an access control system to record occupants' entrance and exit time to the building. In order to understand occupant presence and behavior in building, January and February occupants' entrance and exit time records were examined. According to this data, occupancy density heat, which is given in Figure 4.8, was created. Red areas show peak occupied periods and green areas represent least occupied periods.



| | | Hours | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 00:00 | 01:00 | 02:00 | 03:00 | 04:00 | 05:00 | 06:00 | 07:00 | 08:00 | 09:00 | 10:00 | 11:00 | 12:00 | 13:00 | 14:00 | 15:00 | 16:00 | 17:00 | 18:00 | 19:00 | 20:00 | 21:00 | 22:00 | 23:00 |
| Days | 1.Jan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 2.Jan | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 3 | 4 | 4 | 4 | 5 | 4 | 3 | 2 | 3 | 2 | 1 | 1 |
| | 3.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4.Jan | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 16 | 51 | 76 | 98 | 102 | 86 | 103 | 108 | 106 | 106 | 96 | 60 | 24 | 10 | 3 | 1 | 0 |
| | 5.Jan | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 14 | 47 | 80 | 96 | 101 | 86 | 97 | 98 | 99 | 99 | 91 | 56 | 23 | 9 | 2 | 1 | 0 |
| | 6.Jan | 1 | 0 | 0 | 0 | 0 | 0 | 11 | 19 | 50 | 69 | 89 | 91 | 78 | 96 | 98 | 95 | 92 | 80 | 48 | 19 | 8 | 3 | 3 | 2 |
| | 7.Jan | 1 | 0 | 0 | 0 | 0 | 0 | 5 | 15 | 50 | 74 | 96 | 102 | 84 | 94 | 102 | 105 | 104 | 94 | 55 | 26 | 12 | 6 | 0 | 0 |
| | 8.Jan | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 16 | 42 | 81 | 94 | 97 | 82 | 93 | 95 | 94 | 93 | 87 | 43 | 8 | 4 | 1 | 1 | 0 |
| | 9.Jan | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 4 | 4 | 3 | 4 | 5 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | 1 |
| | 10.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 3 | 4 | 3 | 3 | 2 | 1 | 1 | 2 | 2 | 2 | 0 | 0 |
| | 11.Jan | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 19 | 56 | 79 | 96 | 100 | 82 | 87 | 104 | 104 | 100 | 89 | 49 | 21 | 9 | 5 | 2 | 0 |
| | 12.Jan | 2 | 0 | 0 | 0 | 0 | 0 | 6 | 13 | 47 | 72 | 96 | 102 | 92 | 103 | 103 | 101 | 99 | 87 | 49 | 21 | 13 | 5 | 3 | 2 |
| | 13.Jan | 2 | 1 | 1 | 1 | 1 | 1 | 6 | 14 | 53 | 73 | 85 | 91 | 77 | 89 | 98 | 98 | 96 | 87 | 51 | 24 | 14 | 7 | 2 | 2 |
| | 14.Jan | 2 | 1 | 1 | 1 | 1 | 1 | 8 | 16 | 43 | 74 | 99 | 101 | 89 | 95 | 99 | 98 | 96 | 88 | 56 | 20 | 12 | 11 | 2 | 2 |
| | 15.Jan | 2 | 2 | 2 | 2 | 2 | 2 | 9 | 19 | 55 | 73 | 91 | 97 | 78 | 87 | 92 | 95 | 92 | 78 | 46 | 20 | 12 | 8 | 6 | 5 |
| | 16.Jan | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 6 | 6 | 7 | 9 | 8 | 4 | 4 | 3 | 4 | 4 | 3 |
| | 17.Jan | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 2 |
| | 18.Jan | 2 | 2 | 2 | 2 | 2 | 2 | 7 | 18 | 51 | 78 | 98 | 103 | 87 | 100 | 105 | 106 | 100 | 68 | 38 | 11 | 3 | 4 | 3 | 1 |
| | 19.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 5 | 22 | 50 | 75 | 103 | 106 | 95 | 99 | 111 | 109 | 108 | 102 | 67 | 39 | 12 | 6 | 4 | 1 |
| | 20.Jan | 2 | 0 | 0 | 0 | 0 | 0 | 3 | 20 | 56 | 80 | 99 | 105 | 92 | 101 | 106 | 108 | 107 | 93 | 50 | 24 | 13 | 7 | 4 | 4 |
| | 21.Jan | 3 | 2 | 2 | 2 | 2 | 2 | 6 | 19 | 53 | 86 | 107 | 112 | 98 | 106 | 112 | 113 | 109 | 102 | 66 | 15 | 8 | 3 | 2 | 2 |
| | 22.Jan | 2 | 2 | 2 | 2 | 2 | 3 | 6 | 19 | 49 | 78 | 108 | 113 | 97 | 110 | 110 | 110 | 103 | 82 | 53 | 16 | 4 | 2 | 1 | 1 |
| | 23.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 2 | 2 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 2 | 1 | 1 | 0 | 0 |
| | 24.Jan | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 5 | 5 | 4 | 3 | 2 | 2 | 2 | 1 | 1 |
| | 25.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 18 | 50 | 82 | 102 | 102 | 84 | 96 | 98 | 99 | 96 | 85 | 61 | 26 | 9 | 4 | 2 | 2 |
| | 26.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 17 | 43 | 70 | 93 | 96 | 84 | 103 | 103 | 102 | 98 | 93 | 60 | 24 | 14 | 2 | 1 | 1 |
| | 27.Jan | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 15 | 49 | 78 | 94 | 98 | 84 | 96 | 98 | 98 | 95 | 79 | 45 | 16 | 8 | 1 | 2 | 2 |
| | 28.Jan | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 17 | 44 | 76 | 92 | 95 | 84 | 96 | 98 | 96 | 97 | 90 | 49 | 18 | 7 | 3 | 3 | 2 |
| | 29.Jan | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 15 | 49 | 84 | 96 | 98 | 82 | 97 | 99 | 94 | 92 | 84 | 54 | 24 | 7 | 3 | 3 | 2 |
| | 30.Jan | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 6 | 7 | 6 | 6 | 7 | 7 | 7 | 6 | 6 | 4 | 2 | 2 | 1 | 1 | 1 |
| | 31.Jan | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| | 1.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 21 | 51 | 72 | 94 | 99 | 81 | 100 | 101 | 97 | 95 | 85 | 49 | 23 | 10 | 0 | 0 | 0 |
| | 2.Feb | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 16 | 54 | 84 | 105 | 107 | 96 | 105 | 107 | 110 | 108 | 95 | 60 | 29 | 9 | 5 | 2 | 0 |
| | 3.Feb | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 14 | 50 | 83 | 96 | 102 | 87 | 98 | 105 | 104 | 104 | 93 | 65 | 15 | 5 | 4 | 1 | 1 |
| | 4.Feb | 3 | 0 | 0 | 0 | 0 | 0 | 5 | 15 | 48 | 79 | 104 | 105 | 90 | 104 | 103 | 104 | 99 | 87 | 54 | 20 | 10 | 4 | 4 | 3 |
| | 5.Feb | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 16 | 54 | 83 | 99 | 102 | 100 | 90 | 102 | 101 | 99 | 90 | 58 | 28 | 9 | 3 | 2 | 2 |
| | 6.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 7 | 4 | 5 | 3 | 2 | 2 | 2 | 2 | 2 |
| | 7.Feb | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | 8.Feb | 4 | 3 | 3 | 3 | 3 | 3 | 9 | 20 | 52 | 76 | 99 | 102 | 81 | 106 | 110 | 109 | 107 | 96 | 67 | 26 | 11 | 8 | 7 | 7 |
| | 9.Feb | 4 | 4 | 4 | 4 | 4 | 4 | 9 | 19 | 48 | 76 | 100 | 102 | 81 | 100 | 105 | 105 | 101 | 84 | 48 | 18 | 7 | 6 | 4 | 2 |
| | 10.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 17 | 53 | 81 | 105 | 109 | 94 | 104 | 111 | 109 | 102 | 88 | 53 | 21 | 8 | 4 | 2 | 2 |
| | 11.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 6 | 11 | 47 | 66 | 87 | 95 | 88 | 95 | 96 | 95 | 95 | 90 | 59 | 27 | 16 | 9 | 7 | 3 |
| | 12.Feb | 2 | 1 | 1 | 1 | 1 | 1 | 8 | 19 | 51 | 77 | 95 | 97 | 83 | 90 | 97 | 98 | 93 | 83 | 51 | 26 | 7 | 3 | 2 | 2 |
| | 13.Feb | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 6 | 8 | 8 | 6 | 8 | 8 | 7 | 6 | 7 | 7 | 5 | 4 | 4 | 3 | 3 |
| | 14.Feb | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 5 | 6 | 5 | 4 | 5 | 6 | 3 | 3 | 3 | 3 | 2 | 2 | 2 |
| | 15.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 7 | 19 | 59 | 80 | 98 | 107 | 93 | 102 | 101 | 98 | 98 | 87 | 53 | 21 | 8 | 7 | 4 | 4 |
| | 16.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 9 | 20 | 49 | 75 | 97 | 102 | 83 | 100 | 107 | 108 | 106 | 87 | 53 | 16 | 6 | 3 | 3 | 3 |
| | 17.Feb | 3 | 3 | 3 | 3 | 3 | 3 | 7 | 20 | 50 | 76 | 92 | 99 | 83 | 98 | 102 | 103 | 102 | 89 | 47 | 20 | 7 | 3 | 2 | 2 |
| | 18.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 9 | 21 | 55 | 85 | 103 | 109 | 102 | 107 | 110 | 110 | 108 | 94 | 59 | 21 | 8 | 5 | 3 | 3 |
| | 19.Feb | 2 | 1 | 1 | 1 | 1 | 1 | 7 | 17 | 55 | 81 | 98 | 99 | 86 | 90 | 101 | 102 | 99 | 85 | 51 | 30 | 20 | 7 | 6 | 3 |
| | 20.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 4 | 5 | 6 | 7 | 7 | 6 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| | 21.Feb | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 1 | 1 |
| | 22.Feb | 1 | 1 | 1 | 1 | 1 | 1 | 6 | 16 | 55 | 80 | 93 | 98 | 88 | 97 | 103 | 101 | 99 | 92 | 63 | 23 | 10 | 4 | 1 | 1 |
| | 23.Feb | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 16 | 49 | 79 | 87 | 88 | 77 | 84 | 93 | 95 | 96 | 86 | 61 | 23 | 13 | 7 | 5 | 2 |
| | 24.Feb | 1 | 0 | 0 | 0 | 0 | 0 | 5 | 18 | 45 | 71 | 91 | 96 | 82 | 93 | 95 | 97 | 95 | 87 | 52 | 19 | 10 | 4 | 4 | 4 |
| | 25.Feb | 2 | 1 | 1 | 1 | 1 | 1 | 7 | 12 | 56 | 86 | 106 | 107 | 86 | 99 | 106 | 106 | 104 | 94 | 56 | 24 | 9 | 5 | 4 | 3 |
| | 26.Feb | 2 | 2 | 2 | 2 | 2 | 2 | 12 | 24 | 67 | 93 | 103 | 109 | 100 | 76 | 93 | 91 | 93 | 85 | 48 | 21 | 6 | 2 | 1 | 1 |
| | 27.Feb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 4 | 4 | 4 | 5 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 2 |
| | 28.Feb | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 4 | 3 | 4 | 5 | 5 | 4 | 4 | 3 | 4 | 4 | 4 | 2 | 1 |
| | 29.Feb | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 15 | 50 | 77 | 90 | 91 | 80 | 94 | 99 | 99 | 96 | 88 | 53 | 24 | 14 | 6 | 3 | 0 |

**Figure 4.8 :** Hourly occupancy density for January and February.

Due to the fact that the building is a technopark, operational activities are different from the normal building. As depicted in above figure, people can work in night time period and it can be said that building is actively operated all day period.

### 4.2.2 Building material properties

The building was designed and constructed with using different construction material and technologies, e.g. a green wall, photovoltaic integrated wall, and roof in order to provide high energy efficiency. Building construction materials and their U values, which can be found in Table 4.6, were calculated based on architectural and constructional plans of the building.

**Table 4.6 :** Building construction material U values.

| Construction | U Value (W/m$^2$K) | Construction | U Value (W/m$^2$K) |
|---|---|---|---|
| Exterior Wall | | Exposed Floor | |
| Exterior Wall | 0,240 | Conference room floor | 0,126 |
| Concrete Wall | 0,499 | Cafeteria floor | 0,146 |
| PV Integrated Wall | 0,182 | Ground Floor | |
| Cafeteria Wall | 0,139 | Office ground floor | 0,206 |
| Green Wall | 0,216 | Corridor ground floor | 0,206 |
| Interior Wall | | Roof | |
| Concrete Interior Wall | 2,036 | Green roof | 0,115 |
| Office Interior Wall | 1,639 | PV Integrated Roof | 0,215 |
| Interior Floor | | Cafeteria Roof | 0,218 |
| Office interior floor | 0,739 | Concrete Roof | 0,412 |
| Corridor interior floor | 0,489 | | |

Exterior windows cover approximately 33% of the total building envelope. As given in Table 4.7, building windows were selected triple glazed with argon filled in order to decrease heat loss and gans from the window and ensure energy reduction.

**Table 4.7 :** Windows thermal and visual properties.

| Construction | U-Value (W/m$^2$K) | Total Solar Transmission (SHGC) | Light Transmission |
|---|---|---|---|
| Exterior Windows | 0,6 | 0,48 | 0,69 |

#### 4.2.2.1 HVAC system

In order to meet heating, cooling and ventilation requirement of building, VRF (Variable Refrigerant Flow) and AHU (air handling unit) system was installed. VRF systems consist of two part; indoor unit and outdoor unit. VRF indoor unit use refrigarnt medium to use heat and cool the air. This refrigarant is preaperd in outdoor unit and serve to the indoor units based on space heating and cooling demand. In this building AHUs also connect to VRF outdoor units to utilise refrigarant medium to conditioned fresh outdoor air before sent to zone. Schematic representation of building HVAC system, was created by using Design Builder, can be seen in Figure 4.9.

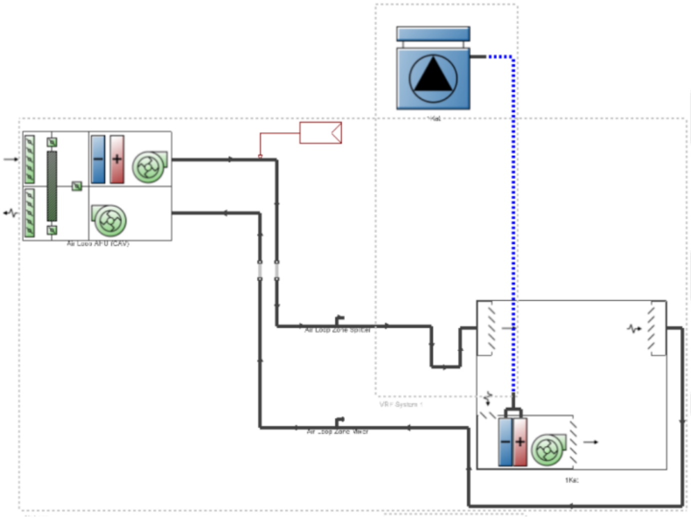


**Figure 4.9 :** Schematic representation of building HVAC system.

Seven different outdoor units are located in the building to provide conditioned air for different floors and spaces, and Table 4.8 gives technical specifications of these systems.

**Table 4.8 :** Specifications of VRF outdoor units.

| Outdoor Unit | Cooling Capacity (kW) | COP | Operating Temperature Range (°C) | Heating Capacity(kW) | COP | Operating Temperature Range (°C) |
|---|---|---|---|---|---|---|
| Ground Floor | 125 | 3,29 | (-5) - 48 | 140 | 4,34 | (-20) - 24 |
| First Floor | 125 | 3,29 | (-5) - 48 | 140 | 4,34 | (-20) - 24 |
| Second Floor | 80 | 3,88 | (-5) - 48 | 89 | 4,57 | (-20) - 24 |
| Cafeteria | 55 | 3,88 | (-5) - 48 | 65 | 4,57 | (-20) - 24 |
| Conference Room | 31 | 3,03 | (-5) - 48 | 38 | 3,36 | (-20) - 24 |
| AHU 1 | 26 | 3,6 | (-5) - 48 | 36 | 4,4 | (-20) - 24 |
| AHU 2 | 26 | 3,6 | (-5) - 48 | 36 | 4,4 | (-20) - 24 |

VRF indoor units are controlled by zone thermostats, which work in two modes; heating and cooling. These units can provide independent heating and cooling for different areas at the same time.

### 4.2.3 Operational details of selected office

The office, which is selected for this study, is located on the north facade of the building. Interior photos and office plan can be seen in Figure 4.10 and Figure 4.11. The office has only one exterior wall (with a window) facing north and has a rectangular shape with a floor area of 108m$^2$.

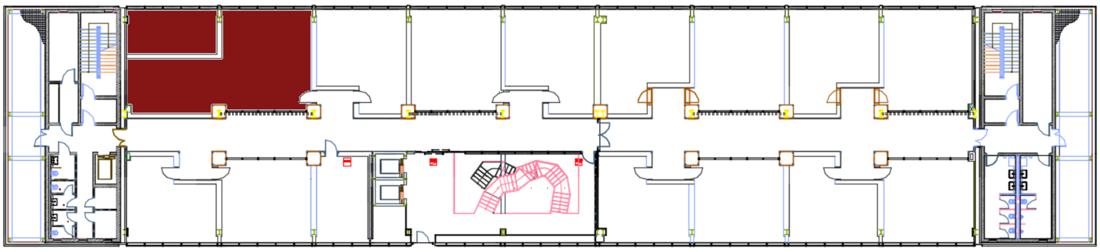


**Figure 4.10 :** Office plan and location at first floor.

Office is seperated in two zones; small meeting room and an open plan office. Only office area were involved to this study.

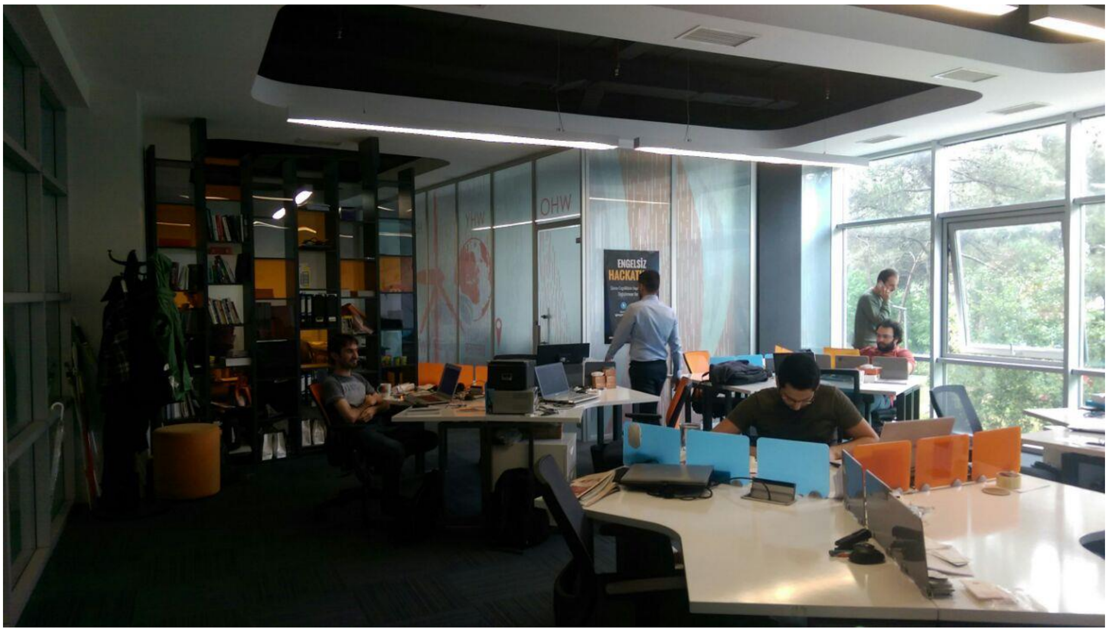


**Figure 4.11 :** Selected office in ARI 6 building.

In this officce eight personnel participate the study. This participants' personal information can be found in Table 4.9.

**Table 4.9 :** Occupant profile of selected office.

| Occupant | Gender | Age | Height (m) | Weight (kg) | BMI |
|---|---|---|---|---|---|
| Occupant1 | Male | 27 | 1.70 | 68 | 23,5 |
| Occupant2 | Male | 26 | 1.68 | 77 | 27,3 |
| Occupant3 | Male | 29 | 1.80 | 94 | 29,0 |
| Occuapant4 | Male | 25 | 1.82 | 86 | 26,0 |
| Occuapnt5 | Female | 26 | 1.60 | 45 | 17,6 |
| Occupant6 | Male | 26 | 1.78 | 60 | 18,9 |
| Occupant9 | Male | 28 | 1.89 | 90 | 25,2 |
| Occupant10 | Male | 27 | 1.92 | 80 | 21,7 |

## 4.3 Generation of Building Simulation Model

To evaluate effects of the dynamic thermostat schedules, in terms of comfort and energy, building simulation models use to predict building behavior under different operations. For this purpose, a model of the building has been created by using Design Builder (v4.6.0). Model of the building is shown in Figure 4.12. Energy and comfort analyses were performed by Energy Plus (v8.4.0). Building model was modeled based on architectural, mechanical and electrical plans of the building. For other system's schedule ASHRAE 90.1 schedules were applied to the model.

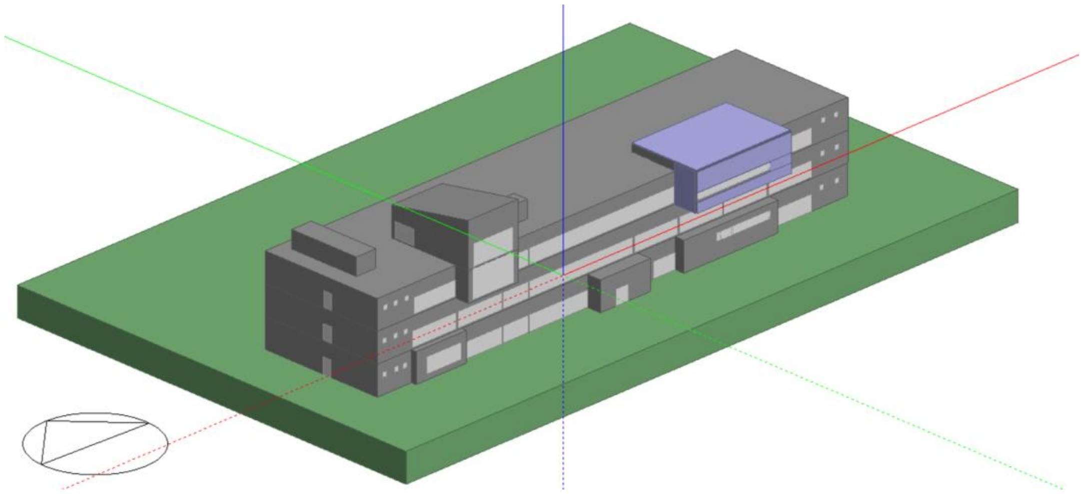


**Figure 4.12 :** Case study building model.

# 5. FIELD STUDIES: MEASUREMENT AND SURVEY

Field studies carried out in two phase, measurement and survey (questionnaire). Measurements were carried out for two weeks. In the first week, natural behavior of zone and occupant were observed under natural ventilation conditions. In the second phase, in addition to the temperature and humidity data measurement, in order to create optimized dynamic temperature schedule occupant feedback about their thermal sensation were collected via website. This week is called as baseline period. In addition to the data collection process, thermal comfort survey was conducted to gather information regarding occupant experience of thermal comfort within the building and overall satisfaction.

## 5.1 Thermal Comfort Survey

Besides environmental monitoring tools and dynamic modeling software, surveys also can be used to evaluate the comfort of the indoor environment. Occupant thermal sensation is affected by psychological, social and cultural conditions. With surveys, occupants' subjective responses can be evaluated. Also, the reason of the uncomfortable environment can be determined.

There are two types of thermal environment surveys. First, one is the “point-in-time survey” and it is used to determine thermal sensation of occupants at a single point in time. A second form is called “satisfaction survey” and the purpose of this survey is evaluating thermal comfort response of occupants in a certain span of time [27].

In order to evaluate that how the occupants perceived the thermal comfort conditions in their office, satisfaction survey, which is adopted from ASHRAE 55, was conducted to occupants. Thermal comfort survey questions are given in Appendix A. The survey results shows that the 50% of occupants feel discomfort during the year as shown in Figure 5.1.

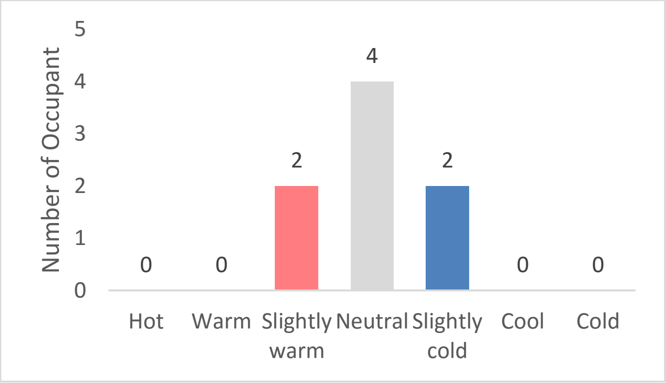


**Figure 5.1 :** Occupant perceived general satisfaction in workspace.

As depicted in Figure 5.2, when 50% of occupants feel neutral, 12,5% of occupants describe their thermal environment as a cold in warm/hot and cold/cool weathers, for same period, %37,5 of occupants feels hot.

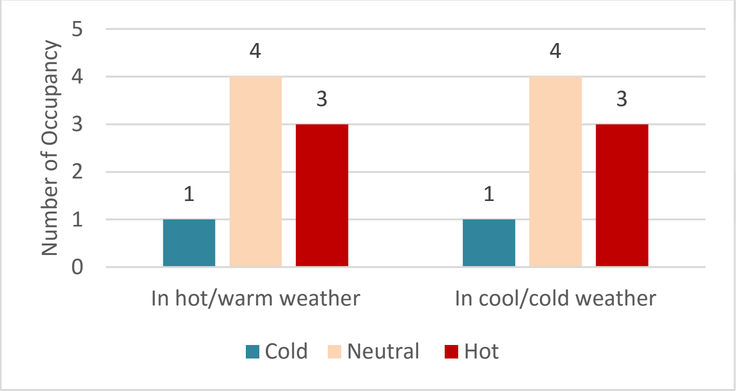


**Figure 5.2 :** Occupants description of thermal conditions in different sessions.

The questionnaire includes questions that can help to determine the main reasons of discomfort. According to the output of the survey, inadequate temperature settings, direct air movement by the reason of wrong mechanical system design and drafts from the ventilation system cause discomfort, as seen in Figure 5.3.

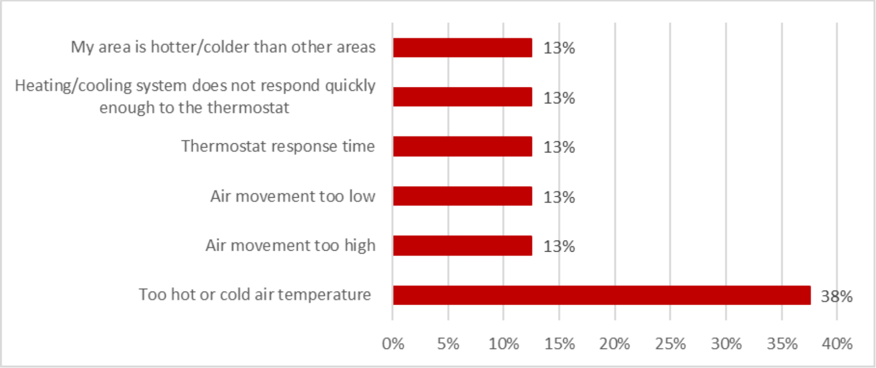


**Figure 5.3 :** Survey results for the source of discomfort.

In 2009, The International Facility Management Association (IFMA) oncduceted a survey to identify thermal comfort complains and the survey sent to 3.357 member of IFMA which are located in United State and Canada. Accoring to the findings of this survey, the main complaint is too hot or too cold air temperature comes from HVAC system through the year. In similar with the IFMA's results, the outcome of survey for case study office provides almost same results [52].

Furthermore, during the survey, personal, activity and clothing data are gathered. Table 5.1 shows this information.

**Table 5.1 :** Participants' information.

| | Gender | Age | Weight | Height | BMI | Clothing Insulation (clo) | Activity (W/m$^2$) |
|---|---|---|---|---|---|---|---|
| Occupant1 | Male | 27 | 1,7 | 68 | 23,5 | 0,54 | 55 |
| Occupant2 | Male | 26 | 1,68 | 77 | 27,2 | 0,46 | 55 |
| Occupant3 | Male | 29 | 1,8 | 94 | 29,0 | 0,63 | 55 |
| Occupant4 | Male | 25 | 1,82 | 86 | 26,0 | 0,25 | 55 |
| Occupant5 | Female | 26 | 1,6 | 45 | 17,6 | 0,61 | 55 |
| Occupant6 | Male | 26 | 1,78 | 60 | 18,9 | 0,46 | 55 |
| Occupant9 | Male | 28 | 1,89 | 90 | 25,2 | 0,63 | 55 |
| Occupant10 | Male | 27 | 1,92 | 80 | 21,7 | 0,46 | 55 |

## 5.2 Temperature and Humidity Measurement

In order to moitored and record dynamic changinc profile of indoor environment, the HOBO UX100-003 data logger recorded temperature and humidity data with 10 minute time interval. Data logger was positioned on the interior wall, as can be seen in Figure 5.4 to avoid direct sunlight.

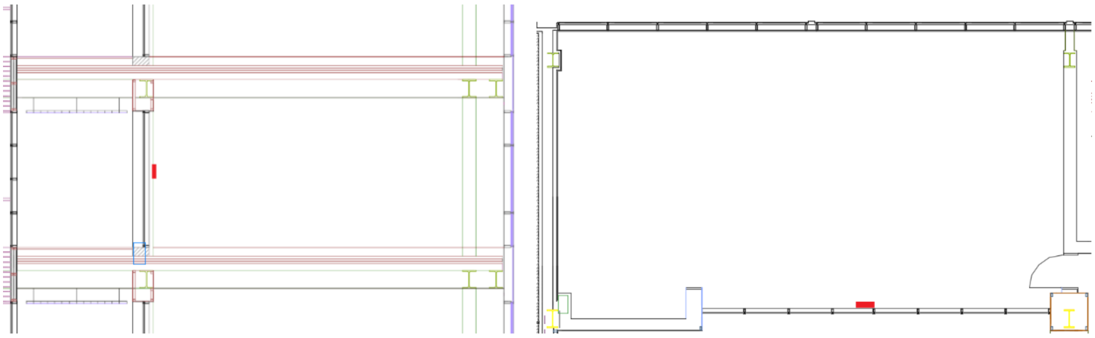


**Figure 5.4 :** Temperature and humidity sensor position in the office.

The data logger records temperature within ±0.21°C accuracy and the operation range is between -20°C and 70°C. For the realtive humiditiy, the measurement accuracy within ±3.5% and working range is between 25% and 85% [53].

Indoor temperature and humidity data are collected for two different periods, which are called observation and voting. In observation period, natural behavior of occupants and building were monitored under the operation of natural ventilation condition. Measurements were conducted between 14th to 20th of April. Figure 5.5 shows recorded data in this period.

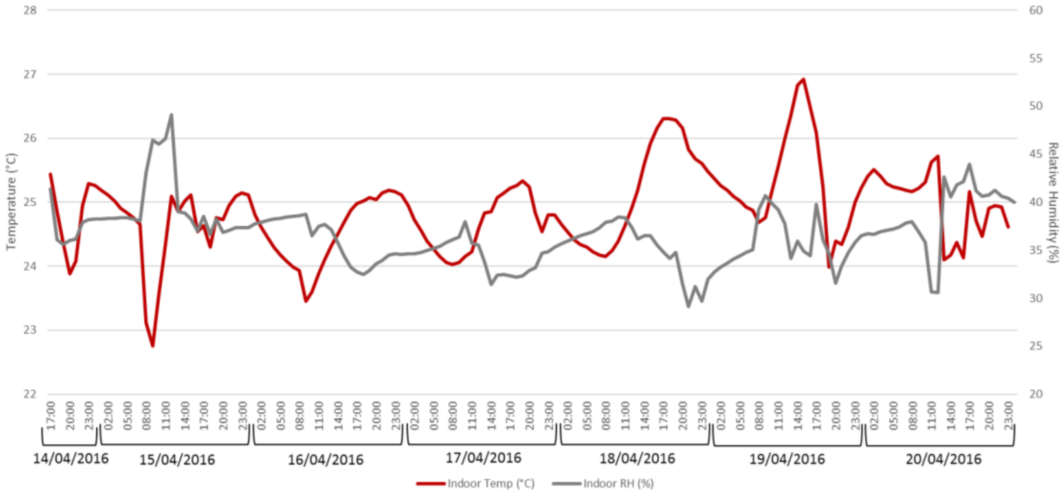


**Figure 5.5 :** Indoor temperature and relative humidity measurements result for the observation period.

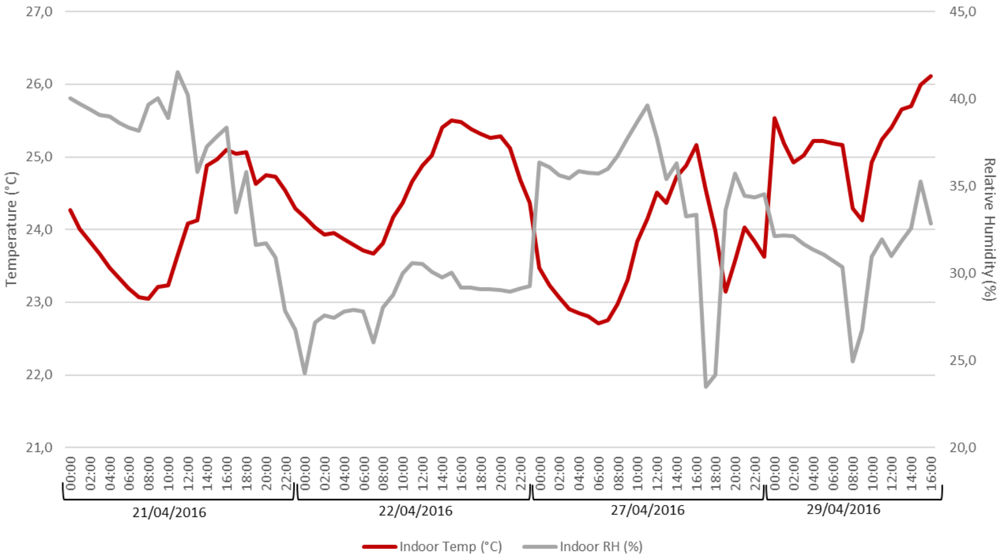


**Figure 5.6 :** Indoor temperature and relative humidity measurements result for the voting period.

For voting period, collected indoor temperature and relative humidity data are given in Figure 5.6. This part of the measurement process takes for four days which are 21st, 22nd, 27th and 29th of April. During the measurement process for voting period, at an occupied hour, indoor VRF unit operates with fixed set point temperature (24°C) in heating mode and for the observation period, HVAC system did not use to condition the space. A summary of monitoring study findings are given in Table 5.2.

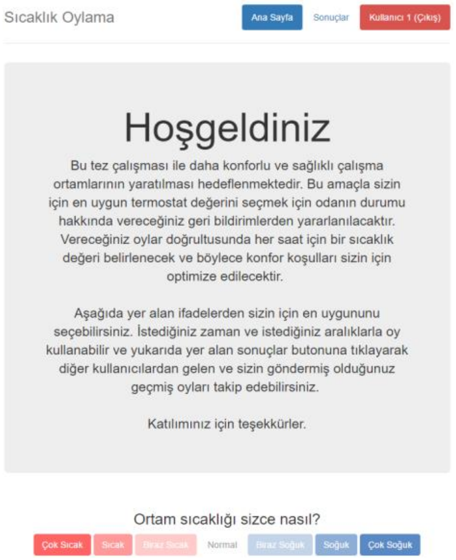
**Table 5.2 :** Summary of monitoring findings.

| Monitored Data | | Observation Period | Voting Period |
|---|---|---|---|
| Indoor Air Temperature (°C) | Min | 22,8 | 22,7 |
| | Max | 26,9 | 26,1 |
| | Average | 24,9 | 24,3 |
| Relative Humidity (%) | Min | 29,1 | 23,5 |
| | Max | 49,1 | 41,5 |
| | Average | 36,7 | 32,9 |

## 5.3 Collecting Occupancy Feedback

Real-time and continuous input of their thermal sensation were collected via the website, which is created for this study, to provide dataset to the optimization process.

A website gathered actual mean votes (AMV) of occupant in order to obsere occuapant real-time response to the dynamic indoor conditons and determine optimum thermostat schedules based on these feedbakcs. For this purpose, the internet site with a simple interface was shown in Figure 5.7, was designed. In order to collect occupant feedback, seven-point PMV scale was used.



Hoşgeldiniz

Bu tez çalışması ile daha konforlu ve sağlıklı çalışma ortamlarının yaratılması hedeflenmektedir. Bu amaçla sizin için en uygun termostat değerini seçmek için odanın durumu hakkında vereceğiniz geri bildirimlerden yararlanılacaktır. Vereceğiniz oylar doğrultusunda her saat için bir sıcaklık değeri belirlenecek ve böylece konfor koşulları sizin için optimize edilecektir.

Aşağıda yer alan ifadelerden sizin için en uygununu seçebilirsiniz. İstediğiniz zaman ve istediğiniz aralıklarla oy kullanabilir ve yukarıda yer alan sonuçlar butonuna tıklayarak diğer kullanıcılardan gelen ve sizin göndermiş olduğunuz geçmiş oyları takip edebilirsiniz.

Katılımınız için teşekkürler.

Ortam sıcaklığı sizce nasıl?

**Figure 5.7 :** User interface of voting application.

Baseline period covers four days, 21st, 22nd, 27th and 29th April. 8 Participants provide 83 feedbacks during this period. Figure 5.8 shows raw data of occupant real-time response to the environment.

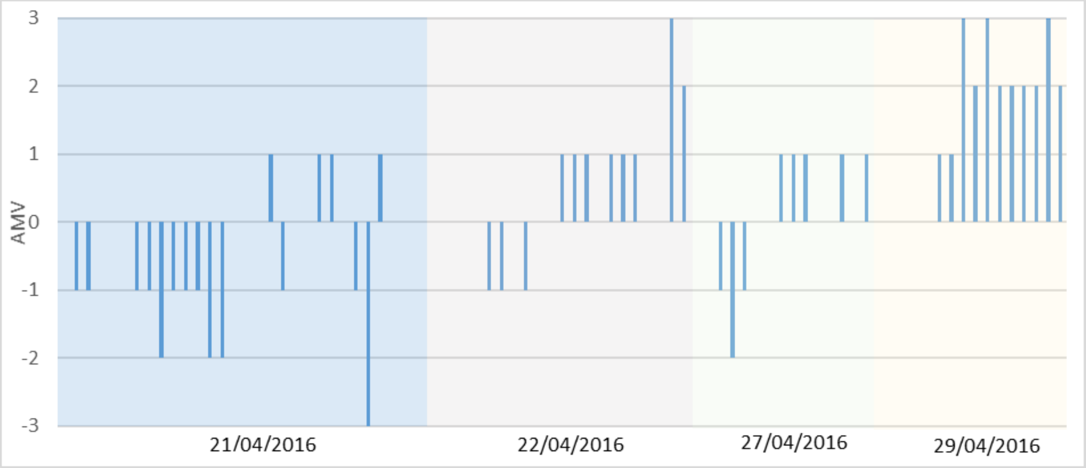


**Figure 5.8 :** Occupant Actual Mean Votes (AMV) during the measurement period.

If the votes are examined, it can be seen that 57% of the occupants feel discomfort during the baseline period and the details of the vote distribution is given in Table 5.3.

**Table 5.3 :** Thermal comfort vote distribution.

| Thermal Comfort | Percentage | Thermal Comfort | Percentage |
|---|---|---|---|
| Cold | 1,2% | Slightly warm | 20,6% |
| Cool | 4,8% | Warm | 8,4% |
| Slightly Cool | 16,9% | Hot | 4,8% |
| Neutral | 43,3% | | |

## 5.4 Model Validation

In this study, in order to investigate effects of different set point optimization strategies on thermal comfort and energy consumption, building energy simulation tools were used. These tools attempts to model impacts of large number input data that affect the energy consumption and thermal environment of building as accurately as possible.

To determine the accuracy of the building model, two statistical indices are used to address the error of simulation model. The first index is Normalized Mean Bias Error (NMBE), and it is used to determined how to close the prediction by the model to the measured data. A second is the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)). It expresses how well a simulated data fits the measured data. The lower

CV(RMSE) value indicates, the better-calibrated model. Following equations show the calculation methods of these two indices [54].

$$\mathrm{NMBE} = \frac{\sum_{i=0}^{n}(y_i - \hat{y}_i)}{(n-p)\bar{y}} 100 \tag{5.1}$$

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\frac{\sum_{i=0}^{n}(y_i - \hat{y}_i)^2}{(n-p)}}}{\bar{y}} 100 \tag{5.2}$$

In equations, $y_i$ represents measured data, $\hat{y_i}$ is simulated data, n is the number of data point and p is the number of parameters.

Based on ASHRAE, a value of CV(RMSE) should be under the 30% for hourly calibrated model and NBME should fall within ±10%.

In order to accurately reflect the actual building performance, building model is calibrated with various inputs [55]. The calibration is crucial to get true results from the model. Four calibration methodologies are proposed and used for building simulation models;

- Manual calibration methods based on an iterative approach,
- Graphical-based calibration methods
- Calibration based on special tests and analysis procedure
- Automated techniques for calibration, based on analytical and mathematical approaches.

In this study, manual calibration methodology and graphical techniques were used to tuning model with using zone usage profile of occupants. It includes “trial and error” approaches, and it is relies on an iterative manual tuning of the model input parameters according to the knowledge about the building and operation. In addition to the manual calibration methodology, graphical representation and comparative display of the results were generated in order to understand tuning process [56].

In order to calibrate the model, monitored temperature and humidity data was used. Occupancy, equipment and lighting system schedules were created based on the card access control system records. Weather data was also updated using measured outdoor temperature and humidity data which was taken from the web service.

Mesaured indoor air temperature and relative humidity data were used to examine the ability of building model to predict zone temperature accurately. Based on recorded and simulated data, the errors were calculated and accumulated got the indoor air temperature and relative humidity of actually monitored zone in case study building. Limit of statistical indices for model validation and calculated errors of calibrated model are given in Table 5.4.

**Table 5.4 :** NMBE and CV(RMSE) values for calibrated models.

| Statistical Indices | NMBE (%) | CV(RMSE) (%) |
|---|---|---|
| ASHRAE Guideline 14 | ±10% | 30% |
| Observation Period Indoor Temperature | 0,1% | 1% |
| Observation Period Relative Humidity | -9% | 16% |
| Voting Period Indoor Temperature | -1% | 3% |
| Voting Period Relative Humidity | 5% | 10% |

It can be seen above table, MBE and CV(RMSE) values of calibrated model fall within the ASHRAE acceptance limits of within ±10% and below 30% and it shows that the simulation model is accurated to predict thermal comfort and energy consumption. Figure 5.9 and Figure 5.10 give a visual comparison of simulated and measured temperature and humidity data.

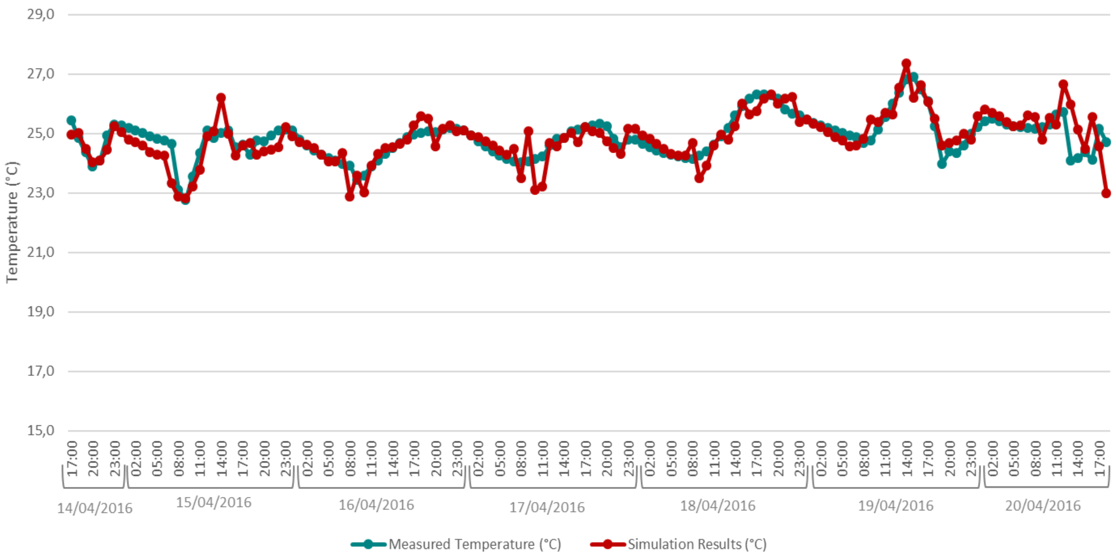


**Figure 5.9 :** Measured and simulated indoor air temperature data comparison for the observation period.

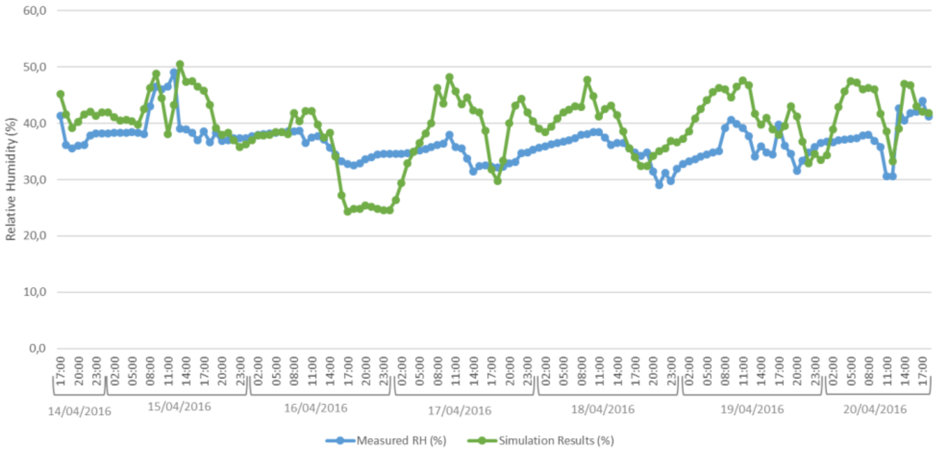


**Figure 5.10 :** Measured and simulated relative humidity data comparison for the observation period.

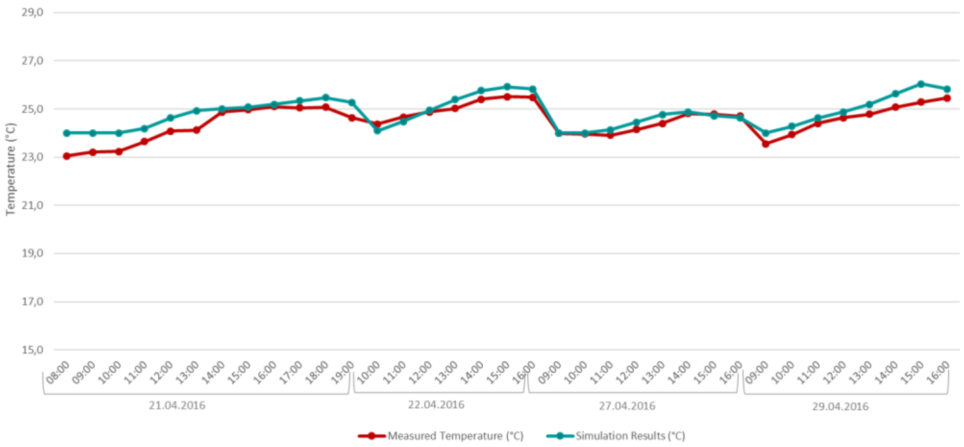


**Figure 5.11 :** Measured and simulated indoor air temperature data comparison for voting period.

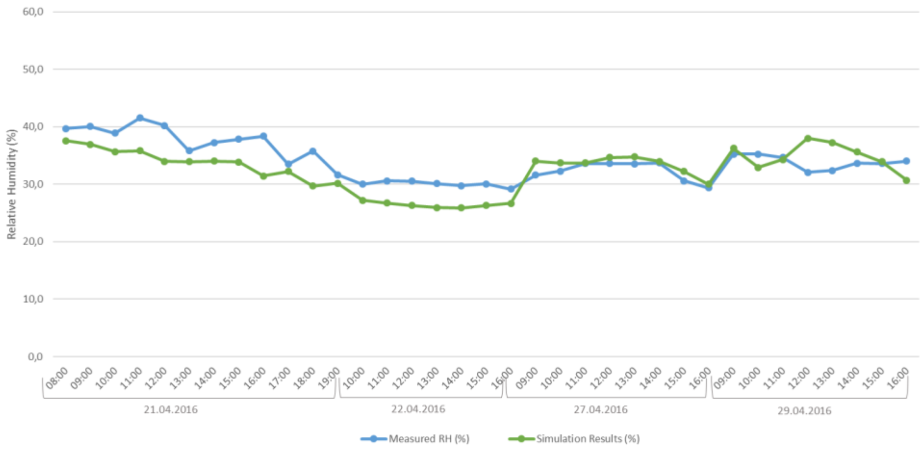


**Figure 5.12 :** Measured and simulated relative humidity data comparison for voting period.

# 6. IMPLEMENTATION OF THERMAL COMFORT OPTIMIZATION METHODS

The main goal of this study fulfills the thermal comfort requirement of occupants in shared spaces via dynamic thermostat control. To adjust set temperature, various approaches have been developed, and these methods mainly rely on measured indoor physical parameters and real-time occupant feedback about thermal sensation to optimize temperature setting and Figure 6.1 gives the general workflow of the optimization methods.

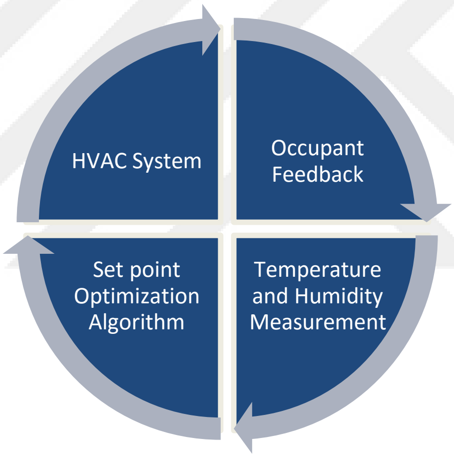


**Figure 6.1 :** Occupant participate thermostat set point optimization method workflow.

Dynamic thermal comfort assessment and control can be done by using various methods. In order to used in practice, the method should be simple and applicable for different building management and control system. As described in section 3, thermal comfort assesses by using six environmental and personal parameters, which are air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, clothing properties and activity level. The most of the existing BMS systems cannot measure these parameters and generally indoor air temperature, and relative humidity can be monitored and recorded. Due to the lack of adequate equipment, PMV estimation cannot be done accurately. To overcome this issue, the occupant participating approach is utilized to a large number of studies.

Dynamic control methods were investigated with reviewing literature studies and commercial products. Finally, three different control methods were selected to examine in this study based on their applicability in practice;

- **Scenario 1:** This scenario is based on thermal comfort optimization method developed by Erickson and Cerpa [12]. This approach integrates the PMV model to estimate initial thermal comfort conditions with temperature and humidity sensor outputs. In order to correct the estimation, occupant feedbacks are used. Based on corrected PMV value, thermostat set point temperature are adjusted.
- **Scenario 2:** The second scenario is used the model-free approach, which is developed by Purdon et al. [17]. In this method, only occupant feedbacks are used to adjust the set point temperature of indoor HVAC system to measure.
- **Scenario 3:** The last scenario is integrated the Temperature-comfort correlation (TCC) model to the case study offices. This model was developed by Lam et al. [19]. This approach calculated set point temperature based on occupants' individual thermal comfort requirements.

In this section, thermal comfort model and set point optimization methods are explained, and implementation details in case studyoffice are given in details.

## 6.1 Scenario 1

As mentioned above, one of the optimization methods, which is developed by Erickson and Cerpa and called Thermovote, adjusts the temperature based on PMV estimation and occupant feedback as shown in Figure 6.2 [12].

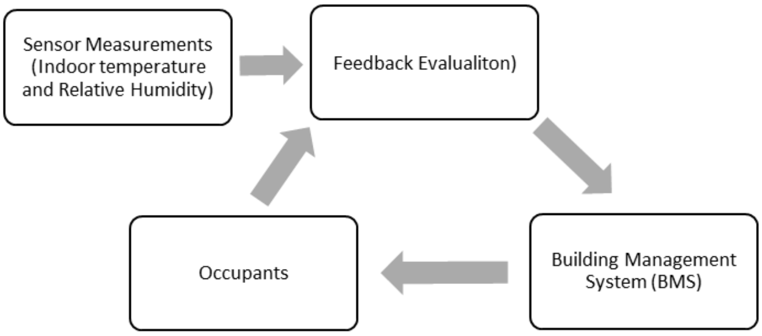


**Figure 6.2 :** The workflow of scenario 1.

PMV is an index to show thermal sensation of occupants and is calculated based on the thermal balance of human body. Physical quantities related to the indoor environment, air temperature, mean radiant temperature, air velocity, relative humidity, etc., and personal parameters, clothing insulation, metabolic rate, affects heat balance of body consist of the PMV model and is calculated by using equation (6.1).

$$PMV = \left[0{,}303.\exp(-0{,}036M) + 0{,}028\right].\left\{\begin{array}{l}(M-W) - 3{,}05.10^{-3}\left[5733 - 6{,}99(M-W) - p_a\right] - 0{,}42\left[(M-W) - 58{,}15\right] \\ -1{,}7.10^{-5}M(5867 - p_a) - 0{,}0014M(34 - T_a) \\ -3{,}96.10^{-8}.f_{cl}\left[(T_{cl}+273)^4 - (T_{mrt}+273)^4\right] - f_{cl}.h_{cl}.(T_{cl} - T_a)\end{array}\right\} \tag{6.1}$$

PMV model required measurement of different parameters dynamically, and it is hard to apply in practice. In order to become suitable to implement dynamic environment, the model should be simple with regard to operation and economy. For this purpose, only humidity and temperature data, which can be collected from many of existing BMS system, are used. Other parameters; clothing insulation, metabolic rate, mean radiant temperature, air velocity; are assumed as a fixed value for different seasons of year. Table 6.1 gives this fixed value for winter and summer periods. These values are selected based on recommended tables for offices in ISO 7730.

**Table 6.1 :** Assumptions for thermal comfort parameters.

| Parameters | Summer | Winter |
|---|---|---|
| Metabolism | 58 | 58 |
| Clothing | 0,5 | 1,0 |
| Air velocity | 0,19 | 0,16 |
| MRT | Equal to air temperature | Equal to air temperature |

Summer period represents the months April to September and winter is the rest of the year. The optimum set point temperature at a specific time can be determined by using PMV formula with using given parameters in abbove table and measured temperature and humidity data. The fixed parameters, which are assumed as fixed value, decrease the model accuracy. In order to minimize error, occupant feedbacks (AMV) are used to correct PMV estimation.

In this model, the occupant can provide feedback about their thermal sensation in ASHRAE seven-point scale, hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (-1), cool (-2) and cold (3), on a website. With this metholody, occuapnt feedbacks can turn into numerical values. Rooms with multiple occupants, AMV is calculated based on the average of the feedbacks.

$$\mathrm{P\widehat{M}V}(\mathrm{M}, \mathrm{RH}, \mathrm{T_{mrt}}, \mathrm{T_{air}} + \mathrm{T_{offset}}, \mathrm{I_{clo}}, \mathrm{v}) = \mathrm{AMV} \tag{6.2}$$

By using equation (6.2), $T_{offset}$ is calculated to correct initial PMV estimate to match AMV. The set point adjusts based on this temperature offset value.

This process is performed only difference between set-point and air temperature is greater than the threshold. The threshold is determined by HVAC system response speed. For selected office, the threshold is defined as 1°C.

During the baseline period, indoor air temperature and humidity is measured to calculated estimated initial PMV value and also, occupant feedback is collected. Figure 6.3 gives occupants feedback (AMV) and estimated PMV values during the baseline period. Based on this PMV and AMV values, offset temperature is calculated.

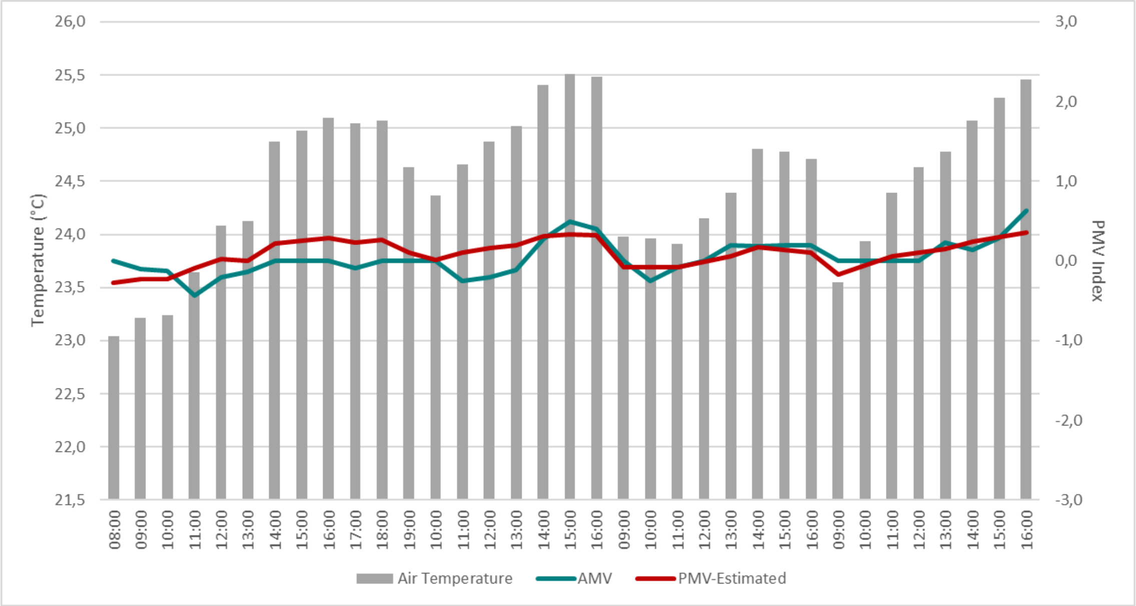


**Figure 6.3 :** PMV vs. AMV.

In Figure 6.4, green bars represents the adjusted set point temperatures based on scenario 1; red line is the baseline thermostat temperature, and the gray bars indicates the measured indoor temperature and the green bars represent optimized temperature values for each hour.

**Figure 6.4 :** Corrected set point temperature for the first scenario.

## 6.2 Scenario 2

In second scenarios, model-free approach, which is developed by Purdon et al. is adapted to this study [17]. In this method, occupant feedback is directly used to adjust set point temperature as shown in Figure 6.5.

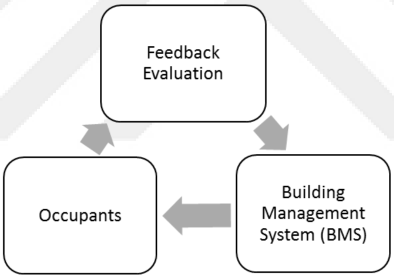


**Figure 6.5 :** The system architecture of scenario 2.

Occupant vote collected based on three scales; hot (+1), neutral (0) and cold (-1). Occupant feedback and indoor measured temperatures are given in Figure 6.6 for baseline period.

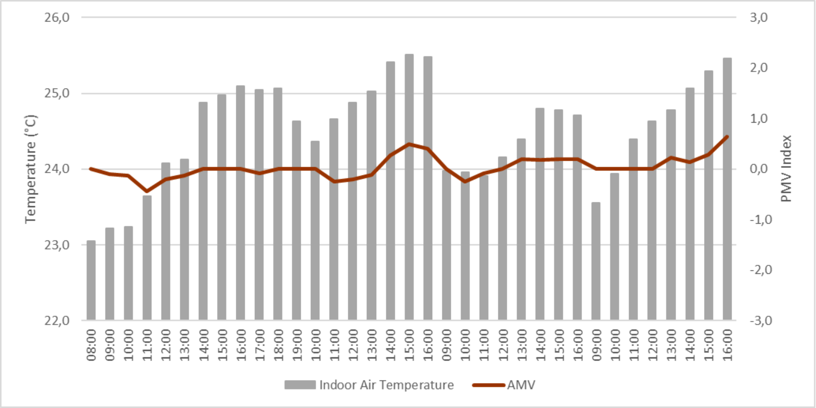


**Figure 6.6 :** Occupant feedback and indoor air temperature.

This method determines the overall comfort of a group of users by summing votes. To decrease discomfort level, thermostat set point temperature changes by a fixed value at every turn. This step size is determined based on HVAC system reaction time. For this study, the step size is determined as 1°C. According to this method, new set point schedule was created as given in Figure 6.7. In this figure, green bars represent the optimized set point temperature.

**Figure 6.7 :** Corrected set point temperature for the second scenario.

## 6.3 Scenario 3

Lam et al. develop Temperature-comfort correlation (TCC) model based on thermal balance model and adaptive comfort model [19]. Thermal comfort model is a function of indoor, outdoor temperature and the elapsed time a person stays in the space.

$$C(T_i, T_o, t) = G(t) + L(T_i, T_o) \tag{6.3}$$

C(Ti,To,t) indicates level of thermal comfort of an occupant, given indoor and outdoor temperatures at a specified time and it is calculated based on heat generation (G(t)) and losses (L(Ti, To)) of human body as given in equation (6.3) [19].

In order to find an optimum set point for the majority of occupants, occupant feedbacks are used to adjust estimated set point value, which is calculated based on TCC model. Figure 6.8 gives the workflow of this process [19].

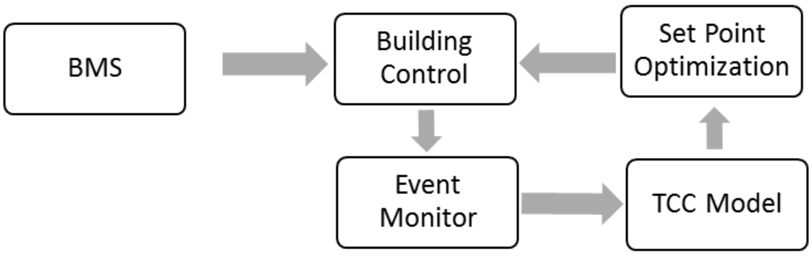


**Figure 6.8 :** The workflow of set point optimization model of scenario 3.

### 6.3.1 Heat generation model

Human body tries to maintain energy balance between two actions; production and expenditure and the amount of heat generation depend on this balance. In order to determine average dietary energy intake to maintain energy balance in a healthy human, Institute of Medicine (IOM) conducted a study. In this study, estimated energy requirement (EER) is used to define average daily energy intake. Equation (6.4) gives calculation method of daily EER using age, gender, height, weight and level of physical activity data.

$$EER=A-(B\times age)+PA\times(D\times weight+E\times height) \tag{6.4}$$

This equation and coefficients, which are A is the constant term; B is the age coefficient; PA is the physical activity coefficient, which depends on physical activity level (PAL) categories (sedentary, low active, active, very active); D and E are coefficient for weight and height respectively. This equation was developed by stepwise multiple linear regression analysis. The correlations between EER and other independent variables were established with using experiment data which is generated from the test subject.

In order to determined energy expenditure level for humans, doubly labeled water technique is used. The result of DLW (Doubly labeled water) was used to establish database and prediction formula for the people who are 19 years old and older and in different BMI (body mass index) class. Equation (6.5) and (6.6) is represented EER for man and women which are 19 years and older and normal weight (BMI from 18.5 up to 25 kg/m$^2$), respectively [44].

$$EER=662-(9.53\times age)+PA\times(15.91\times weight+539.6\times height) \tag{6.5}$$

$$\text{EER}=354-(6.91\times\text{age})+\text{PA}\times(9.36\times\text{weight}+726\times\text{height}) \quad (6.6)$$

Equation (6.7) and (6.8) is generated for overweight/obese men and women (BMI ≥25 kg/m$^2$) respectively.

$$\text{EER}=1086-(10.1\times\text{age})+\text{PA}\times(13.7\times\text{weight}+416\times\text{height}) \quad (6.7)$$

$$\text{EER}=448-(7.95\times\text{age})+\text{PA}\times(11.4\times\text{weight}+619\times\text{height}) \quad (6.8)$$

Physical activity coefficient is equal to 1 for sedentary activity and both gender. If the activity type is active, this coefficient is equal to 1,25 for men and 1,27 for women [44].

Metabolic rate changes smoothly after physical activity changes. For this reason, the elapsed time a person stay in place should be considered. To obtain the corresponding EER at time t, EER can be calculated from equation (6.9).

$$\text{EER(t)} = \begin{cases} \dfrac{(\text{EER}_\text{s}\text{-EER}_\text{e})}{\text{t}_\text{c}}(\text{t}_\text{c}\text{-t}) + \text{EER}_\text{e} & \text{t} < \text{t}_\text{c} \\ \text{EER}_\text{e} & \text{t} \geq \text{t}_\text{c} \end{cases} \quad (6.9)$$

In this equation, $\text{EER}_s$ and $\text{EER}_e$ are EER of a person at active and sedentary stage respectively. $t_c$ is the time to recover from active to sedentary.

To describe heat production, equation (6.10) is used.

$$\text{G(t)}=\text{a}_1\text{x EER(t)}+\text{b}_1 \quad (6.10)$$

a1 is the coefficient for activity sensitivity and b1 is coefficient for comfort preference. These parameters are derivate based on personal recovery time data. In this study, coefficient [a1, b1, t1] is selected according to the body mass index of the occupant. Profiles from occupant in overweight (OW), normal weitgh (NL) and underweight (UW) category are [-0,0027, -4,99, 30], [0,0041, -7,08, 40] are [0,002, -2,5325, 25] respectively [19].

### 6.3.2 Heat Loss Model

The comfort temperature is calculated by using equation (6.11) based on adaptive methods as a function of outdoor temperature.

$$T_c(T_o) = 17{,}8 + 0{,}31T_o \tag{6.11}$$

The temperature difference between the measured temperature of indoor air ($T_i$) and comfort temperature ($T_c$), which is determined based on above equation, is used to predict heat losses by using following equation.

$$L(T_i,T_o)=\begin{cases} 3 & T_i\text{-}T_c(T_o)\geq R \\ k\big(T_i\text{-}T_c(T_o)\big) & \text{-}R<T_i\text{-}T_c(T_o)<R \\ \text{-}3 & T_i\text{-}T_c(T_o)\leq R \end{cases} \tag{6.12}$$

ASHRAE 55 defines comfort range 7°C (PMV range is -1 to +1), in another word, indoor air temperature should remain between limit values, -3,5°C and +3,5°C. Since heat loss is a linear function of indoor air temperature, k can be calculated as 3,5 and R is equal to 3k, which is boundaries for the comfort zone of a person [19].

### 6.3.3 The set point optimization algorithm

The aim of the set point optimization algorithm is to find the optimum set point temperature for the majority of the occupant. The first step of the algorithm is identification the comfort temperature for each occupant. Then, the candidate set point temperature is selected and apply to the BMS in order to meet the comfort condition. If the person who stay in the zone, does not satisfied with this set point temperature, give a feedback in ASHRAE seven-point scale by using smart-phone application and the optimized set point temperature iteratively for all occupants until the majority of occupant satisfy the thermal comfort. Iteration is applied when occupant give feedback in ASHRAE [19].

In this study, for each of occupant optimum set point temperature are determined by using TCC model and optimal temperature is determined by using occupant feedback. In Figure 6.9, adjusted hourly corrected set point temperatures (green bars) are given for the third scenario.

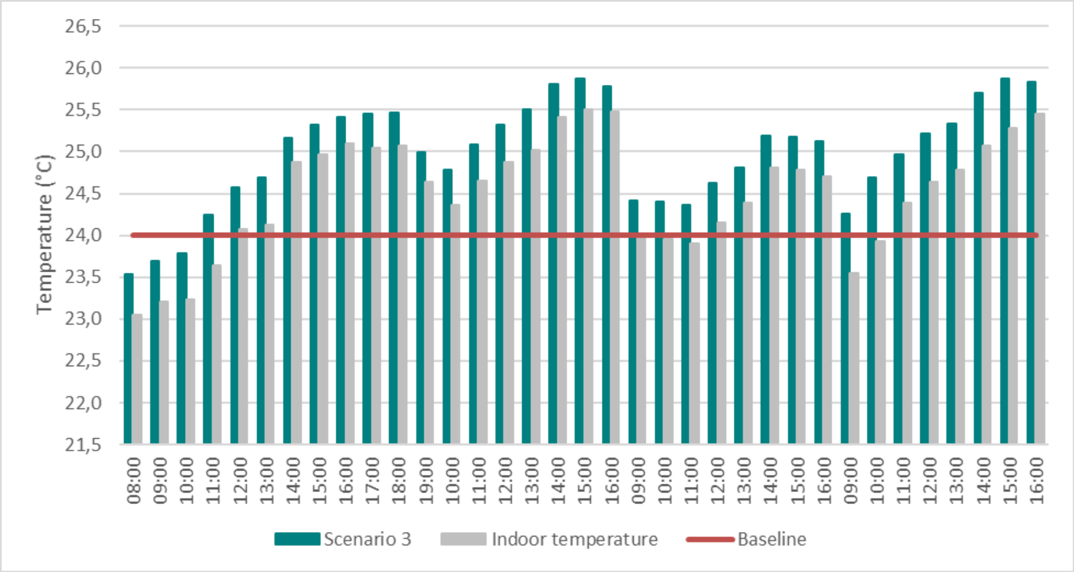


**Figure 6.9 :** Corrected set point temperature schedule for the third scenario.

# 7. RESULT AND CONCLUSION

According to the Environmental Protection Agency (EPA), people spend 90% of their time indoors. Consequently, a significant number of study is performed in order to determine the effect of thermal environment on occupant health and productivity [57].

The findings of these studies show that thermal environment has a significant impact on occupant thermal sensation and well-being. With the development of HVAC and building management systems, total control of the indoor environment becomes possible, and comfort bears a higher level of importance in order to maintain healthy indoor conditions.

In single occupant offices, a thermally comfortable environment can be created simply based on occupant requirement. However, it 's hard to find an optimal thermostat setting temperature for multiple occupants sharing the same office. In order to determine optimal temperature for the majority of the occupant, time-varying indoor environmental parameters, which varies depends on changing occupant density, equipment, and lighting system operation, solar radiation should be taken into consideration. On the other hand, in many buildins, control system does not design to inclued dynamic control strategies. As a result of issues, most of the occupants have to stay at uncomfortable environments during the day because of the lack of proper control to fulfill comfort requirement in buildings. Standard thermal comfort assessment method required various data e.g. air temperature, relative humidity, air speed, mean radiant temperature, clothing properties of occupants and their activity level. Based on these methods, HVAC system can be controlled, but it is hard to apply in existing systems mainly because of the absence of adequate measurement equipment. Even with the proper equipment, it would be nearly impossible to meet absolute satisfaction because of the subjectivity of the matter.

The main objective of this study is evaluating methods to create optimum indoor conditions for occupants in order to maximize thermal comfort and productivity by using dynamic thermostat control. For this purpose, thermal comfort assessment and control methods were reviewed, and three different thermal comfort optimization methods are selected to evaluate by building simulation tool in terms of thermal comfort, and energy consumption in a selected office. Besides thermal comfort and energy consumption analysis, effects of these methods on productivity were examined based on the thermal comfort conditions.

The effectiveness of these methods were evaluated for an open-plan office. Within this framework, field measurements are conducted in the selected office to determine baseline conditions. Apart from the measurement process, a simulation model of this building was generated by using Design Builder and EnergyPlus software to evaluate thermal comfort conditions and energy consumption of HVAC system. In order to perform the effects of different optimization methods, this model was calibrated with using measuremed temperature and humidity data.

This chapter summarizes the study and gives the findings of physical monitoring and field studies and simulation results. The results of these studies were examined four different aspects; field studies, thermal comfort, productivity, and energy consumption.

## 7.1 The Results of Physical Monitoring and Field Studies

An occupant satisfaction with thermal comfort conditions was evaluated by survey technique and mathematical models. For eight paticipants, the survey was conducted. The findings of questionnaires show that the 50% of the personal feel discomfort through the year. The International Facility Management Association (IFMA) conducted a survey in order to determine occupant complaints about indoor thermal conditions. The survey findings indicate that the main complaint is too hot or too cold air temperature comes from HVAC system through the year [52]. Similar to this study, the results of the survey, which was conducted in the thesis context, show that the most important reason of discomfort is the high or low air temperature in the office.

Two different monitoring period is created. The first period, HVAC system did not operate and temperature, humidity variation was observed. For the second, the building is operated at fixed temperature set point (24°C) and heating mode. In this period, besides the questionnaires, the field measurements were conducted, and occupant feedbacks about their thermal sensation were collected via the website application in order to assess the comfort conditions.

Baseline period covers four days, 21st, 22nd, 27th and 29th April. During this period, 83 occupant feedbacks were collected from 8 participants. Figure 7.1 depicts raw data of occupant votes.

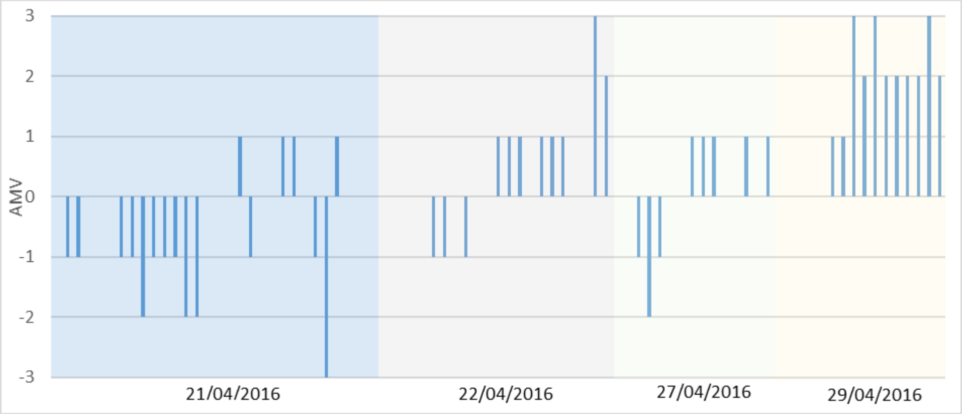


**Figure 7.1:** Occupant thermal sensation feedback (AMV) during the baseline period.

If the votes are examined, it can be seen that 57% of the occupants feel discomfort during the baseline period, similar with the survey results.

This study was carried out in April and because of the time of year, heating and cooling requirement can occur during the day. As t can be seen above figure, occupants feel cool or cold in the morning periods. However, hot and warm votes increased after midday.

In Figure 7.2 gives the comparison of occupant thermal sensation feedback (AMV) and simulation results for the same period. AMV is calculated as the average of the votes for hourly periods.

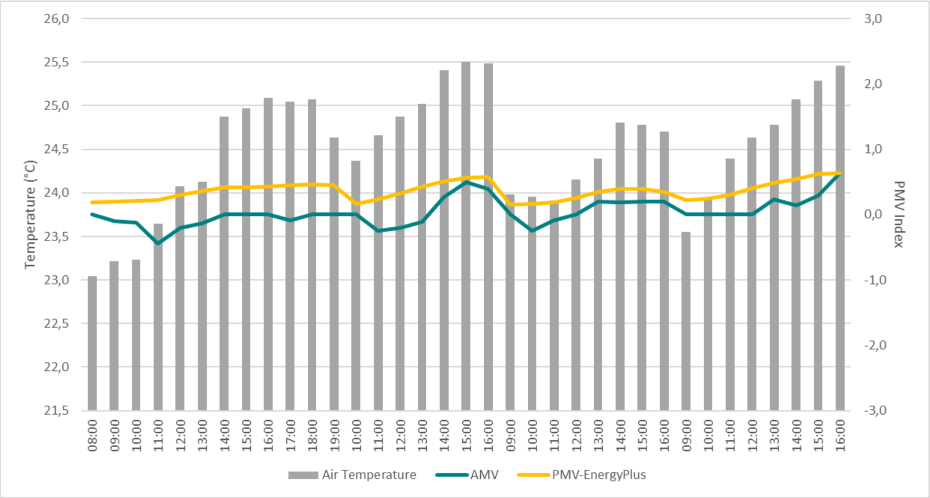


**Figure 7.2**: The comparison of simulation results and occupant feedback.

It can be seen from the Figure 7.3, a thermal sensation of occupants is a subjective matter and cannot be predicted with 100% accuracy. Especially in practice, most of the parameters that affect the thermal comfort, cannot be measured dynamically, and it causes low prediction accuracy for the model. In order to eliminate this accuracy problem, the occupant participating approach is developed, and their feedbacks are integrated to the model in order to improve the estimation.

## 7.2 The Results of Thermal Comfort Optimization Studies

In order to optimize the thermal comfort, three different dynamic set point control is applied based on occupant feedback and field measurements for three scenarios as described in Section 6. The result of the studies show that indoor conditions can be improved based on the user's requirements by using selected methods.

Figure 7.3 depicts the calculated hourly optimized set point temperature based on three different optimization methods. The effect of these dynamic thermostat schedules on thermal comfort was evaluated via building simulation tools and compared with baseline, which was operated with constant thermostat schedule as can be seen in figure 7.3.

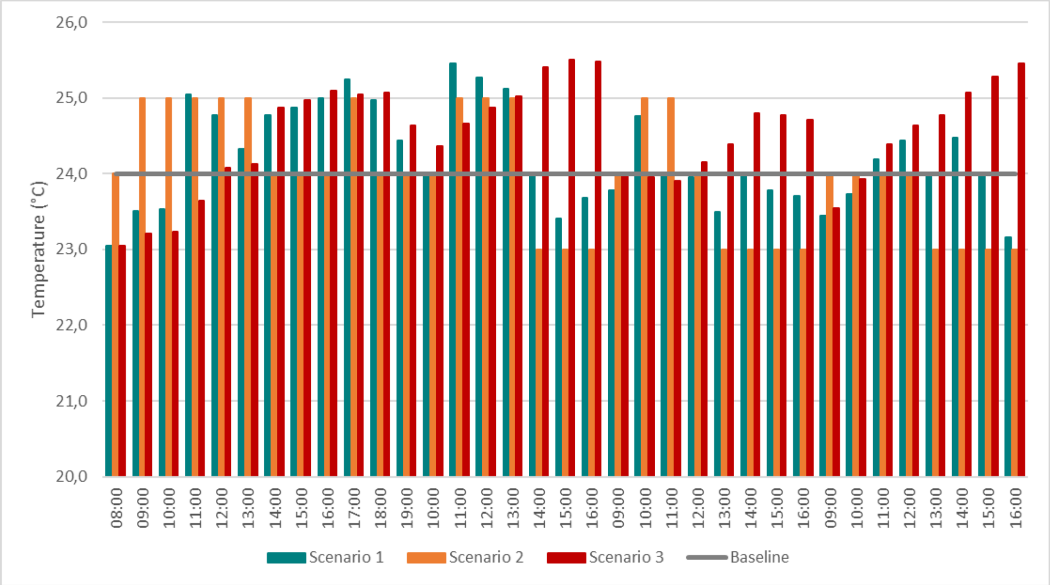


**Figure 7.3 :** Corrected hourly set point temperatures for each scenario.

Figure 7.4 gives the comparison of hourly PMV values and Figure 7.5 shows the daily PMV values for each scenario. The PMV values are calculated based on optimized set point temperature which is given in Figure 7.3.

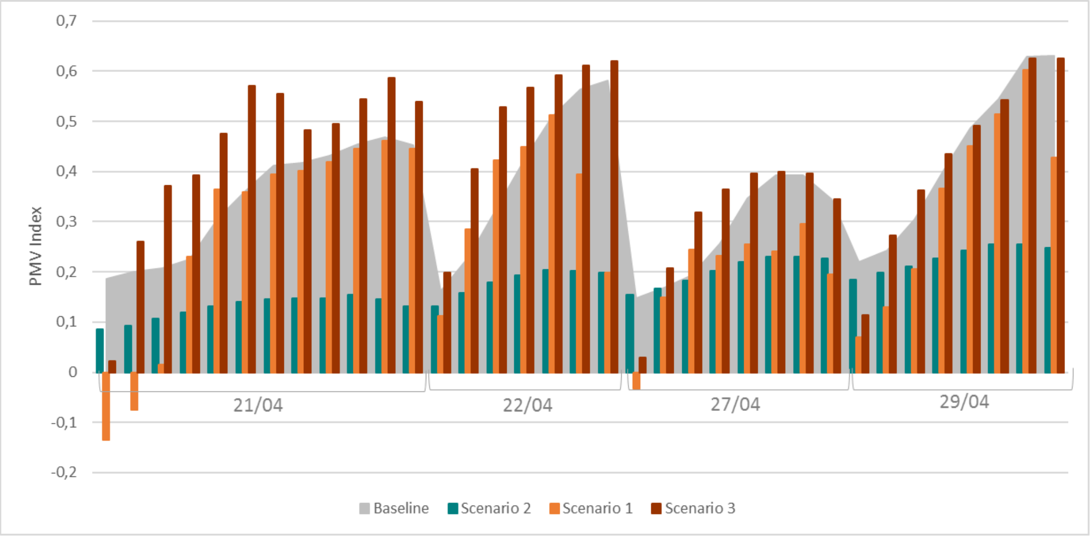


**Figure 7.4 :** Comparison of hourly PMV indices for scenarios and baseline.

According to ASHRAE 55 and ISO 7730, in order to create an adequate indoor environment for the occupant, PMV should remain between -0,5 and +0,5. As can be seen in Figure , baseline condition generally meet the thermal comfort criteria. However, baseline model's PMV exceed the threshold values.

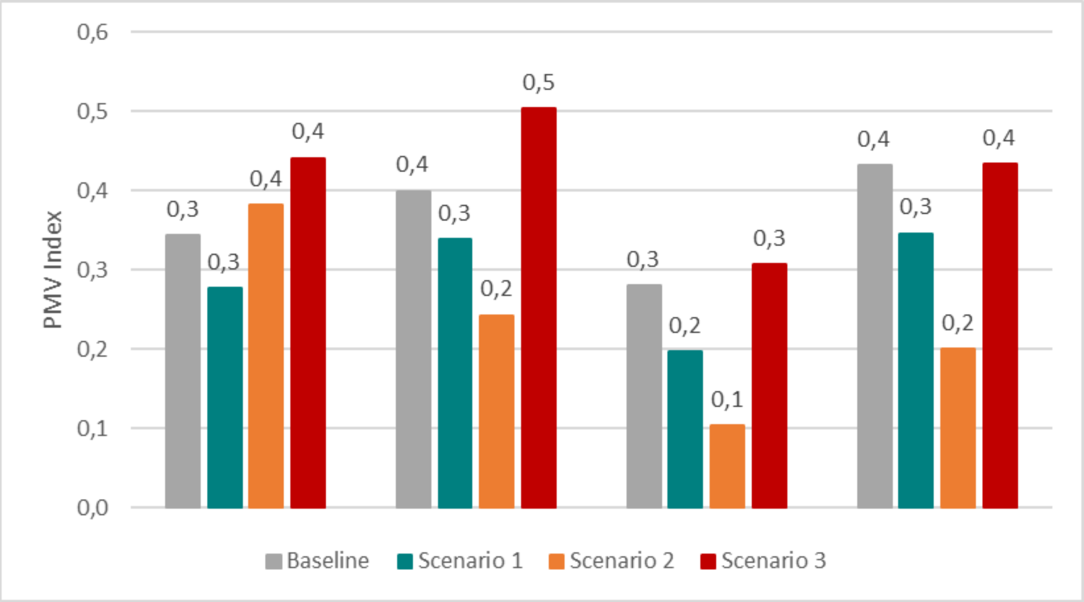


**Figure 7.5 :** Daily PMV values for the occupied period based on different scenario analysis.

The daily analysis results show that the Scenario 2 and 3 are more proper and effective in order to improve indoor thermal comfort in the selected office. On the other hand, scenario three cannot improve thermal conditions of the space.

## 7.3 Effect of Scenarios on Productivity

A large number of studies are carried out to examine the relationship between indoor thermal conditions and productivity. In one of this studies, Kosonen and Tan establish curve fitting equation to predict thermal comfort of the occupant based on the field studies. With this equation, productivity losses can be calculated as a function of PMV.

In this study, in addition to the thermal comfort, the effects of dynamic temperature control on the productivity was examined.

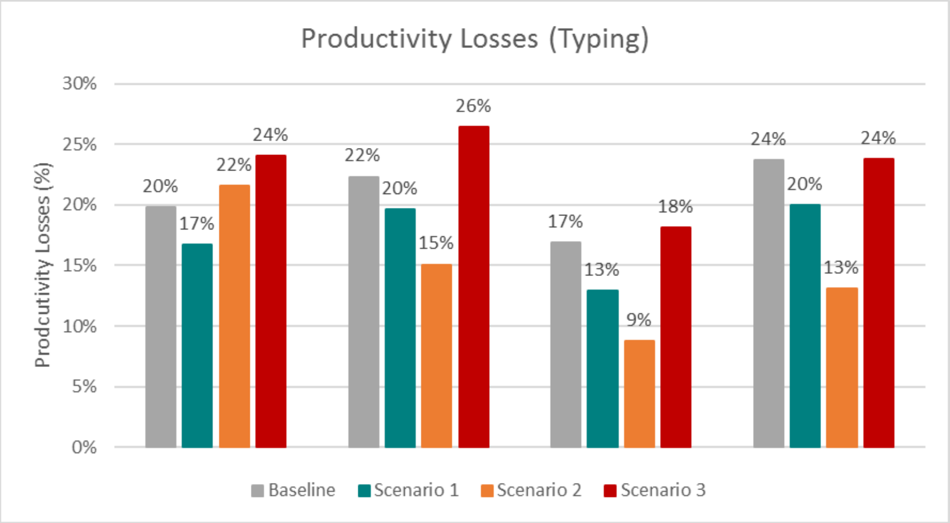


**Figure 7.6 :** Thinking process productivity losses for various scenarios.

Figure 7.6 and Figure 7.7 gives the typing and thinking productivity losses for each scenario respectively based on PMV values which is given in Figure 7.5.

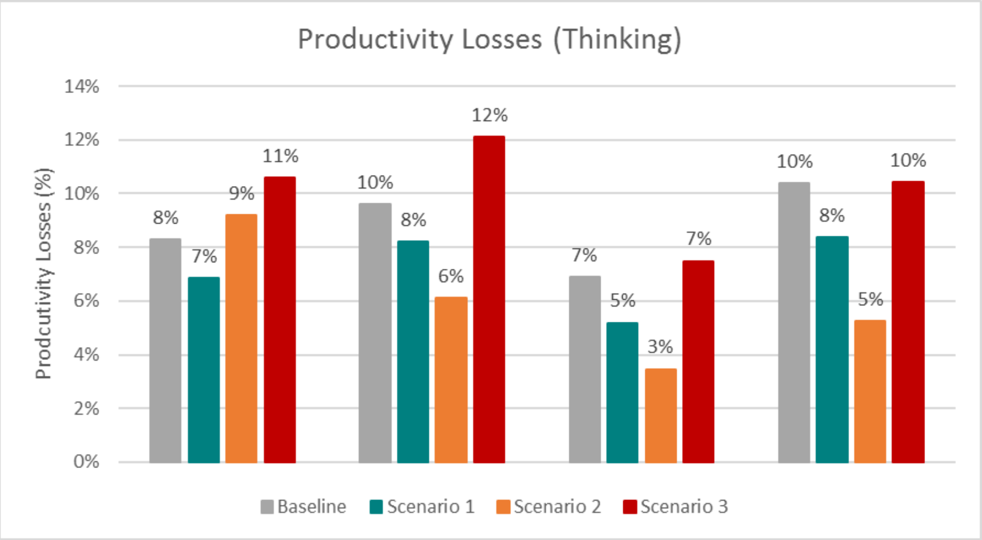


**Figure 7.7:** Thinking process productivity losses for different scenarios.

According to the findings from the building simulation, it can be said that scenario 1 and 2 performed significant improvement in productivity similar to thermal comfort results. On the other hand, scenario three cannot improve thermal comfort level and consequently, productivity losses increase or remain same.

## 7.4 Effect of Scenarios on Energy Consumption

Using building simulation model, this study has shown that improving the thermal condition in buildings is possible by using dynamic control techniques based on real time requirement od space and occupant. Besides the results regarding thermal comfort, the simulation results provide the effect of the selected scenarios on energy consumption of HVAC system.

The findings of this study indicate the trade-off between energy consumption and thermal comfort of occupants. In baseline period, HVAC system operates in heating mode. However, the occupant feedback shows that system could not achieve thermal comfort conditions in afternoon and evening period because of the high temperature. Because of the spring season, heating and cooling requirements can occur during the day as mentioned before. Operation mode and the set temperature of HVAC system is adjusted based on real-time occupant feedback and the HVAC system operates in cooling mode after the midday in optimization scenarios.

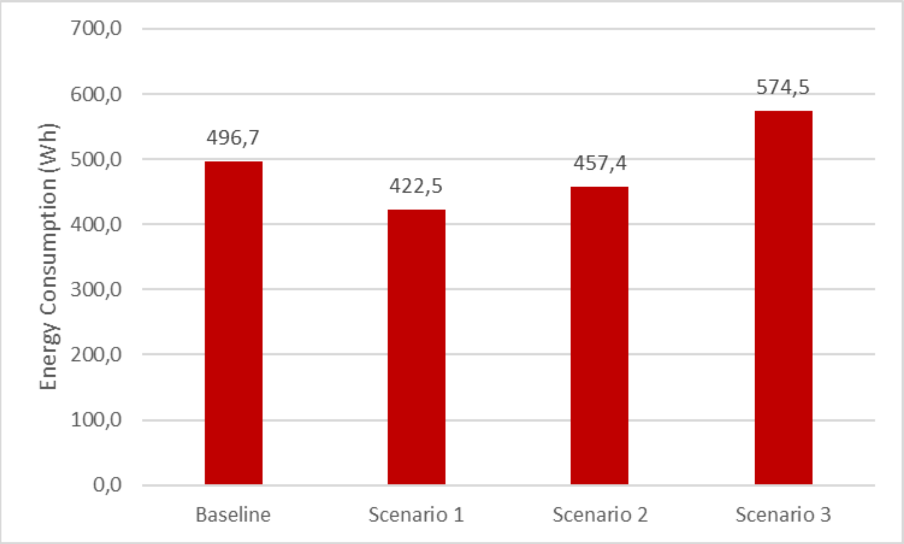


**Figure 7.8 :** Heating energy consumption of VRF systems for different scenarios.

As it can be seen in Figure 7.8, in scenario 1, required operation time decreased to heat the space when compare with baseline and consequently, heating energy consumption decreases by 15%. Similarly, scenario 2 consume 8% less energy. On the other hand, scenario 3 consume more energy to meet set point requirement.

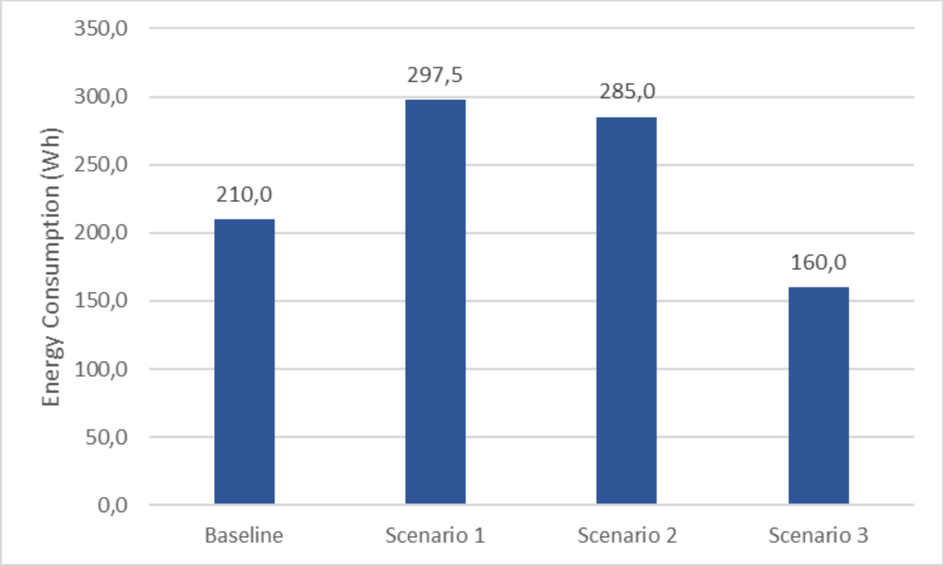


**Figure 7.9 :** Cooling energy consumption of VRF systems for different scenarios.

Figure 7.9 gives the comparison of cooling energy consumption for baseline and thermal comfort optimization scenario. According to the occupant feedback, cooling requirement was apperad and it increawsed the energy consumpiton.

Because of the operational conditions of baseline period, all scenario consumes more energy than the baseline period. In Figure 7.10 is depicted total energy consumption of HVAC system for baseline and three scenarios.

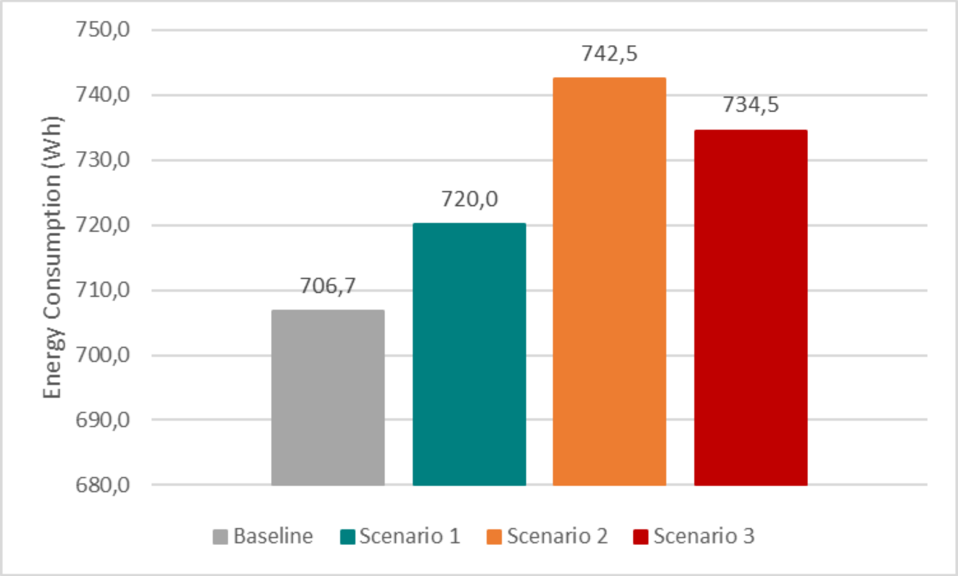


**Figure 7.10 :** Total energy consumption of HVAC system for each scenario.

### 7.5 Discussion

During the day, outdoor air temperature, solar radiation value, occupancy density and equipment operation can cause fluctuation in indoor air temperature and consequently, a thermal sensation of occupant changes in time. The aim of this study is creating dynamic thermostat control based on variable indoor parameters to maximize indoor comfort. Besides real-time monitoring of environmental parameters, occupants' feedbacks about their thermal sensation also taken into account to determine optimum thermostat value for the majority of occupants because of the subjectivity of the matter, optimum thermal comfort conditions vary from person to person.

In order to optimize thermal comfort, three different optimization models were evaluated in terms of thermal comfort, productivity and energy consumptio. The findings of the evaluation of thermal comfort optimization methods are summarized as follow;

- Scenario 1 uses Fanger's thermal comfort model and estimates PMV via temperature and humidity sensors output. Fanger's heat balance approach required to monitor and record the six physical and personal parameter, which are indoor air temperature, relative humidity, air speed, mean radiant temperature, activity type and level of the occupant, and occupant clothing's thermal insulation values, in order to predict PMV value. However, it is difficult to measure these parameters with using existing BMS system in building. To overcome this issue, this method only takes account of air temperature and humidity sensor measurements data to estimate PMV and other parameters which cannot be measured dynamically, chose as a fixed value. Due to this simplifying approach, prediction accuracy decrease. In order to overcome this issue, occupants are used as a sensor to correct this prediction with their real-time thermal sensation feedbacks. The results of the simulation model indicate that the model can improve thermal comfort of the occupant and decrease the performance losses for typing and thinking process. On the other hand, this optimization approach consumes 2% more energy than constant temperature operation. On the other hand, this increment is negligible when compare other scenarios as mentioned above.

- Scenario 2 is a sensor-free approach and relies on only occupant feedback to adjust set point temperature. The temperature changes iteratively in accordance with real-time occupant thermal sensation votes. The advantage of this method is reduction of model complexity and decrement potential errors of standard methods for dynamic thermal comfort assessment. As examined in above section, the model has a potential to improve thermal comfort and productivity of occupant when compared with constant temperature operation. On the other hand, when energy consumption of scenario 2 and baseline is examined, it can be seen that the energy consumption of HVAC system increase by 5%.
- The final thermal comfort optimization method also relies on occupant participating technique in order to adjust the temperature to create an optimal indoor environment for the occupant. Different from the other studies, thermal comfort assessment model is developed based on PMV and adaptive model. The simulation results show that this model cannot improve the thermal comfort and energy consumption of HVAC system in the spring period. This model examined in summer conditioned, and results show the increment of thermal comfort of occupant and energy performance of HVAC system by the developer.

In order to analysis performance of these optimization methods in detail, experiments should be conducted for different seasons of the year and in the extended period.

According to the studies, occupants stay uncomfortable environment during the day, and it causes a decrement in performance and well-being of a person. The findings of the different research indicate that the indoor environmental condition has also indirect effects on the economy. Due to the poor thermal conditions SBS syndrome can occur and it causes productivity loss is equal to 2%, and annual costs of this decrements are $60 billion.

As a consequence, dynamic control is should be adapted in shared space in order to maintain comfortable and healthy conditions of the majority of occupant and occupant’s feedback take account to improve prediction of the optimization model. For the further studies, energy efficiency issue should take into account and the performance of optimization model, which establish to decrease energy consumption of HVAC system while maintaining thermal comfort, can be examined.

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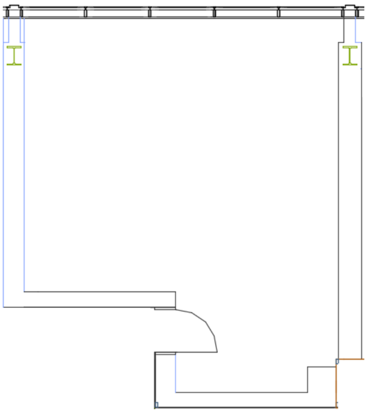
## APPENDICES

### **APPENDIX A:** Thermal comfort survey

# APPENDIX A

## Thermal Environment Satisfaction Survey

Either a plance an “X” in the appropriate place where you spend most of your time.



Are you near an exterior wall (within 5m)?

- ☐ Yes
- ☐ No

Are you near a window (within 5m)?

- ☐ Yes
- ☐ No

Using the list below, please check each item of clothing that yoy are wearing right now. (Check all that apply):

- ☐ Short-Sleeve Shirt
- ☐ Long-Sleeve Shirt
- ☐ T-shirt
- ☐ Short-Sleeve Sweatshirt
- ☐ Sweater
- ☐ Vest
- ☐ Jacket
- ☐ Knee-Length Skirt
- ☐ Ankle-Length Skirt
- ☐ Dress
- ☐ Short
- ☐ Athletic sweatpants
- ☐ Trousers
- ☐ Undershirt
- ☐ Long Underwear Bottoms
- ☐ Long Sleeve Coveralls
- ☐ Overalls
- ☐ Slip
- ☐ Nylons
- ☐ Socks
- ☐ Boots
- ☐ Shoes
- ☐ Sandals
- ☐ Other: (Please note if you are wearing something not described above, or if you think something you are wearing especially heavy.)

____________________________________________________

____________________________________________________

What is your activity lecel right? (Check the one that is most appropriate)

- ☐ Reclining
- ☐ Seated
- ☐ Standing relaxed
- ☐ Light activity standing
- ☐ Medium activity standing
- ☐ High activity

Which of the following do you personally adjust or control in your space? (Check all that apply.)

- ☐ Window blinds or shades
- ☐ Room air-conditioning unit
- ☐ Portable heater
- ☐ Permanent heater
- ☐ Door to interior space
- ☐ Door to exterior space
- ☐ Adjustable air vent in wall or ceiling
- ☐ Ceiling fan
- ☐ Adjustable floor air vent (diffuser)
- ☐ Portable fan
- ☐ Thermostat
- ☐ Operable window
- ☐ None of these
- ☐ Other:______________________________________________

How satisfied are you with the temperature in your space? (Check the one that is most approprriate)

- ☐ Hot
- ☐ Warm
- ☐ Slightly warm
- ☐ Neutral
- ☐ Slightly cool
- ☐ Cool
- ☐ Cold

If you are dissatisfied with the temperature in your space, which of the following contribute to your dissatisfaction:
In a warm/hot weather, the temperature in my space is (check the most appropriate box):

- ☐ Always too hot
- ☐ Often too hot
- ☐ Occasionally too hot
- ☐ Occasionally too cold
- ☐ Often too cold
- ☐ Always too cold

In cool/cold weather, the temperature in my space is (check the most appropriate box):

- ☐ Always too hot
- ☐ Often too hot
- ☐ Occasionally too hot
- ☐ Occasionally too cold
- ☐ Often too cold
- ☐ Always too cold

When is this most often a problem? (check all that apply):

☐ Morning (before 11am)
☐ Midday (11am-2pm)
☐ Afternoon (2pm-5pm)
☐ Evening (after 5pm)
☐ Weekends/holidays
☐ Monday mornings
☐ No particular time
☐ Always
☐ Other:________________________________________________

How would you best describe the source of this discomfort? (Check all that apply):

☐ Humidity too high (damp)
☐ Humidity too low (dry)
☐ Air movement too high
☐ Air movement too low
☐ Incoming sun
☐ Heat from office equipment
☐ Drafts from windows
☐ Draft from vents
☐ My area is hotter/colder that other areas
☐ Thermostat is inaccessible
☐ Thermostat is adjusted by other people
☐ Clothing policy is not flexible
☐ Heating cooling system does not respond quickly enough to the thermostat
☐ Hot/cold surronding surfaces (floor, ceiling, walls, or windows)
☐ Deficient window (not operable)

Please describe any other issues related to being too hot or too cold in your space:

____________________________________________________________

# CURRICULUM VITAE

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