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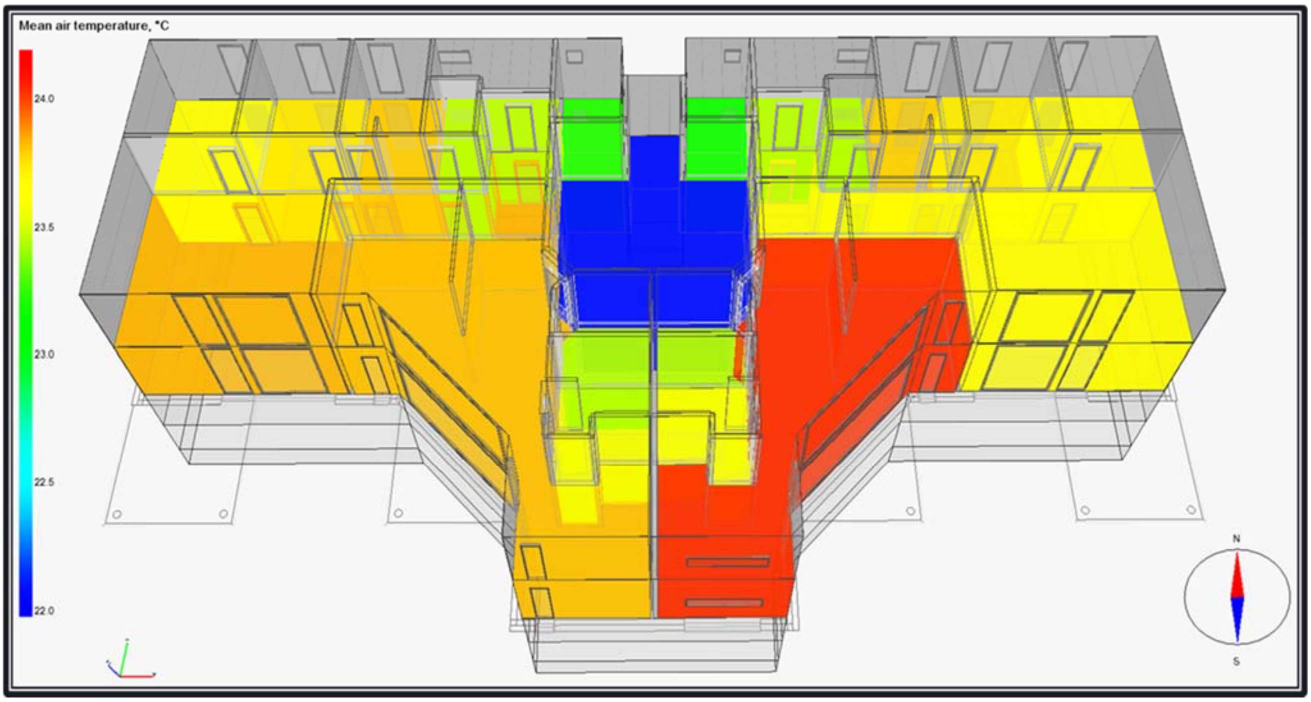

Thermal Comfort and Energy Consumption Of a Typical Office Building

A parametric study using IDA ICE

Master's thesis in the programme of "Design and Construction Project Management"

GÖKHAN GÜNGÖR

Department Of Civil and Environmental Engineering
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Gothenburg, Sweden 2015

MASTER’S THESIS 2015:09

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Department Of Civil and Environmental Engineering
Division Of Building Services Engineering
Chalmers University Of Technology
SE - 412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 1000

Cover:
Screen cap from IDA ICE (Indoor Climate and Energy) building simulation software, illustrating indoor temperatures of the zones during a simulation day

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ABSTRACT

According to Hoppe's study (1998) most of the people living in urban areas are spending more than 90% of their time in air conditioned indoor spaces. Same study also suggests that estimated costs of unideal thermal environment are higher than the energy cost which would be spent to improve the conditions to the ideal standards. The traditional cost calculation methods usually take the energy demand of heating and cooling systems of the building into account; however the potential health and productivity benefits are often disregarded.

Thermal comfort has been studies in several ways. Theoretical studies were mostly based on energy equations which are built in between human and environment and required very extensive mathematical work. Practical studies on the other hand were done by experimenting humans under various thermal environments, which were time consuming and could be misleading because of the personal opinions of people regarding to comfort. Compared those two methods, measuring thermal comfort by using simulation software gave the benefit of both by being able to simulate many conditions at once and carrying out the huge mathematical work by the aid of computers. Increased reliability in the measurement incentivized several standardization organizations around the world and standards are created.

In this report, how much of an impact do the selected parameters make on the thermal comfort and annual energy demand have been investigated by making experiments using a simulation software called IDA ICE (Indoor Climate and Energy) on an artificial building designed for a typical office use. In other words, the report aims to investigate what consequences occur when the actual conditions in the building are varied from the ideal state. As a secondary purpose of the study the annual energy demand of the building under different settings is examined. By analyzing the building from two perspectives simultaneously, it is aimed to find out if there is an observable correlation between comfort and energy aspects of the simulation.

In order to observe the change in the thermal comfort, the case building is simulated under five different settings. The iterations started with an ideal case, where the heating and cooling units had unlimited capacity. It proceeded with replacing the ideal units with designed ones then progressed with applying different scheduling, changing occupant position inside the room and installment of external shadings as the final case. From the simulation results it is found that the building showed best comfort performance with ideal or large capacity heaters and coolers but it came with an overbearing energy cost. Taking specific measures to reduce energy consumption have proved to be successful although sacrificing from comfort slightly.

The comparative analysis indicates that there is a semi-situational relationship between two aspects. While thermal comfort is relatively easy to maintain, keeping energy consumption at acceptable levels is equally hard. If the goal is to achieve a better grade of building certification, it is a necessity to take improving measures for both aspects simultaneously.

Keywords:thermal comfort, annual energy demand, building certification, building simulation

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1 INTRODUCTION

1.1 Background

Most of the people living in the urban areas are spending more than 90% of their time in air conditioned indoor spaces (Hoppe, 1998). All indoor volumes which are frequently used are conditioned with various HVAC systems. Inadequate conditioning not only causes discomfort and disturbances, also significantly impacts the productivity. From an economic standpoint, some calculations show that the estimated cost of unideal indoor environment is higher than the energy cost which would be spent to improve the conditions to ideal standards. However, the potential health and productivity benefits are not yet taken into account by building professionals in the conventional calculation methods while designing the energy demand and cost of heating and cooling systems. Fanger emphasizes that in certain occasions the heating and cooling systems may not be sufficient to create a comfortable feeling, so the mindset behind managing the indoor climate should be considered as a whole (Fanger, 2001).

Thermal comfort could be considered as a subjective concept since it involves personal choices and preferences of people sharing the same environment. Naturally, there are multiple definitions for it in the literature. From the ASHRAE handbook such definitions can be found;

- The state of being content with the thermal environment
- Requirement of minimum effort for maintaining internal body temperature
- Conditions of being satisfied with the thermal environment

In order to investigate thermal comfort, various experimental, theoretical and simulation based studies have been made. Although experimental studies could reflect the actual conditions better given that they involve the personal preferences of the users, they are usually costly, time consuming and not easily applicable in varying conditions. Theoretical studies on the other hand, investigate the correlations and interrelations between human and environment by modeling the heat and mass transitions. Compared to those two methods, indoor climate simulation could be regarded as a relatively new method which gained popularity with the improvement of computer software technology. While it provides the benefits of complicated calculations which would be practically impossible to do manually, it also gives the option to apply the same principles from the smallest zones to mass building complexes. Although one could argue that the simulation results are significantly dependent on the person conducting the work and some other standard data such as climate files, wind profiles etc. many case comparisons with actual measurements showed in the past that with the correct application and interpretations, high precision results are very achievable. That has been said; it is safe to say there is still room for improvement in tools and technology so that potential economic outcomes of health and productivity can be integrated with energy cost calculations.

In order to serve as a guideline and ensure the thermal comfort in all buildings, different types of standards can be found. The standards could be regional such as LEED for USA and BREEAM for Europe, while it can also be domestic for countries likewise the Miljöbyggnad of Sweden. In this thesis work, a simulation is going to be made using the software IDA ICE (Indoor Climate and Energy) to illustrate the thermal comfort parameters (PMV and PDD) with regards to Miljöbyggnad standards. After obtaining the results for the case building in ideal conditions, the simulation will be re-run several times with changing the parameters which are thought to be most influential on the thermal comfort outcomes. By making correlations and sensitivity analysis, it is planned to document how thermal comfort and total energy demand of the building is affected under different circumstances.

1.2 Purpose

The purpose of this project is to illustrate how the outcome of thermal comfort changes under different circumstances and how sensitive is the thermal comfort in regards to the changes in different parameters. While designing the simulations for indoor areas, there are certain assumptions made such as the allowable operative temperature range, orientation of heating and cooling units, points of measurement and so on. In most of the cases, the calculated thermal comfort index is derived from ideal conditions where the chosen design values reflect the most desired situations. This report aims to investigate what consequences occur when the actual conditions are varied from the ideal ones and how significant is the impact on the dissatisfaction of the users. It is intended to make correlations between different scenarios so that a designer reading this report would know the after effects of different adjustments.

Another point which can be considered as a secondary aim in this project is investigating the change in the energy demand of the case building in the different scenarios. Although the requirements for good indoor climate and energy efficiency have believed to contradict each other traditionally, there are not enough quantitative data found to support this argument. By comparing the total energy demand of the building in ideal and unideal thermal comfort conditions, it will be possible to find out if there is any remarkable difference. In the end of the correlations it is expected to see if it is feasible to sacrifice from the comfort slightly to save from energy usage or is the energy saving just going to be in a marginal amount which wouldn't be enough to justify lessening the comfort.

1.3 Method

This project mainly consists of two parts, divided into several chapters. The two chapters after the intro strive for creating a theoretical framework by filtering through existing studies on the topic of thermal comfort and indoor climate. Main sources used here are the articles by several authors with acknowledging P. O. Fanger specifically for developing the mathematical model of PMV and PDD comfort indices. It is also worth to mention the book named "Achieving the Desired Indoor Climate" which is written by the contribution of thirteen authors, since it constitutes one of the pillars of the theoretical basis of this thesis.

For channeling the knowledge to practical applications, standards play a major role. As stated before, there are several organizations worldwide which develop and publish the standards. Although most standards show a lot of resemblance when their goal is to serve as a guideline for the same purpose, the nuances are not negligible. While Miljöbyggnad is going to be taken as reference for this specific project, couple of other standards is also going to be mentioned. The manuals on the webpages of the respective organizations are the main source of information; however since Miljöbyggnad only provides a Swedish guide, several reports in English are also used in the research for a better comprehension.

The empirical part of this study revolves around the software named IDA ICE (Indoor Climate and Energy) for simulating different scenarios for the same case building. The main purpose of the software is simulating different parameters for a building such as heating/cooling energy demand, zone temperatures, average PDD and many others for 365 days of a year and 24 hours of a day. It provides the opportunity to estimate the indoor conditions of any area of a given building for any desired time frame. Running a simulation requires the 3D modeling of the building, configuration and giving inputs. The detailed assessment of inputs and results will be presented in their respective chapters.

1.4 Limitations

This thesis specifically takes the in-built sample building design in IDA as a case study which results in certain estimates and assumptions in the simulation. The location and orientation is a unique characteristic for every building, thus the same results may not be observable in another case with the same building envelope and same inputs. Climate file and wind profile chosen in the simulation software represents the characteristics of a typical year for a given location so drastic differences in the climate conditions for a specific year may vary the actual heating or cooling energy demands. It is also important to note that the case building is designed for office use which brings certain limitations. First of all it makes the cooling an essential part of the HVAC system while residential buildings in the same area do not have the same requirement. Furthermore the level of physical activity, type of clothing, density of furniture, lighting and other related characteristics are taken into account under the given condition. The criteria for thermal comfort are reflected by PPD and PMV indices and Miljöbyggnad is chosen as the standard for indoor climate and energy demand regulations.

1.5 Research Questions

The two main questions investigated in this thesis project are as follows;

- What are the variables affecting the thermal comfort and how much of an impact do they make individually on the overall result?

- How the total energy demand is fluctuating between different degrees of thermal comfort and is there an observable correlation?

1.6 Abbreviations

AHU	"Air Handling Unit" – Heaters, coolers and air exchange units in a room.
BBR	"Boverkets Byggregler" – A publication regulating construction in Sweden.
BREEAM	"Building Research Establishment Environmental Assessment Methodology"
HVAC	"Heating Ventilating Air Conditioning"
IDA	Simulation software used in the project.
ISO	"International Organization for Standardization"
LEED	"Leadership in Energy and Environmental Design"
PMV	"Predicted Mean Vote" – Explained in chapter 2
PPD	"Predicted Percentage Dissatisfied" – Explained in chapter 2
U-value	Amount of heat passing through one square meter of material for each degree of temperature difference on the opposite sides. (W/m^2K)
WSP	An international consultancy company - Refers to WSP Gothenburg in the thesis

2 INDOOR CLIMATE

There are several parameters which directly or indirectly influences the physical well-being of people in indoor spaces. While thermal climate is one of these; noise, light, odor can be considered as others. With the combination of the mentioned parameters, a perception for an indoor environment is created. Although it is evident that some factors such as disturbing noise and odor, or health threatening materials should be completely minimized, some factors cannot be avoided but only adjusted. Thermal climate is one of those adjustable indoor properties alongside with humidity, air flow, and illuminance. The goal for the adjustable properties is always to optimize the conditions where people feel the most comfortable, in the boundaries of available budget and technology. Indoor temperature is obviously the most influential determinant of thermal comfort which is also the main focus of this study. In the following chapter, the concepts or indoor environment and thermal comfort will be explained. To represent the thermal comfort in numbers, comparable indices developed by Fanger will be discussed in detail to be used later in the empirical part of the study.

2.1 Indoor Environment Quality

A good indoor climate cannot occur by coincidence most of the time (Nilsson et al, 2003). It is a product of a systematic design, created by the configuration of different parameters in order to answer specific needs. While some of the requirements show resemblance; depending on the purpose, size, and profile of users, the perception of good indoor climate can significantly differ. Before discussing the best indoor climate or creating a design towards it, the context has to be given with the following questions.

- What is the desired environment?
- Which parameters should be considered?
- What levels of disturbance can be accepted?

As expected the answers would differ between the buildings with different purposes such as residential, office, industrial, school, hospital etc. Moreover, perception of users which do not stem from any physical conditions may also show variances. The behavioral patterns and psychosocial parameters may change the preferences of people in terms of indoor climate. Although the environmental quality of closed spaces may seem to have many dependencies, the most significant and adjustable levers are physical climate factors. In the light of given conditions, the indoor environment should be handled by considering multiple components of physical factors which can be named as thermal climate, indoor air quality, sound and light. The book named “Achieving The Desired Indoor Climate” may serve as a good guidance for one who seeks for knowledge in detail for all mentioned factors. However, the emphasis is going to be on thermal climate in this section, which is a major influencer of thermal comfort.

2.1.1 Thermal Climate

The heat balance is an essential part of a well-functioning human body and sense of comfort. The human body tries to maintain a steady temperature around 37^{o}C even though it is exposed to different temperatures. The stimulations such as sweating, increased or reduced blood flow or shivering may be observed as regulation mechanisms during undesired thermal conditions. Aside from the automatic responses, a person would actively seek for shade, sunlight, increasing or reducing the amount of clothing to respond temperature changes. All these given active or passive responses require energy consumption to some degree and distracts the person from the work in an office environment for instance, with the feeling of discomfort. The thermal climate is perceived differently by different people, which is dependent to four environmental factors. These factors are;

- Air temperature
- Mean radiant temperature
- Air velocity
- Relative humidity

From the factors above, air temperature and mean radiant temperature directly affect the heat balance of the body, however air velocity and humidity affect indirectly by changing the rate of evaporation and draught on the skin. The water saturation of the air surrounding the body changes convection and evaporation, in other words the speed of sweat's evaporation. Although sweating in indoors is not a desired situation, humidity also aggravates the issue.

In addition to the factors described above, there are two more factors that affect the susceptibility of a person to the thermal climate. Namely, these are metabolic rate of the human body and thermal resistance of the clothing. The metabolic rate changes with the level of activity and measured by the unit (met). 1 met is equivalent to a heat production of 58 W/m^2. The "m^2" in the equation refers to the surface area of the body which is taken as 1.77 for Scandinavian countries. That means for an indoor climate design for a building in Sweden the average heat produced by one person can be taken as 102 W. On the other hand, thermal resistance of the clothing represents the insulating capability of the clothing and measured as (clo). 1 clo corresponds to 0.155 m^2K/W, which is the amount of insulation on a person at rest and in a 21^oC environment with normal air flow. Clo can vary between 0 (naked) and 2.2 (outdoor winter clothing). Those units are necessary to calculate the thermal comfort in a given closed space, as it will be seen later on in the Fanger's formula (Nilsson et al, 2003).

2.1.2 Indoor Air Quality

Indoor air quality is traditionally used as a catch-all term for the overall cleanliness of the indoor air. In other terms, cleanliness responds to lack of pollutants in the air which would cause deterioration and an unhealthy environment (Nilsson et al, 2003). The significance of the pollutants is measured by the concentration and period of exposure. While this is generally not a problem for residential buildings or conventional office spaces, workplaces such as laboratories or pharmaceuticals might be prone to deteriorated air. Apart from the health risks to the users, contaminated air may also affect the processes in the building which are sensitive to the surrounding conditions. The classification of buildings according to their purpose also plays a big role here. Industrial buildings are controlled by specific occupational health and safety guidelines in the form of threshold limits for different industries. However, since non-industrial buildings such as school, residential or office buildings don't have such distinctive guidelines, indoor air quality becomes even more of a vague concept to deal with.

In several sources, the factors endangering the indoor air quality is defined in different ways. The two most common ways of classifying the source of pollution are based on their point of generation and physical properties (Walsh et al, 1983). If the source of pollution is investigated according to point of generation, it is important to note that, properties of the indoor air is highly dependent to the quality of air supplied from outside. If the outdoor air is not at the sufficient quality to meet the healthy conditions, it is possible to fix the problem during the transmission from outdoors to indoors. According to Nilsson et al (2003), with the proper equipment placed on the air ducts, issue can be solved under favorable circumstances. However, if the contaminated air is generated indoors by emission from an odorous substance it becomes significantly harder to overcome. As for the physical classification, Walsh et al

(2003) states that; one has to know about physics, chemistry and biology in order to understand how to deal with contaminators thoroughly. The physical aspect covers properties of air quality in terms of time dependence, concentration, temperature and pressure differences. Knowledge in chemistry is required to analyze what are the consequences when more than one contaminator co-exist at a given time. As for the biological side, it obviously considers the effects of the indoor air on the human health. There are more classifications existing such as phenomenological aspects or pollutant-specific aspects, however they can only serve as a guideline depending to the relevancy of the specific in-situ conditions.

2.1.3 Sound

When discussing indoor environment quality, “sound” refers to unwanted noise which causes disturbance and an unpleasant experience in general. From the definition it is possible to figure out unlike air quality which has very specific indicators, sound is a subjective concept. Different types of sound may be found pleasant of unpleasant by different people and they can also be annoyed by different levels of sound. Most of the low level noise produced in the indoor areas is masked by another source anyhow, but since the sensitivity is also variable among the users it may be perceived as a problem by a partition (Nilsson et al, 2003).

As mentioned above, the complaints from noise in a closed space are not always necessarily from high sound levels. Due to the working mechanism of many different utilities such as ventilation fans in houses, water drop in the sink or ticking of the clock and computer fans in offices many different types of sound are generated in a regular pattern. If the level is so low, it is already masked by another source of sound, or some noises with a regular pattern such as the ticking of clock is eliminated by the human brain and is not heard after some point. On the other hand some types of sound especially with low frequency and a continuous character such as the fans in ventilation systems of the building or in computer could be very annoying for users. Although they are often considered as low level sounds, progressive exposure may cause health and psyche issues for acoustically sensitive people (Abbaszadeh et al, 2006).

A good environment in terms of sound often described as not only eliminating unwanted noise but also endorsing the desired sounds. The desired sounds change depending to the purpose of the building thus the characteristic volume, frequency, pitch etc. may differ. However for a conventional office building reducing the inevitable ambient noise from the mentioned resources would be sufficient to obtain a good sound environment.

2.1.4 Light

The importance of lighting for the indoor spaces is usually underestimated. Light strongly influences the perception of people in terms of how they feel about a given indoor environment (Nilsson et al, 2003). Depending to the amount of light people may even interpret the rooms as warm or cold which shows the influence of light on human perception.

Light is usually classified into day light and illumination in terms of their source. Benefiting from daylight at the optimum level has gained popularity with the introduction of green buildings to the construction sector and nowadays it takes place in almost every standard. A common trend for green building is reducing the electric consumption for ambient lighting to save energy. It is also used as a source of thermal gain through the glazing at windows, to help heating and save from the heating energy in the same manner. Even though the building doesn’t have any design towards using the daylight as an energy source, adequate amount of daylight is necessary for a good indoor environment. Whether there is an indoor lighting system or natural daylight, it is a vital part of the visual comfort (Abbaszadeh et al, 2006).

2.2 Thermal Comfort

With the most fundamental definition, comfort in the context of indoor climate is the degree of satisfaction experienced by the users which they would like to live or work with (Nilsson et al, 2003). As mentioned in the previous section, temperature range, air quality, noise levels and arrangement of lighting all contribute to the acceptability of the indoor environment. However, those are not the sole determinants for the perception of comfort of a human being and it may be influenced by many physical and social variables as shown in the Table1 below.

Table 1 - Variables Affecting The Comfort Conditions (Nilsson et al, 2003)

Physical Variables	Physiological Variables	Behavioral Variables	Psychological Variables
Safety and security Protection from elements Thermal variation Air quality Acoustic variation Light Aesthetics Controllability Size	Metabolism Age Gender Time Health Medication Acclimatization	Clothing Location Activity Posture Use of controls	Personal Relations Relations at work Stress Work satisfaction Perception of control Psychosis

For the thermal comfort in particular, the conditions are not so different than the criteria for overall satisfaction with the indoor environment but only narrower. Thermal comfort is defined as the condition when a person feels comfortable and is satisfied with the thermal environment. Due to the several differences mentioned before, it is practically impossible to provide a thermal environment where the dissatisfaction is absolutely zero. In most standards the lowest value for thermal dissatisfaction is taken as 5% (ISO 7730:2006, Miljöbyggnad). Accordingly, it is necessary to create a model for calculation and define a set of factors to be used in calculations, which have the most impact on the perceived indoor climate. There are also pre-calculated charts that are developed for a faster and easier determination which are using similar factors. Figure1 exemplifies 5 factors illustrated in a typical indoor environment.

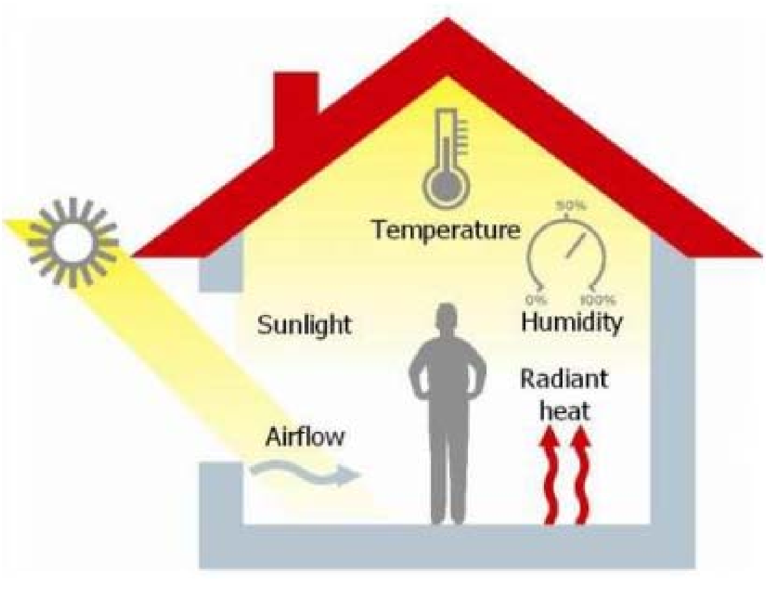

Figure 1 - Factors Affecting The Perceived Indoor Climate (Worker, Hovard V, 1979)

Aside from people using it, buildings also differ in a number of ways according to their individual physical form and services. That affects what sort of heating or cooling system is provided and whether it is used (Nicol, 2002). The control mechanisms they offer to the occupants are also directly related with the form of service. Occupants need different levers to adjust and adapts to the thermal load they are bearing. The factors affecting the thermal load on a person according to ISO 7730:2006 are as follows;

- Operative temperature
- Clothing
- Activity level
- Relative humidity
- Air movement

Leaman and Bordass (1997) have demonstrated that there is more tolerance in buildings which occupants have more access to building controls. The tolerance means the attitude of the occupants to the thermal environment of the building and how acceptable they can be to the slight variations. The amount of control a single user possesses is usually defined with how the building is facilitated. In centrally controlled buildings, variability is usually perceived as a negative characteristic since the occupants are expected to adapt to a specific temperature. Frequent change from the targeted temperature is believed to cause discomfort. Hence in the environment of central control, only available levers left for occupants are changing the amount of clothing, opening the window, closing the shade and so on. On the other hand, variability can be a good characteristic in an environment where occupants are in control and adjust the conditions to fit themselves. Many HVAC systems actually give occupants some sort of control on the indoor climate, in order to let them be more forgiving to changes and more adaptable as well. In that case, as long as control is provided to users to some extent, variability can be a good thing in terms of thermal comfort (Nicol, 2002).

American Society of Heating and Refrigerating and Air Conditioning Engineers (ASHRAE) define the thermal conditions for human occupancy, under the Standard 55-2010. For office environments in particular, Canadian standard CAN/CSA Z412-00 (R2011) – "Office Ergonomics" adopts the exact same values as acceptable range or humidity and temperature as shown in Table 2. The values shown in the tables are drawn from the research and calculations by ASHRAE, aiming to meet the comfort criteria of 80% or more individuals.

Table 2 - Temperature / Humidity Ranges for Thermal Comfort (ASHRAE 55:2010)

Conditions	Relative Humidity	Acceptable Temperature ºC
Summer (light clothing)	If 30%, then If 60%, then	24.5 – 28 23 – 25.5
Winter (warm clothing)	If 30%, then If 60%, then	20.5 – 25.5 20 - 24

However in reality, it has been found difficult to quantify the adaptive opportunity which is provided by the building controls. Nicol and McCartney (2002) shows that the mere existence of a control unit does not mean that it is used and increasing the number of controls just for the sake of it does not give a good measure of the success of a building in terms of adaptive opportunity. Some control measures can be situational; for instance solar shading may be useless on one face of a building, but essential on another to maintain the same comfort levels uniformly throughout the building. It does seem that as well as the existence of a control, a judgment is needed as to whether it is useful in the particular circumstances.

2.3 Comfort Indices

P.O. Fanger was the first who developed an extensive model for thermal comfort. The studies which were published in 1967 (Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation) and 1970 (Thermal Comfort-Analysis and Applications in Environmental Engineering) constituted the basis for many other researches and today, his mathematical model is probably the most well-known and most used in various standards and programs.

In the process of developing the method, Fanger used a seven-point thermal sensation scale alongside with several experiments involving human subjects in different environments. Then, he built a correlation between the subjects and their response to the variables, which influence the condition of thermal comfort. Fanger's model is based on an energy equation that takes into account all the means of energy loss from the body, including the convection and radiant heat loss from the outer surface of the clothing, the heat loss by water vapour diffusion through the skin, the heat loss by evaporation of sweat from the skin surface, the latent and dry respiration heat loss and the heat transfer from the skin to the outer surface of the clothing (ASHRAE, 2001). The model assumes that the person in experiment is thermally at steady state with his environment and also has the skin temperature and evaporative sweat rate of a thermally comfortable person. First, the model calculates the energy loss; then, using the thermal sensation votes from the subjects, a Predicted Mean Vote (PMV) thermal sensation scale is created based on how the energy loss deviates from the metabolic rate.

Study of Fanger proposes that the condition for thermal comfort in terms of skin temperature and sweat secretion lies within a narrow range. The data is obtained from climate chamber experiments, in which sweat rate and skin temperature were measured on people who considered themselves comfortable at various metabolic rates. Fanger proposed that optimal conditions for thermal comfort were expressed by the regression line of skin temperature and sweat rate on metabolic rate in data from these experiments. In this way an expression for optimal thermal comfort can be deduced from the metabolic rate, clothing insulation and environmental conditions. The final equation for optimal thermal comfort is fairly complex and explained in detail in the next section. Fanger has solved the equations by computer and presented the results in the form of diagrams from which optimal comfort conditions can be read given knowledge of metabolic rate and clothing insulation. Fanger extended the usefulness of his work by proposing a method by which the actual thermal sensation could be predicted. His assumption for this was that the sensation experienced by a person was a function of the physiological strain imposed on him by the environment. This he defined as "the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level" (Fanger 1970). He calculated this extra load for people involved in climate chamber experiments and plotted their comfort vote against it. Thus he was able to predict what comfort vote would arise from a given set of environmental conditions for a given clothing insulation and metabolic rate. Tables of PMV are available for different environments for given clothing and metabolic rates.

Fanger realised that the vote predicted was only the mean value to be expected from a group of people, and he extended the PMV to predict the proportion of any population who will be dissatisfied with the environment. A person's dissatisfaction was defined in terms of their comfort vote. Those who vote outside the central three scaling points on the ASHRAE were counted as dissatisfied. PPD is defined in terms of the PMV, and adds no information to that already available in PMV other than representing the dissatisfaction in terms of a percentage.

2.4 An alternative approach – Adaptive Thermal Comfort (ATC)

The Predicted Mean Vote (PMV) is a well-known and widely used index for thermal comfort however; alternative comfort related indicators have gained interest over the last decade (Linden et al, 2008). The adaptive thermal comfort approach (ATC), which is applying the indoor operative temperature in relation to the outdoor air temperature is one of the main alternatives in that sense. This approach is specifically developed to respond to the differences observed between PMV/PDD assessment and actual thermal comfort response from the occupants for specific type of buildings (mainly non-air-conditioned) (Linden et al, 2008).

The fundamental assumption of the adaptive approach is expressed by the following principle: If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol, 2002). By linking the comfort vote to people's actions, the adaptive principle gives context of how comfort temperature is influenced. According to adaptive approach, comfort temperature is a result of the interaction between the subjects and the environment they are occupying. The primary contextual variable is the climate. Climate is a predominant influence on the thermal attitudes of people and on the design of the buildings they occupy. There are several ways which people are influenced by the climate they live in and these play a cumulative part in their response to the indoor climate. The second major context of most comfort surveys is building itself. The nature of the building and its services play a part in defining the results from the comfort surveys. The third context is time. Human activity and responses take place in a time frame. This leads to a continually changing comfort temperature. The rate at which these changes occur is an important consideration if the conditions for comfort are to be properly specified.

The adaptive approach to thermal comfort is based on the findings from thermal comfort surveys conducted in the field (Linden et al, 2008). Field surveys focus on gathering data about the thermal environment and the thermal response of occupants simultaneously in real situations while the interventions from the researcher tried to be kept at minimum. The aim is to predict the temperature or combination of thermal variables (temperature, humidity and air velocity) which are perceived as comfortable. The problems with field study are the difficulty to measure environmental conditions accurately and the difficulty to generalize from the statistical analysis. Results from one survey most of the time do not apply to the data from another survey even in similar circumstances because of the variability mentioned above.

Application of the ATC approach has a distinct advantage over the PMV/PDD approach. Since it allows for a relatively simple comfort assessment for buildings in use; the results can be communicated directly to building users. On the other hand the ATC approach currently only can be applied for office type indoor environments with including related average conditions such as metabolic rate, clothing and so on. There is not enough quantitative data to evaluate the comfort in context of different environments. Henceforth, it can be said that ATC is less flexible and limited in its application range compared to the PMV/PDD approach.

The results of the comparative research between ATC and PMV methods conducted by Linden et al (2008) states that; application of the PMV/PDD or the ATC approach do not result in a different conclusion for a moderate outdoor thermal environment. The advantage of the ATC method is the communicability of information because of its simplicity. The PMV/PDD approach however has a much wider applicability. From the results of the same study, Linden et al came to the conclusion that ATC approach is optimal for naturally conditioned spaces. Since the mainstream office environments are mechanically conditioned spaces, the PMV/PDD model is a more suitable option for more precise solutions.

2.5 Calculation Methods

As there are multiple indicators of thermal comfort, there are also multiple ways to measure and calculate comfort indices. While some methods are rather simple to use and do not require any prior knowledge with the issue such as simply asking to the workers and using the charts provided by ASHRAE, some methods such as Fanger's equation provide very precise results however requires extensive analytical knowledge. Depending to the extent the comfort results are going be used, it is possible to choose from suitable methods. In Table 2, there is an exemplary survey provided by "Health and Safety Executive" (HSE), which recommends simply asking to the workers about their workplace conditions and see if they are satisfied. That survey and the likes of can be used for building facilitators to assess the current state of satisfaction and initiate improvements depending on the result. However, if the purpose is more than an investigation, such as certifying the building according to any of the standards, then more advanced methods like Fanger's theorem shall be applied.

Table 3 - Thermal Comfort Checklist (HSE, 2015)

Factor	Description	YES
Air temperature	Does the air feel warm or hot?	
	Does the temp. in the workplace fluctuate during a normal day?	
	Does the temp. in the workplace change a lot across seasons?	
Radiant temp.	Is there a heat source in the environment?	
Humidity	Is there any equipment produces steam?	
	Is the workplace affected by external weather conditions?	
	Are the employees wearing PPE that is vapor impermeable?	
	Do the employees complain that the air is too dry?	
	Do the employees complain that air is humid?	
Air movement	Is cold or warm air blowing directly into the workspace?	
	Do the employees complain of draught?	
Metabolic rate	Is the work rate moderated according to warm or hot conditions?	
	Are employees sedentary in cool or cold environments?	
Personal protective equip.	Is there any PPE being worn by the employees?	
	Can employees make individual alterations to their clothing?	
Thoughts	Do the employees think there is a thermal comfort problem?	

The most commonly cited researches and experiments conducted on the thermal comfort are done by P. O. Fanger. The method developed by him constitutes the basis for many standards as ISO 7730 for instance. According to his theorem, PMV (Predicted Mean Vote) is calculated from an equation of thermal balance of the human body, involving the internal heat generation and heat exchange with the surrounding environment. As illustrated in Figure 2, the heat exchange may occur from sweating, respiration, physical convection and conduction, as well as the radiation. Factors changing the metabolic rate are also taken into consideration.

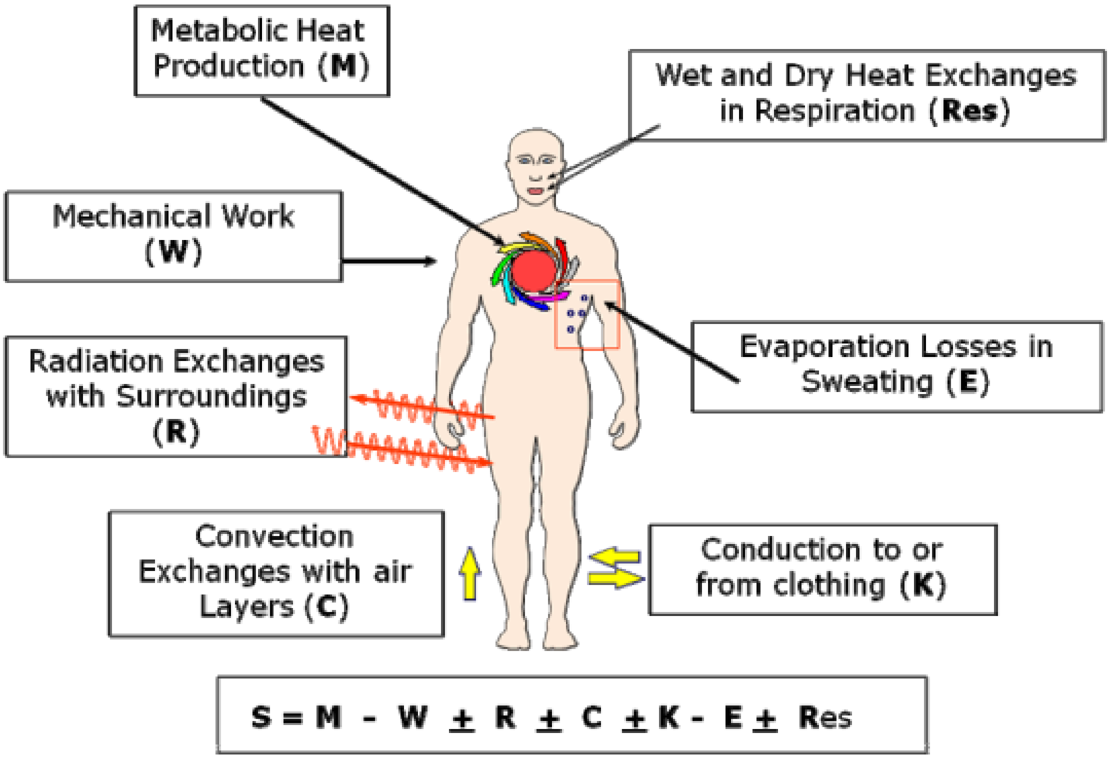

Figure 2 - Human Body Thermal Balance (Threlkeld, 1970)

$$PMV = (0{,}303e^{-2{,}100*M} + 0{,}028) * [(M - W) - H - E_c - C_{res} - E_{res}] \quad (1)$$

where the terms of the equation represent respectively:

M - the metabolic rate, in Watt per square meter (W/m^2);

W - the effective mechanical power, in Watt per square meter (W/m^2);

H - the sensitive heat losses;

E_c - the heat exchange by evaporation on the skin;

C_{res} - heat exchange by convection in breathing;

E_{res} - the evaporative heat exchange in breathing.

In equation 1, the terms H, E_c, C_{res}, and H_{res} correspond to the heat exchange between the body and the surrounding environment and are calculated from the following equations:

$$H = 3{,}96 * 10^{-8} * fcl * [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} * h_c * (t_{cl} - t_a) \quad (2)$$

$$E_c = 3{,}05 * 10^{-3} * [5733 - 6{,}99 * (M - W) - p_a] - 0{,}42 * [(M - W) - 58{,}15] \quad (3)$$

$$C_{res} = 0{,}0014 * M * (34 - t_a) \quad (4)$$

$$E_{res} = 1{,}7 * 10 - 5 * M * (5867 - p_a) \quad (5)$$

Where the nominators in the equation represent the following variables;

I_{cl} is the clothing insulation, in square meters Kelvin per watt (m2K/W);

f_{cl} is the clothing surface area factor;

t_a is the air temperature, in degrees Celsius (°C);

t_r is the mean radiant temperature, in degrees Celsius (°C);

v_{ar} is the relative air velocity, in meters per second (m/s);

p_a is the water vapor partial pressure, in Pascal (Pa);

t_{cl} is the clothing surface temperature, in degrees Celsius (°C).

The problem with this series of equations is that "t_{cl}" which is the external temperature of clothing is unknown and practically not possible to measure. To be able to find that value, the following equation is used;

$$(t_{sk} - t_{cl})/I_{cl} = 3{,}96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} * h_c * (t_c - t_a) \qquad (6)$$

And in Equation 6, "t_{sk}" represents the skin external temperature which can be found from;

$$t_{sk} = 35{,}7 - 0{,}028 * (M - W) \qquad (7)$$

With the PMV index, the Predicted Percentage Dissatisfied people, in other words PPD index can be calculated. The PPD index is a quantitative measure of the reaction of a group of people at a specific situation and often used to indicate the thermal comfort for thermal environments. The range for the PPD index is between 5% and 75% according to ISO 7730, which states that the index should only be used for values of PMV between -2 and +2. The 5% of dissatisfaction always exists because of the different perceptions on the comfort. Fanger concludes his studies that the variation of PMV index can be approximated by an analytic expression, which is an inverted Gaussian distribution curve as show in the Figure 3.

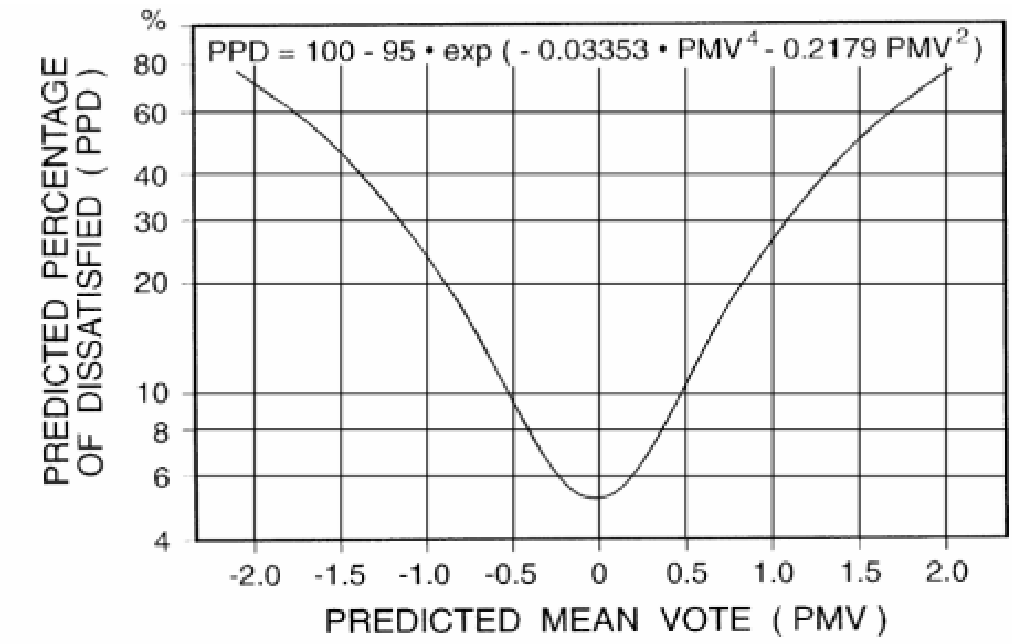

Figure 3 - Predicted Percentage of Dissatisfied as a Function Of PMV

3 STANDARDS

There are several national and international organizations existing which have influence on either creation of knowledge about thermal comfort or enforcing the practical application. To make certain set of standards accepted worldwide has numerous challenges. Firstly, the organization developing standards has to make certain assumptions about the average state of the buildings, routines of the users, clothing traditions, perception of comfort and so on. On the other hand, even if there are similarities observed for the given parameters, the application may be impossible for practical reasons. That dependency to local conditions naturally results in tendency to develop their own standards for countries while taking the global ones as a basis or guideline while creating their own. Hereby in this part of the thesis, the emphasis will be given to Miljöbyggnad since it is believed to be adjusted better for Swedish conditions while couple of other influential standards is also going to be mentioned.

3.1 ISO 7730

The International Standards Organization (ISO) was founded in 1947 and has more than 130 member countries. It creates worldwide proprietary, industrial and commercial standards (Parsons, 2002). ISO 7730 in particular is an international standard covering the evaluation of moderate thermal environments which was developed in parallel with the ASHRAE standard 55. It belongs to a series of ISO documents which is explaining methods for measurement and evaluation of moderate and extreme thermal environments to which human beings are exposed (ISO 7730:2005, Genava).

While mentioning standards, it is important to specify its scope since it specifies where the standard does and does not apply. For ISO 7730 in particular, it can be interpreted as the range of thermal conditions and the demography of people where it is valid for. The PMV and PDD indices used in the mentioned document are derived from the results of a research applied on North American and European people. The standard itself notifies that differences may be observed in varying ethnic, geographic profiles. A regular person taken into account in the standard is a healthy adult who can be either male or female but elders, children, disabled or people with special needs are not considered. As for the environment, a steady state indoor area is taken as default where people are light clothed with the western type. People are assumed to be in thermal neutrality, thus differences in posture, activity or body temperature of individuals may result them to respond differently (ISO 7730:2005, Genava).

ISO 7730 considers PMV and PDD as reliable indices for measuring and classifying thermal comfort. The standard also proposes calculation methods for other discomfort situations such as radiant temperature asymmetry (cold or warm surfaces), draught (local cooling of the body caused by air movement), vertical air temperature difference and cold or warm floors. However, PMV and PDD which are also the two indices used in this project are the most conventional ones because of their reliability.

The indices mentioned in the standard are exactly as described by Fanger (1970) who is the researcher that develops the related formulas. So according to both Fanger and ISO 7730, PMV predicts the mean value of the votes of a large group of people on the ISO thermal sensation scale based on the heat balance of the human body. Thermal balance is achieved when the internal heat production of the body equalizes the loss to the external environment. In moderate conditions, thermoregulatory system automatically attempts to balance skin temperature with sweat secretion; so that metabolic factors of the body are also taken into account in Fanger's equation as well as the factors from environmental condition.

Table 4 - Thermal Sensation Scale (ISO 7730)

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

ISO 7730 suggests three different ways to calculate the PMV. First one of those is calculating manually or via a computer program by using the equations developed by Fanger. However, since the equation is too complicated to be solved manually, most convenient way is to use either a software like IDA where the Fanger equations are integrated, or use the basic code provided in the ISO appendix. In both cases computer aid is needed. Another way to find PMV is using the tables in the ISO 7730 Annex E, where the PMV values are pre-calculated according to various different combinations. If the indoor environment in question does not have any extraordinary characteristics, it would be possible to find PMV value directly from the chart without going through the equations. Lastly, the third method is direct measurement with an integrating sensor. However it is not that common considering the practical reasons.

While PMV predicts the mean value of the thermal votes of a group which is exposed to the same thermal environment, it doesn't distinct the distribution of individual votes. All votes are assumed to scatter around the mean value. In real case scenarios it might be necessary to identify how many people are not satisfied with the indoor environment so the necessary precautions could be taken. PDD is an index that gives a quantitative prediction on the percentage of people dissatisfied who are feeling either too hot or too cold. More specifically PDD covers the people who votes cool, cold or warm, hot in the scale given above. Since both PMV and PDD indices can be derived from each other, they can be used interchangeably. Most standards include limit values for both indices to make the comparisons possible. For ISO 7730 in particular, the chart taken from Annex A below can be used to check whether a given thermal environment complies with comfort criteria. Each category shows a maximum percentage of dissatisfied for the body as a whole on the left side and local discomfort on the right side where draught is represented by DR and percentage of dissatisfied as PD.

Table 5 - Categories of Thermal Environment (ISO7730)

Category	**Thermal state of the body as a whole**		**Local Discomfort**			
	PDD %	**PMV %**	**DR %**	**PD % Caused by** vertical air temperature difference	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

3.2 Miljöbyggnad

Miljöbyggnad is a Swedish environmental certification system for certifying buildings in relation to energy, indoor climate and materials (SGBC, 2015). It is developed by the collaboration of researchers with companies in the building sector involving banks, insurers, consultants and related authorities. Its main purpose is to protect human health and environment. Thus, it is concerned about the issues that are considered to affect buildings environmental impact and users' health.

In recent years, with the increase in demand among the property owners for getting their buildings assessed to document the environmental quality excellence, the need for an easily accessible certification system became more apparent. On the other hand leaseholders were in search for residential or commercial buildings to satisfy their climate and health requirements. As described by the Swedish Green Building Council (SGBC), the certain characteristics of Miljöbyggnad such as simplicity and cost efficiency are designed to answer those needs, thus it allowed the system to become popular quickly in the construction sector. The ability to reuse existing project documents lessened the amount of work for certifying a building which led to lower costs for the property owners. Furthermore, since the Miljöbyggnad system is developed with the influence ISO standards as well as the BBR (Boverkets Byggregler) codes, it eliminated any chance of compatibility issues while maintaining the international legitimacy. Henceforth it became a more preferable certification system compared to others.

The system rates the buildings on a scale consisting of Bronze, Silver and Gold ranks which are applicable for both existing buildings as well as the buildings on the design phase. Building which cannot meet the requirements for a Bronze certificate can be labeled as "Rated" still. The usage of the building in pursue for a certificate could be residential or commercial. While it has no effect on the eligibility for a Miljöbyggnad certificate, different criteria could be applied on certain requirements.

Table 6 - Miljöbyggnad Structure

INDICATOR	ASPECT	AREA	GRADE
Bought energy	Energy usage	Energy	Final Grade
Heating power req.	Power demand		
Solar heat load			
Fraction of energy carriers	Energy source		
Noise protection	Acoustic environment	Indoor Environment	
Radon content	Air quality		
Ventilation rates			
Nitrogen dioxide			
Moisture prevention	Moisture		
Thermal climate winter	Thermal climate		
Thermal climate summer			
Daylight	Daylight		
Legionella	Legionella		
Documentation of building materials	Documentation of building materials	Materials and Chemicals	
Absence of hazardous substances	Absence for hazardous substances		

In table 3, the structure of Miljöbyggnad assessment system is summarized. As seen, there are 15 indicators classified into 11 different aspects. Then, the aspects are combined into three major areas. For grading, Miljöbyggnad uses an aggregating grading system. That means the lowest grade obtained by one of the indicators can only be one level below compared to total grade. For instance a Gold rated building must not have any Bronze ratings in any of the indicators. Each indicator is graded in itself with a set of criteria. Then, while transitioning into aspect grade, the lowest grade of the corresponding indicators is taken. In the same fashion, area grade consists of the lowest of aspects grades in its section and for the final grade the lowest of the area grades is taken. The only exception is the possibility to increase the area grade by one level if more than 50% of the indicators are rated higher (SGBC, 2015).

Primarily relevant parts of Miljöbyggnad for this thesis are the indicators under the Thermal climate aspect which are thermal climate summer and winter. Secondarily it is also helpful to check the energy demand of the building by comparing the simulation results with the threshold values given under the aspect of energy usage. The current limitations in Miljöbyggnad for energy usage are adjusted according to the demands in BBR. In the table below the demand from BBR can be seen corresponding to different zones in Sweden.

Table 7 - Max Energy Demand According to BBR

Energy Demand	Zone I	Zone II	Zone III
$kWh/m^2.A_{temp}.year$	130	110	90

It should be noted that the values given above are for the buildings which are not heated with an electric system. In the definition set by BBR the energy demand of the building takes into account heating, hot water, cooling and utilities electric consumption (elevator, lights etc.). The electricity used by the tenants is not taken into consideration. With respect to the values above, Miljöbyggnad defines its requirements as a portion of BBR limits for different ranks. Since Gothenburg region belongs to Zone III, 90 is taken as BBR limit in the table below.

Table 8 - Max Energy Demand According to Miljöbyggnad

Demand (% of BBR)	Bronze	Silver	Gold
$kWh/m^2.A_{temp}.year$	≤90 (100%)	≤67.5 (75%)	≤58.5 (65%)

The indicator for thermal comfort is represented by PPD in Miljöbyggnad standard. The method of calculation is taken directly from ISO, since they both use the same equations developed by Fanger. Although there are two different sections in the structure for winter and summer climates, the same PPD limits are used. There are also two additional calculation methods suggested by Miljöbyggnad such as *transmission factor* (TF) and *solar heat factor* (SVF) for winter and summer respectively, however PPD is more accurate when computer aid is available. The maximum allowable PPD limits are shown below for 3 different ranks.

Table 9 - Max Allowed PPD According to Miljöbyggnad

Thermal Climate	Bronze	Silver	Gold
PPD %	≤20%	≤15%	≤10%

In addition to the requirements above, a survey must be held by the participation of users in the building to ensure that the perceived climate is acceptable or higher if Gold is desired.

3.3 Other Certification Systems

In this section of chapter 3, several other standards are going to be mentioned. The reason the standards under this headline grouped together is, although they are worldwide accepted and constitute a guideline for Swedish standards, they are not particularly as significant as ISO or Miljöbyggnad for Swedish construction sector. Furthermore, given that the case building used in this project also aims to meet Miljöbyggnad demands, it is considerably more important. The criterion for representing thermal comfort is determined as PPD in this project which uses the calculation methods in ISO standards. Henceforth, while the mentioned two certification systems have exceptional importance, having the knowledge of other standardization systems is also important to get a better understanding of why and how the buildings are rated.

The trend towards sustainable design started in 1990s (Vierra, 2014). With the realization of various benefits of certifying buildings, the demand towards certification organizations increased rapidly in the developed construction markets. Although the mentioned benefits come into existence in different forms for the different stakeholders of a building, from a holistic perspective they all served for a better purpose. For instance, energy efficiency which is a focal point for all certification programs can be beneficial to property owner's financial commitment by decreasing the operational expenses as well as to the environment by reducing carbon emissions. In the same fashion, using sustainable materials can improve the quality of indoor environment by avoiding materials with unhealthy ingredients. From the economic standpoint, certified green buildings may command higher rents and market values. Thus why, certification can be a distinguishing factor in competitive real estate markets. In the graph below an estimation of how the certified area will increase is shown until year 2020.

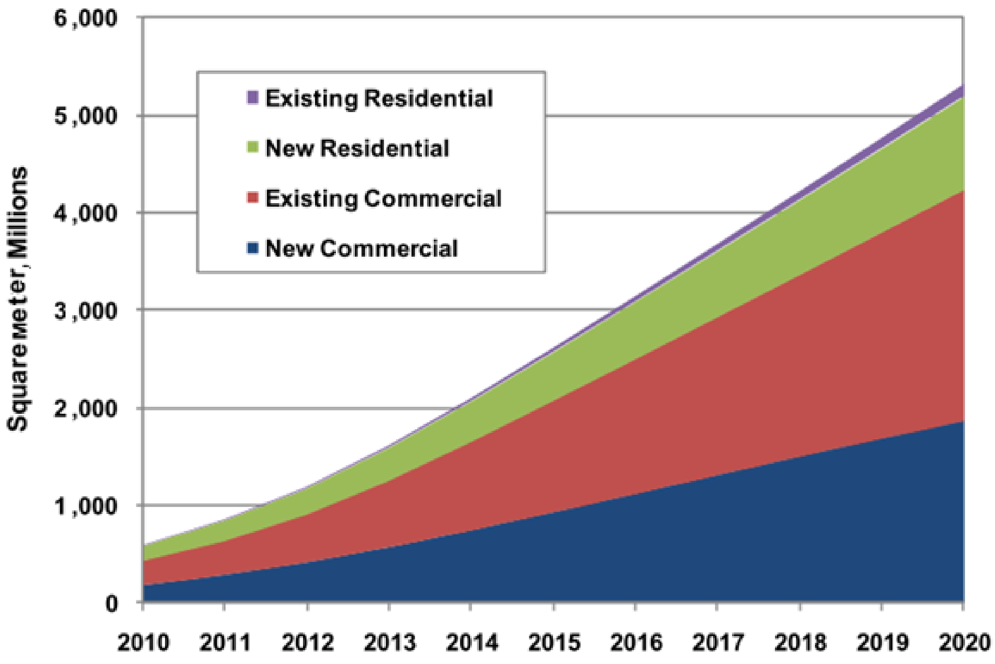

Figure 4 - Certified Green Building Segment (Vierra, 2014)

The first organization created to answer the need was Building Research Establishment's Environmental Assessment Method (BREEAM) which is an UK based organization. In the early 1990s it evolved from BRE (Building Research Establishment) which was formerly a governmental organization and became a recognized certification authority. With the same purpose U.S. Green Building Council (USGBC) was formed in 1993 as the American form of green building certification. USGBC released a set of criteria aimed towards improving the environmental performance of buildings through Leadership in Energy and Environmental Design (LEED) for new construction. In the later years LEED grew into a rating system also for existing buildings and even neighborhoods. Other countries also responded to the trend with the involvement of "Beam" for Hong Kong, "CASBEE" for Japan, "Green Mark Scheme" for Singapore, "Green Star SA" for South Africa and so on. World Green Building Council currently recognizes 20 established green building councils worldwide with more than 40 similar structures seeking to achieve same status in the next few years (Bloom, 2010).

Table 10 - Summary of Green Building Certification Systems (Bloom,2010)

Certification System	General		Types Of Buildings	Phases		Geographical Spread
BREEAM	Country	UK	All including neighborhoods	New construction	Yes	Worldwide
	Year	1990		Refurbishment	Yes	
	Certified	200,000		Management	Yes	
LEED	Country	USA	All including neighborhoods	New construction	Yes	Worldwide
	Year	2000		Refurbishment	Yes	
	Certified	32,200		Management	Yes	
DGNB	Country	Germany	All including neighborhoods	New construction	Yes	Germany, China, Brazil, Thailand
	Year	2009		Refurbishment	Yes	
	Certified	224		Management	Yes	
Green Star	Country	Australia	All including neighborhoods	New construction	Yes	Australia, New Zealand, South Africa
	Year	2002		Refurbishment	Yes	
	Certified	400		Management	Yes	
HQE	Country	France	Houses Non-residential	New construction	Yes	France, Belgium, Germany, UK, Italy, Brazil
	Year	2004		Refurbishment	Yes	
	Certified	7,200		Management	Yes	
Green Building	Country	EU	Non-residential buildings	New construction	Yes	Europe
	Year	2005		Refurbishment	Yes	
	Certified	600		Management	Yes	
Minergie	Country	Switzerland	Houses Non-residential	New construction	Yes	Switzerland Luxemburg
	Year	1998		Refurbishment	Yes	
	Certified	24,000		Management	No	
Passive House	Country	Germany	Houses Non-residential	New construction	Yes	Worldwide
	Year	1998		Refurbishment	Yes	
	Certified	4,400		Management	No	
CASBEE	Country	Japan	Houses Non-residential Neighborhoods	New construction	Yes	Japan
	Year	2002		Refurbishment	Yes	
	Certified	216		Management	Yes	
Energy Star	Country	USA	Houses Non-residential	New construction	Yes	USA
	Year	1999		Refurbishment	Yes	
	Certified	18,800		Management	No	
Effinergie	Country	France	Houses Non-residential	New construction	Yes	France
	Year	2007		Refurbishment	Yes	
	Certified	16,925		Management	No	

The current struggle of building certification systems is mainly keeping up with the fast developing technology of building materials. Many of the greener methods or materials have not been tested long enough, so the actual performances are hard to assess. Since many of the certification systems require energy, indoor climate calculations and such, the characteristic properties of new materials are occasionally hard to find. Taking into account the hurdles that are mentioned and localization issues, continuous change and development are nothing but expected. Therefore actuality must be the major concern for the ones looking for certification.

4 CASE PROJECT

In order to practice how different circumstances in a given building reflect on thermal comfort, a case study has been made on a sample building. The building used in the case study is an artificial 2-storey office building with office spaces in differentiating in size. A 3D model has been constructed in the building simulation software called IDA ICE and necessary configurations have been made to observe the indoor climate conditions during winter and summer seasons. The reason of using an artificial building is the nature of the study; which has a parametric basis. That means; the effect of different parameters on the outcome of thermal comfort is the primary target to observe, so that a generalization can be made upon the all office buildings in general. So, it is important that the test subject should have the basic and similar characteristics to real life examples without having a very distinct characteristic which can sway the outcome significantly. In this chapter, the information can be found about the building envelope and how the aforementioned building properties have been selected.

4.1 Building Description

The case subject is a 2-storey office building with a total of 655.82 m² of surface area. As seen in Figure 5, the sample building has 2 long facades on north and south, and 2 shorter facades on the eastern and western side. The building has the same pattern in terms of dividing the floor area into different zones in both floors. One floor includes 2 big offices, 6 small offices, 4 rooms (multi-purpose), 2 large areas (kitchen and recreational), 4 bathrooms with shower and 2 toilets. There is also an entre for connecting different parts, which also includes the elevator shaft, however not a relevant party when concerned for thermal comfort.

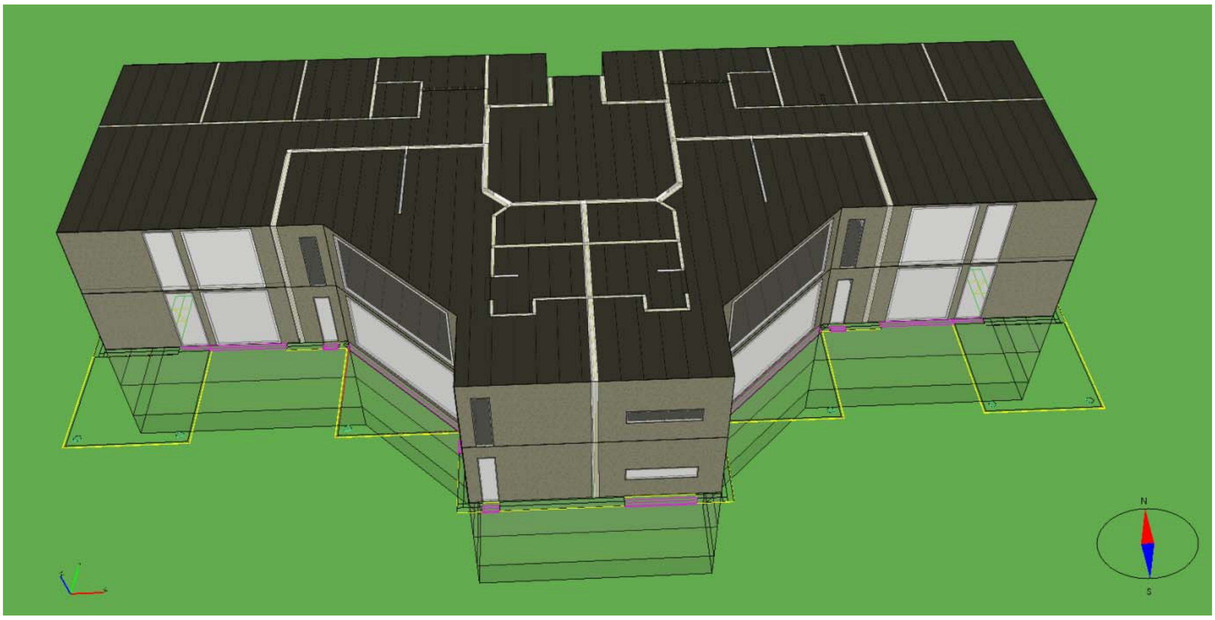

Figure 5 - 3D View Of The Case Building

From Figure 5 and Figure 6, it is possible to notice that most of the larger windows are used on the southern side, which has the most exposure to sunlight during daytime. The small offices are lined in the north with relatively smaller openings, while no windows are found on the eastern and western facades. The two large zones in the southern half of the building have the largest windows and highest window to wall ratios throughout the whole building. While the general architecture of the building seems ordinary for office use, those two mentioned zones may require special precautions to maintain thermal comfort during summer time.

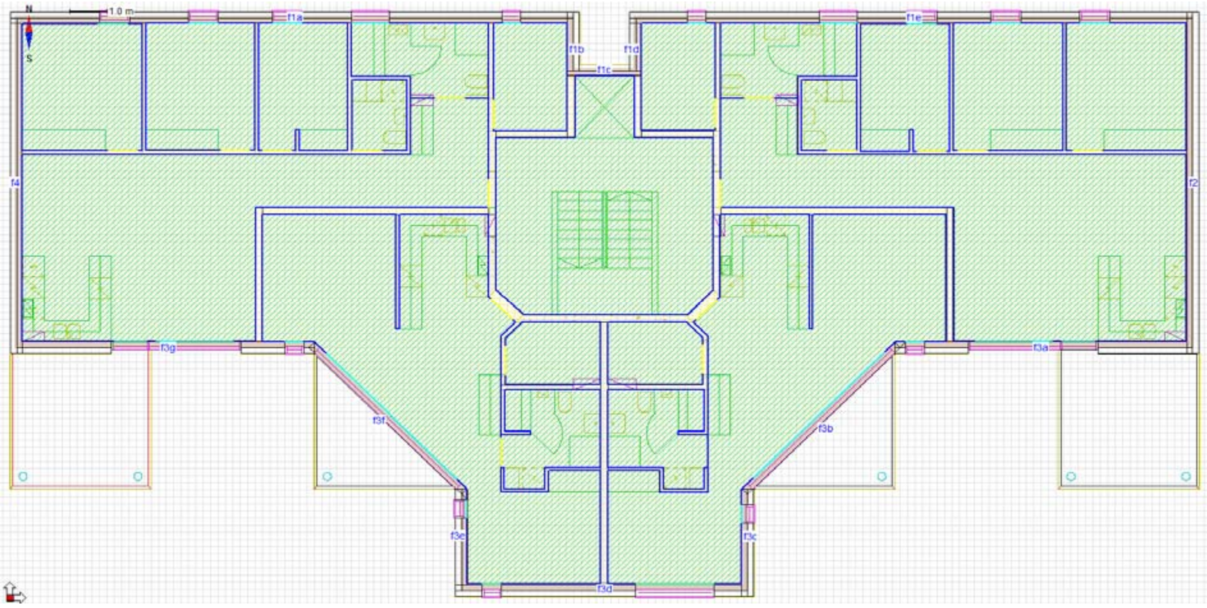

Figure 6 - Floor Plan Of Case Building

In order to run a simulation in IDA for any given building, there are some parameters called “Global Data” (see Figure 7) which are unique for local conditions such as daily temperatures, wind profile, public holidays etc. Therefore, the building should be located either in a city with existing climates files or climate files have to be created by defining the daily/hourly values of outside temperature. For that particular reason, the case building is assumed to be located in Gothenburg and Gothenburg, Säve (1977) exemplary climate file has been chosen from the IDA database. For the wind profile, since the case building is designed for office purposes, it is assumed to be in the city center and the relevant wind profile has been assigned. The wind file contains the information about the wind regime in the area, so the amount exposure to the wind and the infiltration can be simulated by the software. As the last parameter of the global settings, the public holidays should be defined so that the program makes exceptions on the assigned schedules of energy sources such as occupancy, lighting, heating/cooling units etc. Those mentioned units operate on a schedule, which is expected to be created by the user. That allows adjusting the operating hours of utilities such as lighting, fans or other heat producing machinery in the room and it also allows setting unoccupied hours during the day (i.e. lunch break) which creates a better representation of the hourly feeling of indoor conditions. This parameter can be considered as mostly relevant for those who pursue to examine the energy consumption of the building in a given period so that the unoccupied days of the building are not taken into account, however for one who wants to monitor the daily/hourly thermal comfort it also bears significant importance.

Figure 7 - Global Data Tab In IDA

4.2 Building Envelope

Table 11 - Building Envelope For The Case Building

Building Element	Value	Comments
Wall Construction	$U_{(exterior)}$ = 0.17 W/m²K $U_{(interior)}$ = 0.62 W/m²K	Ex. Walls are insulated with 150 mm light insulation.
Roof Construction	U_{roof} = 0.10 W/m²K	Insulation 365, Wood panel 22, Gypsum joint roof.
Slab Construction	U_{slab} = 2.39 W/m²K	150 mm concrete floor with 20 mm l/w and 5mm coating.
Doors	Not included	Not included
Window Area	111.76 m² 31% of total wall area	According to arch. design
Fenestration Type	2-pane glazing 3-pane glazing	Assigned by user
Fenestration Frame U-value	U_{frame} (2-pane) = 2 W/m²K U_{frame} (3-pane) = 2 W/m²K	Same windows frames are used for both window types
Fenestration Glass U-value	U_{glass} (2-pane) = 3.04 W/m²K U_{glass} (3-pane) = 1.90 W/m²K	Main determinant of U_{total} for windows (U_{frame} adds 10%)
Visual Light Transmittance	0.6 for 3-pane 0.7 for 2-pane	Default for window types
Fixed Shading Devices	N/A	No external shading designed
Automated Shading Devices	N/A	No automated shading exists
Thermal Bridges	Total thermal bridges 53.01 W/K	The sum of all thermal bridges btw walls, slab, roof
Air Tightness	N/A	Fixed infiltration
Infiltration	0.1044 (L/s.m² ext. surf.)	Fixed flow in zones

The physical properties of the case building which have either a direct or indirect influence on thermal comfort are listed in Table 11. Since most of the uncontrolled heat transfer (or heat loss) occurs through the heat exchange between surfaces such as walls, floors and windows, the transmittancy characteristics of these building elements have significant importance.

In the case of walls, slabs and roof the determinants of the U-value are mostly products of the structural design. The type and thickness of the concrete are the major determinants; however insulation material can be used as a lever to adjust the U_{total}. For that particular case, light insulations of 150mm and 30mm have been used on the exterior walls and interior walls respectively, in order to reflect the standard wall elements of a real life office building. In the same manner 20mm of light-weight concrete and 5mm of coating applied on the floor area.

Windows are the major instruments in heat loss and solar gain of a building. The case building has a 31% of window to wall area, which can be considered as typical among the buildings with similar purposes (e.g. Ullevi Office Arena, Gothenburg has 36%). The U_{total} for windows are inspected under two entries. First and most effective is the glazing from the window which is dependent on the glass itself and the layering. Second and less effective influencer is the window frame which is conventionally made of a non-glass material. Since the influence of the frame is significantly lower compared to the glass body, only a fraction (10% as default) is taken into account. By adding up the U-glass and 10% of U-frame the U_{total} is calculated for windows. For this particular building, two different types of window are used. While the main reason is the different amount of exposure to the sunlight, more detailed explanation will be given in the assessment section of the simulation results.

Thermal bridges (also referred as cold bridges) are another source of heat loss/transfer between different zones and outside which occur on the connection and joint points of different building elements. In a typical case, thermal bridges are observed between external wall-internal wall, external wall-internal slab, external wall-roof and external wall-window. In the simulation program, the condition for thermal bridges can be defined on a scale consists of None-Good-Typical-Poor-Good for each of the different joints that are creating a thermal bridge. The selection among the 5 grades automatically assigns a coefficient for that particular joint, which is later used in calculation with other parameters. Since the case building in this project is perceived to represent the standard conditions, the option “Typical” has been chosen for every joint. The value in Table 11 gives the total amount of thermal bridges overall, but the individual values for the rooms are varying according to their location in the building.

4.3 Process Loads and Internal Gains

Table 12 - Internal Gains For The Case Building

Building Element	Value	Comments
Interior Lighting	10 W/m² 100W per unit	Same for all zones. Number of units is auto assigned.
Interior Lighting Schedule	06:00 to 18:00 in weekdays and Saturday. Off on Sunday	Turned off during night, Sunday and holidays.
Lighting Occupant Controls	N/A	Lighting is automated.
Daylighting Controls	N/A	Fixed amount of lighting.
Exterior Lighting	N/A	Not concerned.
Receptacle Equipment	7.5 W/m² 75W per unit	Same for all zones. Number of units is auto assigned.
Receptacle Eq. Schedule	06:00 to 18:00 in weekdays and Saturday. Off on Sunday	Turned off during night, Sunday and holidays.
Occupants	Activity level: 1.2 MET Clothing: 0.7 ±0.25 CLO	Standard activity level for office work. Fixed clothing.
Occupants Schedule	08:00 to 17:00 in weekdays Saturday and Sunday off.	There is a lunch break between 12:00 – 13:00

As much as the solar gain through windows from the sunlight, the internal sources existing in the room during the operational hours also make a remarkable contribution to the total heat gain. Even in an empty room, the presence of humans affect the heat balance in the zone with the heat produced by their metabolic activity. In an ordinary office environment, lighting and equipment also adds up to the humans as a resource of heat emitting units. As a result, the number and specifications of the mentioned units become a determinant of thermal comfort.

The typical heat producers in any given indoor space are grouped as lighting, occupants and the equipment. In a general sense, lighting is the most standardizable of the three which has completely predictable effects due to product selection and scheduling. How many Watts of electricity is consumed by a light bulb is easy to find out and the simulation software also allows adjusting luminous efficacy and convective fraction as more advanced properties. Combining this data with the operation schedule of the lighting units, the amount of heat generated is calculated. If the user control is minimized and control of the switches is done centrally, a steady amount of heat generation can be observed in all zones simultaneously. In the case building the lighting bulbs of 100W have been used and all zones are illuminated with a value of 10W/m². Operational hours are defined as from 6am to 6pm during weekdays and Saturday, with the exception of scheduled public holidays.

The heat generation by the equipment in a zone has the potential to be more variable depending on the purpose of usage. If high heat generating machineries are used as an instrument of work, they need to be defined and taken into consideration specifically. Other than that, the typical equipment in an office space are usually computers and printers/copy machines, which have relatively presumable heat generations. Although these equipment may not be existing in all zones, the value for them is also defined in terms of per square meters in order to make it equally applicable in the entirety of the building. 7.5W/m² is assumed to be the average heat production in the zones due to the equipment where each individual equipment has the capacity of 75 Watts. The number of units in a zone is assigned automatically by the simulation software, which is dependent on the floor area of the specific zone. The equipment assumed to be working during the same interval as the working hours for the occupants, noting that the lunch break is not an exception here.

Internal gains from the occupants are the most varying parameter due to various reasons causing from their mobility, level of activity and preference of clothing. Although it is hard to predict whether a given zone will be occupied all the time in its full capacity, activity level and clothing are more presumable depending on the type of work in a closed space. To measure those two factors, standards have been defined in ISO 7730 as MET for activity level and CLO for clothing respectively, which are derived from Fanger's studies. Since the case building contains offices spaces, the average values of 1.2 MET and 0.7 CLO have been selected which are reflecting the typical conditions in an office environment. 08:00 to 17:00 is assigned as the typical working hours for the occupants with an inserted one hour of lunch break between 12:00 and 13:00 where the occupants are not present in the building.

4.4 HVAC System

Table 13 - HVAC Parameters For The Case Building

Building Element	Value	Comments
Temperature Setpoints	Minimum: 20 ºC Maximum: 24 ºC	Different setpoints are applied in the later iterations
HVAC System	Ideal heater and cooler, AHU Central heating and cooling	Configurations may change depending on the iteration
Air Flows	Supply air: 1 L/s.m² Return air: 1 L/s.m²	Constant Air Volume (CAV)
Supply Air Temp. Setpoint	Constant 16 ºC Supply air temperature	Supply air temperature is not scheduled
Humidity and CO_2	Humidity: 20%-80% Level Of CO_2: 700-1100ppm	Values are for ideal heaters & coolers. Ambient CO_2:400
AHU Schedules	Always on	Assumed to be always on in ideal conditions
Chiller type, cap. and eff.	100% eff. Unlimited cap.	Electric cooling
Heating type, cap. and eff.	100% eff. Unlimited cap.	District heating
Hot Water System	25 L per occupant and day	Uniform distribution

The HVAC (Heating, Ventilating and Air Conditioning) system of a building is a key component for the indoor climate thus, also an indicator of thermal comfort. Given the enough budget and technology, it is possible to provide the desired temperatures, humidity, CO_2 level and air circulation at all times. However, in a more realistic perspective the aim is to keep the indoor conditions at a comfortable level as much as possible with a minimum dissatisfaction, while keeping the costs and energy consumption at a reasonable level.

To start with, it is crucial to define the HVAC system of the building before going into detail about specific components. Since the project is a parametric study and several cases will be compared and analyzed in the later chapters, the HVAC system is also one of the parameters that are subject to change. For the basic and ideal conditions, the heating, cooling and ventilation units are selected to be "ideal" units, which define them in the software as units with unlimited heating and cooling power (capacity) so, they can supply whatever amount of heating and cooling is necessary. The units are also assumed to be always on, which maintains the indoor temperature at a constant level all the time and prevents the disturbances during the temperature shifts at the ramp-up times. Desired temperatures in the building are set to 20 ºC minimum and 24 ºC maximum, which are the set points as well to trigger the heaters and coolers. Between that range, a constant 21 ºC is observed during the majority of the time.

A specific case worth to mention with temperature set points is the "night time setback". Although the base case, which has the ideal conditions, has the air handling units running all the time, it is not a very realistic practice as far as the office buildings are concerned. Keeping the indoor temperature stable and steady is important however; running the heaters and coolers during the unoccupied time is waste of energy. In order to optimize the energy consumption and climatization, the effort of heating and cooling should be channeled towards the working hours and unoccupied hours should be kept uncontrolled or semi-controlled depending on the outdoor conditions. For that specific purpose, the iterations other than base case have night time setback schedules which apply different heating and cooling regimes.

Furthermore, the heaters and coolers in the building are described to be ideal in the base case scenario, however those units are artificial and do not exist practically. In the further iterations radiators are placed on the wall as the heating units and coolers are placed on the ceiling as the cooling units. The power, schedule and such characteristics of the units and the heat exchanger and chiller they are connected to are detailed further under the relevant cases.

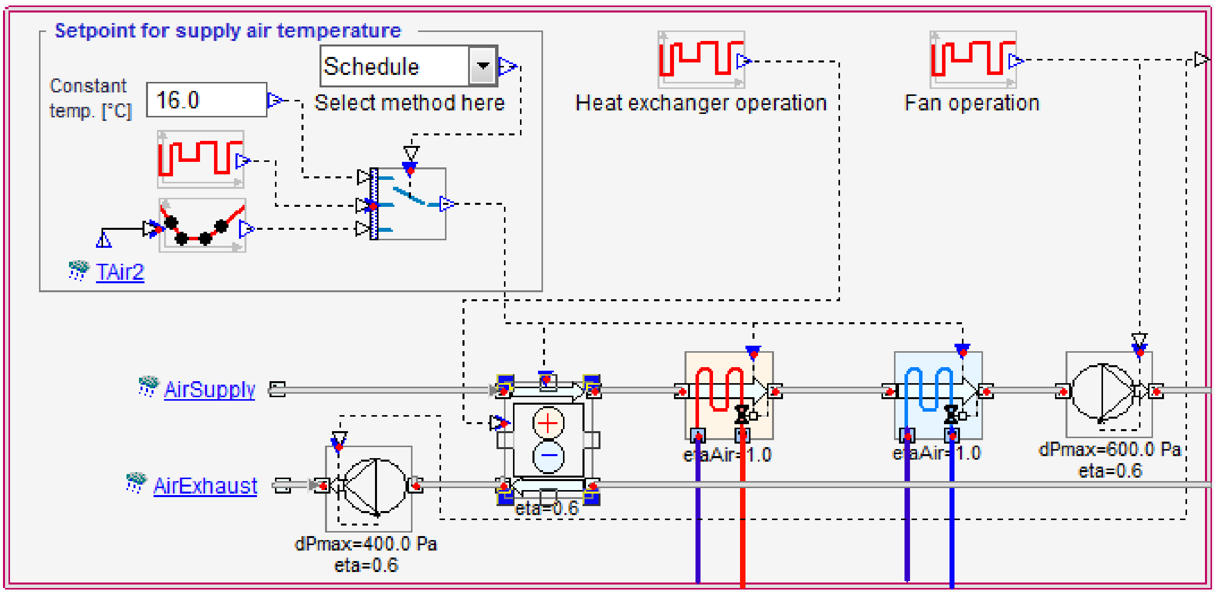

Figure 8 - Air Handling Unit Operation

5 THE SIMULATIONS

In this chapter, the outcomes generated from various runs of simulation according to the building envelope given above will be documented. The parameters listed in the internal gains and HVAC system however are subject to change since different configurations will be applied to the building in order to inspect what kind of impact do they make on the thermal comfort. The chapter starts with the base case to illustrate what would the conditions be like in an ideal state and then, changes to different parameters will be applied systematically. The results from the simulation give the opportunity to observe the state of the indoor temperature and thermal comfort under specific occasions. The impact of individual parameters will be shown in the next chapter, with the cross-comparison of the results that are listed here.

5.1 Base Case

The base case or in other words the ideal case is the set of configuration where all the variable parameters are either in default or optimal condition. That means, the building envelope is unchanged and the exact same design values for building elements are used. For the internal gains, there assumed to be 100% occupancy by the workers, who have typical activity and clothing suitable for an office environment. The equipment density is standard for an office where no significant heat producing device exists and lighting is working according to the defined schedule. The most notable setting for this case is that the HVAC components are ideal, which means they have unlimited capacity to supply any amount of heating or cooling required. The HVAC system also works 24/7 with the exception of scheduled holidays and there is no night time setback applied. The occupant is assumed to be located in the center of the room however that doesn't have any significance for this case since the heating and cooling devices are ideal, the temperature in the room is identical in every possible location. In Table 14 below, a list of temperatures and comfort indices have been shown for the zones.

Table 14 - Zone Temperatures & PPD's For Base Case

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Large Area 3	23.0	24.1	25.1	26.4	9.70
Large Area 2	22.5	24.1	24.8	26.3	9.37
Large Area 4	22.9	24.0	23.8	26.1	8.65
Large Area 1	22.5	24.0	23.4	26.0	8.44
Big Office 4	22.7	24.0	23.9	25.6	7.56
Big Office 1	22.4	24.0	23.6	25.6	7.38
Big Office 3	22.6	24.0	23.4	25.4	6.59
Big Office 2	22.2	24.0	23.1	25.3	6.48
Office 1	21.6	24.0	22.4	24.1	6.11
Office 6	21.6	24.0	22.4	24.1	6.05
Office 5	22.3	24.0	22.9	24.4	5.47
Office 2	22.3	24.0	22.9	24.4	5.45
Office 4	22.3	24.0	23.0	24.5	5.43
Office 10	22.7	24.0	23.3	24.6	5.42
Office 3	22.3	24.0	23.0	24.5	5.42
Office 9	22.7	24.0	23.3	24.6	5.42
Office 12	22.4	24.0	23.1	24.3	5.35
Office 7	22.4	24.0	23.1	24.3	5.32
Office 11	22.7	24.0	23.3	24.4	5.32
Office 8	22.6	24.0	23.3	24.4	5.31

As seen from Table 14, all the PPD values for every single zone are under 10%, which is a sufficient threshold for getting Gold for thermal comfort aspect according to Miljöbyggnad. However it is still worth to investigate the reason of discrepancy occurring between the zones.

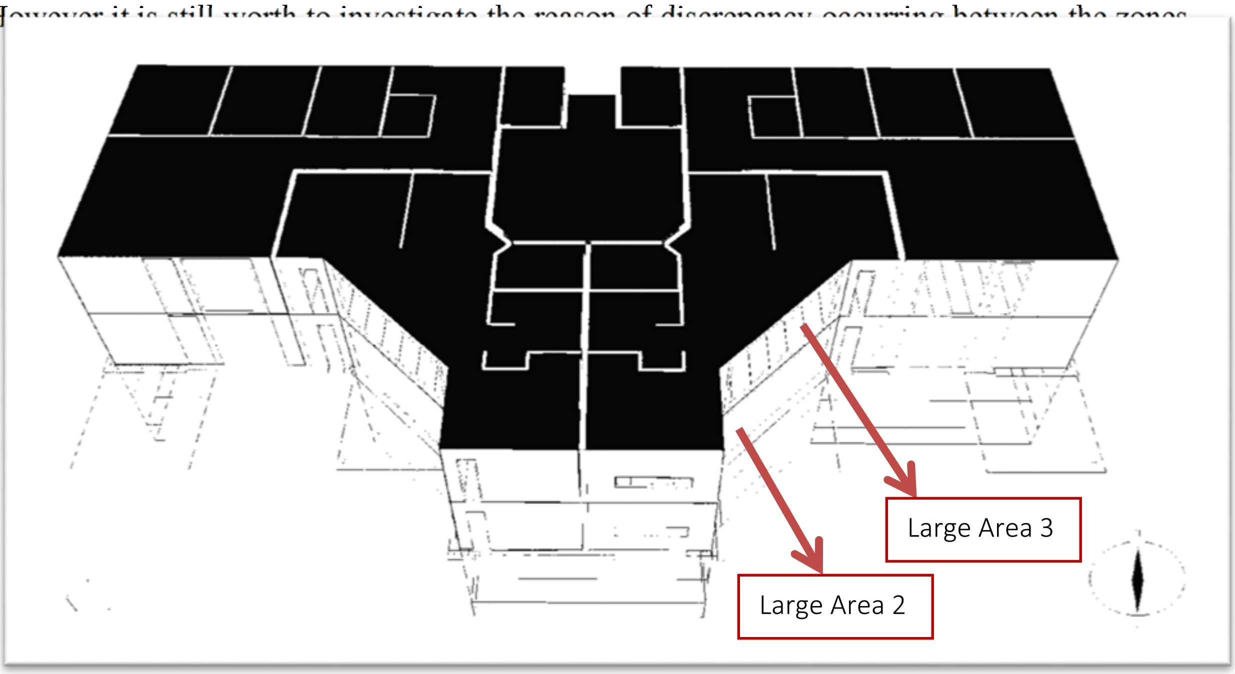

Figure 9 - Location Of The Most Dissatisfied Zones

Looking at the illustration in Figure 9, it is apparent that the two worst zones in terms of highest PPD are the large areas, which are on top of each other on the southern façade of the building. That means, these two zones are exposed to sunlight more than others during most of the working hours. Furthermore, by looking at the geometry of the zones, it is seen that they both have very large glass surfaces on the southern wall as well, which is increasing the solar gain even further. In order to distinguish the difference, it is helpful to look at the hourly

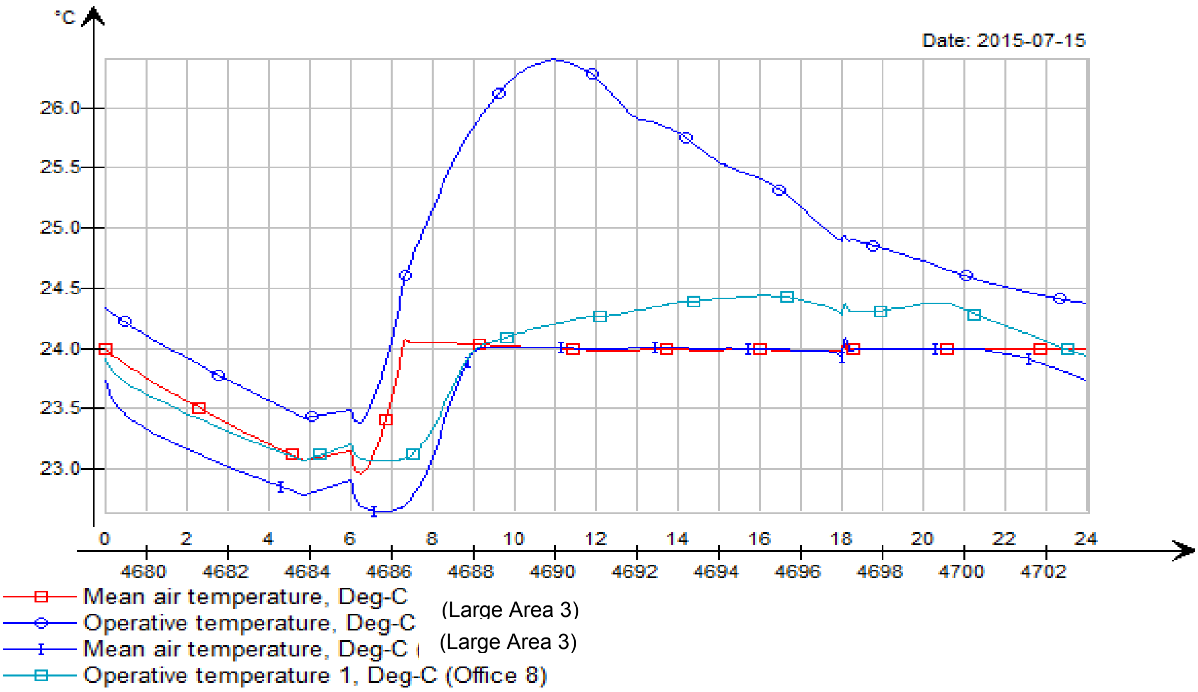

Figure 10 – Large Area 3 & Office 8 Zone Temperatures

temperature graph given in Figure 10. Although the outside temperature is higher, HVAC units are keeping the indoor temperature at a steady 24 ºC. However the operative temperature of Large Area 3 shows a very steep increase during the morning hours which it gets the most exposure to the sunlight. Office 8 on the other hand, is not suffering from the same problem since it is located on the northern façade of the building and has a trend line very similar to the mean air temperatures. As the hours progress, it is observable that the discrepancy between the lines gets smaller and the difference in operative temperature drops under 0.5 ºC. From this outcome, it can be said that the rooms facing south may need shading during morning-midday for a better thermal comfort, although current values are also acceptable.

Since it is noted that the solar gain is causing most of the discrepancy between the zones, it is also required to investigate the conditions in winter where the solar gain is significantly lower. In Figure 11 below, the graph shows the temperatures in two zones for a simulation date set in winter. As illustrated in the graph, the "Big Office 4" which is located on the western façade of second floor heats up to 24 ºC during the midday-afternoon. However "Office 8" which is one of the best zones for summer conditions can barely reach the minimum of 21 ºC with the help of heaters. Being on the northern façade eliminates almost all possibility of benefiting from sunlight for Office 8 and the indoor climate is entirely dependent on the heating devices.

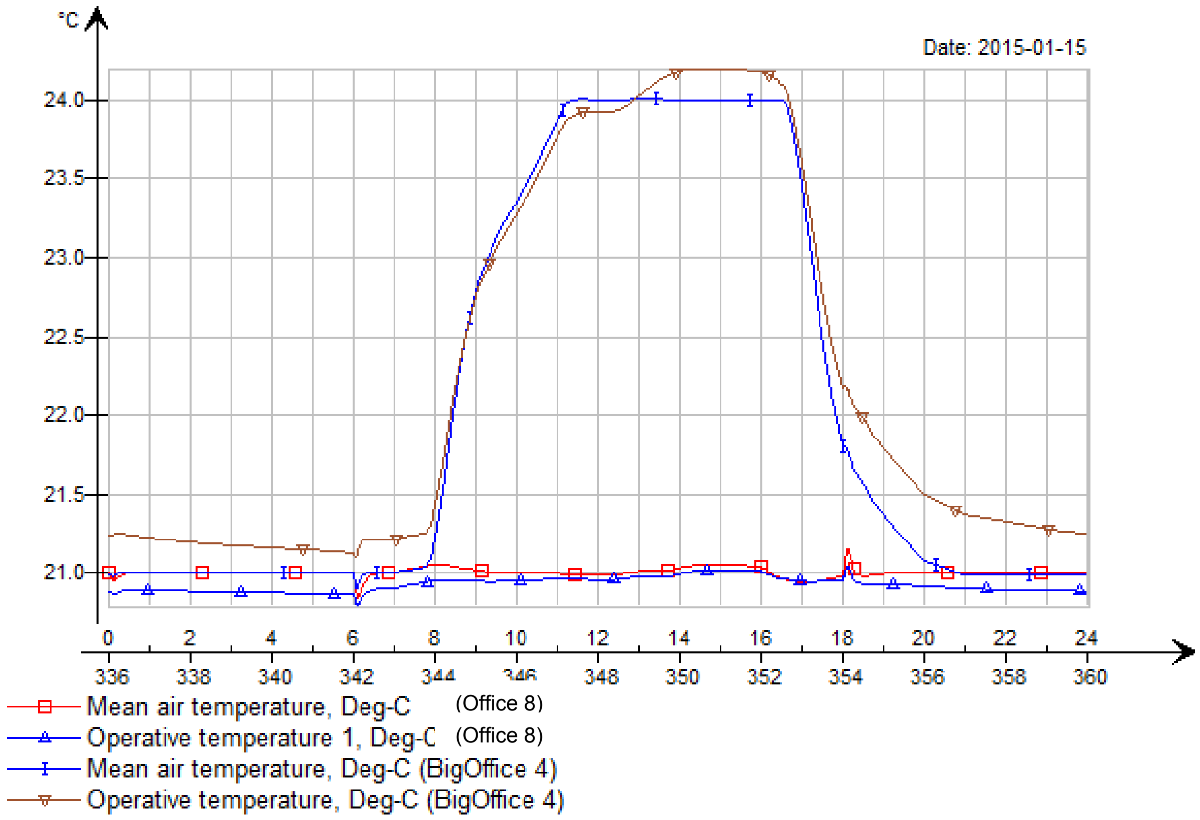

Figure 11 - Big Office 4 & Office 8 Zone Temperatures

For both summer and winter runs of the simulation it is important to note that although some differences in temperatures is observed between the zones, the PPDs are similar which is the real indicator of thermal comfort. As expected from the ideal case, none of the zones give a PPD higher than 10% which is the limit for best grade for thermal comfort aspect of the Miljöbyggnad certificate. The small variances are natural which stem from the geometry and orientation of the building as long as they keep in the allowed limits and not cause discomfort.

5.2 Actual Heaters & Coolers

The “Base Case” in the previous title was representing an unrealistic scenario with the most optimal conditions with the purpose of serving as a benchmark in the cross comparison with further iterations. The case described in this section however, is the first step for looking into the effects of different parameters since there are not unlimited capacity heating/cooling units existing anymore which can tolerate and nullify all the negative implications. For that purpose ideal heaters and coolers are removed from the zones and water radiators and cooling devices have been placed. As described in the HVAC system of the building description before, the heating units are connected to the heat exchanger, which the heating power is supplied from district heating. For the coolers there is central chiller in the building, operating on electricity.

The first hurdle with this iteration is determining the heating or cooling capacity of the room units, since they do not have unlimited capacities anymore as they had in the previous case. In order to determine that characteristic for the units, the heat balance graph is used from the ideal case, which gives a detailed report on how much heating and cooling power is used for the rooms hourly. An exemplary part of this report is shown below in Table 15.

Table 15 - Heat Balance Table For a Sample Zone

Hour	Variables (averages for preceeding hours)									
	Heat from air flows	Heat from occup. W	Heat from equip. W	Heat from walls and floors W	Heat from lighting, W	Heat from solar and diffuse, W	Heat from heating and/or cooling room units, W	Heat from windows and openings, W	Heat from thermal bridges	Net losses
6	-118.2	0.0	0.0	-69.2	0.0	0.0	**294.6**	-62.8	-42.8	3.4
7	-159.0	0.5	0.3	-87.7	0.4	-0.0	**357.7**	-62.7	-42.6	2.2
8	-172.2	30.3	17.2	-99.1	23.0	-0.1	**312.4**	-62.8	-42.7	0.9
9	-192.1	118.5	67.5	-106.6	90.0	-0.3	**142.0**	-63.0	-42.7	-2.2
10	-206.0	148.6	84.8	-102.9	113.0	4.3	**70.8**	-62.4	-42.7	-3.2
11	-209.3	148.3	85.0	-110.1	113.3	19.6	**60.0**	-59.8	-42.7	-3.3
12	-205.5	118.2	85.0	-110.2	113.3	33.7	**64.8**	-57.4	-42.6	-3.5
13	-197.0	60.8	85.0	-104.5	113.3	37.7	**97.7**	-56.5	-42.6	-3.4
14	-197.3	118.4	85.0	-105.3	113.3	33.1	**63.5**	-57.4	-42.7	-3.6
15	-205.5	148.2	85.0	-92.8	113.3	20.2	**44.1**	-59.8	-42.7	-3.7
16	-212.1	148.2	84.7	-82.1	112.9	5.6	**52.7**	-62.3	-42.6	-3.7
17	-216.9	118.8	67.8	-72.1	90.4	-0.3	**112.7**	-63.2	-42.6	-3.4
18	-198.7	30.6	17.4	-66.1	23.2	-0.1	**286.9**	-63.0	-42.6	-1.0
mean	-163.0	49.6	31.9	-80.7	42.5	6.4	**218.8**	-62.9	-43.3	0.4
min	-216.9	0.0	0.0	-110.2	0.0	-0.3	**44.1**	-70.7	-48.0	-3.7
max	-116.4	148.6	85.0	-57.1	113.3	37.7	**357.7**	-56.5	-42.6	3.7

The table above shows the heat balance of Office 6, taking into account the heat gained or lost due to various sources. The highlighted column represents the amount of heat provided during the day by the heating unit. So, when the ideal heater is eliminated, it is required put a source of heating as a replacement which can supply the amount of Watts taken from the heat balance for its particular zone. Using this method, the capacity of the room units are assigned individually with an adequate power so that they supply the enough heating or cooling even in the worst hours of the day in terms of indoor condition. In Figure 12, a screenshot from the simulation has been given, illustrating the placement of the room units in several rooms.

Figure 12 - Placement Of Room Units On The Western Wing

After making placement and capacity adjustment of the room units, the simulation was ready to run. Other parameters such as schedule of the room units, lighting and occupants are kept the same for an objective comparison. Thermal comfort is measured in the middle of the rooms same as in the ideal case and same temperature range has been applied (21ºC - 24ºC). After the run, the PPD and temperature results for summer have been listed as shown below.

Table 16 – Zone Temperatures and PPD's For Actual Heaters & Coolers

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Big Office 1	23.0	26.2	24.1	27.3	14.84
Large Area 3	23.1	25.3	25.1	27.3	14.40
Big Office	22.7	25.9	23.8	27.0	13.15
Large Area 2	22.5	25.1	24.8	27.1	12.64
Large Area 4	22.9	24.6	23.7	26.4	9.84
Large Area 1	22.5	24.4	23.3	26.3	9.15
Big Office 3	22.7	24.7	23.5	25.9	7.70
Big Office 2	22.3	24.5	23.1	25.7	7.18
Office 1	21.8	24.0	22.5	24.2	5.96
Office 6	21.8	24.0	22.5	24.1	5.95
Office 5	22.3	24.0	22.9	24.3	5.47
Office 4	22.3	24.0	22.9	24.4	5.47
Office 2	22.4	24.0	22.9	24.4	5.43
Office 3	22.4	24.0	23.0	24.5	5.42
Office 10	22.7	24.0	23.3	24.5	5.36
Office 9	22.6	24.0	23.2	24.5	5.35
Office 12	22.4	24.0	23.1	24.3	5.32
Office 7	22.5	24.0	23.1	24.3	5.31
Office 11	22.8	24.0	23.3	24.4	5.27
Office 8	22.7	24.0	23.2	24.4	5.26

In the first glance to Table 16, an overall increase in the PPD is the first thing to notice compared to the base case. On top of the table the 4 large areas and 4 big office spaces are found which are located on the eastern and western facades of the building. While it can be said that those zones may not have adequate amount of cooling, it is also important to note that they are heavily under exposure to sunlight during work hours, as opposed to small office spaces in the bottom of the table which are located on the northern façade. The most probable cause of rise in PPD's is that since there are not ideal coolers anymore, the peak hours during the day cannot be tolerated and compensated by the room unit as easily. Although the coolers are selected with adequate capacity, the cooling rate may not be balancing the heating rate caused from the sunlight and causing slight discomfort as a result. The hourly temperatures of the best and worst zones in this case have been given below to see the hourly difference.

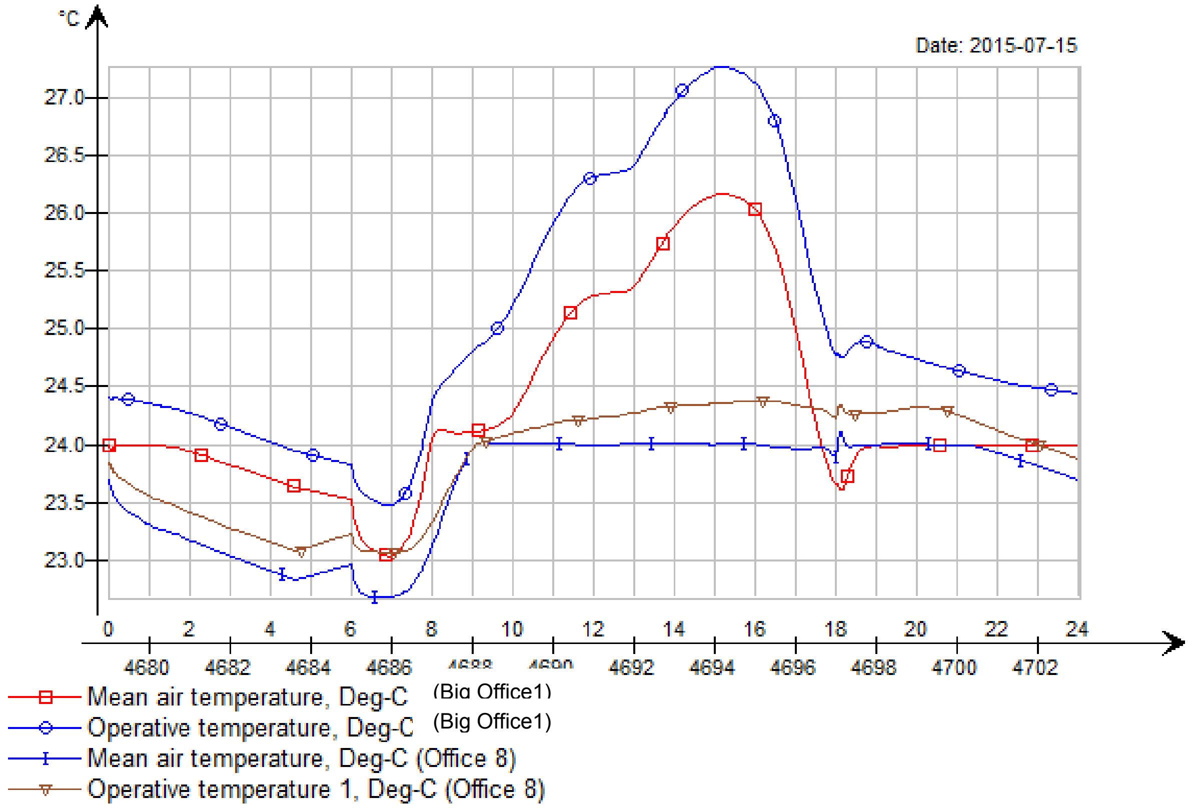

Figure 13 - Daily Temperature Graph of Big Office 1 and Office 8

From Figure 13, it is seen that the trends of the lines are very similar to the temperature graph in the base case, however the temperature values are slightly higher. The increase of the indoor temperature starts at 7:00 am with the turn on of the lighting and equipment. With the arrival of occupants at 8:00 am, the rate of increase gets even higher. Taking into account the metabolic heat exchange of occupants and emission from the lighting and equipment, 9:00 am is the earliest hour to start making comparison. It takes time until the heat sources and indoor air can finish the exchange and come to a heat balance. After that hour it is observed that Office 8, which is the best room in terms of comfort during summer, comes to a steady 24 ºC and stays there until the end of the day with the help of coolers. Since upper limit of the allowed temperature range is set to 24ºC, the cooling devices are not letting it go above that value, hence eliminating the possibility of any thermal discomfort. From the Table 16, the PPD of Office 8 is read as 5%, which is the lowest possible in the Fanger scale. "Big Office 1" on the other hand, fails to maintain in the desired range of temperatures during the day. Since the mentioned zone is on the western façade, it has relatively acceptable temperatures during the first couple hours in the morning. However, starting from the midday and afterwards, a very rapid increase is observed at the indoor temperature with a peak value around 15 o'clock. After the end of working hours and leaving of the occupants, the temperature in the Big Office 1 converges to Office 8 and almost becomes equal. In that case, the difference between these two zones during the day can be attributed to either lack of cooling power, effect of the occupants, exposure to sunlight or a combination of those factors in different percentages. Although increasing the cooling power might seem to be the "go to option", shading might be a solution to consider which is also examined in later stages.

As it is done in the base case, this case should also be investigated separately for winter conditions. Since the solar gain and amount of exposed hours are significantly lower during winter, the degree of thermal comfort in the zones may change drastically. Figure 14 shows the temperatures of the same two zones for a simulation day selected from winter season.

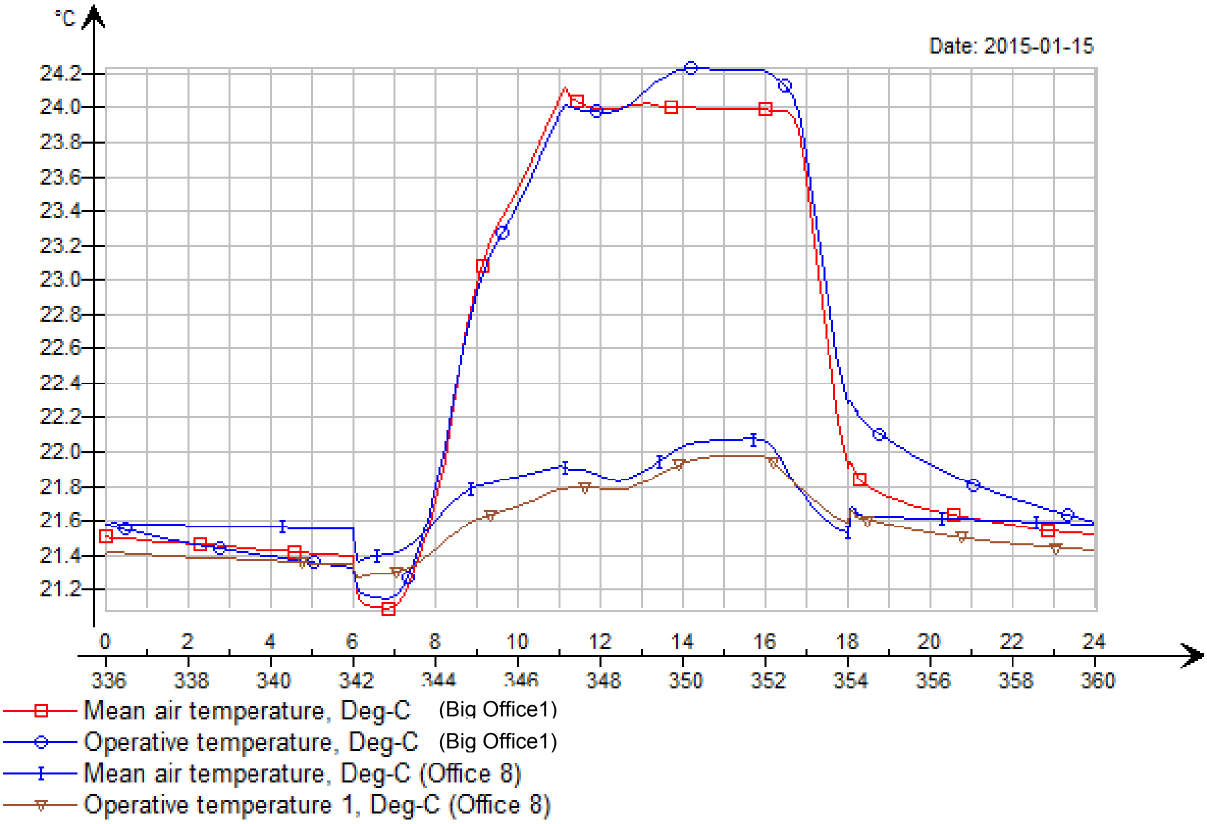

Figure 14 - Hourly Temperatures Of Big Office 1 and Office 8 (in winter)

In line with the expectations, the comfort performance of Big Office 1 relative to Office 8 is remarkably better in winter. While Big Office 1 hits the upper limit of the temperature range around 24.2 °C, Office 8 keeps just above the minimum at 21.8 °C average. Although the graph may give a sense of drastic differential, in reality both zones are still in the desired range and have 7.5% and 8.5% of PPD respectively. That results in a conclusion that the heating power of the radiators put in place as replacement for ideal heaters are sufficient for winter however, there are uncomfortable hours experienced by the occupants during summer.

5.3 Night Time Setback

Next case after replacing ideal room units with actual heaters and coolers is making changes on the schedule. The two previous cases had a fixed schedule for the operation of heating and cooling units which were fixed to a certain temperature for the entire day. The only time where the units were off was the Sunday in every week and the designated public holidays. For this particular case, the indoor temperature is set to be semi-controlled, which means the system let the temperatures go down or up to a certain degree depending on the season. That set point is selected in such a way that the limit temperature causes discomfort however since the building is not occupied during the off-hours, there is nobody to be affected. When the working hours about to start, the heating/cooling system turns on and brings the indoor temperature to comfort conditions. That difference between the day and night regimes of air control units is called "night time setback" which is a common application in non-residential buildings. Since the building in question also is used for office purposes here, instead of conditioning the indoor climate 24/7, applying a night time setback schedule is more realistic. The main purpose of the buildings managers to use such schedules for HVAC system is saving from the energy consumption. Residential units such as apartments, hotel, hospitals etc. are required to be conditioned continuously since there are occupants found inside at all times. However, office buildings which are being used in the normal work hours without night shift do not require conditioning during night. Albeit, conditioning those types of buildings is waste of resources and additional cost to the total energy consumption.

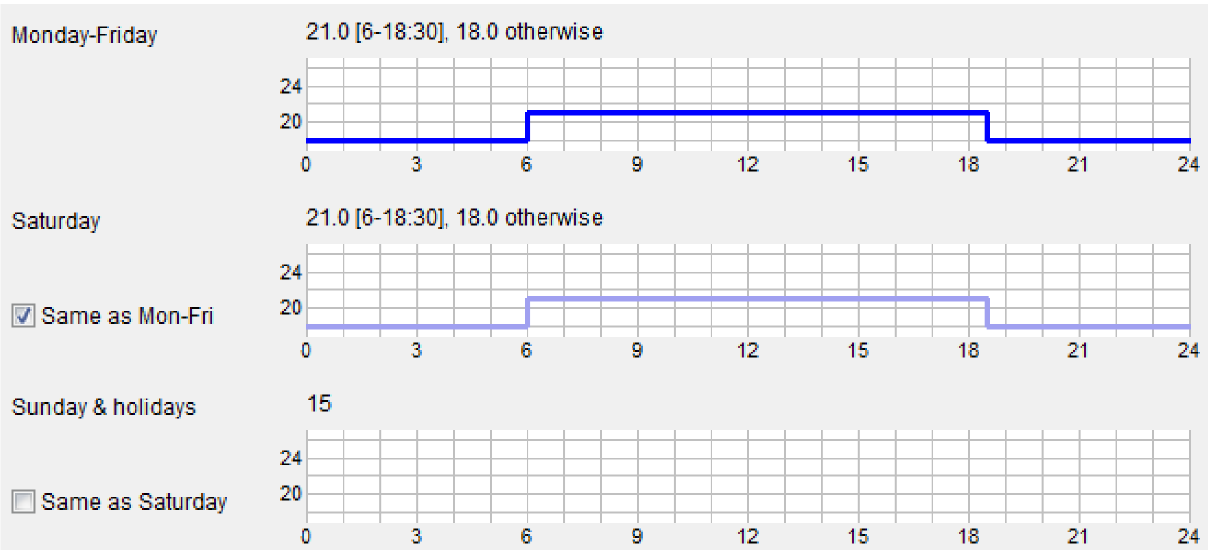

Figure 15 - Winter Schedule For Minimum Allowed Temperature

An important thing to consider while applying night time setback schedules is considering the "ramp up" times. Ramp up time means the amount of time required which the room units heat or cool the space to the desired temperatures. Depending on the type, capacity and efficiency of the system and size of the area to be conditioned, ramp up times may vary. Naturally, larger spaces require longer time to heat up compared to smaller spaces. Furthermore, that difference in size between the zones may cause an irregularity in terms of the individual temperatures. After the zones come to a heat balance within themselves, there is also a time required for the entire building to finish the initial heat exchanges and come to a steady state. Considering these facts, the schedule for the heating and cooling system should be designed in a way, which gives enough ramp-up time to the HVAC system and let the heat balance to occur before occupants start to use the indoor space.

In Figure 15, there is an example of how the night time setback is applied in the case project. The schedule is relevant specifically for winter season, since the most problematic application of such scheduling is experienced while controlling the minimum temperature in the building. To breakdown the schedule, the middle part represents the working hours where the minimum is set to 21ºC. As it is noticeable from the graph that, although the working hours start at 08:00 and end at 17:00, the operation of the heaters is turned up between 06:00 and 18:00. It is assumed that the first occupants arrive to the building starting from 07:00, so the indoor temperature should be risen to a relatively comfortable degree up until that time. By the start of the working hours, the indoor temperature is desired to be completely in the desired range. By the end of working day, the occupants are assumed to start leaving around 17:00, so that the heaters operate one extra hour to compensate for the occupants stay overtime or leave late. After 18:00 the controller set-point is dropped to 18 ºC since there are no occupants left in the building after that hour. The reason why the heaters are not completely turned off is that due to the very low outdoor temperatures in winter, leaving the indoor climate totally uncontrolled results in a drastic drop in temperature during the night. When the heaters start to operate again early in the morning, the ramp-up time becomes significantly higher because of the temperature difference they meant to neutralize. Then, it is required to either over-perform the heaters to increase the heating rate which possibly causes inefficient energy consumption, or set the starting schedule even earlier to compensate the ramp-up time discrepancy. Overall, both having a strict control and no control at all is not efficient in terms of the benefit gained from the heating system by the users. There is an optimal spot in between where the energy cost is lower than full-time heating and despite the comfort is relatively similar. For this case, the optimal spot is predicted to be around 18 ºC, and the simulation is run accordingly. To see how the night time setback affects the zones, the graph in Figure 16 can be inspected below.

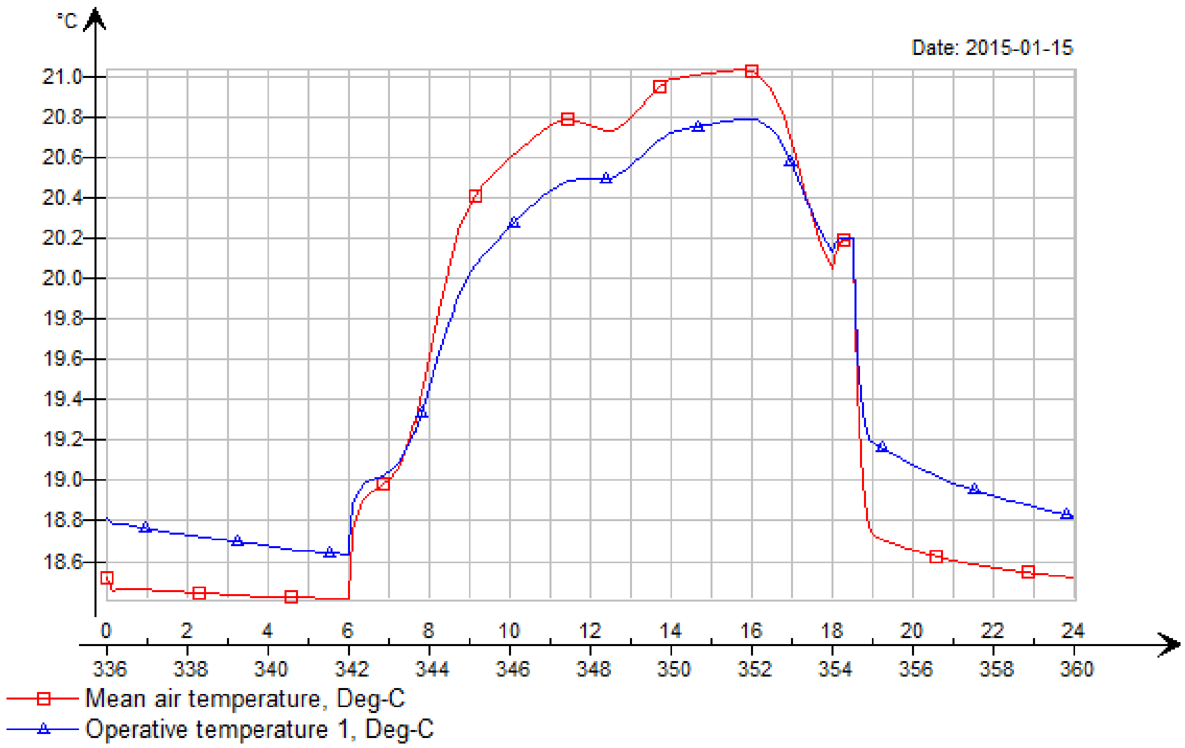

Figure 16 - Indoor Temperatures For Office 6

In Figure 16, the hourly temperature graph is given for one of the worst zones in terms of thermal comfort during winter which is located in the north-eastern corner of the building. The graphic shows that the temperature values follow a steady trend slightly above 18 ºC during night time. With the start of scheduled operation at 6:00, the indoor temperature starts to rise rapidly and the increasing trend continues until the desired minimum is reached, which is 21 ºC. Although the general temperature trend in the zone seems to be following the expectations, the most important thing to note is that the allowed minimum is not reached until midday. In the first working hour (08:00-09:00) the temperature is between 19.5 ºC and 20 ºC, which means there is a high possibility that the occupants would consider the space slightly cold. However after 10 am and afterwards, the temperature rises above 20 ºC, which is almost in the comfort range and stays around acceptable degrees until the work day is over. As it can be observed clearly, night time setback affects the first couple of working hours slightly, and may cause a discomfort during these hours temporarily.

For an objective inspection on the effects of the night time setback, it is necessary to look at multiple zones to assess whether the observed difference applies everywhere. For that purpose the temperature graph of Big Office 1 is given below in Figure 17, which was one of the best zones according to prior case with no setback in schedules.

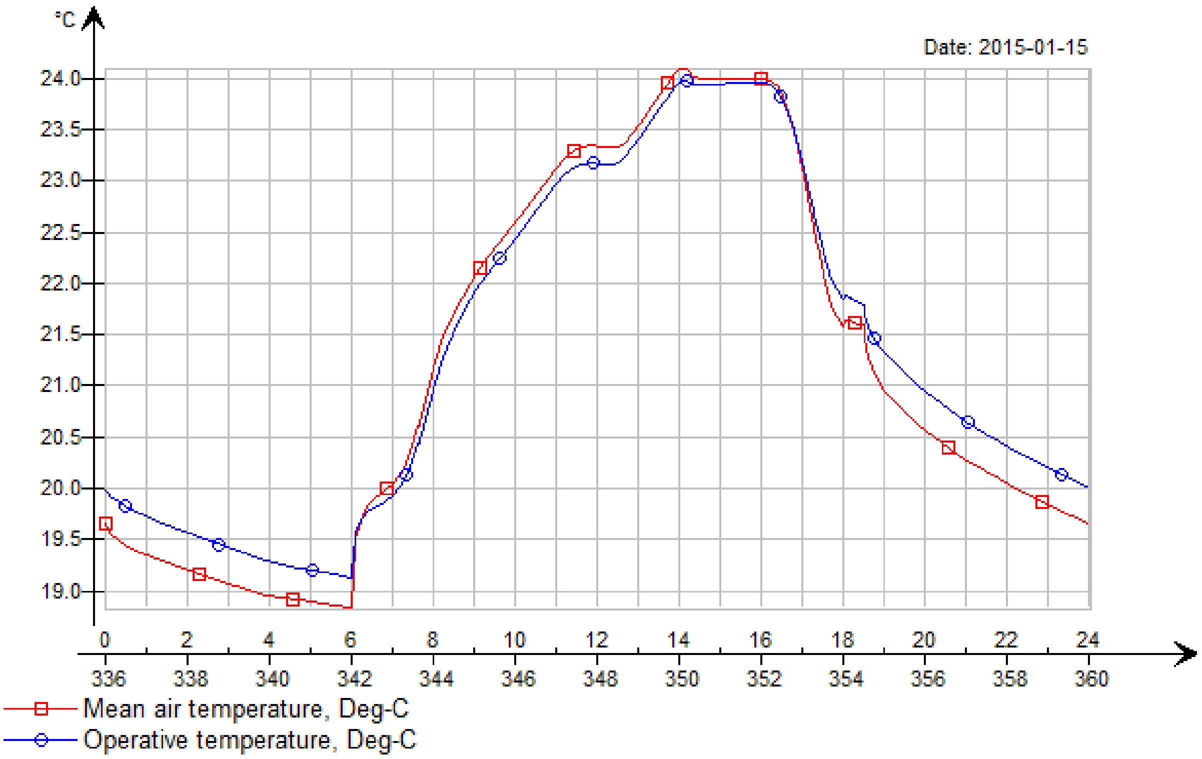

Figure 17 - Indoor Temperatures For Big Office 1

When the temperatures are compared during the first working hour in Big Office 1 and Office 6, it is seen that there is a 1.5 ºC difference where Big Office 1 starts the day in better conditions. It can be mostly related to that since Big Office 1 is located on the eastern façade, despite the winter season it slightly benefits from the sunlight in the morning. As expected, the temperature continually rises in the proceeding hours and caps at 24 ºC which is the maximum limit. Although it seems like Big Office 1 is not affected from the setback schedule, the temperature diagram of the same zone in case 2 indicates that the working hours start in this zone around 22 ºC. That concludes there is still a marginal drop in the first few hours in Big Office 1, however with the help of sunlight it doesn’t reach to a degree which can cause discomfort. In Table 17, the PPD percentages for office spaces are shown together, which illustrates the comfort situation in the relevant zones after the application of setback schedule.

Table 17 - Zone Temperatures and PPD's For Night Time Setback Schedule

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Office 6	18.4	21.0	19.4	20.8	15.22
Large Area 2	18.4	21.6	19.4	21.5	14.95
Office 1	18.4	21.1	19.4	20.9	14.93
Large Area 1	18.5	21.6	19.4	21.6	14.93
Large Area 3	18.5	21.7	19.6	21.6	13.94
Big Office 2	18.5	21.7	19.6	21.7	13.91
Large Area 4	18.5	21.8	19.6	21.7	13.89
Office 7	18.6	21.4	19.8	21.1	13.51
Office 12	18.6	21.4	19.8	21.1	13.21
Big Office 3	18.6	21.8	19.9	21.8	12.95
Big Office	18.7	23.6	20.4	23.6	10.88
Office 5	18.7	21.7	20.5	21.5	10.70
Office 2	18.7	21.7	20.5	21.5	10.62
Office 4	18.7	21.7	20.6	21.7	10.37
Office 8	18.8	21.8	20.6	21.6	10.35
Office 3	18.7	21.7	20.6	21.7	10.28
Office 11	18.8	21.8	20.7	21.6	10.25
Office 9	18.8	21.8	20.7	21.7	10.10
Office 10	18.8	21.8	20.8	21.8	9.96
Big Office 1	18.9	24.1	20.7	24.0	9.75

In the first glance to Table 17, first noticeable change compared to the case without a setback schedule is the increase in PPDs across the board. As explained before regarding to the temperature graphs, since night time setback schedule introduces the ramp-up time, first few hours in the morning are slightly less comfortable. After the heaters reach their full capacity and the heat balance is maintained, the dissatisfaction rates return to normal values, however because of the PPD increment in the morning hours, the overall average and peak point is found to be higher.

Another observation worthwhile to mention from this table is the upper and lower limits of PPD across the building. In Case 2, where the heaters were constantly on, the PPDs were ranging from 5% minimum to 15% maximum across all zones. In Case 3 however, it is seen that although the upper limit still hovers around 15%, the dissatisfaction experienced in the most comfortable zone rose up to around 9.75%. In a similar fashion, the other office rooms with a 5% PPD in the previous case have all risen up to 10% or more. An important detail here is, all the zones with a remarkable increase in maximum PPD are located in the northern façade. What can be derived from that situation is, while night time setback schedule is impactful on every zone, the effects are observed more clearly on the zones which do not have the opportunity to heat up with solar gain. The zones which are mostly located on the eastern façade can partially negate the temperature drop because of benefiting from the sunlight.

Despite the winter season, the effects of night time setback schedule cannot be observed as easily during the summer period. Since the outside temperature during the night in summer is closer to the comfort temperatures, it is apparent that there is no need to control the indoor temperature during the off hours. The heat stored in the building is partially released at the night naturally, so the coolers can bring the indoor air to desired temperatures quickly, with little to no ramp-up time. Hence applying setback schedule or not is insignificant for summer.

5.4 Location Of Occupant Inside The Zone

Another parameter which is expected to affect the measured value of thermal comfort is the location of occupant inside the zone. As mentioned before, naturally occupants are the most mobile factor in the thermal comfort equation since their presence, activity and orientation regarding to room units (heaters and coolers) cannot be determined. In different hours of the day different zones may show high or low occupancy rates regarding to the necessities of the work or people may even change their positions in the room during the day. In ideal circumstances where the room is equally heated or cooled in every section homogeneously, the occupants are not expected to experience a change in thermal comfort according to their locations. However in a more realistic case where there is the presence of a single heating or cooling source in the room, the local feeling may differ even in boundaries of small areas. To investigate this prediction, the simulation shall be run with occupants placed different positions in the zones while keeping rest of the settings for building exactly similar.

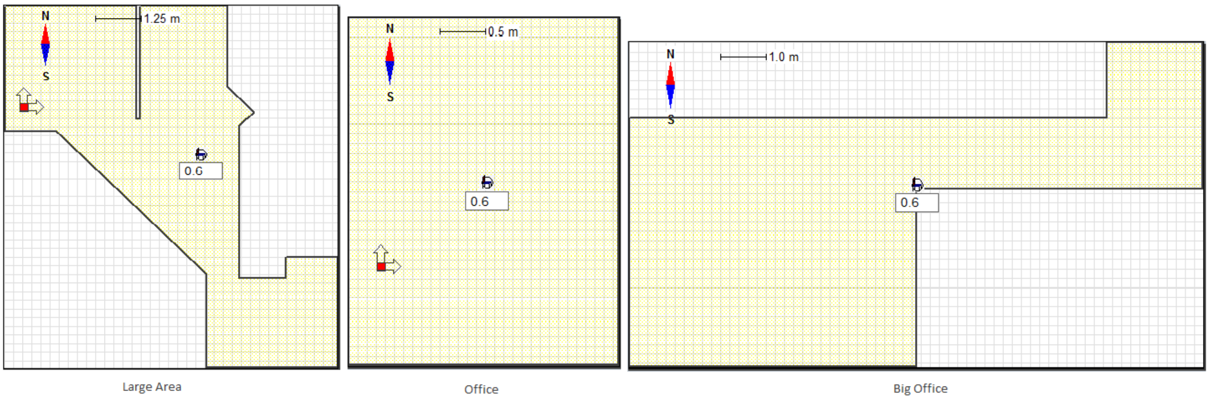

Figure 18 - Zone Types and Default Occupant Positions

In Figure 18, the locations of the occupants are illustrated for three different zone types in the building. On the left side, there is a floor plan for the large areas, which are located on the both flanks of the building. In the middle, there is a simple rectangular room which is the shape of all office spaces lined next to each other on the northern façade. At the right side there is a plan for the big offices which are located on both wings of the building right above the large areas. In Figure 19, the orientation of zones can be seen on the floor plan.

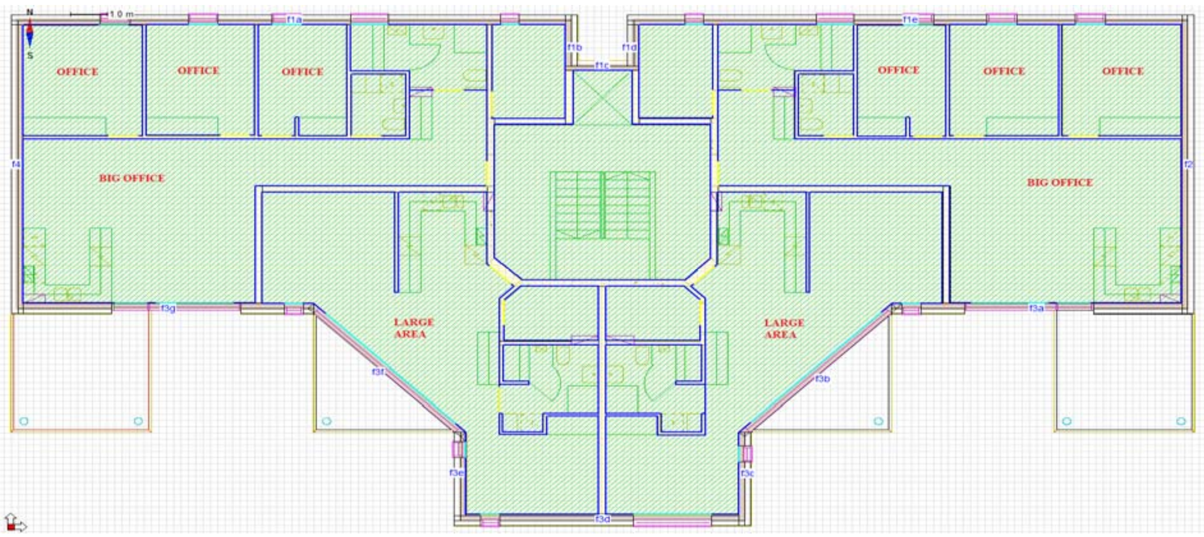

Figure 19 - Floor Plan With Zones Labeled

The shape and geometry of the zones have significant importance while examining the impact of the occupant location since the zone size, location of windows and placement of the heat sources are major determinants on the comfort feeling of the occupant. The size of the zones influence the number of room units placed, therefore indirectly affects the distance of the occupant to the closest room unit. The size and distance of windows are influential as well especially during summer season where the zones are exposed to sunlight for a long period. Given the fact that every zone type is unique in terms of the mentioned characteristics which are geometry, size and room units; the relocation of the occupants also should be handled separately according to the zone configurations. Different to previous cases, the changing parameter cannot be applied in a catch-all pattern and should be applied to zones manually.

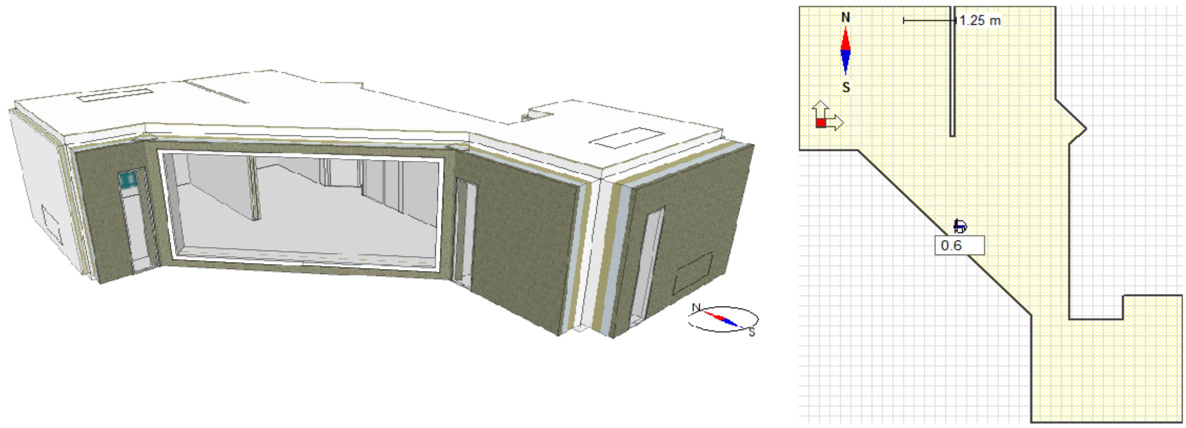

Figure 20 - Occupant Placement For Large Areas

Starting with the large areas, the most noticeable characteristic of this type of zone is the presence of a very large window on the diagonal wall. Large Area 2 and 3 which are located on top of each other on the eastern façade gathering extensive amounts of solar gain through these windows until midday and the same scenario applies for the Large Area 1 and 4 after midday. The zone geometry is in a long, irregular shape which consists of two large spaces on both ends and a semi-corridor in between. From Figure 20, it is noticeable that the radiators which are represented with rectangular shapes on the bottom of walls are found in both ends and nonexistent through the corridor. In the same manner, the coolers are also represented with rectangles which are mounted on the ceiling and in the same way they are located on the both ends to condition the semi-open rooms efficiently.

In Figure 18, it is seen that the default location of the occupant was assumed to be in the very center of the room geometrically in previous cases and calculations are done accordingly. For this case, the occupant is located very close to the nearest window as seen in Figure 20, for a couple of reasons. First, hence the half-open rooms at both ends have their own room units, so it is assumed that these zones crate their own climatic environment which is relatively independent from the corridor. Placing the occupant in either of these spaces would only measure the comfort in those two areas and not reflect the overall condition of the zone entirely. The corridor however does not include any room units and the conditioning occurs through the air flow coming from its both ends. In this manner, the corridor can be considered as the place where heat balance happens thus measuring the comfort here would be a better representative for the zone it belongs. The other reason is the presence of the large window as mentioned previously which is too influential to be neglected. Surrounding the occupant with walls by placing them at either southern or northern end of the zone would negate some of the influence. Therefore somewhere on the corridor very close to the large window is found to be the most suitable spot for investigating the thermal comfort in four large areas of the building.

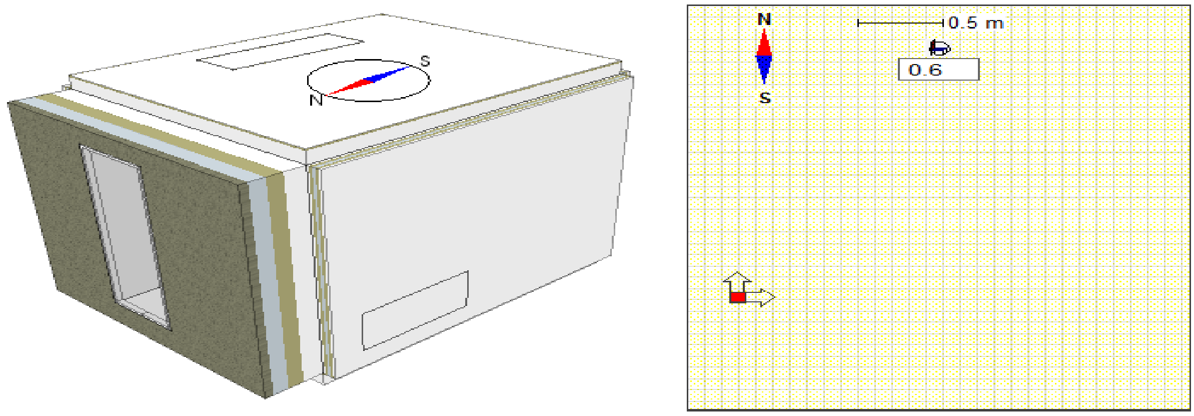

Figure 21 - Occupant Placement For Offices

Compared to the large areas, the office rooms on the northern façade are smaller and simpler in terms of shape. Although their sizes are slightly varying from each other, the general geometry is typical rectangle. Apart from shape it is seen that each of these offices has a slim long window facing north which would possibly not contribute much in terms of solar gain. For room units, there are radiators placed on the longer walls which are very close to the intersection line with window mounted walls. The cooling units on the ceiling are relatively centered. For a room approximately 10 m², there is a single unit for each heating and cooling. Under those circumstances, the most logical case is moving the occupant next to the northern wall as much as possible due to two reasons. Being closer to the windowed wall provides the possibility to observe whether the comfort is affected positively or negatively by being closer to the heat source and window especially in winter. Since the window is facing north and the cooler is mounted centrally on the ceiling, not a remarkable difference is expected in summer.

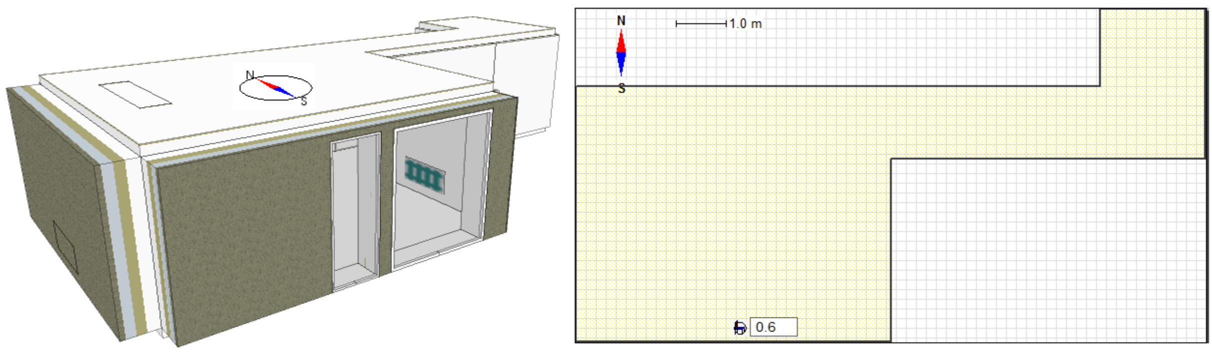

Figure 22 - Occupant Placement For Big Offices

Big offices consist second largest zone type in the building which have similar floor surface to Large Areas around 45 m². Unlike the Large Areas, Big Offices have a single large space and a corridor which serves as a hallway to three smaller office rooms at the same time. As seen from Figure 22, the zone has 2 radiators on the walls opposite to each other, and a single cooler mounted on the ceiling. There are two windows on the southern wall which have the potential of providing significant solar gain through the day especially in summer. When it comes to measuring thermal comfort, it is evident that the occupant should be placed somewhere in the main area since it consist the majority of the zone. Also considering the fact that the corridor here only serves as an interconnector, all of the occupants and equipment are expected to be found in the main area. Therefore, the default location may not be the best representative for this particular zone and different results can be observed by placing the occupant around the windows in the main area.

After the locations of the occupants are changed in all corresponding zones according to the pattern explained above, the simulation is run to investigate the new values for thermal comfort measured. In Table 18, the zones are listed with new temperatures and PPDs.

Table 18 - Temperatures and PPDs For Altered Occupant Locations

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Large Area 3	23.7	25.6	25.1	27.6	20.85
Big Office 1	23.6	26.4	24.6	27.4	19.81
Large Area 2	23.9	25.3	25.2	27.2	17.55
Big Office	23.7	25.9	24.8	27.0	16.00
Big Office 3	23.4	25.1	24.3	26.2	10.72
Large Area 4	23.4	24.1	24.4	25.7	9.46
Big Office 2	23.7	24.8	24.5	25.9	9.30
Large Area 1	23.9	24.1	24.6	25.6	9.05
Office 10	23.4	24.0	24.2	24.7	6.55
Office 11	23.4	24.1	24.1	24.8	6.55
Office 8	23.4	24.1	24.1	24.8	6.53
Office 9	23.4	24.0	24.2	24.7	6.53
Office 3	23.9	24.1	24.4	24.7	6.45
Office 2	23.8	24.1	24.3	24.8	6.43
Office 4	23.8	24.1	24.4	24.7	6.43
Office 5	23.8	24.1	24.3	24.7	6.41
Office 7	23.3	24.1	24.1	24.5	6.21
Office 12	23.3	24.1	24.1	24.5	6.18
Office 6	23.8	24.1	24.3	24.5	6.14
Office 1	23.7	24.1	24.3	24.5	6.11

The PPDs values shown in Table 18 which are taken from a simulation day during summer season show that there is a drastic increase in discomfort for Big Offices and Large Areas. On the other hand, the dissatisfaction percentages for smaller office spaces are hovering around at almost ideal numbers. The discrepancy between the zone types is vastly remarkable and the distribution of discomfort is totally heterogeneous. The numbers indicate that specific zone types are either very comfortable or uncomfortable and there are very few zones which are in between. There could be more multiple possible explanations for that particular instance.

First of all, when the common property of the worse zones is investigated, it is found that all four zones above 15% PPD are zones with high window to wall ratios. It means that there are large windows mounted on every one of these four zones which may be contributing to the dissatisfaction. Furthermore, recalling the pattern for occupant placement, the occupants are relocated closer to the window compared to their default locations. Their exposure to sun may be increased according to the new setup, since they are closer to the primary inlet of sunlight.

Another common characteristic is, the top three zones on the table with highest PPDs are all located on the eastern façade of the building. Considering the fact that the pattern of getting the occupants closer to the windows is applied for all zones including the small office rooms, the implications have been observed most intensely at the zones on the eastern façade. Apart from the relocating pattern itself, not having bad results on the small office rooms with slim window openings on the northern façade might be an indicator that the orientation of a particular zone in the building and the window area are the contributors of the problem.

Due to both estimated reasons are applicable for summer conditions, the PPDs should also be looked at for a simulation day in winter for a more precise evaluation.

Table 19 - Temperatures and PPDs For Altered Occupant Location in Winter

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Large Area 3	18.4	21.6	19.3	21.5	15.59
Large Area 4	18.4	216	19.3	21.6	15.51
Big Office 3	18.5	21.6	19.5	21.7	14.31
Office 7	18.3	20.9	19.6	21.0	14.21
Office 12	18.4	21.0	20.0	21.3	12.67
Large Area 2	18.7	21.7	20.1	21.5	12.12
Large Area 1	18.7	21.7	20.1	21.6	12.01
Office 8	18.7	21.7	20.2	21.1	11.90
Office 11	18.7	21.7	20.2	21.2	11.72
Office 6	18.7	21.3	20.4	21.2	11.27
Big Office 1	18.6	23.5	20.4	23.6	10.94
Big Office 2	18.9	21.8	20.4	21.8	10.89
Office 5	19.2	21.8	20.6	21.2	10.60
Office 9	18.7	21.7	20.6	21.7	10.51
Office 2	19.3	21.9	20.6	21.3	10.40
Office 10	18.7	21.7	20.6	21.7	10.40
Office 1	18.7	21.4	20.7	21.5	10.03
Office 4	19.1	21.8	20.9	21.7	9.47
Office 3	19.2	21.8	20.0	21.8	9.30
Big Office	20.0	24.0	20.4	23.9	8.03

As seen in Table 19, the PPD values across the zones got slightly better in terms of having a more homogeneous distribution. While the summer simulation was stating that the most uncomfortable zone is three times worse than the best one and there is next to no middle ground; that is not the case for winter. Although the dissatisfaction in the better zones went up marginally, the worse zones showed much more of an improvement in terms of comfort. Taking into account that having 6% or 8% of PPD is not a distinguishable quality by the occupants, improving the worst zone by 5% can be the difference for a grade of certificate. Apart from the leading zones in both ends of the comfort scale, having most of the remaining zones hover around the average values is a healthier condition for the building. Under any given circumstance there will be best and worst zones according to several parameters in the building however, having the majority around the same comfort level indicates the balance.

In order to find the reason of improvement, investigating the changes at Offices 1 to 6 could be the best starting point. In the PPD tables of Case 3 and the other cases before, the small office rooms lined up in north notoriously showed lesser performance in terms of thermal comfort during winter seasons. Meanwhile the occupants in these particular zones have been moved closer to the window for Case 4, they also got closer to the radiators because from the HVAC design it is seen that the radiators are placed to the longitudinal walls in a position where they can be as close as possible to the windows. Also from the night time setback, it is known that most of the discomfort is observed during morning hours at the small office rooms. Therefore considering these factors together, it can be concluded that moving the occupants closer to the heat source have improved their feeling of indoor environment during the problematic hours and less number of occupants have voted for dissatisfaction.

5.5 Installment Of External Shaders

In almost every case before except the Base Case, a common problem is observed no matter what the configurations are. The 4 Large Areas, which have very large windows and facing towards east and west directions are suffering from excessive solar gain especially during summer time. Since the Base Case had ultimate capacity coolers, the amount of dissatisfaction seemed to be in the desirable range. However, all iterations after that made the problem more apparent. As mentioned in Case 2, there were two possible solutions that proposed for this particular problem. One was increasing the cooler capacity which may be problematic in itself due to excessive air speed and draught; and other one was placing shaders to limit the allowed sunlight. Since second option is more plausible, its implications are investigated in Case 5.

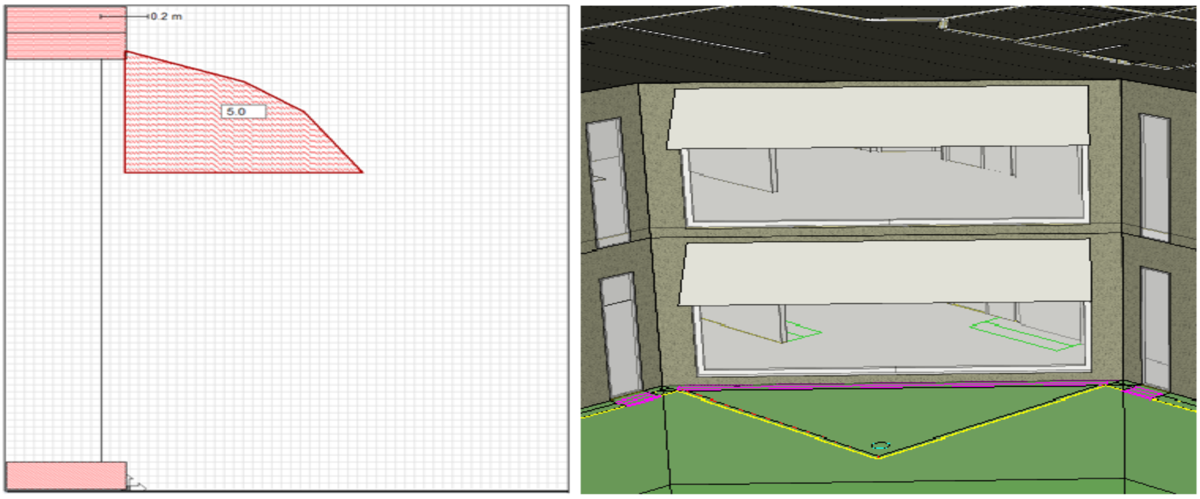

Figure 23 - 2D and 3D Model Of The External Shaders

For this specific configuration, the shaders are designed in a way to fit the wide windows of the Large Areas 1 to 4. The stock shader in the simulation software have been taken as a reference which is 3mx1m in dimension and the intersection line has been extended to 5m to cover the entirety of the window. The perpendicular extension to the window has been kept as 1m, which is the reference value and transparency is set to 0 to fit the desired purpose. In Figure 23, the 2D sketching of the shader can be seen on the left and the 3D illustration of the finished design on the right. The Figure 24 shows the appearance of building after installation.

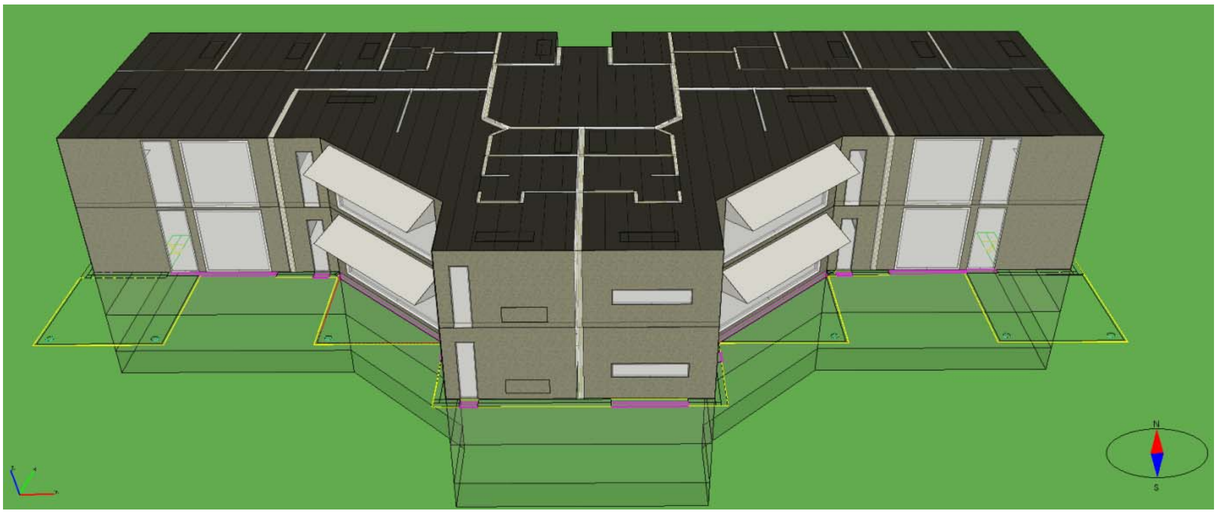

Figure 24 - 3D View Of The Building After The Installment Of Shaders

After the placement of the shaders, the simulation is set to run. As it has been a pattern in all of the previous cases, the parameters have been kept the same with the previous iteration, except the one which is uniquely specific for the particular case. In regards to that, the same configuration has been applied which is also used in Case 4, in order to observe how the outcomes change. Since the application in this case can be considered as a precaution for the discomfort in summer, the simulation is run for June 15th and following results are obtained.

Table 20 - Internal Temperatures and PPDs in Summer After Shader Installment

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Big Office 1	23.6	26.4	24.6	27.4	19.77
Big Office	23.7	25.9	24.7	27.0	16.03
Big Office 3	23.4	25.0	24.3	26.1	10.48
Big Office 2	23.7	24.7	24.5	25.8	9.14
Large Area 3	23.2	24.0	24.6	25.3	7.84
Large Area 2	23.8	24.0	24.7	25.3	7.73
Large Area 4	23.0	24.0	23.9	25.1	7.60
Large Area 1	23.7	24.0	24.4	25.1	7.39
Office 10	23.4	24.1	24.2	24.7	6.56
Office 11	23.4	24.1	24.1	24.8	6.55
Office 9	23.4	24.1	24.1	24.7	6.53
Office 8	23.4	24.1	24.1	24.8	6.53
Office 3	23.9	24.1	24.4	24.7	6.45
Office 2	23.8	24.1	24.3	24.8	6.43
Office 4	23.8	24.1	24.3	24.7	6.43
Office 5	23.8	24.1	24.3	24.8	6.41
Office 7	23.3	24.1	24.1	24.5	6.21
Office 12	23.3	24.1	24.1	24.5	6.18
Office 6	23.8	24.1	24.3	24.5	6.14
Office 1	23.7	24.1	24.3	24.5	6.12

The internal temperatures in the relevant zones and PPD values are given in Table 20. Since the results are from a summer day simulation, the small office rooms in the northern façade are listed at the bottom of the table hence they don’t suffer much from the sunlight in working hours. However when the top quarter of the table is examined, there is a very major difference observed in the PPDs of Large Areas. Those Large Areas especially Large Area 2 and 3 had over 15% dissatisfaction rate according to Case 4. That PPD rate is out of the boundaries even for Miljöbyggnad silver and overshadowing the good PPDs obtained in other zones. But in Case 5, all the zones which shaders are mounted (LA 1 to 4) have PPDs around 7% which is in under the limit for Miljöbyggnad gold. Large Areas 2 and 3 in particular, which are found on top of each other in the eastern façade showed more than 100% of improvement. Recalling the values from Case 1, the Base Case which had ideal coolers gave around 9% of PPD for Large Areas. Therefore the 7% PPD obtained by the influence of shaders is something that cannot be achieved even with the best coolers. That indicates the significance of improvement

For that new list of zones in terms of maximum thermal dissatisfaction, Big Offices took the top of rankings with high PPDs, while Large Areas drastically fell down. Big Office and Big Office 1 in particular have considerably high PPDs when the general distribution is concerned among the remaining zones. If those two zones are discounted, it is seen that rest of the building is in a very desirable condition. Therefore, instead of changing a parameter which might impact the entirety of the building, the same shader solution may be applied as well.

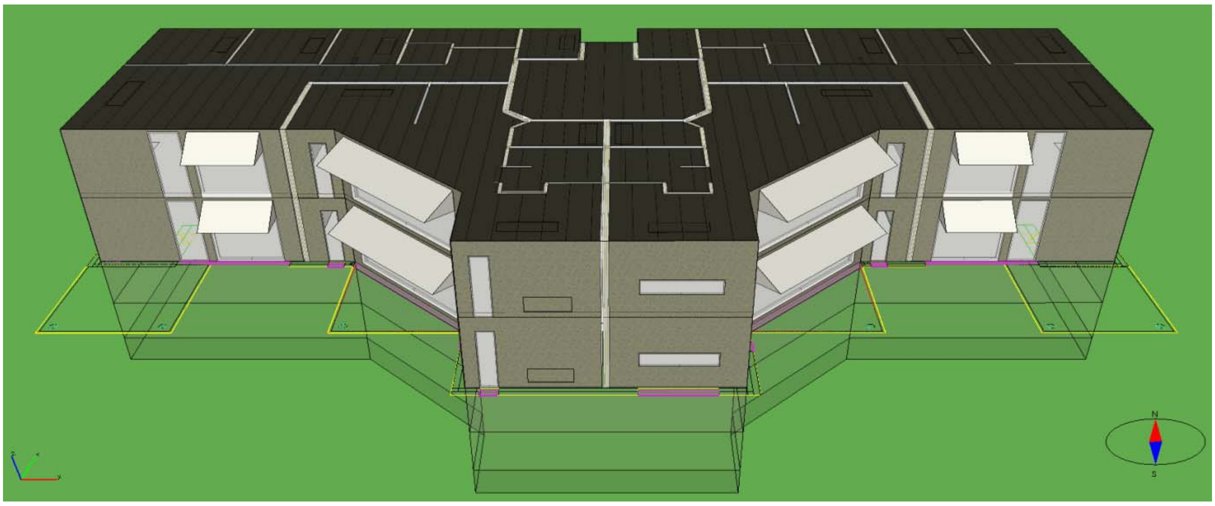

Figure 25 - Shader Installment To Big Offices

After the successful results achieved by mounting shaders on the two most problematic zones, same method has been applied to investigate whether it will have the same effect on the two other high PPD zones, to bring down the overall PPD of the building. As seen in Figure 25, shaders have been mounted on the larger windows of the 4 Big Offices, which are facing south. Narrow windows assumed to be not contributing much with solar gain hence neglected.

Table 21 - Internal Temperatures and PPDs After Shader Installment To Big Offices

Zone	Min temp	Max temp	Min Op. Temp	Max Op. Temp	Max PPD %
Large Area 3	23.1	24.1	24.6	25.3	7.82
Large Area 2	23.8	24.1	24.6	25.3	7.71
Large Area 4	23.0	24.0	23.9	25.1	7.55
Large Area 1	23.6	24.0	24.4	25.1	7.35
Big Office 4	23.1	24.1	23.9	25.0	7.07
Big Office 2	23.1	24.1	23.9	25.0	6.97
Big Office 3	23.6	24.1	24.3	25.0	6.91
Big Office 1	23.6	24.1	24.3	24.9	6.84
Office 8	23.4	24.1	24.0	24.8	6.53
Office 11	23.4	24.1	24.0	24.8	6.53
Office 9	23.4	24.0	24.1	24.7	6.51
Office 10	23.4	24.0	24.1	24.7	6.51
Office 4	23.8	24.1	24.3	24.7	6.42
Office 2	23.8	24.1	24.2	24.7	6.41
Office 5	23.8	24.1	24.3	24.7	6.41
Office 3	23.8	24.1	24.3	24.7	6.41
Office 7	23.3	24.1	24.1	24.5	6.20
Office 12	23.3	24.1	24.0	24.5	6.15
Office 6	23.8	24.1	24.3	24.5	6.13
Office 1	23.7	24.1	24.3	24.5	6.09

In Table 21, the PPD values are listed after the installment of shaders on the larger windows of Big Offices. The discomfort values which are all under 10% show that the problem with the southern half of the building is completely eliminated, thus all zones are in a very similar and very comfortable state. The discrepancy in the PPDs cannot be observed anymore and there is also no major temperature difference either. The current state overall, is next to ideal.

6 ANALYSIS & DISCUSSION

In this chapter of the report, the reader is expected find elaborations on results from the simulations presented in Chapter 5. These elaborations will be made on a basis in terms of cross comparing the temperature and PPD diagrams and discussing cause and effect of the observed differences. Following thermal comfort discussion, a special mention will be given to the overall energy demand of the building which is not explicitly investigated in Chapter 5. Hence the climate of an indoor space is strongly tied to the energy consumption of the conditioning devices; a standalone argument about the state of thermal comfort by neglecting the energy usage would not be reflecting an objective opinion. By combining the results from comfort and energy simulations, it is targeted to reach a comprehensive result which can be benchmarked with the criteria of a building certification. The reason for that is, although the tables and graphs draw the shape of overall state of the building, comparing the results with an approved set of limits creates a more vivid perception about the success of the building in terms of comfort-energy correlation. In this report, the numbers obtained from the simulations will be interpreted in context of Miljöbyggnad limitations and will be evaluated accordingly.

6.1 Multi-Case Comparative Analysis

The report presents five different cases for thermal comfort so far, which are *Ideal Case, Designed Heaters and Coolers, Night Time Setback Schedule, Occupant Relocation* and *Installment of External Shading* respectively. As explained before in their particular sections, the iterations began with the most basic and ideal situation and several parameters have been changed one step at a time continuously. To be able to examine the effect of a specific parameter, all other conditions have been kept the same between proceeding cases and just the subject of observation has been altered. Application of this pattern provided the opportunity to make comparisons between cases which come one after another; however the cases which are two or three steps distant from each other have not yet been put in comparison. For that reason, a holistic comparison with all cases found to be necessary and carried on under this section, to be able to examine the state of building under several occasions.

In order to compare the results from several cases, compiling them together in a table has been taken as the first step. Given that there are numerous outcomes from every single run of simulation, choosing and comparing the most relevant ones has major importance. With regards to that, the PPD values of best and worst zones are generally listed as the best indicators of the specific zone, however since the certification system grades upon the highest values, the maximum PPD's observed in all cases in every zone have been listed in Table 22.

Table 22 - Maximum PPD Observed In The Zones Across All Cases (Summer)

Zones \ Cases	Ideal Case	Design Room Units	Night Time Setback	Occupant Location	External Shading
Office 1	6.11	5.96	5.96	6.11	6.09
Office 2	5.45	5.47	5.47	6.43	6.41
Office 3	5.42	5.42	5.42	6.45	6.41
Office 4	5.43	5.47	5.47	6.43	6.42
Office 5	5.47	5.47	5.47	6.41	6.41
Office 6	6.05	5.95	5.95	6.14	6.13
Office 7	5.32	5.31	5.31	6.21	6.20
Office 8	5.31	5.26	5.26	6.53	6.53
Office 9	5.42	5.35	5.35	6.53	6.51
Office 10	5.42	5.36	5.36	6.55	6.51

Office 11	5.32	5.27	5.27	6.55	6.53
Office 12	5.35	5.32	5.32	6.18	6.15
Big Office 1	7.38	13.15	13.15	16.00	6.84
Big Office 2	6.48	14.84	14.84	19.81	6.97
Big Office 3	6.59	7.18	7.18	9.30	6.91
Big Office 4	7.56	7.70	7.70	10.72	7.07
Large Area 1	8.44	9.15	9.15	9.05	7.35
Large Area 2	9.37	12.64	12.64	17.55	7.71
Large Area 3	9.70	14.40	14.40	20.85	7.82
Large Area 4	8.65	9.84	9.84	9.46	7.55

Another important distinction that has to be made is taking summer and winter climates into consideration separately. Not only the outdoor temperature drops significantly during winter, has the amount of reduction in solar radiation also gained major importance. Some zones that are struggling with comfort during summer can be completely comfortable during winter because of the lessened exposure to the sunlight. The vice versa can also be applicable for zones which are in good condition during summer but can experience insufficient heat gain during winter. Because of the differentiation, the analysis begins with comparing the PPD's which are taken from a summer day simulation.

Recalling the knowledge from individual simulation of the cases in Chapter 5, the small office rooms numbered from 1 to 12 were notoriously comfortable during summer. Looking at the Table 22 and Figure 26, those twelve zones are showing best performance in terms of thermal

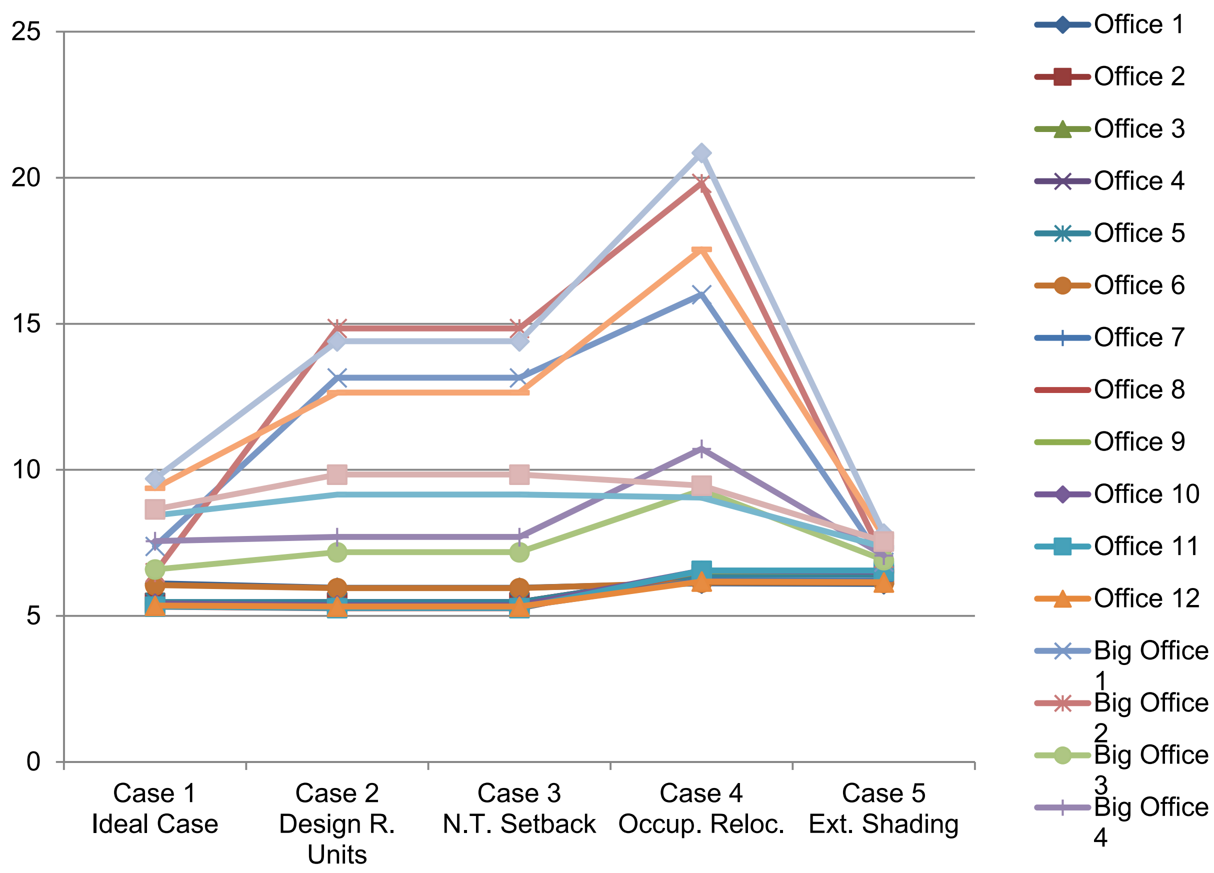

Figure 26 - Combined PPD Graph Of All Zones During Summer

comfort with PPD values ranging between 5% and 10% across all cases. If the corresponding columns to the individual cases are looked separately, it is seen that the trend lines of twelve office rooms are homogeneously distributed in 5%-10% range and keep their steadiness without any peaks or drops. Considering the fact that having the zone PPD's less than 10% grants a Gold certificate according to Miljöbyggnad, these zones are perfectly fine and in the desired range of the graph.

The larger zones of the building which are namely Big Office 1-4 and Large Area 1-4, are usually observed on the more problematic side of the graph. Although these zones start in the same bracket with the office rooms in first case, the discrepancy starts to occur and grows rapidly after cases 2 and 3. Since the zones Big Office 3,4 and Large Area 1,4 are having the advantage of being located on the western façade, they keep a relatively close trend line to Offices 1-12 just right below the bench line of 10%. On the other hand, the same groups of zones located on the eastern façade climb up to 15% after leaving the ideal conditions and continue to grow around 20% during Case 4, which is the limit value for the 3rd degree of certification. It is seen that Large Area 3 even exceeds 20% of dissatisfaction during Case 4 which is jeopardizing the possibility of a better grading, although majority of the zones are seen in a remarkably better state. After Case 4, with the implementation of the external shading, the problematic zones show a drastic improvement while the better zones keep their stabilized trend line. After all, the trend lines for the 20 different zone in the building meet in the same bracket in Case 5, which is between 5 to 10 percent of comfort range again.

To sum up the thermal comfort of the entire building in summer, it appears to be the location of the room in the building and the distance of occupant to the window are two most effective parameters. It can also be stated that once the actual room units are placed, the building overall hovers around Silver (10-15%) level even with the application of an energy saving schedule. On the other hand, if any type of seating configuration requires the occupants to be closer to the windows, the quality of the climate lessens all the way down to Bronze (15-20%) or worse in specific locations. It is also apparent from comparing the 1st Case to Cases 2, 3 and 4, as long as the building has unsubstantially good room units, getting Gold degree from Miljöbyggnad is not possible without taking extra measures. However, Case 5 also proves that the Gold degree is still reachable with those external measures which can improve the quality of problematic zones up to the ideal state. Given the fact that the case building is configured in a way to represent a typical office building; providing a Silver grade quality during summer is manageable just by the proper design alone. In order to reach the best grade, identification and treatment of the problems that are hindering the thermal comfort are necessary.

As stated before, due to various changes in the outdoor climate parameters such as ambient temperature and solar radiation, the comfort state of the zones observed in each case should be investigated separately for winter climate. Referring to the knowledge gained from the five cases in the previous chapter, the office spaces in the northern façade were not as ideal during winter since they were getting little to no sunlight. On the other hand the larger spaces in the southern half of the building were showing a much better performance in terms of comfort. Although these outcomes are already known, comparing the outcomes that are obtained from different cases is expected to provide the opportunity to make a comparison and comment on how the values change across the cases after a parameter is changed in every step. Using that method, any spikes in the trend line such as significant rise or drops would indicate that the change applied in the particular case causing the peak has significant impact on the result, hence an important parameter to be concerned. For that purpose, the data stating highest amount of PPDs that are observed in the zones during winter in all five cases have been collected and listed below in Table 23.

Table 23 - Maximum PPD Observed In The Zones Across All Cases (Winter)

Zones \ Cases	Ideal Case	Design Room Units	Night Time Setback	Occupant Location	External Shading
Office 1	9.19	10.23	14.93	10.03	10.29
Office 2	9.25	8.36	10.62	10.40	10.59
Office 3	8.86	8.19	10.28	9.30	9.52
Office 4	8.88	8.25	10.37	9.47	9.51
Office 5	9.27	8.40	10.70	10.60	10.64
Office 6	9.19	10.48	15.22	11.27	11.32
Office 7	9.47	9.31	13.51	14.21	14.29
Office 8	9.38	8.29	10.35	11.90	11.95
Office 9	9.02	8.16	10.10	10.51	10.56
Office 10	9.00	8.11	9.99	10.40	10.56
Office 11	9.36	8.25	10.25	11.72	11.88
Office 12	9.45	9.19	13.21	12.67	12.93
Big Office 1	8.38	7.83	10.88	8.03	11.19
Big Office 2	8.71	7.56	9.75	10.94	14.66
Big Office 3	8.86	9.56	13.91	10.89	11.15
Big Office 4	8.38	8.98	12.95	14.31	14.58
Large Area 1	8.90	10.40	14.93	12.01	12.52
Large Area 2	8.89	10.46	14.95	12.12	12.44
Large Area 3	9.08	9.84	13.94	15.59	15.93
Large Area 4	9.08	9.80	13.89	15.51	16.02

By looking at the numbers in Table 23, the first characteristic that grabs the attention is the overall distribution of numbers being closer as opposed to the summer simulation. While some zones have their highs and lows throughout the five cases of iteration, the majority have a relatively stable rate of increase or decrease. As discussed before, the significant reduction of sunlight during winter was expected to be a major influence on the comfort state of some significant zones; since it does not have a homogeneous effect on the building unlike the temperature outside. Duration of exposure, area of transmission and angle to the sun are all determining factors on the solar gain of any given zone. Since every zone in the building cannot have the same values for such variables, the influence of the sun would be different. However for winter, the influence of the external conditions is considerably lower compared to summer. Although the southern façade would still benefit from sun especially during first half of a work day, the lessened exposure time and intensity would not result it not to be a major determinant. If it is taken as a fact that external factors are less important on the variety between the zones during winter, the zone specific characteristics automatically gain importance. In a case where external factors are non-existent or equally effective on the whole building; unique qualities of the zones naturally become the target for inspection. Those qualities which are specific to zone can be exemplified as the heater and cooler design, lighting, equipment, occupant scheduling and so on. While interpreting the outcomes from the comparison in Table 23, the mentioned factors needs to be taken into primary consideration.

If the overall state of comfort in winter is analyzed on a case by case basis, it is seen that ideal case presents numbers under the ideal limit of 10% as expected. Whether the simulation is run for summer or winter, the unlimited capacities of ideal units are able to maintain the ideal temperatures under any circumstance. After these units are replaced with actual ones in Case 2, the general assumption would be an overall increase in the PPD's. However, Table 23

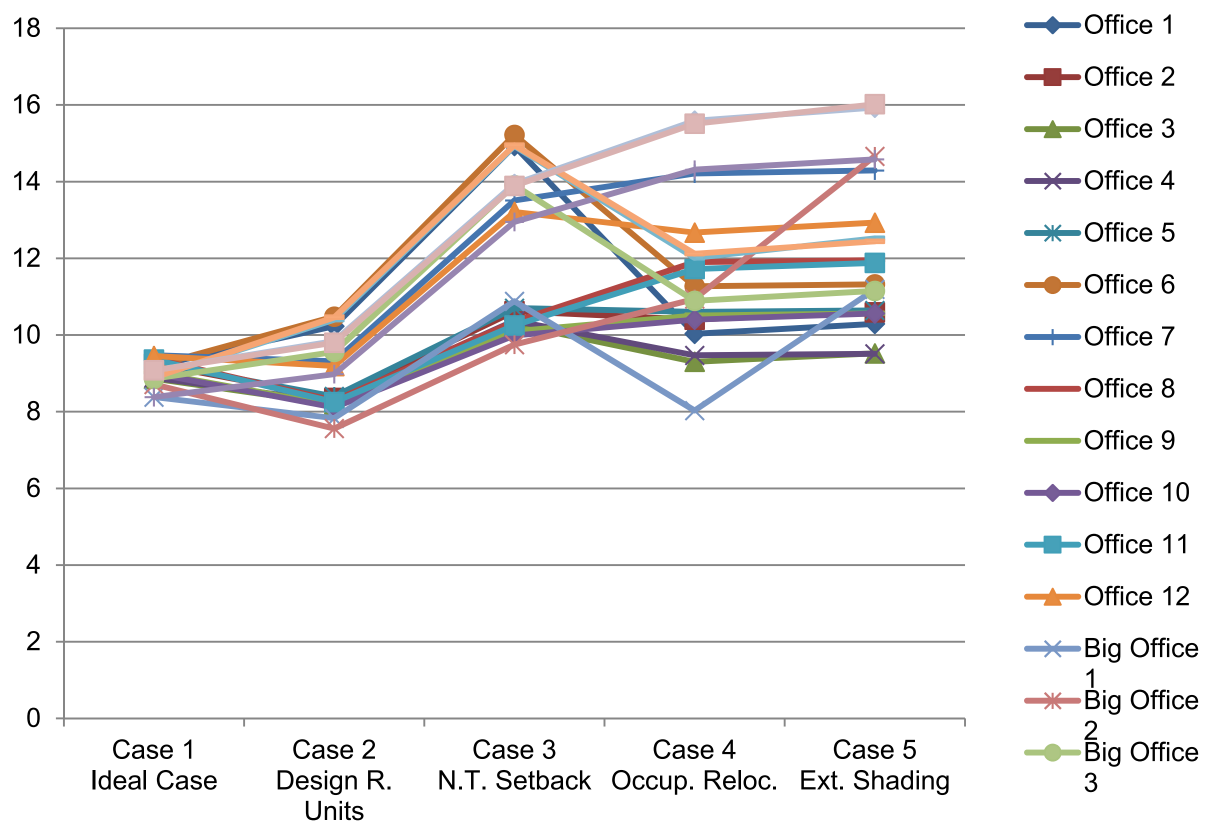

Figure 27 - Combined PPD Graph Of All Zones During Winter

states that the thermal dissatisfaction in the building showed little to no change in majority of the zones. Some marginal variances have been observed in a few zones due to the different configurations of the room units, but not a considerable peak or drop has occurred. The reasoning for that result can be tied to the design principal of the room units as explained before in Case 2. Since the heating and cooling requirements of particular zones have been measured by the energy consumption data of the ideal case, the room units are designed with sufficient capacity and efficiency in order to create a similar condition in the zone as created by the ideal units. The outcome after Case 2 is a proof that, the comfort provided by ideal units is not something unreachable; adequately designed room units can also perform at the same level just well.

Proceeding to Case 3, the parameter which is anticipated to be the most effective in winter climate has been applied. Looking at the column for night time setback schedule in Table 23, it is seen that the PPD values are increased by approximately 40% in majority of the building. While the dissatisfaction was varying under 10% for the previous case, it fluctuates between 10 to 15% which means a regression on the degree of certificate. From Figure 27, it is easier to differentiate which zones are affected the most from the schedule change of the room units. The office rooms on the northern façade are documented in the previous chapter to be not the ideal zones during winter, as they cannot benefit as much from solar radiation. However in the cross comparison it is seen that because of their size, they are able to tolerate the temperature change in the first few hours of the work day better than zones in larger size. Offices 1 to 12 have shown an average 25% increase in discomfort while Large Areas became up to 40% more uncomfortable. Although one may argue that the volume of the spaces in larger zones are causing them to reach ideal temperatures later than the smaller ones; considering the room units are adequately designed the sheer number of occupants voting for thermal dissatisfaction might be the only cause of difference as why the larger zones reacted faster to schedule changes. All in all, comparing the increased PPDs with previous ones, the new values are still under the Silver degree of Miljöbyggnad. If the energy savings of the new schedule is taken into account, it simply becomes a choice of how much comfort should be sacrificed for saving from energy. Considering the highest lapse between two cases is roughly 5%, it is perfectly viable to accept a lesser grade of certificate in exchange of a better energy performance.

Occupant location is the trickiest parameter to analyze in these figures since it includes more than one variable in the equation. As described in the previous chapter, Case 4 is handled separately for all zone types. The main reason for that is, as much as the occupant location is influential on the measured thermal comfort; the relative position of the room units is also a factor. While relocating an occupant to any given place in the zone, the position of windows, heaters and coolers should also be defined. However for this particular building, a common pattern is observed in all zone types except one. Water radiators, which are the heating units, are placed as close as possible to the windows which naturally leads to the occupants being closer to the heat sources when they are placed closer to the windows. The only exception for this pattern is the Large Areas 1-4 due to their geometry. When the results from the Table 23 and Figure 27 are evaluated under the light of this information, it is seen that the zones which share the pattern showed slight improvement after the depreciation in Case 3. Especially if the hourly zone temperatures are investigated from Case 3, the ramp-up time during morning hours seemed to be the most problematic time period. In that sense, it could be argued that being closer to the heat sources has lessened the discomfort during the time span where occupants are feeling slightly cold. However when the overall state of the zone is considered, the comfort state after the completion of ramp-up time does not differ much. The situation with Large Areas should not be considered as a general reflection of comfort state in the building since occupants are assumed to be equally distant from the heat sources on both ends of the zone, which concludes relatively more dissatisfaction than the other zones. In reality, occupants are more likely to be situated in either end of the zone, which has slightly better conditions than the middle. For occupant location in general, it can be concluded that it is a highly dependable parameter which is hard to handle alone without the influential factors; however the results in average state that it is not very effective on comfort in winter climate.

In the specific section for Case 5 which examines the installment of external shading, it is stated that this procedure is effective for summer climate and is not aimed for making any improvements during winter. Apart from that most applications of external shading are either controlled by an automated scheduling system or solar detectors which open or close the shadings depending to the amount of sunlight. For the case building in this project, shadings are also assumed to be off in winter so that it is not any different than previous case in terms of comfort conditions in winter. As the Table 23 and Figure 27 illustrate, the change in results between Cases 4 and 5 is very minor hence negligible. The margin is less than 1% across the board, so there no need for separate consideration on winter implications of external shadings.

To sum up the findings about thermal comfort results, there are several important reminders to make for an objective interpretation. First of all the global parameters which are expected to impact simulations equally may be part of the influencers hence skew the results drastically. Second, there are also some factors which are unique to the zone that should be taken into account although the relevancy to the investigated parameter may not be apparent at the first sight. Thermal comfort as a concept is rather complex and constituted by its components which five of them have been analyzed in this report. Every one of these parameters has their own implications in varying magnitudes. Keeping these in mind, adjustment of the parameters could be problems to tackle with as well as levers to adjust for achieving desired results.

6.2 Energy Demand – Thermal Comfort Relation

In this section of the analysis, the energy demand of the case building will be investigated for each of the cases which are created for thermal comfort measurements. There are several reasons for including energy as a part of analysis which can be summarized as documenting the average energy consumption of a typical two-storey office building, energy demand under various zone configurations and searching for a possible pattern in the results that might be indicating a relationship between energy demand and thermal comfort. Furthermore, since the annual energy consumption constitutes another aspect of Miljöbyggnad building certification system, having the energy results alongside with thermal comfort data provides the foundation for a more in-depth assessment. Moreover, given the fact that the simulation software used in this project to create the thermal comfort profile across the building has energy simulation as its primary purpose; the energy performance of the building comes naturally alongside with the thermal comfort data. Hence the required settings and configurations are already made for running a simulation, obtaining the energy results could be considered as a side benefit which is too valuable to be neglected.

Among the numerous reasoning listed above, the primary goal with carrying this task is looking for the possibility to link thermal comfort to the energy consumption. Since the reference for benchmarking has been predetermined as Miljöbyggnad, evaluating the results from a second dimension could create beneficial arguments. As mentioned in its specific section, the chosen certification system has several aspects which allows assessment of the building in several areas and constitutes a combined grade at the end. Considering the aspects may or may not be connected to each other, reaching the targeted grade in one area can hinder the efforts of reaching the same grade in another area. The measures has been taken to improve a specific aspect of the building could potentially result as a detriment as well. The most common occurrence of this problem is observed between contradicting requirements such as installing shaders for the optimal thermal comfort but keeping the adequate amount of sunlight to meet the designated limits. If such aspects which are suspected to have correlation can be examined together, a well-supported decision mechanism can be created for applying constructive measures to improve one aspect without hindering the other.

On contrary, the mentioned relationships between different aspects do not always have to be contradicting each other and can be benefited in an opportunistic way. The effort for improvement in one area could show positive implications on multiple areas at once. The installment of external shading can be given as an example, which carries the task of reducing the infiltrating sunlight during summer for the comfort of the occupants as the primary purpose. On the other hand, by reducing the amount of sunlight going through, shadings cause less radiative heating, thus less cooling requirement. Apart from such indirect benefits, the positive relationships can also be used as levers to be adjusted, in order to balance the overall grade of the building around the desired level. Some criteria could have stricter limits compared to others, which might naturally cause the building to struggle maintaining same level of performance on both sides. As seen in the ideal case of this report, given the resources are unlimited, it is relatively easy to keep the thermal comfort within Gold level without any special precautions. However, it is also expected to meet with high energy demands for such a case where the heating and cooling devices are working non-stop with unlimited capacities. For energy consumption and thermal comfort in particular, the situation can be considered as a tradeoff in terms of how much sacrifice should be made from one side to improve the other. All in all, to inspect whether the predicted relationships are really existing and how sensitive the balance is between those two aspects, the data should be analyzed from energy simulations and put in cross-comparison across all five cases in order to spot a pattern.

6.2.1 Case 1 & 2 – Energy Demands From Ideal and Designed Room Units

The energy demand of first two cases are decided to be analyzed collectively because in these two cases there are no different parameters, configurations, global or zone specific data. The one and most important change from Case 1 to Case 2 was replacing the ideal room units with actual ones, which had considerable implication on thermal comfort. However, since actual units are designed by the reference of Case 1 data, there is no difference expected to be observed in terms of energy. From the annual simulation of first two cases according to the Gothenburg climate file, the energy demand results are listed as in Table 24.

Table 24 - Annual Energy Demands From Cases 1 and 2

	Case 1		Case 2	
	kWh	**kWh/m²**	**kWh**	**kWh/m²**
Lighting, facility	14559	22.2	13377	20.4
Electric cooling	8598	13.1	7820	11.9
HVAC aux	3251	5.0	3356	5.1
Total, Facility electric	26408	40.3	24553	37.4
District heating	40249	61.4	42184	64.3
Total, Facility district	40249	61.4	42184	64.3
Total	66657	101.6	66737	101.8
Equipment, tenant	10920	16.6	10033	15.3
Total, Tenant electric	10920	16.6	10033	15.3
Grand total	77577	118.3	76770	117.1

As mentioned in the disclaimer for the energy-comfort relationship, first two cases are estimated to be the ones with highest energy demands since they are both left to the sole performance of room units without any tweaks that can reduce the heating and cooling load. As a result of that room units are expected to run close to their maximum capacity to maintain the building in the desired temperature range. In Table 24, the energy demand of operations which are necessary to facilitate the building are listed in the upper side of the highlighted row; and the user centric consumption is listed in the lower part. Since Miljöbyggnad rules do not count user related consumption in the total energy performance, the numbers up to the highlighted row constitute the relevant data.

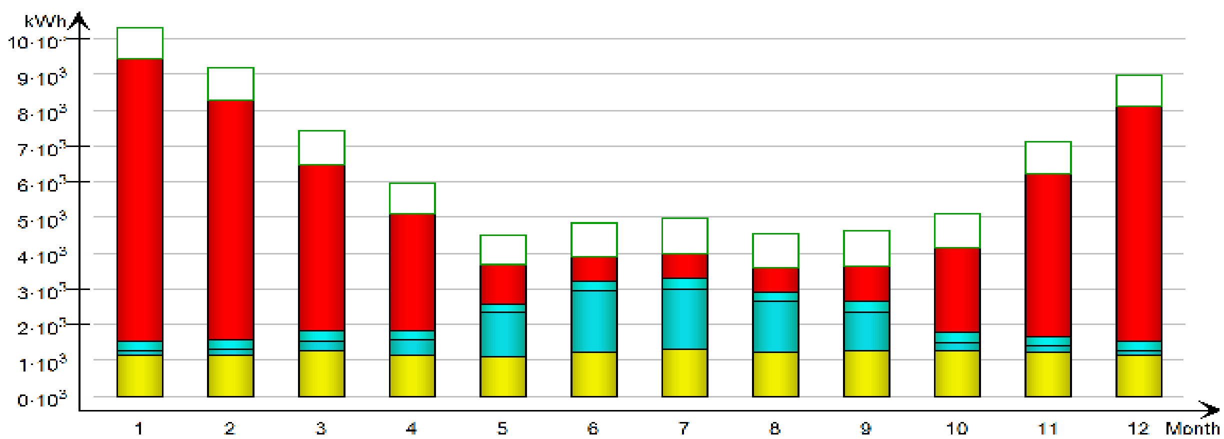

Figure 28 - Monthly Breakdown Of The Consumed Energy From Case 1

From the summary of energy consumption caused by building operations, it is seen that in Case 1 and Case 2, 101.6 kWh/m² and 101.8 kWh/m² energy is required respectively. While most of the total energy demand consists of power purchased from district heating, which also includes the hot water, rest of it is the electricity for lighting and air conditioning. Looking at the illustration at Figure 28 for monthly expenditure, the overbearing expense to the heating can be seen during winter season. Considering the fact that night time heating regime is not applied in these two cases, the expense for heating almost makes the cooling load irrelevant.

Recalling the limit values from Miljöbyggnad, the maximum energy demand for a building in Gothenburg area was determined as 90 kWh/m², 67.5 kWh/m² and 58.5 kWh/m² respectively for the grades ranging from Bronze to Gold. If the results from Case 1 and 2 are put in comparison with the given limit values, the building fails to stay in the certification limits despite its outstanding thermal comfort performance. The analysis in 6.1 indicates that majority of the building hovers around 10% PPD in first two cases which means almost Gold degree certificate; however being out of boundaries in the energy aspect even for the Bronze negates the chances getting any type of certification. Parallel to the expectations, providing the ideal thermal climate with only the help of room units comes with exceeding costs.

6.2.2 Case 3 & 4–Energy Demands From Setback Schedule and Occupant Location

In the same fashion with the two prior ones, Case 3 and 4 are also evaluated under the same table because of their similarities in terms of energy consumption. To start with, the night time setback schedule which is introduced with Case 3 is predicted to be the most influential change for energy results although it is originally intended for investigating thermal comfort. Since the cases before that were representing almost ideal conditions, the energy consumption was not a concern and no such measure was taken to provide the comfort with a cost friendly pattern. It is seen from the PPD values that the new schedule is causing observable discomfort especially during morning hours, but whether the sacrifice from comfort is worth the savings from energy has not shown. By running the simulation for an annual time span with the exact same configuration after the setback schedule, it is aimed to obtain results to discuss if there is a significant saving from energy which can justify the slight loss from thermal comfort. The reason Case 4 is also analyzed together is that there is no change other than occupant position. Although it's effective on the measured comfort, it is not a parameter for energy consumption.

Table 25 - Annual Energy Demands From Cases 3 and 4

		Case 3		Case 4	
		kWh	kWh/m²	kWh	kWh/m²
	Lighting, facility	13377	20.4	13379	20.4
	Electric cooling	7467	11.4	7358	11.2
	HVAC aux	3347	5.1	3347	5.1
	Total, Facility electric	24191	36.9	24084	36.7
	District heating	34132	52.0	33924	51.7
	Total, Facility district	34132	52.0	33924	51.7
	Total	58323	88.9	58008	88.5
	Equipment, tenant	10033	15.3	10033	15.3
	Total, Tenant electric	10033	15.3	10033	15.3
	Grand total	68356	104.2	68041	103.7

Parallel to the assumptions, the annual energy demand from Case 3 and 4 are found to be similar as stated in Table 25. The most noticeable change from the previous two cases is the 10 kWh/m² drop in the required energy from district heating which can be interpreted as a result of the night time setback schedule application. Furthermore, there is also a slight benefit observed from energy spent on cooling hence the schedule also prevents conditioning during summer season off hours in the same manner. Considering that new schedule is put in place with the primary purpose of eliminating the wasted energy during the unoccupied hours, the desired goal can be claimed to be fulfilled according to the reduced demand outcomes.

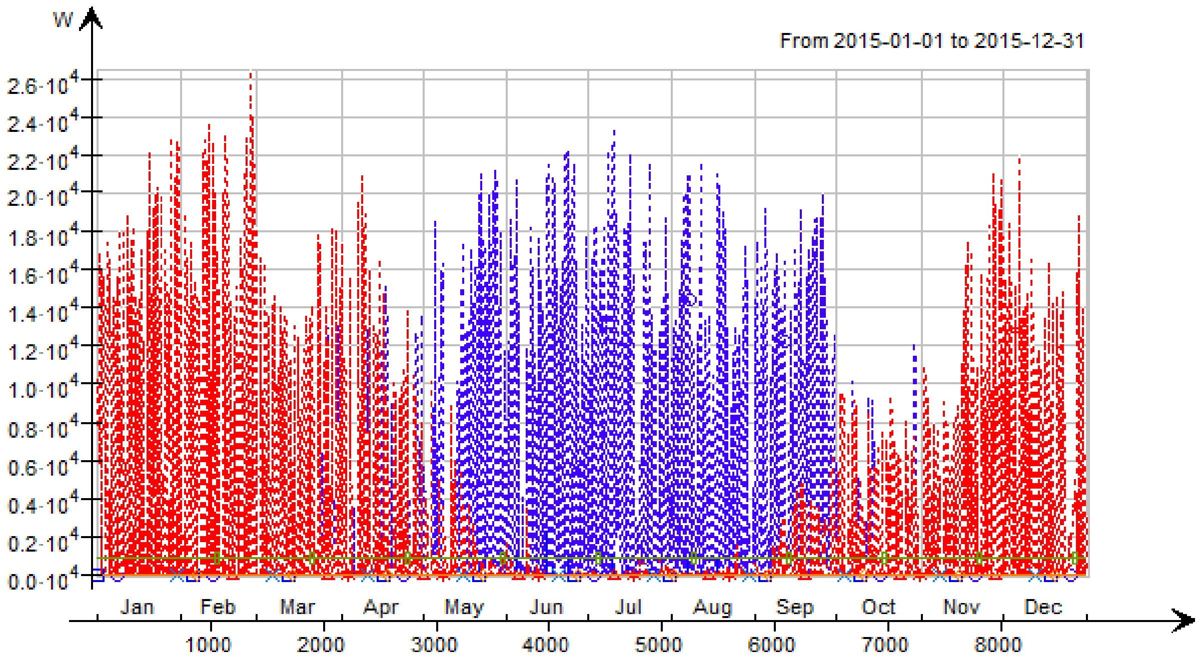

Figure 29 - Monthly Heating and Cooling Power Requirement

According to the new results from Case 3 and 4, the energy demands are found to be 88.9 and 88.5 kWh/m² respectively. Referring to the Miljöbyggnad limits, the energy performance of the building is barely under the 90 kWh/m² limit in both cases, which grants a Bronze certificate. If the thermal comfort results for the two mentioned cases are recalled from the previous chapter of the report, it is seen that the majority of PPD values vary between 10% and 15% which is in the range of a Silver level certificate. Once again, it is observed that although the comfort state of the building calls for a higher degree of certification, the energy consumption to provide that state is still found to be a detriment to the building.

6.2.3 Case 5 – Energy Demand After External Shading Installment

The energy demand of the building according to the configuration in case 5 has been analyzed separately since the unique parameter of the case which is the external shading is expected to have a considerable effect on the required energy. Back in the discussion at Chapter 5 about making a choice between increasing the cooler capacities or shading the sun, the primary reason for choosing the shaders were saving from energy. As a result of the thermal comfort simulations, it is already proven that shading is an outstanding measure in terms of improving the indoor conditions during summer. However, whether it reduces the cooling requirement or not have not been investigated yet. For that particular purpose, an annual simulation has been run using the configuration of Case 5 to see if the anticipated improvement can be observed on the energy results with the installment of external shading devices.

Table 26 - Annual Energy Demand For Case 5

		Case 5	
		kWh	**kWh/m²**
	Lighting, facility	11815	18.0
	Electric cooling	3282	5.0
	HVAC aux	3312	5.0
	Total, Facility electric	18409	28.1
	District heating	33495	51.7
	Total, Facility district	33495	51.7
	Total	46904	79.8
	Equipment, tenant	8862	13.5
	Total, Tenant electric	8862	13.5
	Grand total	55766	93.3

Another important point that needs to be reminded is the cumulative application of changes throughout the five different iterations. That means the changed parameter in the previous iterations are always carried on to the next one and new changes are added upon that. In the light of this fact, it is already known the application of setback scheduling has already resulted with an improvement on the heating demand. Therefore, installment of shading, which is targeted at reducing cooling demand, would reduce the total energy requirement even further and the outcomes obtained from Case 5 are expected to represent possibly the best scenario.

From the highlighted row of Table 26, the annual energy demand of the case building is found to be 79.8 kWh/m². Comparing to the Miljöbyggnad requirements, it is just below 90 kWh/m² which means only sufficient for a Bronze certificate. Considering the comfort state of the building within the configuration of Case 5, it is stated beforehand that all PPD values are between the desired range and Case 5 is as successful as Case 1 in terms of providing the best comfort. If the two cases which constitute the start and finish of a series of iterations are evaluated based on thermal comfort and energy performance, Case 5 appears as the preferable choice from the sheer values of energy demand. However in the bigger scheme as seen in Figure 30, the heating demands are still overwhelming and the savings from cooling power does not manage to carry the overall grade of the building one step further.

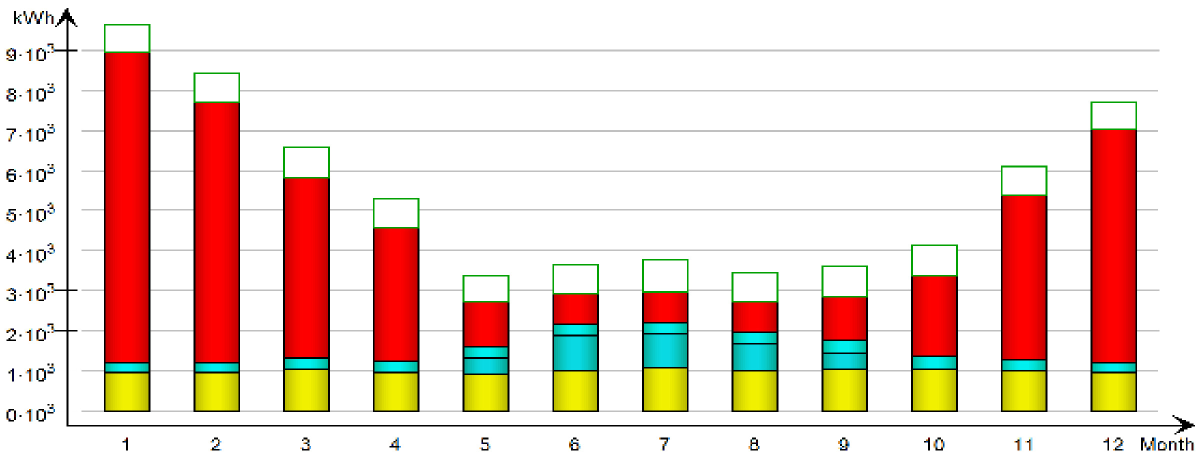

Figure 30 - Monthly Breakdown Of The Consumed Energy From Case 5

6.2.4 Combined Assessment Of Energy Demands For Cases 1 to 5

For a complete assessment of the energy simulation results obtained from all five cases, Table 27 has been made with a highlight on total energy requirements. As mentioned before the electricity used by tenants for their own equipment is not considered in the total energy demand according to Miljöbyggnad; so that it only exists in tables as a rough estimation.

Table 27 - Annual Energy Demand For Cases 1 to 5

		Base Case		Design R. Units		N.T. Setback		Occup. Reloc.		Ext. Shading	
		kWh	kWh/m²	kWh	kWh/m²	kWh	kWh/m²	kWh	kWh/m²	kWh	kWh/m²
	Lighting, facility	14559	22.2	13377	20.4	13377	20.4	13379	20.4	11815	18.0
	Electric cooling	8598	13.1	7820	11.9	7467	11.4	7358	11.2	3282	5.0
	HVAC aux	3251	5.0	3356	5.1	3347	5.1	3347	5.1	3312	5.0
	Total, electric	26408	40.3	24553	37.4	24191	36.9	24084	36.7	18409	28.1
	District heating	40249	61.4	42184	64.3	34132	52.0	33924	51.7	33495	51.7
	Total, district	40249	61.4	42184	64.3	34132	52.0	33924	51.7	33495	51.7
	Total	66657	**101.6**	66737	**101.8**	58323	**88.9**	58008	**88.5**	46904	**79.8**
	Equipment, tenant	10920	16.6	10033	15.3	10033	15.3	10033	15.3	8862	13.5
	Total, ten. electric	10920	16.6	10033	15.3	10033	15.3	10033	15.3	8862	13.5
	Grand total	77577	118.3	76770	117.1	68356	104.2	68041	103.7	55766	93.3

Before proceeding to the total energy demands, there are two other columns in the combined table which are worthwhile to notify, in order to see the implications of different settings. First one is the row of district heating and the discrepancy in values before and after Case 3. As shown in Table 27, the decrease in the required energy from district heating is 12 kWh/m² which means 18.75% saving from the energy. Although the thermal dissatisfaction is slightly increased after the setback schedule kicked in, almost 20% reduction in energy consumption can be argued as a justifiable amount to sacrifice from the ideal comfort state. As a matter of fact, even the thermal comfort is prioritized and Gold level comfort is provided, having an unacceptably high energy demand prevents the chances of getting any type of certification. Thus, instead of a creating a huge cap between two aspects of Miljöbyggnad, pushing the conditions closer to each other may be preferable choice for a balanced building performance.

A similar occasion is also observed in the cooling demand where the shading decreases the cooling load from 11.2 kWh/m² to 5.0 kWh/m². That drop is equivalent to 55% saving from the electricity. However, since the heating requirement is overwhelmingly larger, the savings from cooling only corresponds to 8% of the overall energy. Considering the fact that shadings are installed with thermal comfort improvement in mind, 8% serves just as a side benefit.

As a final judgement from the energy totals it is apparent that neither case can satisfy the limit for a Silver or Gold degree certification from the energy aspect. There might be necessity for additional measures or improvement in material quality for a better energy performance.

However, the outcome which can be drawn from the shown numbers is that better thermal comfort does not always correspond to more energy requirement. Both the comfort and energy simulations show that poor optimization leads to failure in both departments however with identification and application of the appropriate measures it is possible sustain mutual improvement in multiple departments.

6.3 Summary Of The Analysis Referring To Miljöbyggnad

After the analysis of simulation results regarding to both thermal comfort and energy demand aspects, it is possible to comment on how the case building would be evaluated if there were an attempt to get a Miljöbyggnad certificate. By all means there are a lot more aspects which are put into consideration when it comes to certification, however by documenting the influence of several parameters and the correlations between the two aspects, a foundation has been provided for making design decisions. The outcomes drawn from these results can be used as a guide to adjust several parameters of a building in pursue for a better performance.

To start with thermal comfort, the most apparent and natural distinction is shown as the strong difference between summer and winter climates. Although it is a common knowledge that the same room of a building can show very different states of comfort in winter and summer, the results demonstrated that the parameters also show varying influence during different times of the year. In the light of this fact, the building started its cycle with ideal conditions and perfect PPD values independent from the influence of any configuration changes. As expected, that condition resulted the PPDs to stay under 10% which grants a Gold certificate. After the replacement of ideal room units with real ones, PPDs climbed up to 15% which is the limit for a Silver certificate. Although it seems very optimistic that a building can get Silver without any efforts, it needs to be reminded that 24/7 conditioning is costly and unrealistic practice for an office building. Therefore, with the application of night time setback schedule, PPDs rose up to the range of 15-20%. That state of the building could be regarded as very plausible and realistic since the HVAC system and its scheduling are representation of an average office building. Having a PPD range of 15 to 20 percent at this state displays that a building with standard building material, HVAC system and schedule can get a Bronze certificate without feeling the necessity of any special precautions. The Case 4 right after that showed however, if the occupants are located in certain points of the rooms, the buildings thermal state is actually worse than Bronze with PPDs exceeding 20%. During the four different iterations the major source of the comfort problem is identified as the excessive solar radiation. Therefore with the application of an appropriate measure in Case 5, comfort problem is completely solved by decreasing the PPDs of all zones under 10% once again. In the meantime, it is not needed to apply a measure which can increase the energy consumption at all, although the same state of comfort is obtained with a lesser energy cost.

These five iterations overall showed that it is not really difficult to stay in the boundaries of Bronze certification with the mere existence of standard building materials and an average design. However, to push for higher grades from thermal comfort aspect, either the problems have to be identified and solved or high energy costs have to be embraced. From the outcomes of energy analysis, it is evident that the building can barely stay in the limits of Bronze from the energy aspect; therefore second alternative may not even be an option. Overall, it can be concluded from the analysis that there is a resemblance between the comfort and energy patterns when a bare building is investigated. However, after certain tweaks are made to improve the gradation in one aspect, it does not always mean that the impact can be seen elsewhere in the same proportions. That makes the correlation between them semi-situational.

7 CONCLUSIONS

As the building is analyzed under five different cases from thermal comfort and energy demand perspectives, it is possible to draw out some conclusions. However, to put the results in context, it is better to recall some of the simulation outcomes beforehand.

Looking back at the comfort results of Case 1 and Case 2, it is seen that the building can stay in the ideal comfort range just with the help of adequate heating and cooling units. Although it was expected from the first case since it is an unrealistically ideal state, replacement of room units still provide similar comfort values in Case2. It might be arguable that since the capacity of actual units in Case 2 are designed based on the information gathered from Case 1, it still proves that if energy consumption is not a concern, the room units can maintain the building's thermal comfort at ideal levels consistently. However, when the energy demand results are concerned the problem becomes apparent. If a building cannot meet the criteria even for Bronze level certificate while having Gold level quality in thermal comfort, it indicates there is either an imbalance between the criteria or the building is poorly optimized. Given that every possible variable in the building is set around standard levels and there are no measures taken in favor of better comfort or energy results for the first two cases, non-optimization is a fair enough conclusion to be drawn from the drastic difference between two performances.

Case 3 on the other hand, offers a better representation for a more realistic scenario. Since the building is for office use, it is the natural choice not heating it up as much during night time. Looking at the energy results, there is a 20% reduction in energy demand observed which put the building in the limits of Bronze certificate. From the comfort results however, due to the ramp up times in the morning there is a degradation from Silver-Gold to Bronze-Silver levels. Although thermal comfort went one grade down, energy performance could manage to stay in the acceptable limits. That case is one of the critical ones in terms of illustrating the relation between the two aspects. While it supports the claim that better comfort means more energy and vice versa, it also shows that it can be used as a lever as well to adjust up and down and balance the building around a desired level of certificate. The results shown here could also be regarded as more balanced since the building had received a second or third best certificate overall. Reaching the best grade without any special measures would indicate that the limit for that grade is misadjusted; however having the building in a good state just by the design and simple scheduling implies a good prospect because best grade is still reachable with tweaking.

The only interaction which goes out of the pattern between thermal comfort and energy is the shading installation in Case 5. Given that it is a summer specific measure, the primary target was improving the comfort, however there is also a 55% decrease in cooling demand and 8% decrease in annual energy demand have been observed. Although 8% may not seem much, this case shows that thermal comfort and energy do not always have to be contradicting each other. Likewise the setback scheduling, some measures may lessen the performance on the other side, but mutual improvement is also seems to be possible.

As a final conclusion regarding to Miljöbyggnad, it is worth to highlight the grading limits and building's performance correspondingly. Although two different configurations have been applied during the five different iterations with expectance to reduce the energy demand; there could only 27% saving could be made in total and Bronze limits have been satisfied. On the other hand the grading for thermal comfort could be adjusted across the board with every little change and it has ended up under the limits of Gold. Although the changes were mainly targeted towards thermal comfort, the difficulty of improving the grade for energy is a glaring fact which could be hinting the strictness of limits for that particular aspect.

8 FUTURE RESEARCH

In this report, apart from the base design there are four different configurations that have been investigated for a typical office building, with a changing parameter in each consecutive case. The impact of each change has been reported in numbers which are in context of thermal comfort and annual energy demand. Although there are more than four parameters which are thought to be influential on the result, due to the limitations of a master’s thesis only a handful of them have been selected. The selection has been made in accord to the author and if a study in parallel to this report is decided to be studied, the remaining parameters can be investigated further for a more extensive analysis. More cases can be created with the configurations of different room heights, occupancy rates, material selection, HVAC system or any other quality of the building which are identified to be effective by the researcher. Discovering the impact of each individual building element on thermal comfort precisely would establish a numerical proof to theoretical database that can be benefited by the designers in the future.

As long as there is an analysis about a certain aspect of the building whether it is thermal comfort, energy consumption, noise insulation and so on, there is always a need for reference to be used for benchmarking purposes. In this report, the Swedish building certification system “Miljöbyggnad” has been taken as the guideline for thermal comfort and energy performances and the results of the simulation have been compared accordingly. Although the report approaches to the building from two aspects, the certification systems are far more comprehensive and cover the performance at multiple aspects at once. Given that the results of comfort and energy are linked in this report, there are other aspects of Miljöbyggnad which couldn’t be included in the report despite the relevancy due to the limited scope. As stated by the professionals working in the field, daylight usage is one of those aspects which is rather difficult to optimize and worth to analyze. Therefore, it is recommended that further practical studies should be made either in computer environment or in field to report the building performance in correspondence to different aspects. That would provide valuable information regarding to the balance of the certification system overall, which would also consequently identify the crucial parameters which the certification candidates should be considerate for.

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