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X-Maps: A Computational Method for Space Planning Using Multi-Variate
Occupant Comfort

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A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Architecture

University of Washington

2019

Committee:

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Program Authorized to Offer Degree:

Architecture

University of Washington

Abstract

X-Maps: A Computational Method for Space Planning Using Multi-Variate Occupant Comfort

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The indoor experience can be affected by several environmental conditions, including visual, thermal and acoustic comfort, air quality, biophilia, layout, and aesthetic. There are physical metrics for each aspect that are calculating the occupant's comfort. There are also external factors such as occupant's characteristics like metabolic rate and clothing insulation, building's characteristics, and outdoor climate. Most of the conventional practices come up with very similar solutions for different locations and conditions; so, my purpose is to provide a comprehensive tool that overlaps different comfort factors in office buildings and can give designers an overall and broader perspective on space planning based on experiential conditions and locations. Computer simulation is used to provide the information needed. The simulation tools include the visual scripting software Grasshopper and plugins such as Ladybug, Honeybee, and EnergyPlus. The

results are reflected graphically in the form of a tool to guide designers at the early stages of the office interior space planning process.

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ACKNOWLEDGEMENTS

I would like to express my most profound appreciation to my advisors, Prof. Christopher Meek and Prof. Brian Johnson, for their patient guidance, enthusiastic encouragement, insightful suggestions, and constructive critiques of this research work. This study would not have been possible without their support. I would also like to extend my appreciation to the University of Washington professors, from whom I have learned so much.

I would like to extend my deepest gratitude to my parents for their endless amount of love, caring attention, and sacrifices for helping me build a better future by supporting me. Also, I am always thankful to my sisters for their continuous support.

DEDICATION

This thesis is wholeheartedly dedicated to my beloved parents, Zahra Kashef and Akbar Soltani, and my sisters, Maryam and Negar, who have always been a constant source of inspiration, and encouragement, who continuously provide their spiritual, moral, and emotional support throughout my life.

Chapter 1. INTRODUCTION

Nowadays the global economy has shifted towards the knowledge-based sector in contrast with the past focused on the manufacturing sector; so, most people work in indoor office environments (Al Horr, et al., 2016); therefore, it is essential to create comfortable indoor environments for occupants because indoor conditions can affect their health, well-being, and productivity.

The indoor experience can be affected by several environmental conditions such as visual comfort, thermal comfort, acoustic comfort, air quality, biophilia, layout, and aesthetic. In most cases, there are physical metrics for calculating the occupant's comfort inside the building by considering the acceptable ranges defined by widely recognized standards. Unfortunately, some of these aspects are conflicting with each other, and most of the studies have focused on just one aspect of comfort. Also, in most cases, putting the same weight to all factors can result in inappropriate conclusions because occupants give more importance to some factors compared with the others. Therefore, ranking the parameters based on occupants' preference is of great importance. There are also other factors that are not defined by standards such as occupants' characteristics such as metabolic rate and clothing insulation, building's characteristics, and outdoor climate that influence the indoor conditions. Most of the conventional practices come up with very similar solutions for different locations and conditions without considering the factors mentioned above. So, my objective is to provide a comprehensive tool that overlaps different comfort factors in office buildings and can give designers an overall and broader perspective on space planning and comparing different zones inside the office from a comfort point of view based on conditions and locations.

Computer simulation is used to provide the information needed for recognizing occupant's comfort in buildings. A new generation of open-source visual scripting tools offers unprecedented access to environmental and energy performance simulation. The simulation tools are Grasshopper plugins such as Ladybug, Honeybee, and EnergyPlus. In order to produce the X-Maps (experience maps), annual and point-in-time climate-based comfort metrics are selected for comfort evaluation and simulation. The results are reflected graphically in the form of a tool which is intended to guide designers at early stages of the office interior space planning process.

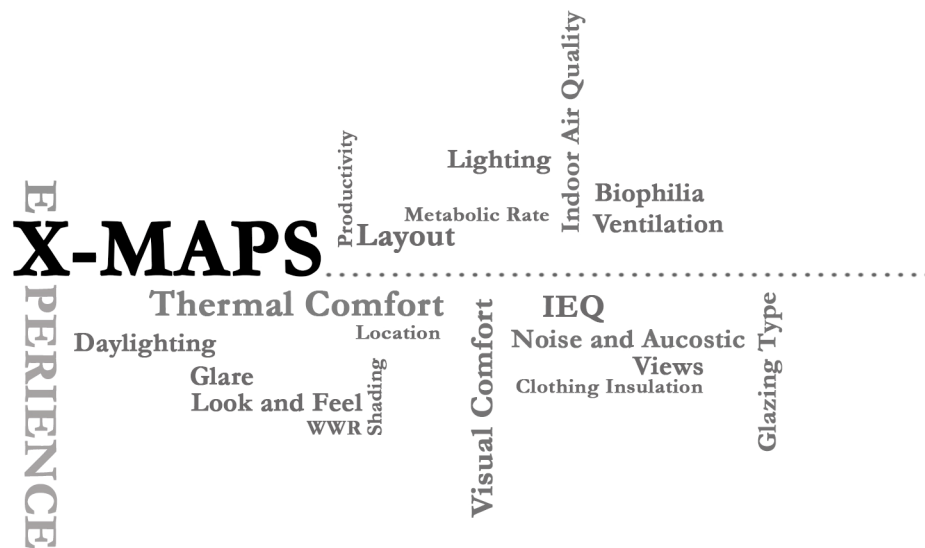


Figure 1. X-Maps (Experience Maps)

One of the first things that I did was to do all the simulations that I was interested in, and I think they are key drivers for space planning and put them all on the graph. One takeaway is that there is too much information and it is too challenging to get that information in a way that is actionable for decision making. It is too dense, has too many layers, and the designer would be overwhelmed by that much information. So, my thesis creates a tool that simplifies that and aligns the space experience goals with simulation outputs in multiple parameters. It takes the information and makes it actionable.

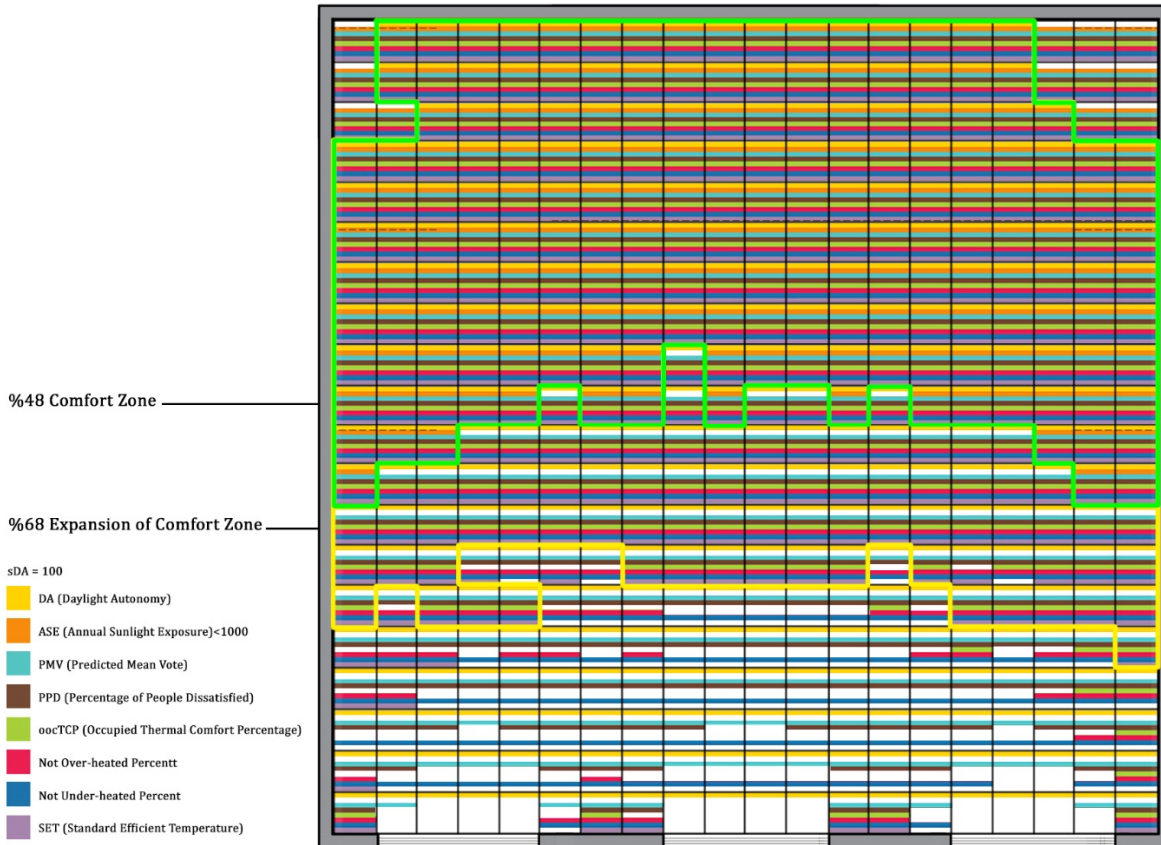


Figure 2. Overlapped graph for several comfort metrics in a 5m by 5m office area

1.1 MOTIVATION

Since the American people spend about 90% of their time inside buildings (EPA, 1989), it is crucial to create a comfortable and productive indoor environment. Negative impacts of buildings on their occupants' health and well-being can reduce their performance and productivity. Therefore, at the beginning stages of design, there should be attention to occupant's well-being and satisfaction factors in order to provide optimum conditions for them (Al horr, et al., 2016). This issue is also important during the building lifecycle in order to maintain the occupants' satisfaction (Wong, Mui, & Tsang, 2018). In most new and existing buildings, designers pay much attention to the energy efficiency issues; however, there is no guarantee that energy efficient buildings provide proper Indoor Environmental Quality (IEQ) for their occupants (Zuhaiba, et al., 2018). Several

environmental conditions, such as visual, thermal, acoustic, and air quality can influence occupants' indoor comfort. Factors affecting occupants' comfort can be physical parameters or psychological, cultural, and sociological dimensions. Most of the building regulations and guidelines revolve around physical factors and ignore other dimensions (ASHRAE, 2004). They also consider just one aspect of comfort since overlapping several aspects and parameters can be so confusing and time-consuming. This thesis presents a framework for predicting occupants' comfort inside the building by overlapping thermal, and visual comfort along with air quality on experience maps for use by designers at early stages of project development. The focus of this study is on commercial and office buildings. So, the produced maps can be used to determine the potential areas inside the building for space planning and locating the sedentary spaces. In order to evaluate the indoor environmental conditions, annual weather file-based comfort metrics are selected for analysis.

Many previous studies indicate the relation between occupant satisfaction and indoor environmental conditions such as thermal, visual, acoustic conditions, and indoor air quality along with rating them according to occupants' preference. Lai & Yik (2007) rated the importance of thermal comfort, air cleanliness, odor, and noise in commercial buildings in Hong Kong. In the study done by Choi, Loftness, & Aziz (2012), occupants of 20 office buildings in the USA rated the satisfaction with indoor air quality, thermal, acoustic, and visual environment by questionnaires.

There is also another group of studies investigating the effects of shape-and-material-related factors on building indoor performance. Most of the studies explore the relationship among window size, orientation, window shadings, window properties (U-value, SHGC, and visible transmittance) and their effects on buildings' energy performance and indoor air conditions

(Zomorodian & Tahsildoost, 2017). According to a literature review by Atzeri, et al. (2014), some studies (Tsikaloudaki, Theodosiou, Laskos, & Bikas, 2012) (Feng, et al., 2017) consider the relationship between window configuration and energy demand in office buildings. Others studied window configuration concerning lighting energy use and visual comfort (Secchia, Scurpia, Pierangioli, & Randazzo, 2015) (Soori & Vishwas, 2013) or thermal comfort (Ruppa, Vásquez, & Lambertsaa, 2015) separately.

Only a few studies go as far as considering indoor air quality, visual, thermal, and acoustic comfort and energy consumption simultaneously. The study done by Vanhoutteghem, et al. (2015) explored the effect of windows' properties, size, and orientation on heating demand, daylighting, and thermal comfort. Also, most studies considered energy performance according to instantaneous rather than annualized metrics. Only a few studies (Atzeri, Cappelletti, Gasparella, Shen, & Tzempelikos, 2014) (Zomorodian & Tahsildoost, 2017) (Arens, et al., 2015) focus on annual spatial thermal and visual comfort metrics. Currently, there is a lack of studies that can guide space planning decisions of interior environments by current long-term personal comfort metrics to maximize comfort and reduce energy use.

This thesis aims to develop an interpretive framework for using experience maps to guide space planning decisions to maximize comfort and productivity and reduce energy use. The focus of this study is on the annualized comfort metrics instead of instantaneous ones. The results, presented in charts and tables, can be used by designers at early stages of office interior space planning process to provide comfortable indoor conditions.

Chapter 2. BACKGROUND

2.1 INDOOR ENVIRONMENTAL QUALITY

Indoor Environmental Quality (IEQ) is defined as the indoor environmental experience perceived by occupants that consider different aspects such as design, analysis, and the performance of the energy efficient, comfortable, and healthy buildings by ASHRAE TC 1.6 (Heizerling, Schiavon, Webster, & Arens, 2013). There are several issues related to IEQ ranging from the older ones such as Indoor Air Quality (IAQ), and Sick Building Syndrome (SBS) to ergonomic issues such as lighting, noise, and furniture, along with psychological issues such as working conditions, and job satisfaction (Cone, 1999). The main parameters for evaluating the indoor environment are the parameters related to building space such as the thermal, visual, and acoustic environments along with the indoor air quality. The focus of early IEQ studies was often on the effects of one environmental factor on occupants without considering the building space.

Regarding building space, most of the studies revolved around examining one parameter such as size, window-to-wall ratio, and color. IEQ researchers changed their focus towards considering multiple factors with the emergence of the Sick Building Syndrome (SBS) topic in the 1980s and 1990s. In these researches, the indoor environmental quality was assessed by integrating the effect of various environmental factors on occupants' satisfaction (Xu, Huang, & Zhang, 2018). SBS is related to the conditions creating health and comfort problems for building occupants (Amin, Akasah, & Razzaly, 2015). Lack of natural openings, proper temperature, and humidity, type of material, furniture, and office equipment, chemical, and biological contaminants, physical and psychosocial conditions are among the leading causes of SBS (Al horr, et al., 2016). Symptoms caused by SBS are “dry eyes, eye strain, watering eyes, blocked or stuffy nose, runny nose, dry or irritated throat, flu-like symptoms, and difficulty in breathing, headache, tiredness as well as dry

skin” (Amin, Akasah, & Razzaly, 2015). Generally, naturally ventilated buildings cause fewer symptoms for occupants compared with the air-conditioned buildings even if the air quality measurements show better results for air-conditioned buildings (Burge, 2004).

Moreover, IEQ related factors affect energy consumption considerably both in design and operations. By evaluating the performance of IEQ at a whole building level, we can increase the building’s efficiency (Heizerling, Schiavon, Webster, & Arens, 2013). So, it seems essential to define building performance considering the effects of IEQ on occupant’s health, well-being, comfort, and productivity in office buildings. These issues will be considered in the next sections.

2.2 BUILDING PERFORMANCE

The definition “building performance” can be divided into two parts: the first one is related to protecting the building’s physical, visual, and mechanical properties from the damages caused by temperature, moisture, air movement, biological and chemical attack, and disasters like earthquake, flood, and fire. The second is related to interior occupancy (human, plant, animal, machine) requirements and related comfort parameters such as thermal, visual, acoustic, and spatial comfort along with air quality, factors that are depend on psychological, physiological, sociological, and economic aspects (Hartkopf, Loftness, & Mill, 1986).

There are acceptable limits for each building performance dimension based on the occupancy type that is defined as a “comfort zone” and reflected in the codes, standards, and guidelines according to occupant’s psychological, physiological, sociological, and economic needs. These limits vary, depending on the building function and the type of occupancy and related factors such as clothing, metabolic rate, and age (Hartkopf, Loftness, & Mill, 1986).

Physiological factors intend to provide a healthy and safe environment for occupants’ basic tasks such as eyesight, breathing, hearing, and feeling. When it comes to psychological factors,

the aim is to provide mental health based on factors such as privacy, clarity, interaction, and change. For sociological (sociocultural) factors, the goal is to provide community well-being, and for economic factors, the goal is to use the resources in the most effective way (Hartkopf, Loftness, & Mill, 1986).

2.3 OFFICE INDOOR ENVIRONMENTAL QUALITY AND OCCUPANT PRODUCTIVITY

Creating a comfortable indoor environment seems to be one of the most critical issues in the built environment since high-quality IEQ can affect occupant's productivity. Studies show that low-quality indoor environment can create discomfort symptoms leading to reduced occupants' performance (EPA, 2003). While it is complicated to define the relationship between IEQ and occupants' productivity, some factors are affecting the occupants' well-being in the short and long term such as thermal, visual, and acoustic. There are also some mental factors that cause significant problems in the long term (Al horr, et al., 2016).

The study on the relationship between IEQ and occupant's productivity was started with the publications of Vernon and Bedford (Vernon & Bedford, 1930), along with Maslow (Maslow, 1943) that investigated the workplace needs. At first, researchers considered the effects of the physical indoor environment on workplace occupants, and then continued their work on evaluating the degree of indoor environment effects on occupants' well-being and productivity (Al Horr, et al., 2016). According to the study done by (Fisk & Rosenfeld, 1997), even a 1% increase in productivity can decrease the sick leave for two days a year, work breaks for 5 minutes a day. Since worker salaries compared with building maintenance and energy costs, along with rental and construction costs, are significantly higher by a factor of almost 100 (Woods, 1989), even a 1% rise in productivity can be adequate to justify the costs (Fisk & Rosenfeld, 1997). Wheeler and Almeida (2006) surveyed professionals in various sectors in the UK indicates that a proper

working environment can increase productivity by about 20%, equivalent to £135 bn yearly (Clements-Croome, 2015). In the UK, the cost for “presenteeism” used to describe workers that are at work but not productive is about £15 bn (\$171 bn) per year, and this issue may be related to the built environment. In today’s world, technology brings the opportunity of working remotely when the workers are traveling or at home, and this provides more productivity; however, there are still regular workplaces without this opportunity. So, the role of the physical environment in improving productivity seems critical (Clements-Croome, 2015).

There are several studies (Romm & Browning, 1994) (Roelofsen, 2002) (Clements-Croome, 2015) investigated the relationship between building performance and occupant productivity and well-being. Also, programs such as the Leadership in Energy and Environmental Design (LEED) offered by the United States Green Building Council (USGBC), Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), and Building Research Establishment Environmental Assessment Method (BREAAAM) have all considered the IEQ and related factors as one category of measurement (Al Horr, et al., 2016). According to a survey (Miller, Pogue, & Gough, 2009) done over 500 LEED certified buildings’ occupants, healthier environment causes the productivity increase and sick time decrease leading to the absenteeism reduction.

Since productivity is defined as the “the ratio of output to input,” it can be different according to the input and output type, and the context. The productivity in office buildings can be defined as “the ratio of company turnover to employee cost” and can be measured by various factors such as individual, team, and organizational performance. Buildings’ operational costs and performance are considered as the input and output respectively in the built environment that the output consists of the performance of building and occupant (Al Horr, et al., 2016). Most of the productivity measurement methods are based on quantitative operation data that are difficult to collect for many

cases; so, it would be easier to use the subjective productivity measures that are based on the workers' subjective assessments and are collected by survey questionnaires. So, productivity can be measured by absenteeism, subjective response, and objective assessments (Miller, Pogue, & Gough, 2009).

There are several factors related to enhancing comfort in office buildings that are categorized as personal, organizational, social, and environmental factors. When an office environment can make 80% of its occupants satisfied, it can be considered as a healthy environment that provides comfort for occupants. The type of comfort can be physical comfort such as air quality, noise, and climate, psychological comfort such as privacy and territoriality, and functional comfort such as inconveniences, work distance, interruptions, and resources that can be varied from person to person (Al Horr, et al., 2016). The focus of this study is the physical aspects of comfort that affect the office indoor environmental quality directly. These physical environmental conditions can be divided to physical conditions such as air quality, temperature, light, and noise, space conditions such as layout, plan, and privacy, ergonomics such as a workstation, and control, and finally aesthetics such as quality and color. There are eight physical factors influencing the amount of satisfaction and productivity in office buildings including 1) Office Layout, 2) Indoor Air Quality and Ventilation, 3) Thermal Comfort, 4) Lighting and Daylighting, 5) Noise and Acoustic, 6) Biophilia and views, 7) Look and Feel, 8) Location and Amenities. There are significant interactions between these factors. For example, thermal conditions can have direct interaction with daylighting and air quality, or the interaction between daylighting and view, along with the crossover between office layout and acoustic properties (Al Horr, et al., 2016). So, it is essential to consider all or at least a number of these factors with each other in order to have a better

performance in office indoor environment. The following sections evaluate the impact of factors as mentioned earlier on occupant's productivity in office buildings.

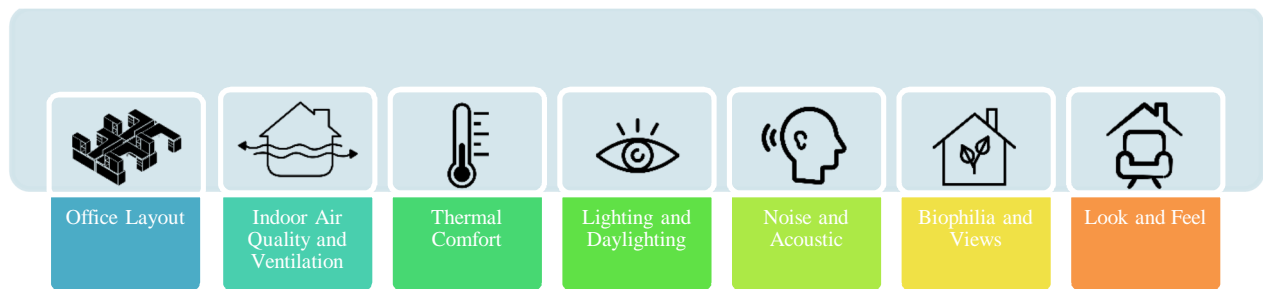


Figure 3. Physical factors related to comfort and productivity

2.3.1 Office Layout

Office spaces can be divided to private, shared, team (two to about five workers in each room), and open-plan offices (more than about five workers) based on their layout (Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016). The idea of an open-plan office was first introduced by “two Germania furniture manufacturers, Eberhard, and Wolfgang Schnelle” by 1960 and is defined by eliminating the partitions and walls (Shafaghat, Keyvanfar, Salemi Ferwati, & Alizadeh, 2015). There are also some types of flexible open-plan offices providing multi-purpose rooms for workers who need focus and privacy; so, the spaces are divided into silent and communicative workstations based on workers' behavior. The idea of innovative offices is the same that occupants can select workstation based on activity needs (Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016). Because of the shift from private office layout to modern open-plan in recent years, there has been much attention towards evaluating its impact on occupants from engineering, architecture, psychology, and health points of view (Kim & Dear, 2013).

There is a considerable difference between open-plan offices and other types of office spaces in terms of physical characteristics such as workstation and overall size, workstations enclosure

and density, the height of the space, and the physical indoor environment quality (Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016). There are many economic benefits for open-plan offices such as the increase of available useful area, occupant density, and easy refurbishment, along with facilitating workers' interaction and communication (Kim & Dear, 2013). However, it is a common perception that open-plan offices provide less job and environmental satisfaction because of the lack of space, visual, and acoustic privacy along with insufficient thermal and air quality, and distractions caused by noise (Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016).

Since improving the environmental conditions in open-plan office buildings can improve the workers' satisfaction and productivity, the relationship between environmental quality and satisfaction is discussed in this section. There are studies (Bodin Danielsson & Bodin, 2009), (De Caroon, Sluiter, Kuijer, & Frings-Dresen, 2005) claiming that open-plan offices provide less satisfaction for their occupants compared with private offices. Although, it is complicated to evaluate job satisfaction in open-plan offices because of the type of activity and since open-plan offices are more suitable for teamwork leading to more satisfaction and productivity for this particular task (Hongisto, Haapakangas, Varjo, Helenius, & Koskela, 2016). In order to understand the patterns of different tasks in office buildings, a useful taxonomy includes four metaphors that Laing considers for workplace affecting the office layout design (Laing, Duffy, Juanzens, & Willis, 1998). These are:

- “Hive”: This type of office is an arrangement of cellular and open-plan offices that is suitable for organizations with low interaction and individual task. In this type, most of the typical tasks are done individually, and the occupancy time pattern is regular.

- “Cell”: This type of office is an arrangement of cellular offices that is suitable for organizations with no interaction and individual task. In this type, the occupancy time pattern is irregular according to the needs.
- “Den”: This type of office is appropriate for group working with a low level of concentration.
- “Club”: This type of office is an arrangement of combi offices and hot desking that is suitable for organizations with knowledge work. In this type, the occupancy time pattern is periodical according to schedules (Laing, Duffy, Juanzens, & Willis, 1998) (Al Horr, et al., 2016).

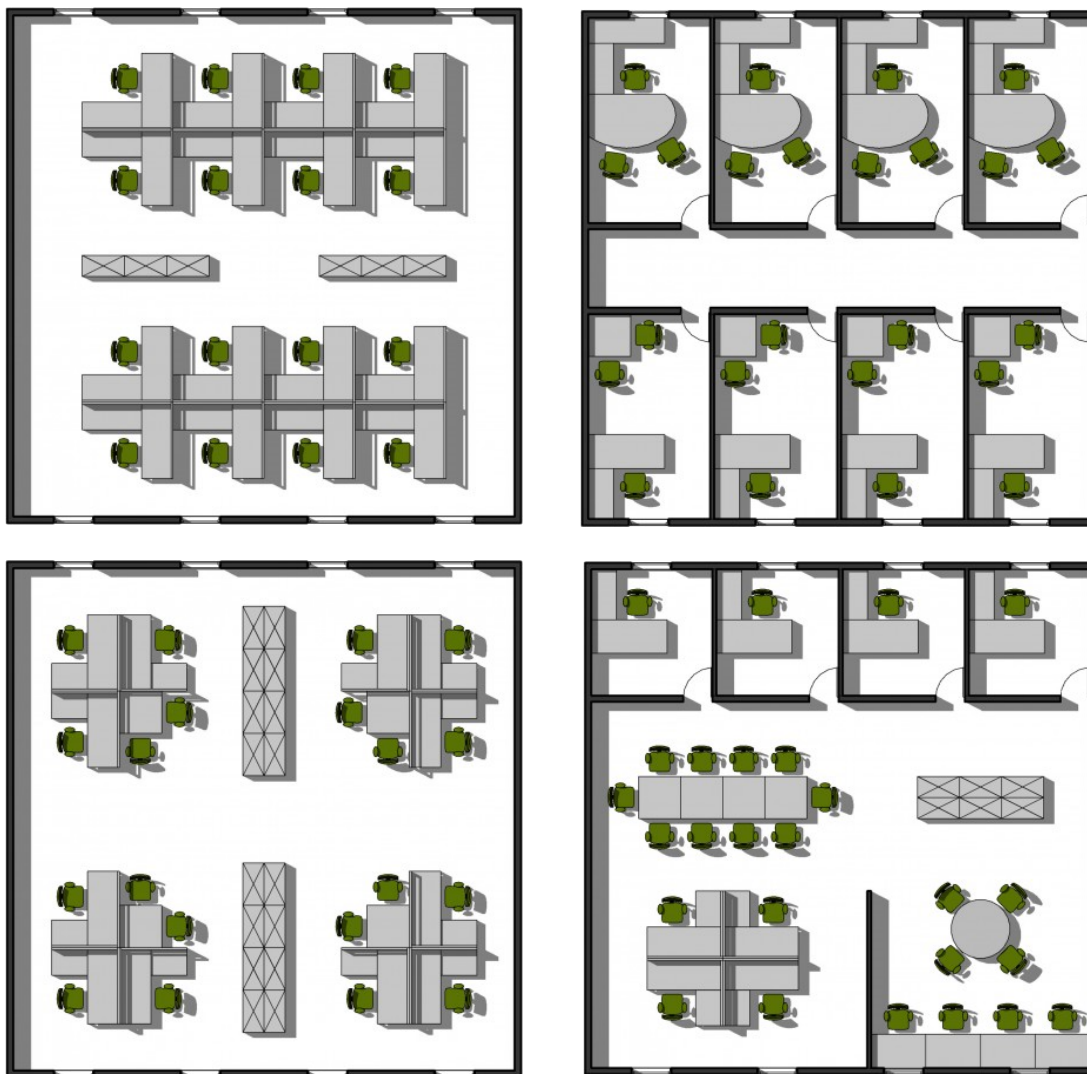


Figure 4. “Hive” (top left), “Cell” (top right), “Den” (bottom left), “Club” (bottom right)

Source: <https://www.hofman.co.za/question/space-planning-models/>

These different office layouts indicate various processes that can be defined for an office according to the spatial parameters (Al Horr, et al., 2016). According to the study done by (Oldham, Kulik, & Stepina, 1991), There are three spatial characteristics of a workplace affecting the occupant's performance and satisfaction including the spatial density, the number of partitions around the workstation, and interpersonal distance (Hua, Loftness, Heerwagen, & Powell, 2011).

Spatial density is the division of the total square footage of an office excluding the hallways by the total number of office employees (Oldham, Kulik, & Stepina, 1991). When the spatial density increases, the employee's satisfaction, and performance will decrease according to the sense of crowding. The number of partitions around the workstation and their height directly affect the employees' perception of privacy leading to environmental performance and job satisfaction based on distraction reduction and acoustic privacy (Hua, Loftness, Heerwagen, & Powell, 2011). Interpersonal distance is "the minimum walking distance between the centers of an employee's and nearest coworker's desks (Oldham, Kulik, & Stepina, 1991). The proximity can improve the possibility of communication while it can also be disadvantageous based on the demands increased by face-to-face conversation (Hua, Loftness, Heerwagen, & Powell, 2011).

Very large workstations can reduce environmental satisfaction according to lack of privacy and enclosure (Marquardt, Veitch, & Charles, 2002). According to the study done by (Charles & Veitch, 2002) from 419 occupied workstations in three Canadian Federal Government open-plan offices, workstation area can be ranged from 41.56 ft² (3.86 m²) to 209.31 ft² (19.44 m²) that the low number was 108.53 ft² (10.08 m²). For partition height, while it can be a number between 0-81 inches (0-2 meters), most of the workstations had partitions with at least 60 to 70 inches (1.5 to 1.8 meters) that the mean number was 61.63 inches (1.6 meters).

In order to choose between traditional cellular offices and open-plan offices, it can be argued that there are shortcomings for open-plan offices according to lack of privacy, higher density, and distraction, along with insufficient thermal and air quality while cellular offices may not be compatible with the most organization's process. (Van Der Voordt, 2004) suggested innovative combi offices that are a mix of private and shared workplaces and make it possible to overcome the shortcomings of open-plan and cellular offices because in this type of office can take advantage of both concentrating on work and having shared interaction spaces (Al Horr, et al., 2016).

2.3.2 Indoor Air Quality and Ventilation

Increasing the ventilation rate or decreasing the pollution source can improve the quality of indoor air. One strategy for better indoor air quality is natural ventilation that can have better impacts on occupants compared with air conditioning systems, but it depends on the location of the building (Al horr, et al., 2016). So, in this thesis, natural ventilation is considered in all simulations for better indoor air quality.

2.3.3 Thermal Comfort

According to “American Society of Heating, Refrigerating and Air-Conditioning Engineers” (ASHRAE) (ASHRAE, 2004), thermal comfort can be defined as “That condition of mind which expresses satisfaction with the thermal environment.” So, it can be affected by cultural, organizational, social, and individual factors. Even in the same environment, it can be different from person to person. What the human perceives thermally in the environment is a complicated subjective issue related to multiple interacting factors that are less tangible and is difficult to have a certain standard for thermal comfort. Generally, when the body temperature falls within particular ranges with low skin moisture and low regulation attempt, it can be said that the body is

in thermal comfort. On the other hand, humans can change their thermal situation by changing the location, type of activity, clothing, thermostat set-points, and closing or opening the windows (Djongyang, Tchinda, & Njomo, 2010).

Thermal comfort is also influenced by quantities such as “Metabolic rate, Effective mechanical power, clothing insulation, clothing surface area factor, air temperature, mean radiant temperature, relative air velocity, water vapor partial pressure, convective heat transfer coefficient, and clothing surface temperature” (Cigler, Prívvara, Vána, Záceková, & Ferkl, 2012). Since peoples’ sense of comfort varies, thermal comfort is generally related to a group of optimal factors and calculated based on the highest percentage of comfortable people in environment (Croitoru, Nastase, Meslem, & Dogeanu, 2015).

Thermal comfort can be defined by physiological, psychological, and rational approaches:

- The physiological approach is based on the body perception of the thermal environment according to warm and cold sensors in the body. The body can maintain its temperature approximately fixed. When the body temperature becomes less than 34°C (93.2° F), the body starts sweating by receiving signals from cold sensors in the body skin. On the contrary, when the body temperature becomes more than 37°C (98.6° F), the body starts shivering by receiving signals from warm sensors in the hypothalamus. Moreover, various parts of the body can have different sensations based on place, time, environmental temperature, and type of clothing.
- The psychological approach is related to “the occupant satisfaction with the thermal environment.” In order to quantify this satisfaction, the number of occupants that are satisfied with the thermal environment can be considered as a measurement. This number can be different in various standards.

- The rational approach is based on “the heat balance of the human body.” When there is a balance between the heat transferred into and emitted from the body, the body can be considered thermally comfortable (Enescu, 2017).

According to the study done by (Liu, Yao, & McCloy, 2012), the physiological approach is the main factor for evaluating the thermal environment, and psychological and behavioral approaches have the same importance.

As mentioned before, thermal comfort can be affected by all the factors influencing the heat exchange between the human body and its surrounding. These factors can be divided into three groups related to the human organism, clothing, and the environment.

- The first group is related to human age, gender, metabolic rate, weight, and activity type.
- The second group is related to thermal resistance, material, and the number of layers.
- The third group is related to air temperature, humidity, velocity, and pressure (Croitoru, Nastase, Meslem, & Dogeanu, 2015).

In the next section, the parameters related to thermal comfort will be evaluated.

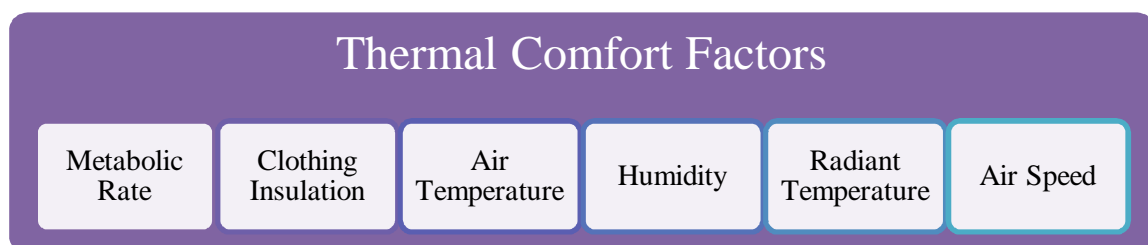


Figure 5. Factors influencing thermal comfort

Thermal Comfort Parameters

Thermal comfort indices can be grouped based on “the calculation of the heat balance of the human body (rational indices), physiological strain (empirical indices), and measurement of

physical parameters (direct indices)” (Carlucci & Pagliano, 2012). Body heat balance can be affected by personal parameters and ambient parameters.

Personal parameters, related to occupant characteristics, are clothing insulation (clothing level), and metabolic heart rate (activity level). Ambient parameters, related to the environment, are air velocity, relative humidity, temperature, and mean radiant temperature.

❑ **Clothing Insulation**

Clothing is defined as the thermal insulation for the heat and humidity exchange between the human body and its surrounding that is a determinant parameter in thermal comfort theory. People can regulate their thermal situation by adjusting their clothes, leading to energy savings in buildings. Indoor clothing is affected directly by outdoor temperature (Liu, Yang, Shen, & Yang, 2018). Inadequate clothing in shallow temperatures causes hypothermia according to drop in body temperature and is slightly uncomfortable, though not physically dangerous, may negatively impact productivity. In high temperature, clothing insulation can act like both protectors against penetrating external heat into the body and escaping the generated heat by the body. The environment, clothing insulation, and the human body are affecting the occupant’s thermal comfort and health collectively. In the warm and cold environments, according to the ability of the human body to adapt to the environment, clothing insulation is considered as the main parameter that affects human thermal comfort. In workplaces, it is vital to choose appropriate clothing insulation compatible with activity type and the environment (Jiao, Yu, Wang, An, & Yu, 2017).

Studies are investigating the relationship between clothing insulation and climate. In a moderate climate, people wear lighter clothing in summer and heavier clothing in winter; on the other hand, they change their garment according to the season (Almeida, Ramos, & Freitas, 2016). In cold climates, people are used to regulating the thermal conditions with clothing insulation

(Wang, Zhang, Zhao, & He, 2010). Also, there are several factors beyond climate conditions affecting the clothing insulation such as gender and age. According to the study done by (Jiao, Yu, Wang, An, & Yu, 2017), while the effect of clothing insulation in the elderly is evident in summer, there is no noticeable effect on them in winter. There are also studies on clothing insulation in kindergartens (Yun, et al., 2014), elementary schools (Alfano, Ianniello, & Palella, 2013), high schools (Havenith, Metabolic rate and clothing insulation data of children and adolescents during various school activities, 2007), and universities (Li, Tan, Liu, Ma, & Zhang, 2010).

According to ASHRAE standard 55, clothing insulation is expressed in clo value (I_{cl}), and different values for this parameter are presented in Table 1, and Table 2. Three methods are calculating the clothing insulation that are arranged according to accuracy. The first method that is presented in Table 1 calculated the clothing insulation for usual clothing ensembles can be used for matched cases. In the second method, the values presented in Table 2 that are for individual garments can be added to or subtracted from the values in Table 1. These values can be used for clothing insulations that have different compositions. In the third method, the clothing insulation can be calculated for a new composition by adding different values presented in Table 2 (ASHRAE, 2013).

Table 1. Clothing Insulation Values for Typical Ensembles (ASHRAE, 2013)

Clothing Description	Garments Included ^{b*}	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

Table 2. Garment Insulation (ASHRAE, 2013)

Garment Description ^{ba}	$I_{clu}(\text{clo})$	Garment Description ^{ba}	$I_{clu}(\text{clo})$
Underwear		Dress and Skirts^{eb}	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half-slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20	Sweaters	
Footwear		Sleeveless vest (thin)	0.13
Ankle-length athletic socks	0.02	Sleeveless vest (thick)	0.22
Panty hose/stockings	0.02	Long-sleeve (thin)	0.25
Sandals/thongs	0.02	Long-sleeve (thick)	0.36
Shoes	0.02	Suit Jackets and Vests^{de}	
Slippers (quilted, pile lined)	0.03	Sleeveless vest (thin)	0.10
Calf-length socks	0.03	Sleeveless vest (thick)	0.17
Knee socks (thick)	0.06	Single-breasted (thin)	0.36
Boots	0.10	Single-breasted (thick)	0.44
Shirts and Blouses		Double-breasted (thin)	0.42
Sleeveless/scoop-neck blouse	0.12	Double-breasted (thick)	0.48
Short-sleeve knit sport shirt	0.17	Sleepwear and Robes	
Short-sleeve dress shirt	0.19	Sleeveless short gown (thin)	0.18
Long-sleeve dress shirt	0.25	Sleeveless long gown (thin)	0.20
Long-sleeve flannel shirt	0.34	Short-sleeve hospital gown	0.31
Long-sleeve sweatshirt	0.34	Short-sleeve short robe (thin)	0.34
Trousers and Coveralls		Short-sleeve pajamas (thin)	0.42
Short shorts	0.06	Long-sleeve long gown (thick)	0.46
Walking shorts	0.08	Long-sleeve short wrap robe (thick)	0.48
Straight trousers (thin)	0.15	Long-sleeve pajamas (thick)	0.57
Straight trousers (thick)	0.24	Long-sleeve long wrap robe (thick)	0.69
Sweatpants	0.28		
Overalls	0.30		
Coveralls	0.49		

❑ Metabolic Rate or Activity Level

Metabolic rate is “the heat generated within the body” and one of the most important comfort parameters (Luo, et al., 2018). The body produces energy by consuming food and oxygen that can be measured as heat. A part of this energy is used for doing mechanical work (W); so, the metabolic heat production (H) is:

$$H = M - W$$

Which W is a ratio of M ranging from 0 to 20% and for sedentary and low activities like office work can be considered as 0 (Havenith, Holmer, & Parsons, 2002). The amount of heat generated by an adult in rest position is about 100W.

On the other hand, the metabolic rate is expressed as the heat produced by per unit of skin area since skin is the primary body heat distributor to the environment (Luo, et al., 2018). The surface area for man and woman is considered 1.8 m² and 1.6 m², respectively. In moving activities such as walking upstairs, body mass is another compelling factor that is considered 70 kg and 60 kg for man and woman, respectively (Havenith, Holmer, & Parsons, 2002). So, the amount of heat generated by per unit of skin area is 58.2 W/m² for a person in the rest position and is called one met. Other metabolic rates are characterized as a ratio of the resting rate. Body heat balance is a combination of the external heat load and metabolic rate, and the required time for the body to provide heat balance is about 20 minutes. Consequently, overheating is caused by inappropriate heat loss, and cooling is caused by ample heat loss (Luo, et al., 2018). In order to determine the metabolic rate, the most common method is to find the related value in tables represented in ASHRAE handbook based on the activity level (Luo, Zhou, Zhu, & Sundell, 2016).

The comfort skin temperature for a person in sedentary activities is about 33-34°C. As Fanger (Fanger, 1970) stated, when the activity increases, the temperature of the skin reduces while the

body internal temperature increases. The environmental temperature the human prefers drops with increased activity level.

Different activities and their related metabolic rate are shown in Table 3.

Table 3. Metabolic rates for typical tasks (ASHRAE, 2013)

<u>Activity</u>	<u>Metabolic Rate</u>		
	<u>Met Units</u>	<u>W/m²</u>	<u>(Btu/h-ft²)</u>
Resting			
<u>Sleeping</u>	<u>0.7</u>	<u>40</u>	<u>(13)</u>
<u>Reclining</u>	<u>0.8</u>	<u>45</u>	<u>(15)</u>
<u>Seated, quiet</u>	<u>1.0</u>	<u>60</u>	<u>(18)</u>
<u>Standing, relaxed</u>	<u>1.2</u>	<u>70</u>	<u>(22)</u>
Walking (on level surface)			
<u>0.9 m/s, 3.2 km/h, 2.0 mph</u>	<u>2.0</u>	<u>115</u>	<u>(37)</u>
<u>1.2 m/s, 4.3 km/h, 2.7 mph</u>	<u>2.6</u>	<u>150</u>	<u>(48)</u>
<u>1.8 m/s, 6.8 km/h, 4.2 mph</u>	<u>3.8</u>	<u>220</u>	<u>(70)</u>
Office Activities			
<u>Reading, seated</u>	<u>1.0</u>	<u>55</u>	<u>(18)</u>
<u>Writing</u>	<u>1.0</u>	<u>60</u>	<u>(18)</u>
<u>Typing</u>	<u>1.1</u>	<u>65</u>	<u>(20)</u>
<u>Filing, seated</u>	<u>1.2</u>	<u>70</u>	<u>(22)</u>
<u>Filing, standing</u>	<u>1.4</u>	<u>80</u>	<u>(26)</u>
<u>Walking about</u>	<u>1.7</u>	<u>100</u>	<u>(31)</u>
<u>Lifting/packing</u>	<u>2.1</u>	<u>120</u>	<u>(39)</u>
Driving/Flying			
<u>Automobile</u>	<u>1.0–2.0</u>	<u>60–115</u>	<u>(18–37)</u>
<u>Aircraft, routine</u>	<u>1.2</u>	<u>70</u>	<u>(22)</u>
<u>Aircraft, instrument landing</u>	<u>1.8</u>	<u>105</u>	<u>(33)</u>
<u>Aircraft, combat</u>	<u>2.4</u>	<u>140</u>	<u>(44)</u>
<u>Heavy vehicle</u>	<u>3.2</u>	<u>185</u>	<u>(59)</u>
Miscellaneous Occupational Activities			
<u>Cooking</u>	<u>1.6–2.0</u>	<u>95–115</u>	<u>(29–37)</u>
<u>House cleaning</u>	<u>2.0–3.4</u>	<u>115–200</u>	<u>(37–63)</u>
<u>Seated, heavy limb movement</u>	<u>2.2</u>	<u>130</u>	<u>(41)</u>
<u>Machine work</u>			
<u>sawing (table saw)</u>	<u>1.8</u>	<u>105</u>	<u>(33)</u>
<u>light (electrical industry)</u>	<u>2.0–2.4</u>	<u>115–140</u>	<u>(37–44)</u>
<u>heavy</u>	<u>4.0</u>	<u>235</u>	<u>(74)</u>
<u>Handling 50 kg (100 lb) bags</u>	<u>4.0</u>	<u>235</u>	<u>(74)</u>
<u>Pick and shovel work</u>	<u>4.0–4.8</u>	<u>235–280</u>	<u>(74–88)</u>
Miscellaneous Leisure Activities			
<u>Dancing, social</u>	<u>2.4–4.4</u>	<u>140–255</u>	<u>(44–81)</u>
<u>Calisthenics/exercise</u>	<u>3.0–4.0</u>	<u>175–235</u>	<u>(55–74)</u>
<u>Tennis, single</u>	<u>3.6–4.0</u>	<u>210–270</u>	<u>(66–74)</u>
<u>Basketball</u>	<u>5.0–7.6</u>	<u>290–440</u>	<u>(90–140)</u>
<u>Wrestling, competitive</u>	<u>7.0–8.7</u>	<u>410–505</u>	<u>(130–160)</u>

Following is a list of critical ambient comfort parameters that are related to the environment:

❑ **Air Velocity**

Air velocity is one of the ambient parameters related to thermal comfort and is defined as “the rate of air movement to a given distance over time.” When its value goes higher than 40 feet/min that is equivalent to 0.2332 m/s, or by mixing cold temperatures with the movement of air, it can cause discomfort (Enescu, 2017).

❑ **Relative Humidity**

The relative humidity is the ratio of water vapor pressure in the air to the water vapor pressure that the air could hold. When its value goes higher than 70%, it can cause discomfort (Enescu, 2017).

❑ **Air Temperature**

The dry bulb temperature or air temperature is “the temperature of the indoor air surrounding the body,” and its comfortable range is between 19° C to 28° C (66° F - 82° F) for general office activities (Enescu, 2017).

❑ **Mean Radiant Temperature**

The Radiant Temperature is related to the amount of heat transferred from a surface according to the ability of materials to absorb or emit heat or its emissivity (Enescu, 2017).

Models of Thermal Comfort

To investigate people’s thermal comfort, several models have been presented. Fanger’s “comfort equation” model (Fanger, 1972) is the most famous and most used. In this model, a thermal vote, based on a seven-point thermal scale, is predicted based on multiple parameters and empirical equations related to heat exchange between the human body and surroundings. The model results

in the Predicted Mean Vote (PMV), which predicts an occupant's thermal vote regarding the specified indoor conditions. Predicted Percentage of Dissatisfied (PPD) is another evaluation metric in Fanger's thermal model. The evaluation of thermal comfort in Fanger's model is done based on Effective Temperature (ET), which includes air temperature, the air velocity, and the relative humidity (Croitoru, Nastase, Meslem, & Dogeanu, 2015).

The accuracy of Fanger's model has been criticized by many researchers, especially for field studies and in cases that the conditions are mainly different from model conditions because Fanger's model is done in laboratory condition. The "adaptive model" based on the body's ability to adapt physiologically, remedies these definitions. It accounts for behavioral, and psychological factors, whereas previous models are physiological models that do not consider the cultural, climate, and social contextual aspects of comfort. It allows for adaptation initiated by occupants or for changes to the environment according to occupant's needs. In this model, climate, building, and time are three different types of context. Climate conditions are used in order to determine the indoor heat. The building is determinant because of services and equipment provided for the occupants. Finally, time is essential because comfort temperature is different in time, and human activities are dependent on time (Croitoru, Nastase, Meslem, & Dogeanu, 2015).

This study considers climate, building, and time as different factors in the simulations and calculates thermal metrics based on these contexts.

2.3.4 *Lighting and Daylighting*

Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" (I.S. EN 12665, 2002). This definition mentions the psychological aspects of comfort, but some physical characteristics of the visual environment are used in order to evaluate its quality (Frontczak & Wargocki, 2011). Reinhart, Mardaljevic, and Rogers (2006) considered

Daylight Factor (DF), view to the outside, and avoidance-of-direct-sunlight as static daylight metrics. There are also dynamic metrics for daylight performance such as Daylight Autonomy (DA) (Reinhart, Mardaljevic, & Rogers, 2006), spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI) (Nabil & Mardaljevic, 2005), and Annual Sunlight Exposure (ASE) for climate-based measurement.

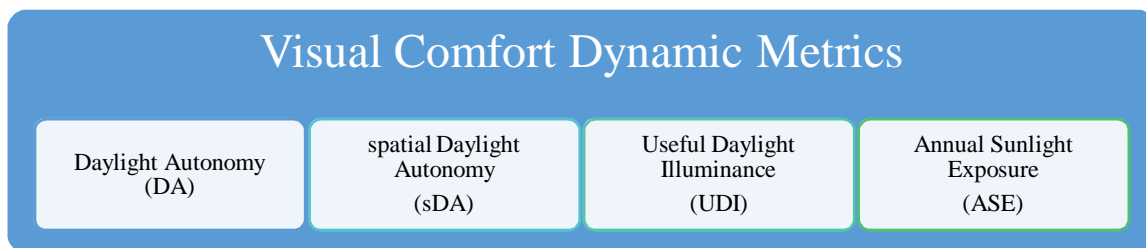


Figure 6. Annual metrics for evaluating visual comfort

UDI is defined as the annual incidence of illuminances on a work plane in a range that occupants consider being “useful.” This “useful” range is according to a survey that investigated occupant preferences and behavior in offices with daylight and shading devices (Mardaljevic, Anderson, Roy, & Christofferson, 2011). Generally,

- Daylight illuminances less than 100 lx are considered as insufficient (Nabil and Mardaljevic 2006).
- Daylight illuminances in the range 100–300 lx are considered as useful (Mardaljevic, Anderson, Roy, & Christofferson, 2011).
- Daylight illuminances in the range of 300 to around 3000 lx are often considered either as desirable or at least tolerable (Mardaljevic, Anderson, Roy, & Christofferson, 2011).
- Daylight illuminances higher than 3000 lx are likely to produce visual or thermal discomfort, or both (Nabil and Mardaljevic 2006).

Appropriate levels of illuminance will vary by space type, visual task, and occupant type. According to IESNA illuminance categories, general and private offices are in category D and E that are “the performance of visual tasks of high contrast and large size” and “the performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size” respectively, and proper illuminance is considered 300-500 lx (IESNA, 1979).

sDA is “a metric describing annual sufficiency of ambient daylight levels in interior environments.” This metric is defined as “the percent of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year” (IES, 2012). In this study, the minimum illuminance level for a task in an office building is considered to be 300 lx. As there is no upper limit for sDA, there is a need for another metric to avoid glare. There is an index called Annual Sun Exposure (ASE) (IES, 2012) created as a companion metric to sDA and describing the amount of space with too much direct sunlight. Consequently, this amount of direct sunlight can make the space visually uncomfortable and increase the cooling load inside the building. “Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year” (Sterner, 2014).

Glare happens when humans are exposed to excessive light or contrast in a particular field of view (FOV) and are related to the distribution of luminance in the observer’s FOV. Glare, a measure of physical discomfort, is generally classified as disability glare, discomfort glare, and veiling glare (Jakubiec & Reinhart, 2011). Discomfort glare is defined as “glare, which causes discomfort without necessarily impairing the vision of object” by the CIE, but the occupant becomes unable to see the objects with disability glare (Karlsen, Heiselberg, Bryn, & Johra, 2015). To predict the degree of perceived discomfort glare, indexes such as the Daylight Glare Index (DGI) (Hopkinson, 1972), the Daylight Glare Probability (DGP) (Wienold & Christoffersen,

2006), Unified Glare Probability (UGP) (Hirning, Isoardi, & Cowling, 2014) that was a modification of Unified Glare Rating (UGR) proposed by the CIE in 1995, VCP (Visual Comfort Probability), and CGI (CIE Glare Index) have been developed.

DGP, developed by (Wienold & Christoffersen, 2006), is for glare caused by daylight and investigates luminance contrast and vertical illuminance on the observer's eye. The study (Mangkuto, 2017) shows that DGP values that are less than 0.35 are considered as invisible, between 0.35 and 0.40 are perceptible, between 0.40 and 0.45 are disturbing, and those that are more than 0.45 are intolerable.

In this study, sDA is calculated for each point of the grid as the lower limit, and DGP along with ASE is used for the upper limit.

2.3.5 Other Comfort Factors

There are also other factors such as Noise and Acoustic, biophilia, views, and “look and feel” that can affect indoor comfort. These factors are not in the scope of this study.

Chapter 3. METHODOLOGY

3.1 SIMULATION INPUTS

According to different physical factors related to comfort and productivity inside office buildings, various parameters can be used as simulation inputs. These include office layout, indoor air quality, thermal comfort, and visual comfort.

There are additional parameters that can affect both thermal and visual comfort and are related to building characteristics. These parameters are the glazing type, window-to-wall ratio (WWR), and shading. Making changes to any of these parameters can affect visual and thermal conditions significantly. So, these parameters are considered in simulations to see their effects on results.

Accordingly, there are several inputs for simulations to be changed that can be categorized, as shown in Figure 7:

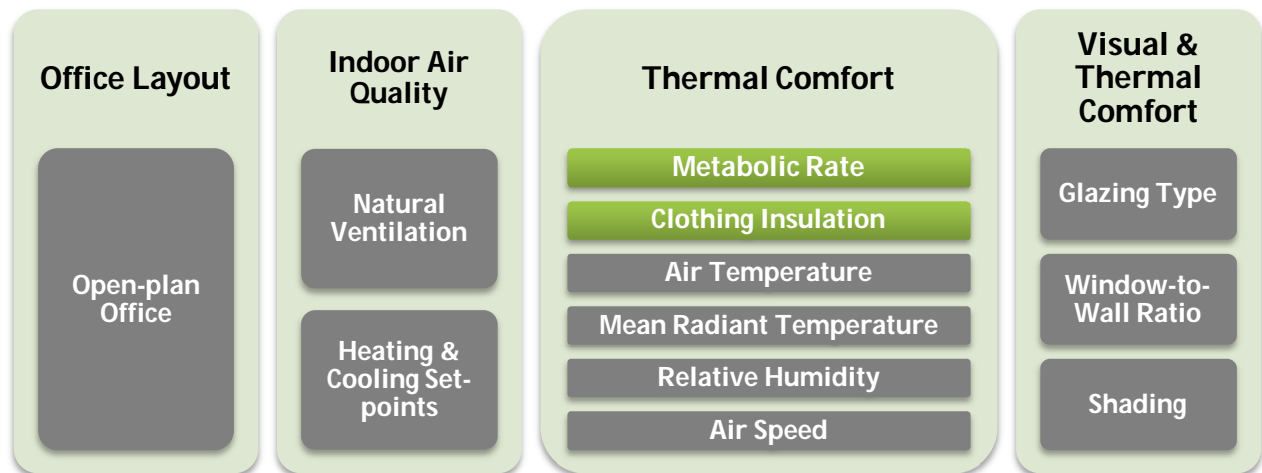


Figure 7. Factors affecting comfort and productivity in office buildings

In order to consider the effect of these parameters on results, different types for each of them are included. Different values for each parameter, the reasons for choosing them, and the research process will be explained in the following section.

3.1.1 Office Layout

As mentioned in Section 2.3.1, an open-plan office is selected in this study according to higher attitude and capability to provide more satisfaction and productivity for occupants. After testing simulation for a range of different floor sizes, it was concluded that the best way to compare the results would be selecting a part of an open-plan office and doing all the simulations for that part. The results can be generalized to wider ranges of floor plans. As can be seen in Figure 9, a 12m by 9m floor plan is selected for simulations with south facing windows.

Moreover, most of the office workstations are 1.5m by 1.5m; so, the floor plan was divided into 6 zones based on the distance from the window. Each zone is a 1.5m by 12m space that is parallel with the window and has been shown in Figure 9.

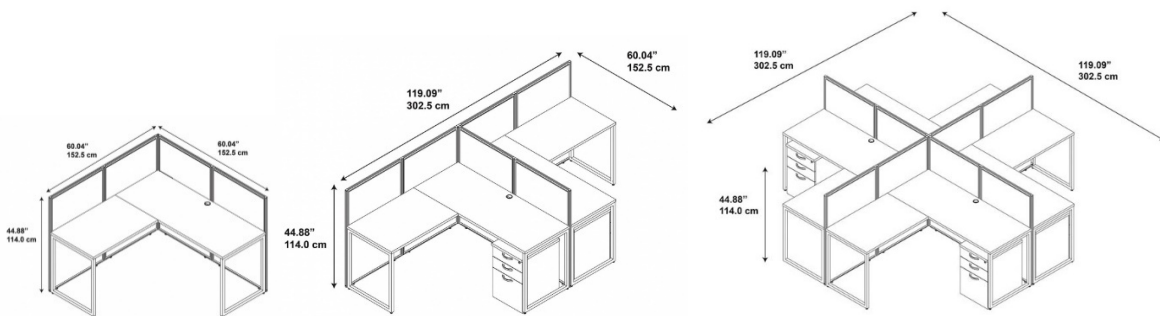


Figure 8. Typical Office Workstations

Source: www.bushfurniture2go.com

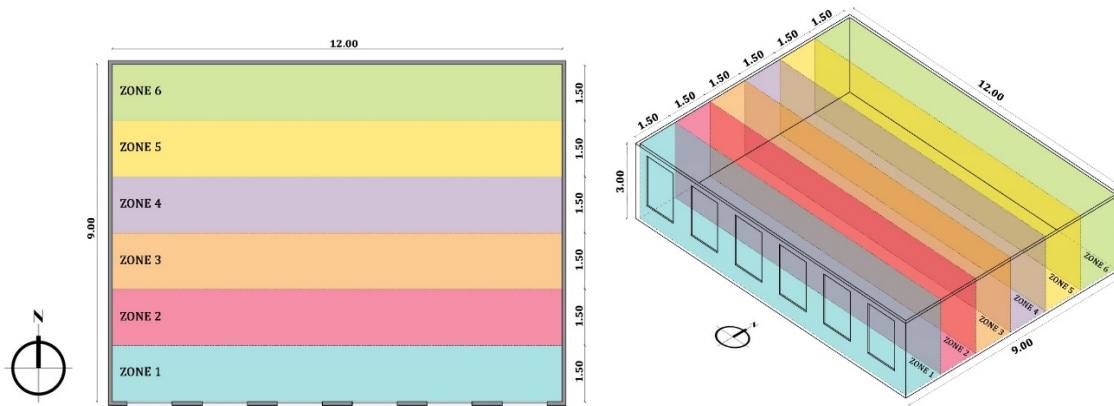


Figure 9. Floor Plan and Zone Divisions

All the vertical walls, floor and roof are adiabatic except the glazing wall exposed to outdoor conditions because this floor plan is a part of a larger floor plan and selected to show the simulation results. ASHRAE defines the adiabatic as “without loss or gain of heat (e.g., an adiabatic boundary does not allow heat to flow through it)” (ASHRAE, 2014). In this way, it allows smaller zones evaluated independently and in isolation.

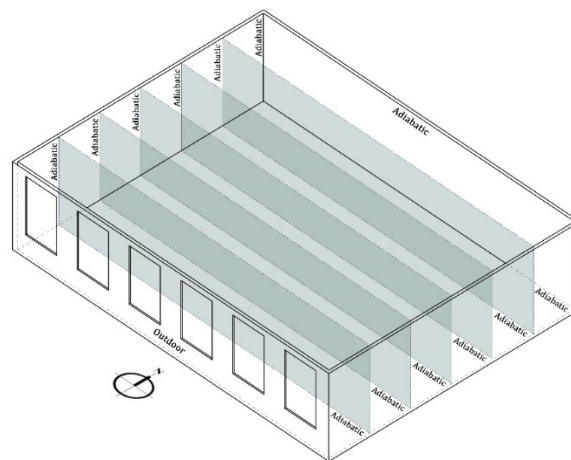


Figure 10. Adiabatic walls, Roof, and Floor

3.1.2 Indoor Air Quality

As mentioned in previous sections, one strategy for improved indoor air quality is natural ventilation which can have better impacts on occupants compared with air conditioning systems

but is dependent on the location of the building (Al horr, et al., 2016). In this thesis, window natural ventilation is considered in all simulations. Based on the Grasshopper component (Honeybee _ Set EP Air Flow), half of each window is considered as operable that is a single sliding window opening with insect screen (discharge coefficient of 0.17)

The parameters related to Indoor Environmental Quality can be set in the following components in Grasshopper.



Figure 11. Honeybee _ Set EP Air Flow Component for natural ventilation

3.1.3 Thermal Comfort

For thermal comfort, there are some personal parameters, related to occupant characteristics, that are clothing insulation (clothing level), and metabolic rate (activity level). There are also some ambient parameters, related to the environment, that are air temperature, mean radiant temperature, relative humidity, and airspeed. These parameters constitute the simulation inputs that ambient parameters are location-based or weather-file based that are exported from the weather file. Based

on Grasshopper component (Ladybug _ PMV Comfort Calculator), all these parameters can be considered and changed in simulations.

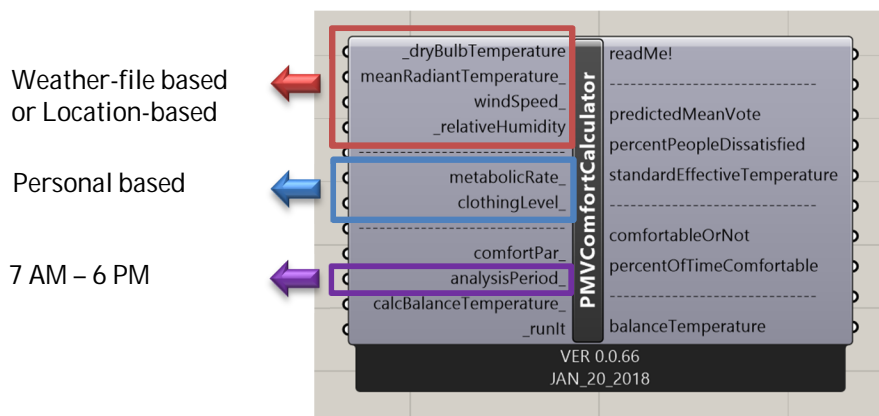


Figure 12. Ladybug _ PMV Comfort Calculator Component

Metabolic Rate

As mentioned before, metabolic rate is “the heat generated within the body” and one of the most critical comfort parameters and is expressed in the MET unit (Luo, et al., 2018).

For metabolic rate, different activities and their related metabolic rate are considered. According to the ASHRAE table for different activities, the following metabolic rates for different activities in an office building are selected:

Table 4. Metabolic rate for different activities in office building according to ASHRAE

Activity Type	Metabolic Rate (MET)
Break Room	1
Open Office	1.1
Conference	1.2
Print Room	1.4
Corridor	1.7

Clothing Insulation

Clothing is defined as the thermal insulation for the heat and humidity exchange between the human body and its surrounding that is a determinant parameter in thermal comfort theory (Liu,

Yang, Shen, & Yang, 2018). According to ASHRAE standard 55, clothing insulation is expressed in clo value (Icl).

The clothing insulation is different for formal and casual dressing that can affect the simulation results significantly. So, these two types of clothing insulation are selected in order to see the changes in results. There are min and max values for clothing factor in simulations. The maximum Clo is the value that someone will wear on the hottest days of the outdoor air temperature, and the minimum Clo is the value that someone will wear on the coldest days of the outdoor air temperature. The maximum and minimum clothing factors are calculated with the CBE thermal comfort calculation tool as the following:

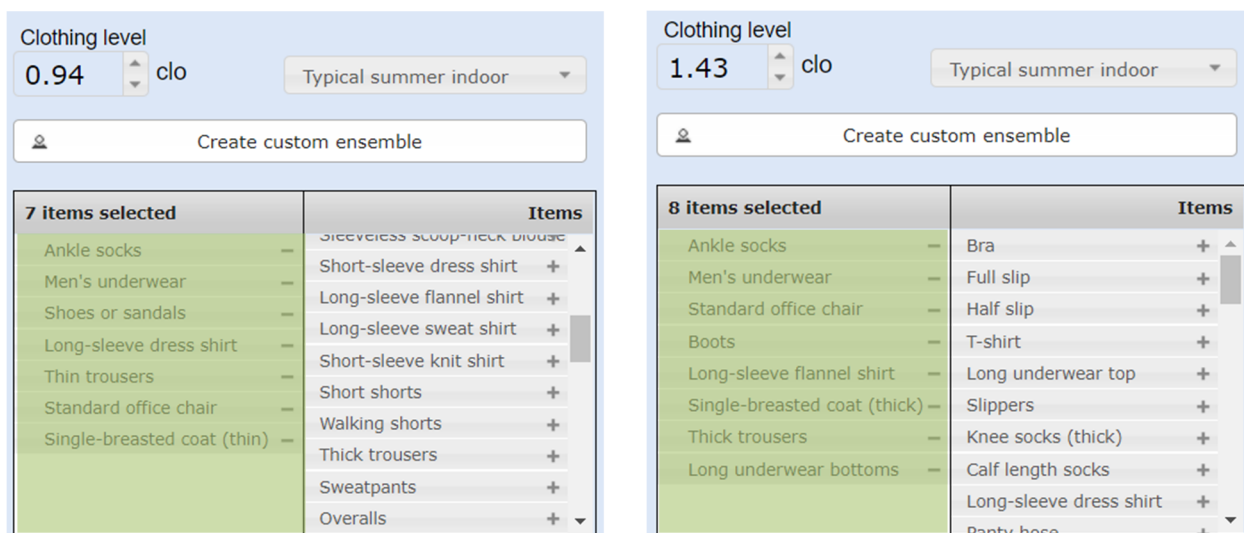


Figure 13 . Minimum Clo factor for formal dressing (left), Maximum Clo factor for formal dressing (right)

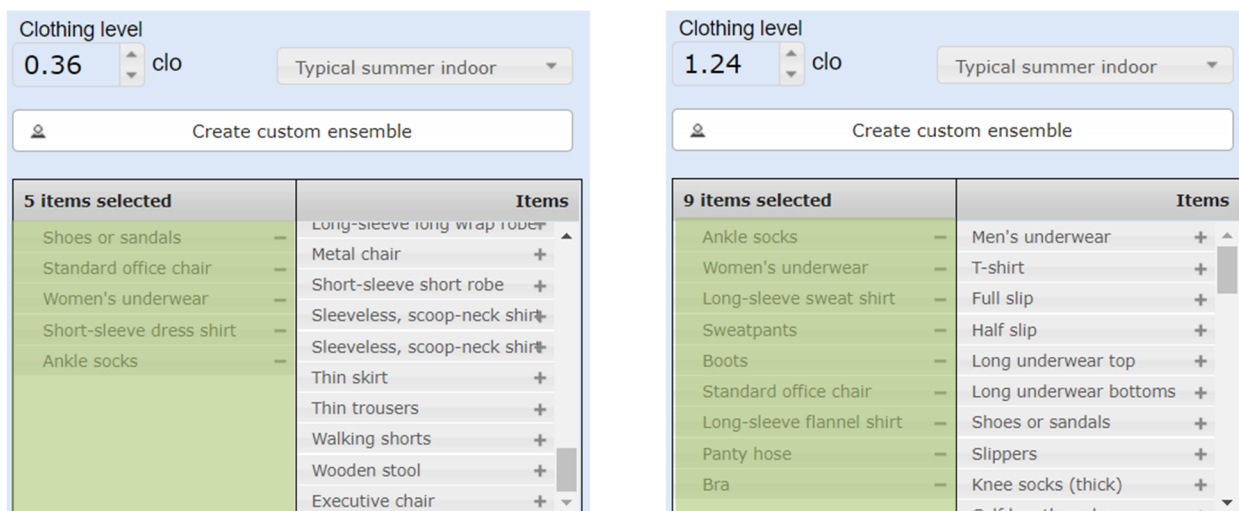


Figure 14. Minimum Clo factor for informal dressing (left), Maximum Clo factor for informal dressing (right)

The numbers are reflected in the following table:

Table 5. Minimum and maximum Clo for formal and informal clothing calculated by CBE thermal comfort tool

	Formal Clothing	Informal Clothing
Minimum Clo	0.94	0.36
Maximum Clo	1.43	1.24

Heating and Cooling Set-point

As the PMV model is for conditioned spaces, critical variables for assessment are the heating and cooling set-points. The Grasshopper component (Honeybee _ Set EnergyPlus Zone Thresholds) is used for changing the cooling and heating set-points. In conditioned buildings, there is a need for thermostatic control setting the heating and cooling target temperature for the zone. The heating and cooling set-point define this target temperature range. Also, there is a cooling and heating setback that is for unoccupied hours (Makela, Russell, Fujita, & Strecker, 2011), which is deployed as an energy conservation measure. The following table shows supposed settings for the

thermostat in most of “energy simulation software protocols” (Parker & Florida Solar Energy Center , 2013).

Standard	Cooling Set Point	Heating Set Point
HSB/Building America	76° F / 25° C	71° F / 22° C
IECC	75° F / 24° C	72° F / 21° C
RESNET/HERS	78° F / 26° C	68° F / 20° C
Home Energy Scoring Tool	78° F / 26° C	68° F / 20° C

Table 6. Supposed settings for the thermostat in most of “energy simulation software protocols” (Parker & Florida Solar Energy Center , 2013)

According to this table, two types of set-points are considered for simulations. One typical arrangement is 20°C (68° F) for the heating set-point and 26°C (78° F) for the cooling set-point. The more comfortable one could be considering 21°C (72° F) for the heating set-point and 24°C (75° F) for the cooling set-point.

The parameters related to heating and cooling set-point can be set in the following component in Grasshopper.

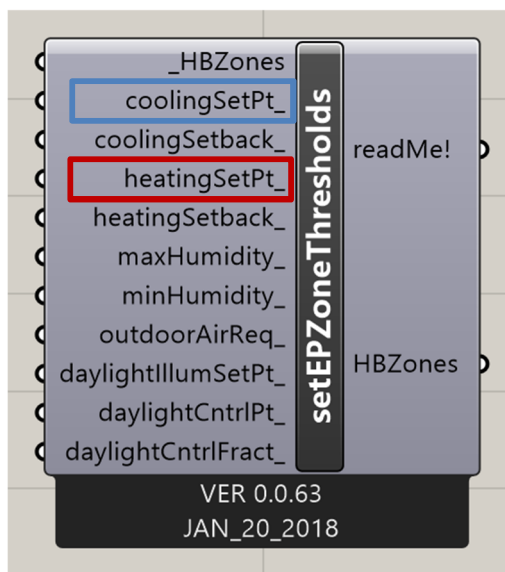


Figure 15. Honeybee _ Set EnergyPlus Zone Thresholds for cooling and heating set-points

Other Parameters

As mentioned in previous sections, most of thermal and visual comfort metrics are location-based or weather-file based. So, it would be essential to define the location for simulations. This could be one of the comparing factors.

There are seven climate regions in the US by International Energy Conservation Code (IECC) (Pacific Northwest National Laboratory & Oak Ridge National Laboratory, 2010). To show the effect of location on the results and to test out this methodology in some different climates, three different US cities in different climate regions are selected: Boston, Phoenix, and San Francisco.

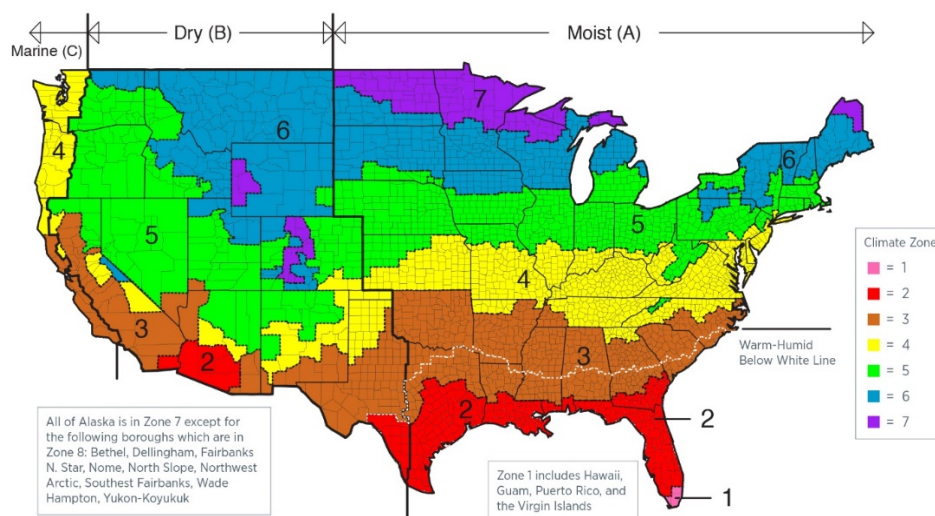


Figure 16. US Climate Zones by IECC

Source:

https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climate_guide_7_1.pdf

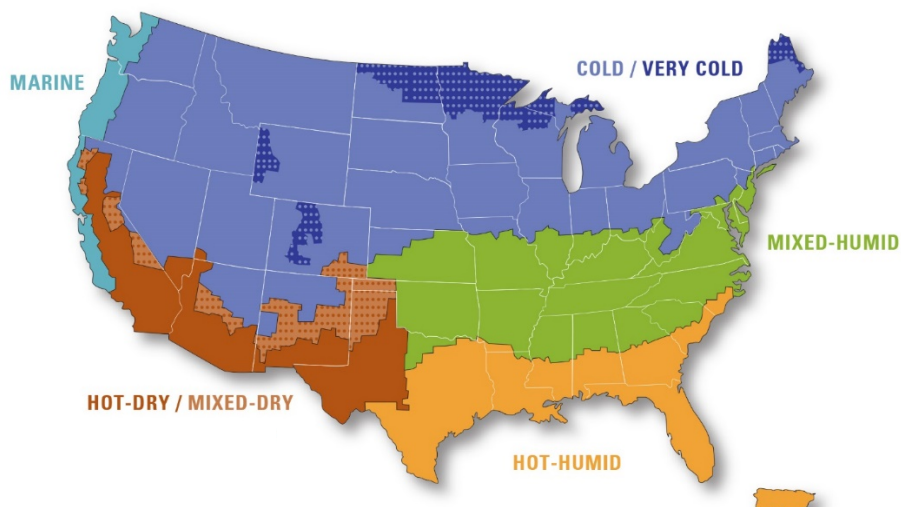


Figure 17. US Climate Zones by Building America

Source:

https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climate_guide_7_1.pdf

Boston (Longitude: -71.03, Latitude: 42.37) is in zone 5 that is defined as cold climate by Building America. The average temperature is 11°C with “very cold and snowy winters, and warm (and sometimes hot) summers” (Airport, 2019). According to EnergyPlus weather data (ddy file), the following table illustrates the design conditions for Boston. In this case, ***Boston-Logan 725090*** (***TMY2***) file is chosen as a weather file.

Table 7. Design Conditions for Boston, MA, USA

Design Conditions for Boston, MA, USA	
Latitude (N+ S-)	42.37
Longitude (W- E+)	-71.03
World Meteorological Organization number (WMO#)	725090
Time Zone Code	NAE
Time Zone Relative to GMT (GMT+/-)	-5.00
Elevation (m)	5.00
Daylight Saving Time Start Date	2nd Sunday in March
Daylight Saving Time End Date	2nd Sunday in November
Coldest Month	January
Hottest Month	July
Min Dry Bulb Temperature	-17° C
Max Dry Bulb Temperature	35.6° C
Extreme Max Wind Speed	27 m/s

Extreme Annual Wind Speed	1% =	8.2 m/s
	2.5% =	7.1 m/s
	5% =	5.8 m/s

Source: (ASHRAE, ASHRAE Handbook - Fundamentals (SI), 2005) & (EnergyPlus Weather Data)

Phoenix (Longitude: -112.02, Latitude: 33.43) is in zone 2 that is defined as a hot-humid climate by Building America. The average temperature is 24°C with “long and scorching summers and short mildly warm winters” (Weather Atlas). According to EnergyPlus weather data (ddy file), the following table illustrates the design conditions for Phoenix. In this case, **Phoenix 722780** (*TMY2*) file is chosen as a weather file.

Table 8. Design Conditions for Phoenix, AZ, USA

Design Conditions for Boston, MA, USA		
Latitude (N+ S-)	33.43	
Longitude (W- E+)	-112.02	
World Meteorological Organization number (WMO#)	722780	
Time Zone Code	NAZ	
Time Zone Relative to GMT (GMT+/-)	-7.00	
Elevation (m)	339.00	
Daylight Saving Time Start Date	-	
Daylight Saving Time End Date	-	
Coldest Month	December	
Hottest Month	July	
Min Dry Bulb Temperature	0.4° C	
Max Dry Bulb Temperature	45.8° C	
Extreme Annual Wind Speed	1% =	12 m/s
	2.5% =	10.8 m/s
	5% =	9.3 m/s

Source: (ASHRAE, ASHRAE Handbook - Fundamentals (SI), 2005) & (EnergyPlus Weather Data)

San Francisco (Longitude: -122.38, Latitude: 37.62) is in zone 3 that is defined as a marine climate by Building America. The average temperature is 14°C with “moist, mild winters, and dry summers” (Golden Gate Weather Services). According to EnergyPlus weather data (ddy file), the

following table illustrates the design conditions for San Francisco. In this case, **San Francisco 724940 (TMY2)** file is chosen as a weather file.

Table 9. Design Conditions for San Francisco, CA, USA

Design Conditions for Boston, MA, USA		
Latitude (N+ S-)	37.62	
Longitude (W- E+)	-122.38	
World Meteorological Organization number (WMO#)	724940	
Time Zone Code	NAP	
Time Zone Relative to GMT (GMT+/-)	-8.00	
Elevation (m)	5.00	
Daylight Saving Time Start Date	2nd Sunday in March	
Daylight Saving Time End Date	2nd Sunday in November	
Coldest Month	January	
Hottest Month	September	
Min Dry Bulb Temperature	1.4° C	
Max Dry Bulb Temperature	34.7° C	
Extreme Max Wind Speed	22.3 m/s	
Extreme Annual Wind Speed	1% =	12.8 m/s
	2.5% =	11.5 m/s
	5% =	10.6 m/s

Source: (ASHRAE, ASHRAE Handbook - Fundamentals (SI), 2005) & (EnergyPlus Weather Data)

These three cities are selected for simulation location, and the results will be compared with each other. Also, the weather data file downloaded from the EnergyPlus website provides the required input for thermal simulation in Grasshopper script. These parameters are dry bulb temperature, mean radiant temperature, wind speed, and relative humidity that are location-based. It is also essential to use weather data for daylighting simulation.

Weather-file based
or Location-based
parameters in PMV
thermal comfort
simulations

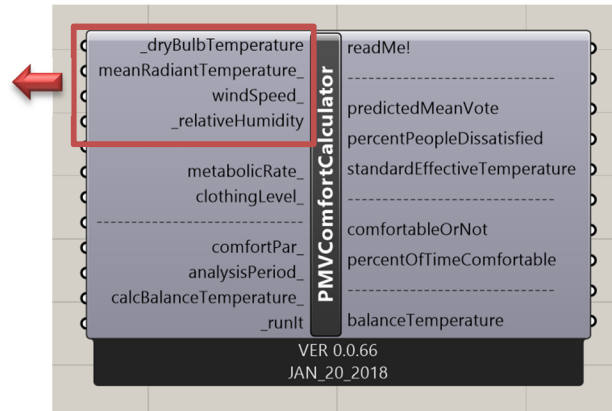


Figure 18. Location-based parameters in thermal simulations

3.1.4 Visual and Thermal Comfort

Other parameters can affect both thermal and visual comfort, such as glazing type, window-to-wall ration, and shading. For each one, the minimum and maximum or the best and the worst are considered that show the most significant results.

For glazing type, since I want to look at the variety of comfort conditions, I picked the single pane glass that we know is not going to be the most comfortable glass (and could be representative of an existing building condition), and triple glass that is assumed to be much more comfortable and thermally resistant and see if these show differentiation. These glazing characteristics are mentioned in the following table:

Table 10. Glazing Characteristics (EWC, 2012)

Glazing Type	U-Value (W/M ² K)	Solar Heat Gain Coefficient (SHGC)	Visible Transmittance (VT)
Triple – Low-e – Low SHGC - Argon - Improved Non-Metal Frame	1.07	0.18	0.37
Triple – Low-e – Medium SHGC - Argon – Improved Non-Metal Frame	1.07	0.28	0.45
Triple – Low-e – High SHGC - Argon – Improved Non-Metal Frame	1.13	0.41	0.50
Double – Low-e – Low SHGC - Argon – Improved Non-Metal Frame	1.53	0.20	0.46
Double – Low-e – Medium SHGC - Argon – Improved Non-Metal Frame	1.59	0.31	0.52
Double – Low-e – High SHGC - Argon – Improved Non-Metal Frame	1.64	0.50	0.57
Double – Tint – Nonmetal Frame	2.95	0.47	0.44
Double – Clear – Nonmetal Frame	2.95	0.57	0.59
Single – Clear – Nonmetal Frame	4.99	0.64	0.65
Double – Low-e – Low SHGC - Argon – Metal Frame – Thermal Break	2.32	0.23	0.49
Double – Low-e – Medium SHGC – Argon – Metal Frame – Thermal Break	2.38	0.35	0.56
Double – Low-e – High SHGC – Argon – Metal Frame – Thermal Break	2.38	0.55	0.61
Double – Tint – Metal Frame – Thermal Break	3.4	0.51	0.47
Double – Clear – Metal Frame – Thermal Break	3.4	0.62	0.63
Double – Low-e – Low SHGC – Argon - Metal Frame	3.57	0.26	0.49
Double – Low-e – Medium SHGC – Argon - Metal Frame	3.63	0.38	0.56
Double – Low-e – High SHGC – Argon - Metal Frame	3.69	0.58	0.61
Double – Tint - Metal Frame	4.7	0.54	0.47
Double – Clear - Metal Frame	4.7	0.65	0.63
Single - Clear - Metal Frame	7.32	0.73	0.69

For window-to-wall ratio since my purpose is to look at the extremes of different comfort ranges, 40% (with 0.8m window sill and 0.2m window head) and 80% (with 0.45m window sill and 0.1m window head) are selected because most of the office buildings have the WWR between 40% and 80% and the minimum and maximum numbers are considered to show the changes in results.

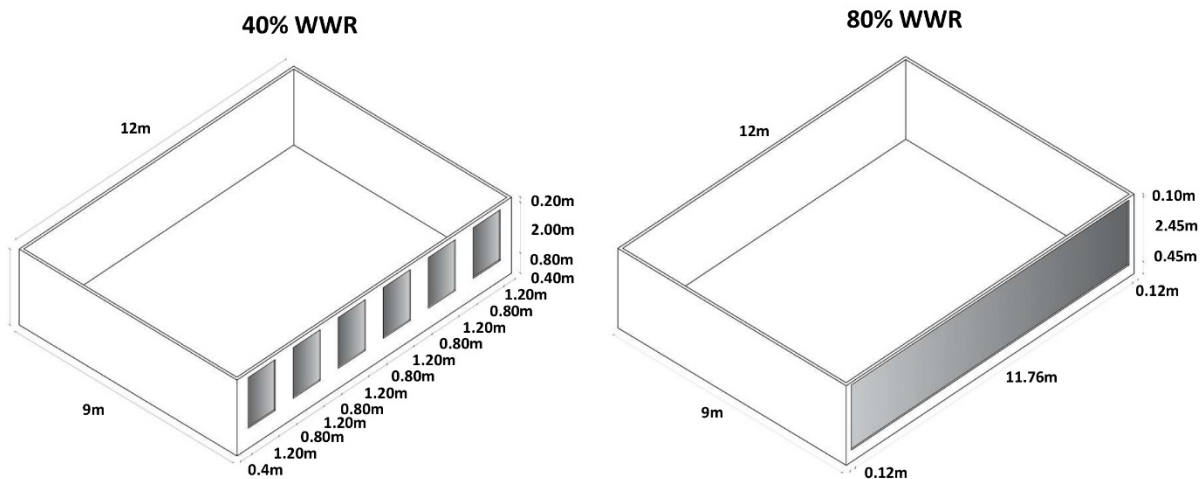


Figure 19. Two types of window-to-wall ratio

Moreover, the simulations are done without shading or with 1-meter overhang.

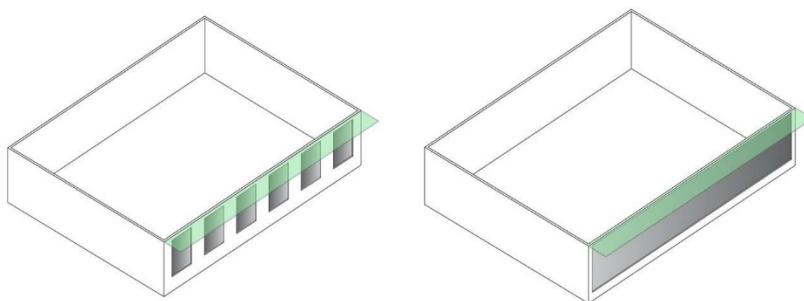


Figure 20. Shading

So, there are seven different factors with defined variables for each of them that are considered as simulation inputs as the following:

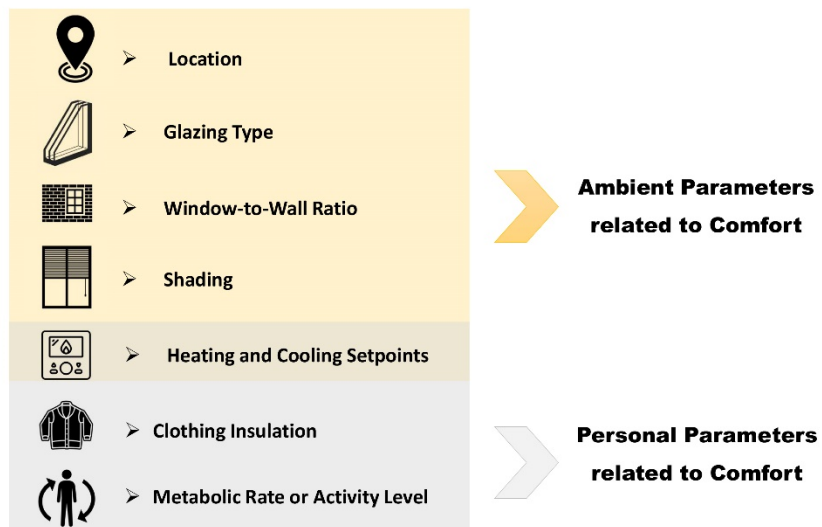


Figure 21. Ambient parameters and personal parameters related to comfort

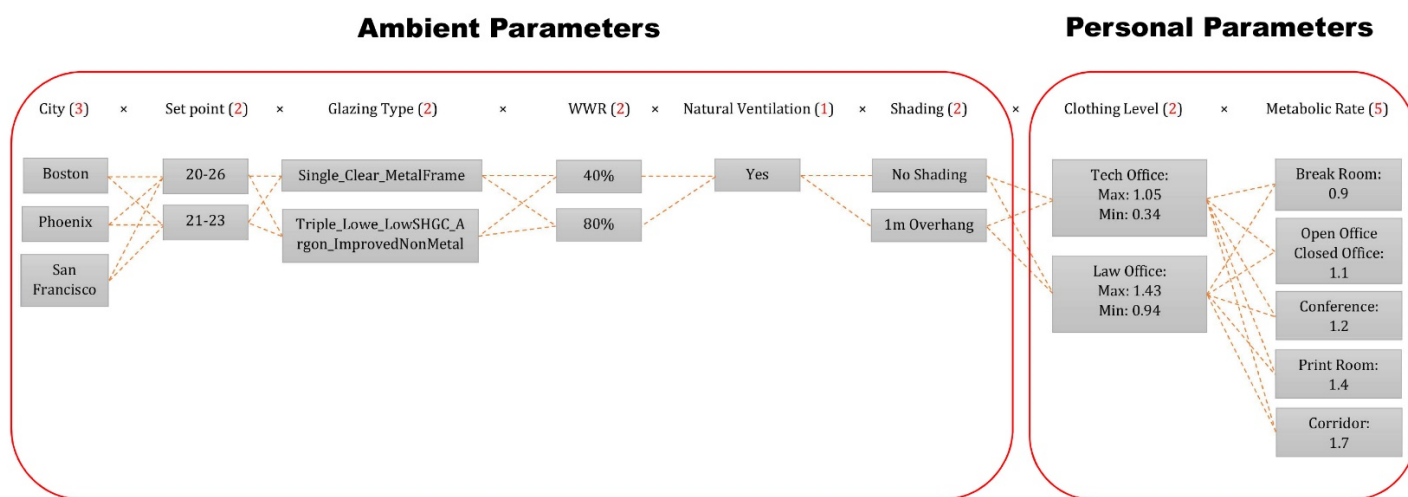


Figure 22. Simulation inputs

So, there are several parameters that their permutation would be 480 simulation cases, and its arrangement would be like this:

	A	B
1		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/Clothing Level (Formal)/Break Room (1)
2		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/Clothing Level (Formal)/ Open or Closed Office (1.1)
3		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/Clothing Level (Formal)/ Conference (1.2)
4		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/Clothing Level (Formal)/ Print Room (1.4)
5		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/Clothing Level (Formal)/ Corridor (1.7)
6		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/ Clothing Level (Informal)/Break Room (1)
7		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/ Clothing Level (Informal)/ Open or Closed Office (1.1)
8		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/ Clothing Level (Informal)/ Conference (1.2)
9		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/ Clothing Level (Informal)/ Print Room (1.4)
10		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/No Shading/ Clothing Level (Informal)/ Corridor (1.7)
11		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/Clothing Level (Formal)/Break Room (1)
12		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/Clothing Level (Formal)/ Open or Closed Office (1.1)
13		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/Clothing Level (Formal)/ Conference (1.2)
14		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/Clothing Level (Formal)/ Print Room (1.4)
15		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/Clothing Level (Formal)/ Corridor (1.7)
16		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/ Clothing Level (Informal)/Break Room (1)
17		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/ Clothing Level (Informal)/ Open or Closed Office (1.1)
18		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/ Clothing Level (Informal)/ Conference (1.2)
19		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/ Clothing Level (Informal)/ Print Room (1.4)
20		Boston/Setpoint (20-26)/Glazing (Single Pane)/WWR (40%)/ Shading (1m Overhang)/ Clothing Level (Informal)/ Corridor (1.7)
21		Boston/Setpoint (20-26)/Glazing (Single Pane)/ WWR (80%)/No Shading/Clothing Level (Formal)/Break Room (1)
22		Boston/Setpoint (20-26)/Glazing (Single Pane)/ WWR (80%)/No Shading/Clothing Level (Formal)/ Open or Closed Office (1.1)
23		Boston/Setpoint (20-26)/Glazing (Single Pane)/ WWR (80%)/No Shading/Clothing Level (Formal)/ Conference (1.2)
24		Boston/Setpoint (20-26)/Glazing (Single Pane)/ WWR (80%)/No Shading/Clothing Level (Formal)/ Print Room (1.4)
25		Boston/Setpoint (20-26)/Glazing (Single Pane)/ WWR (80%)/No Shading/Clothing Level (Formal)/ Corridor (1.7)

Figure 23. Case arrangement

3.2 SIMULATION TOOLS AND THEIR OUTPUTS

The goal of this step is to find the best evaluation metrics and simulation tool for each comfort factor. These metrics for visual and thermal assessment and existing simulation tools are reflected in the following figures.

There are several dynamic metrics for thermal and visual comfort, but to look at the full year, annualized metrics that can give the annualized performance of space are needed. These metrics are the annualized climate dependent percent of time-based metrics that help the designer understand the percentage of time that space is comfortable.

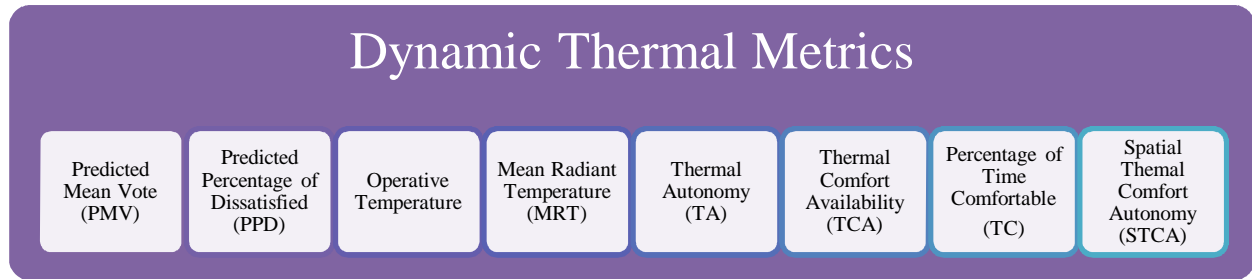


Figure 24. Dynamic thermal metrics



Figure 25. Software tools for thermal comfort

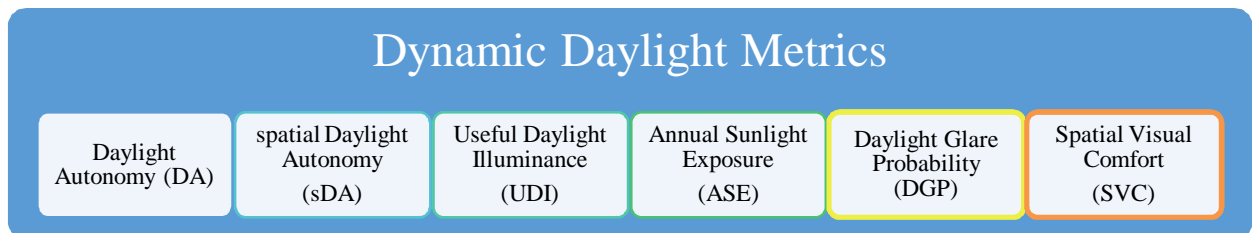


Figure 26. Dynamic Daylight Metrics



Figure 27. Software tools for visual comfort

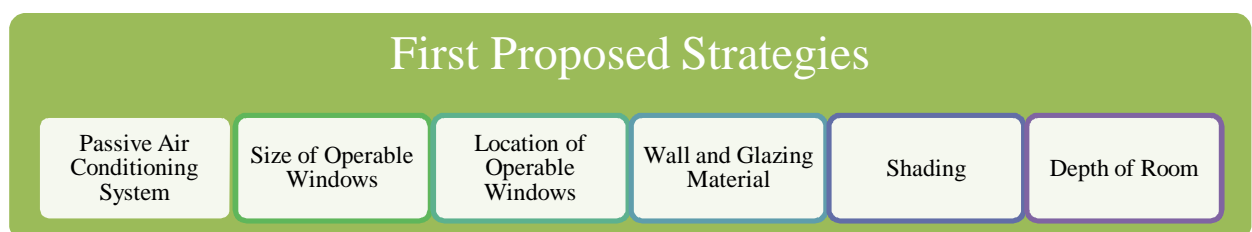


Figure 28. First proposed strategies

For thermal comfort, TC (Percentage of Time Comfortable) is one of the comprehensive metrics that recognize “the percent of input conditions in which the occupant is comfortable” together with PPD (Predicted Percentage of Dissatisfied) can be good evaluating thermal comfort metrics.

In order to do thermal simulations, several CFD analysis software tools such as DesignBuilder, QuickerSim CFD Toolbox for MATLAB, Autodesk CFD, and ANSYS CFD have been developed recently, but the simulation process is very complicated and time-consuming (Zomorodian & Tahsildoost, 2017). Grasshopper plugins such as Ladybug, Honeybee, and EnergyPlus can provide more straightforward spatial thermal analysis, and they are open source, no-cost, and more broadly accessible. The Grasshopper plugins are selected for the thermal simulations.

For choosing the daylight metrics, the proper illuminance levels for office was considered. Appropriate levels of illuminance will vary by space type, visual task, and occupant type. According to IESNA illuminance categories, general and private offices are in category D and E that are “the performance of visual tasks of high contrast and large size” and “the performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size” respectively, and proper illuminance is considered 300-500 lx (IESNA, 1979). So, spatial Daylight Autonomy (sDA) that is defined as “the percent of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year” (IES, 2012). In this study, the minimum illuminance level for a task in an office building is considered to be 300 lx. As there is no upper limit for sDA, there is a need for another metric to avoid glare. So, Annual Sun Exposure (ASE) (IES, 2012) is used as a companion metric to sDA and describing the amount of space with too much direct sunlight. “Specifically, ASE measures the percentage of floor area that

receives at least 1000 lux for at least 250 occupied hours per year” (Sterner, 2014). Also, Daylight Glare Probability (DGP) is selected for glare analysis.

For daylighting simulation, since the goal is to provide simultaneous thermal and visual comfort inside the buildings, it would be better to do thermal and daylighting simulations with the same software. For this reason, the Honeybee plugin for Grasshopper would be the right choice for spatial daylighting simulation.

These are the simulation outputs providing the required information for conclusions. The next step is to arrange the inputs.

Chapter 4. PROTOTYPES

In this study, there are two types of analytical prototypes to test out the methodology: zone-based and grid-based. The floor plan for each type of simulation was defined in section 3.1.1.

4.1 ZONE-BASED PROTOTYPE

The purpose of this prototype is to identify the position relative to the window, and it goes through the Y-axis. For the zone-based simulation, there are six different zones that the Percentage of time thermally comfortable, PPD, sDA, and ASE are calculated for each of them. The results are reflected in the charts in order to be more readable and comparable. So, the effect of metabolic rate, clothing insulation, location, window-to-wall ratio, and improvements such as glazing type, shading, and set-point can be analyzed separately.

4.1.1 *Effect of Activity Level and Metabolic Rate*

To evaluate the prototype, multiple metabolic rates are considered to see their impacts on the results.

The following charts show the effect of activity level and its related metabolic rate. These charts show the section of the office plan. The zones are arranged on the horizontal axis based on the distance from the window, and the vertical axis shows the percentage. There are for trends for Thermal comfort percentage, PPD, sDA, and ASE. TCP and sDA are better to be higher, and PPD and ASE are better to be lower. So, PPD and ASE results are reversed.

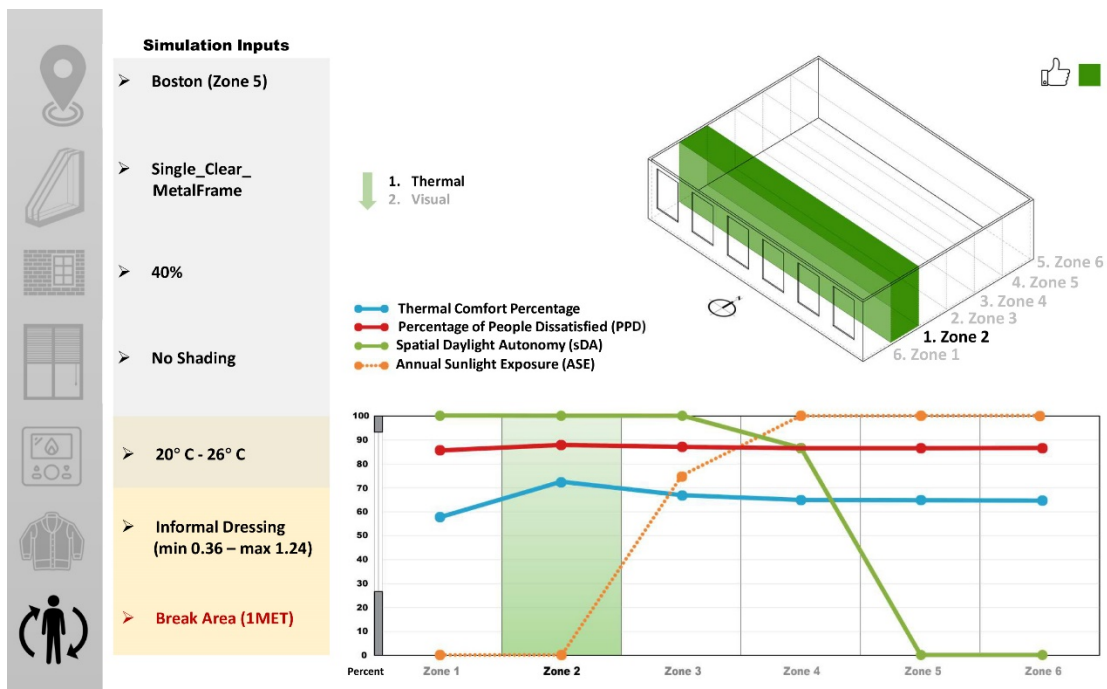


Figure 29. Simulation results for break area

For break Area, thermal comfort is essential, but as there is no particular activity inside the break area, daylighting and glare is not as important as thermal comfort; so, ASE is not an essential factor for evaluating the results. According to the other factors – TCP, PPD, sDA – Zone 2 shows the best results and can be selected as the best zone for the break area.

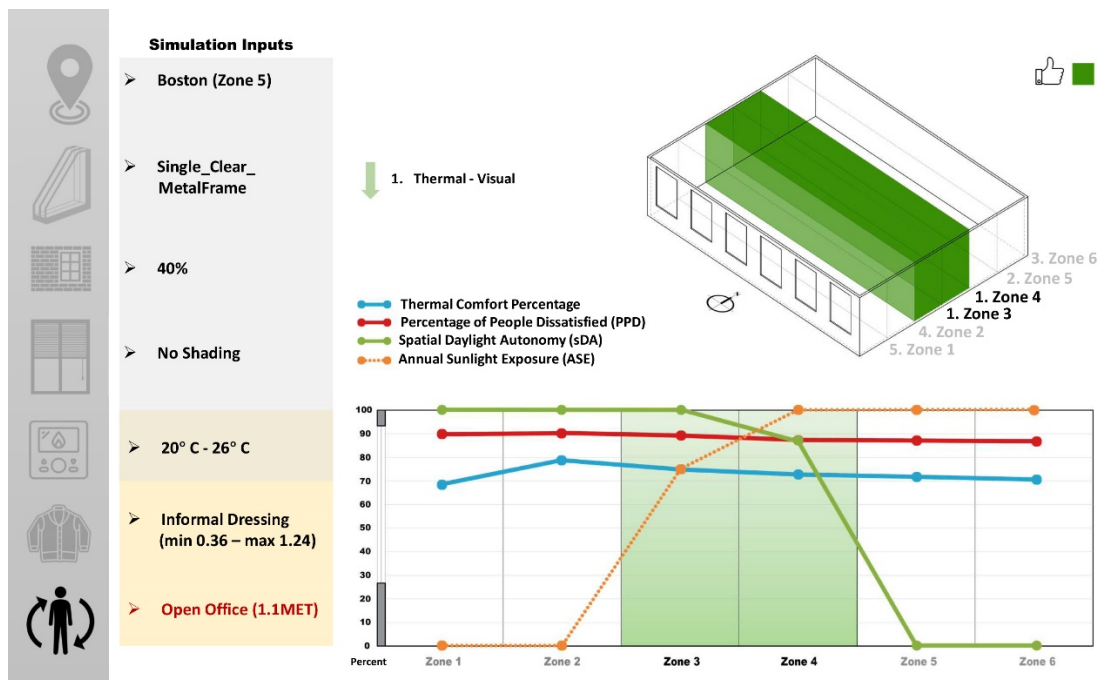


Figure 30. Simulation results for open office

For the open office, both thermal and visual comfort are essential. According to the results for TCP, PPD, sDA, and ASE, Zone 3 and Zone 4 show the best results and can be selected as the best zones for the open office.

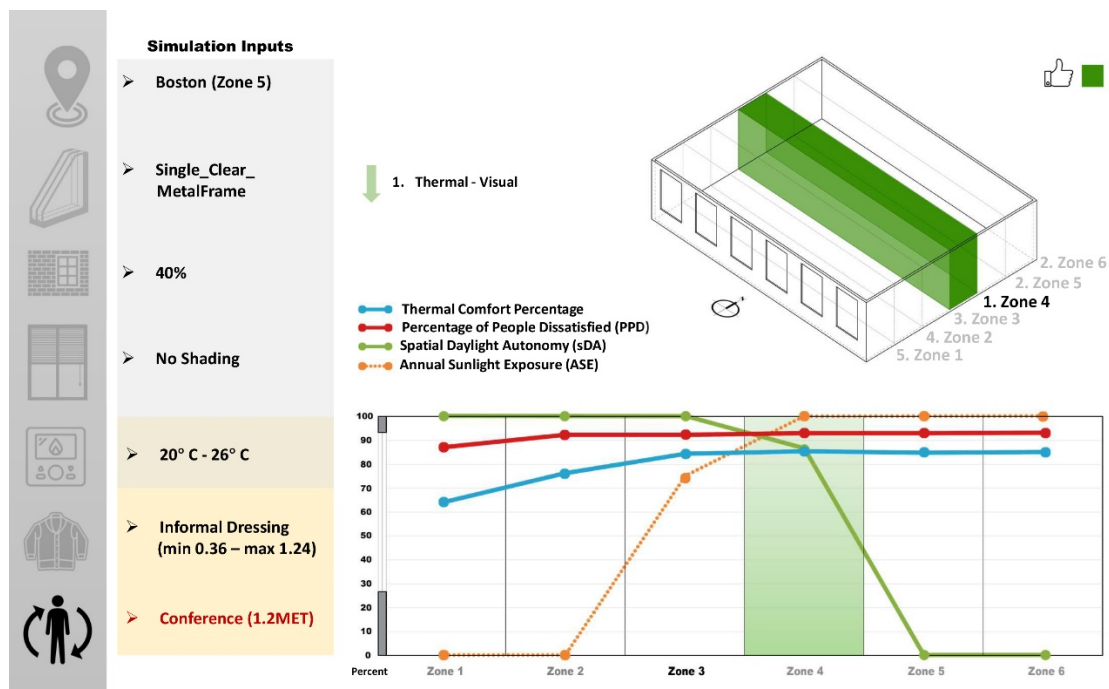


Figure 31. Simulation results for the conference area

For conference area, both thermal and visual comfort are essential, but for visual comfort considering the glare potential is more important than daylight accessibility; so, Zone 4 shows the best results and can be selected as the best zones for the conference area. Consequently, Zone 5 and Zone 6 can be selected according to the results for TCP, PPD, and ASE.

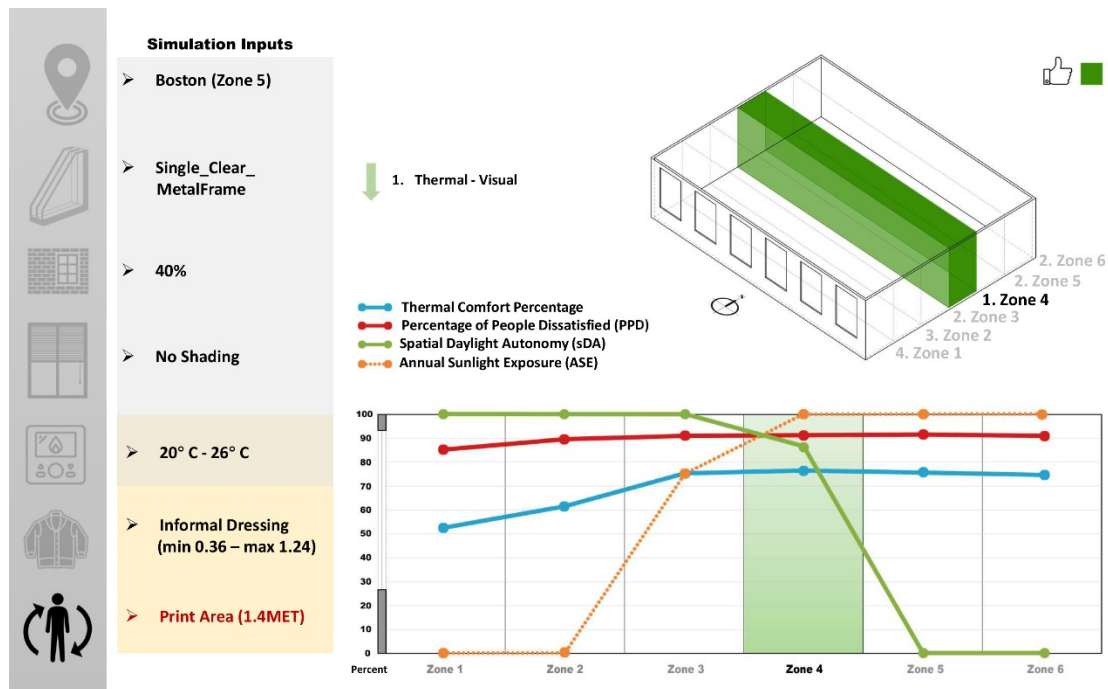


Figure 32. Simulation results for print area

For print area, thermal comfort is essential, but daylighting and glare is not as important as thermal comfort; so, sDA and ASE are not important factors for evaluating the results. According to thermal comfort factors – TCP and PPD– Zone 4, Zone 5, and Zone 6 shows the best results and can be selected as the best zones for the print area.

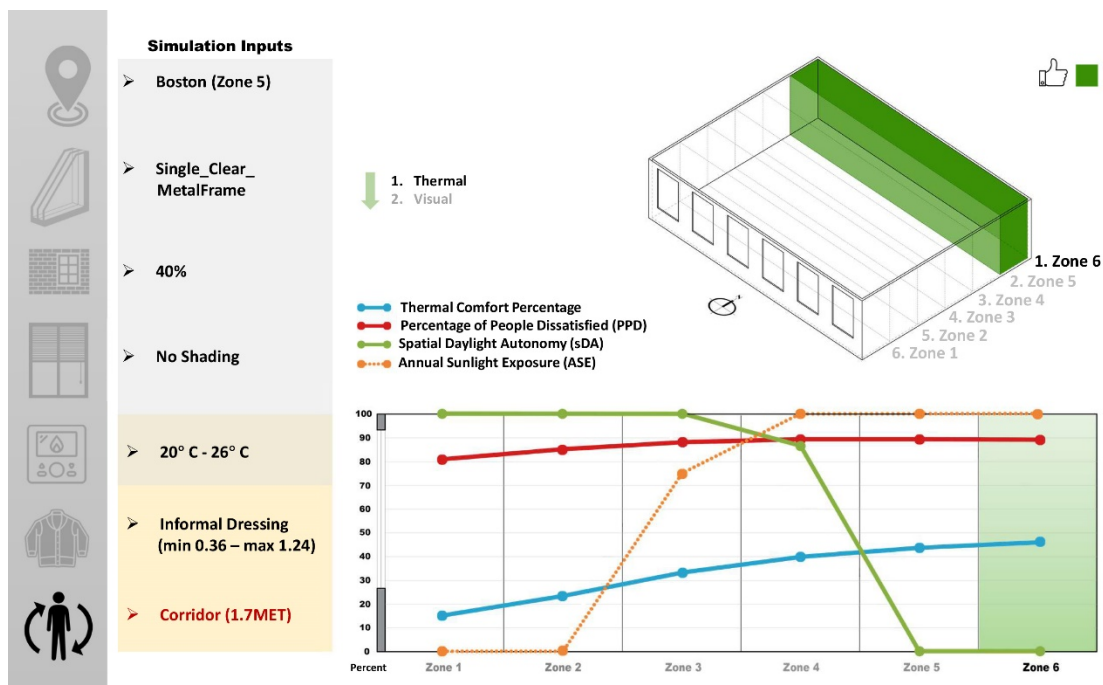


Figure 33. Simulation results for the corridor

For corridor, thermal comfort is essential, but daylight accessibility and glare are not as important as thermal comfort; so, sDA and ASE are not important factors for evaluating the results. According to thermal comfort factors – TCP and PPD – Zone 6 shows the best results and can be selected as the best zones for the corridor.

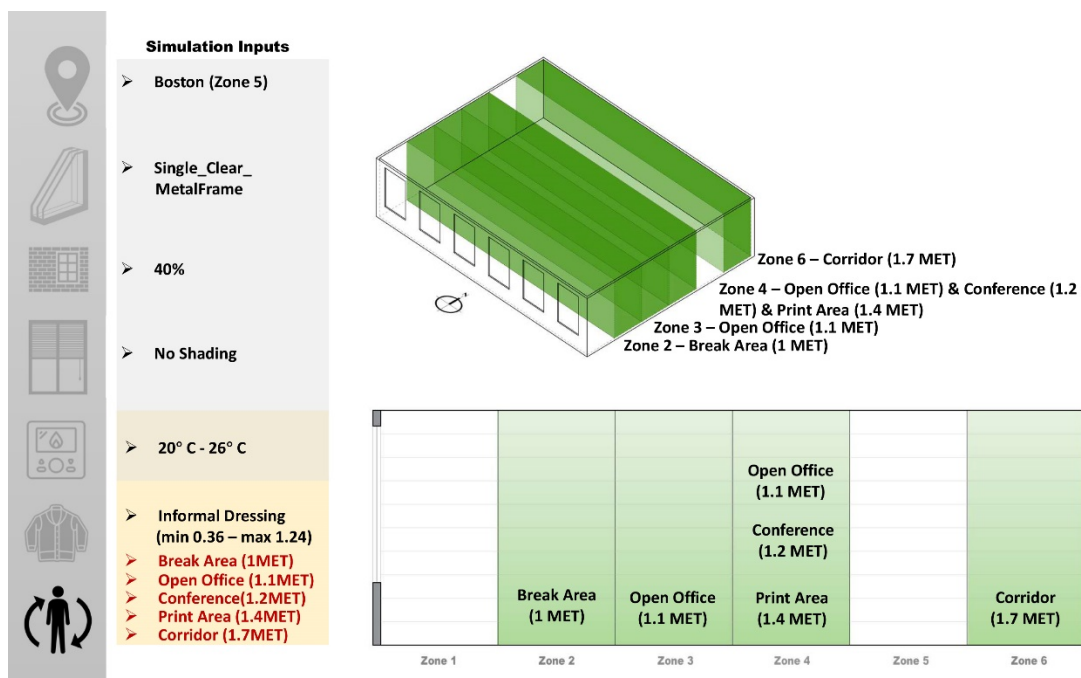


Figure 34. Comparing the best zone for each activity

As can be seen in Figure 34, the best zone for each activity is different. So, the activity type and its related metabolic rate have a significant effect on comfort results in office buildings. Since the conventional design methods are using the same value for all the activities inside the building, the same solutions are used for designing different areas. As the simulation results show dramatic differences in results, putting the same value for all of them leads to discomfort.

4.1.2 *Effect of Clothing Insulation*

As mentioned in Table 2, there are two types of clothing insulation: formal and informal dressing. The minimum and maximum clo are different for each type. Figure 35 and Figure 36 show the results for these two types of clothing insulation when the other factors are fixed. As can be seen, the TCP trend is changing dramatically with the change of clothing insulation.

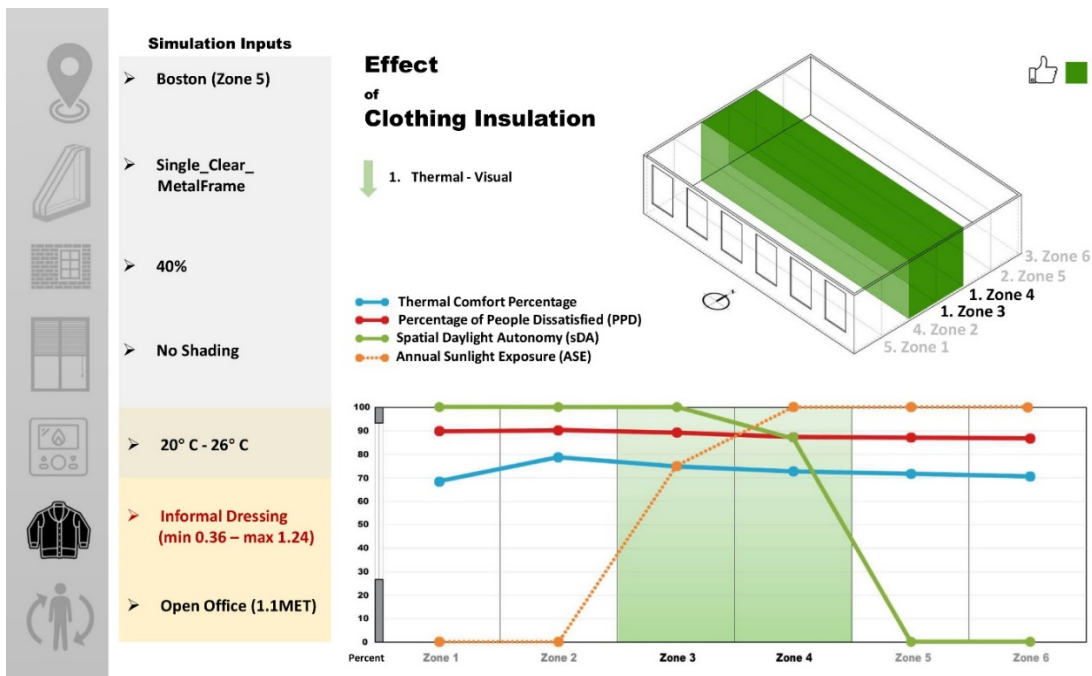


Figure 35. Simulation results for informal dressing in open office

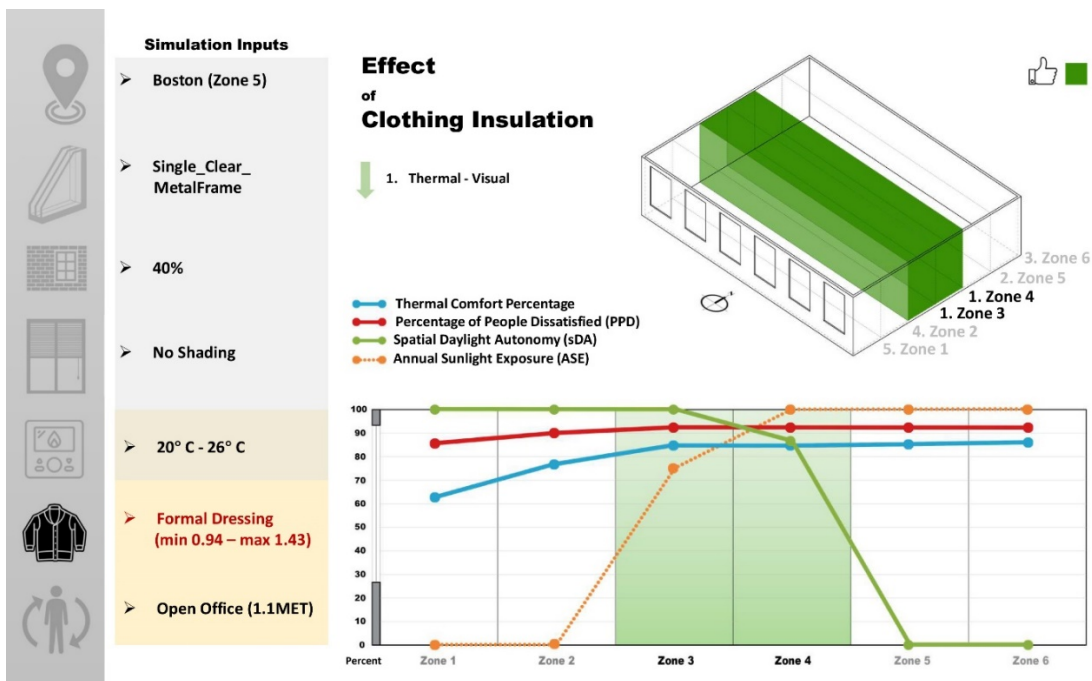


Figure 36. Simulation results for formal dressing in open office

4.1.3 Effect of Location

By comparing the results of simulations in two different cities, we can see that same similar solutions and layouts do not work in different climates, and it needs its configuration. As shown in Figure 39 and Figure 40, even the best zones for each activity are different in various climates.

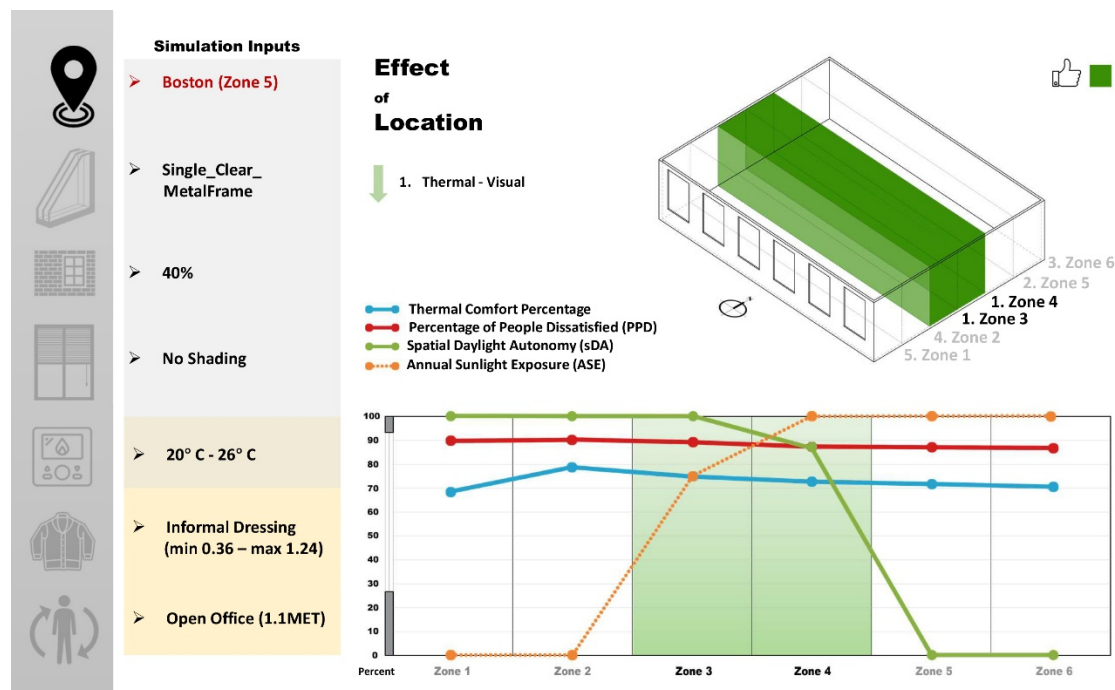


Figure 37. Effect of location - Boston

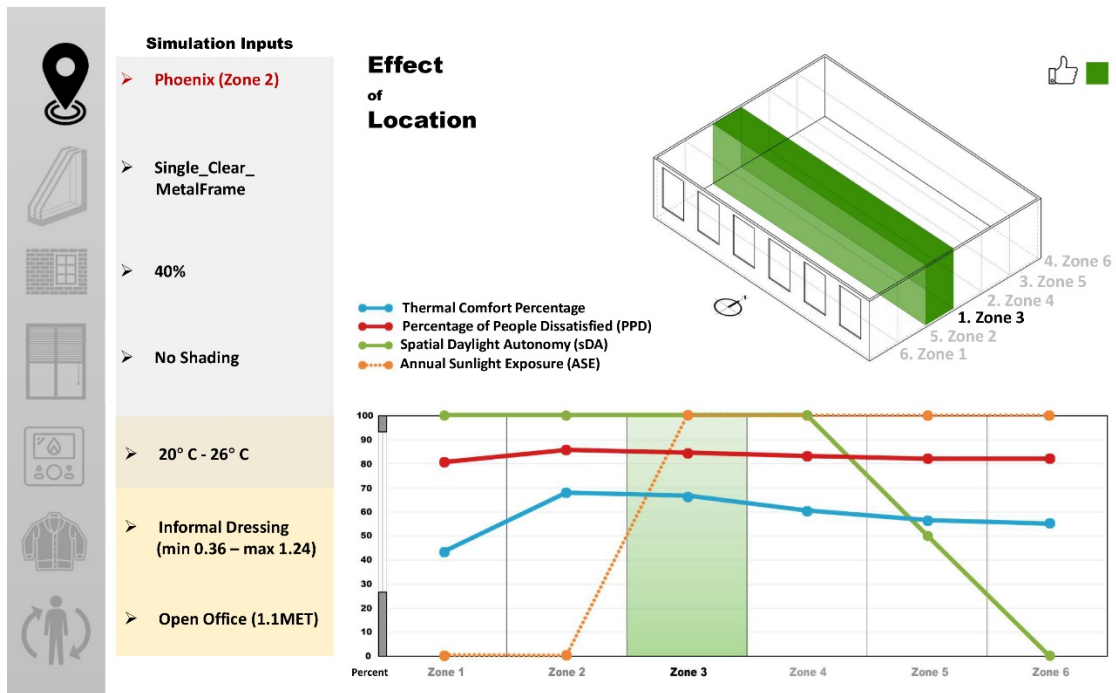


Figure 38. Effect of location - Phoenix

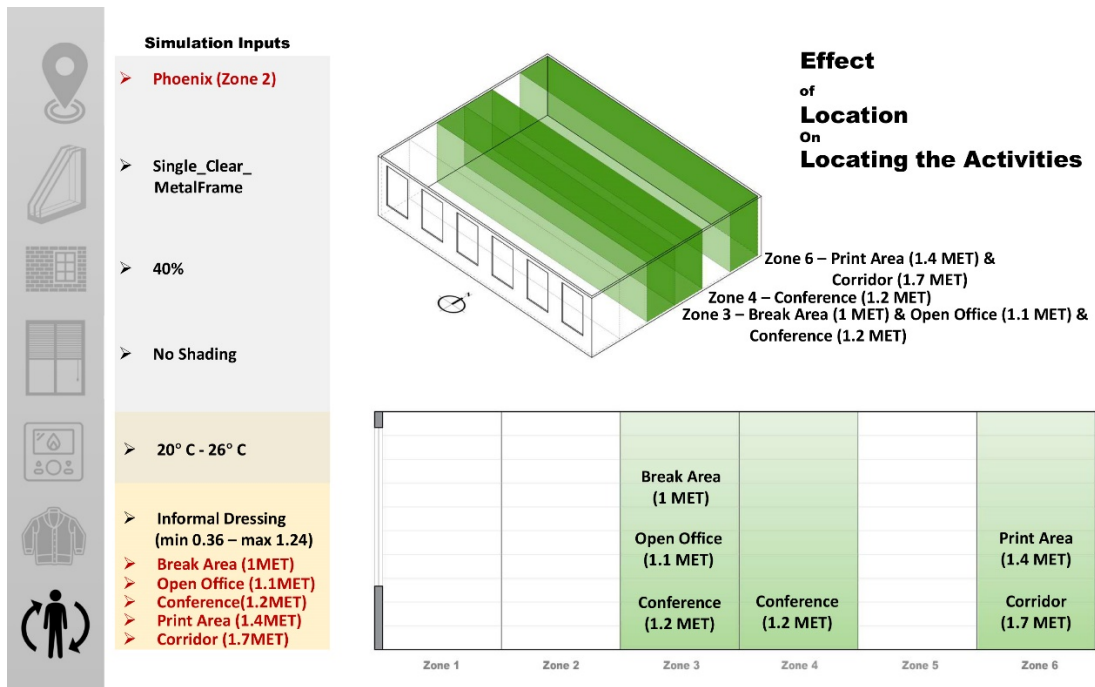


Figure 39. Effect of location - Comparing the results for Phoenix

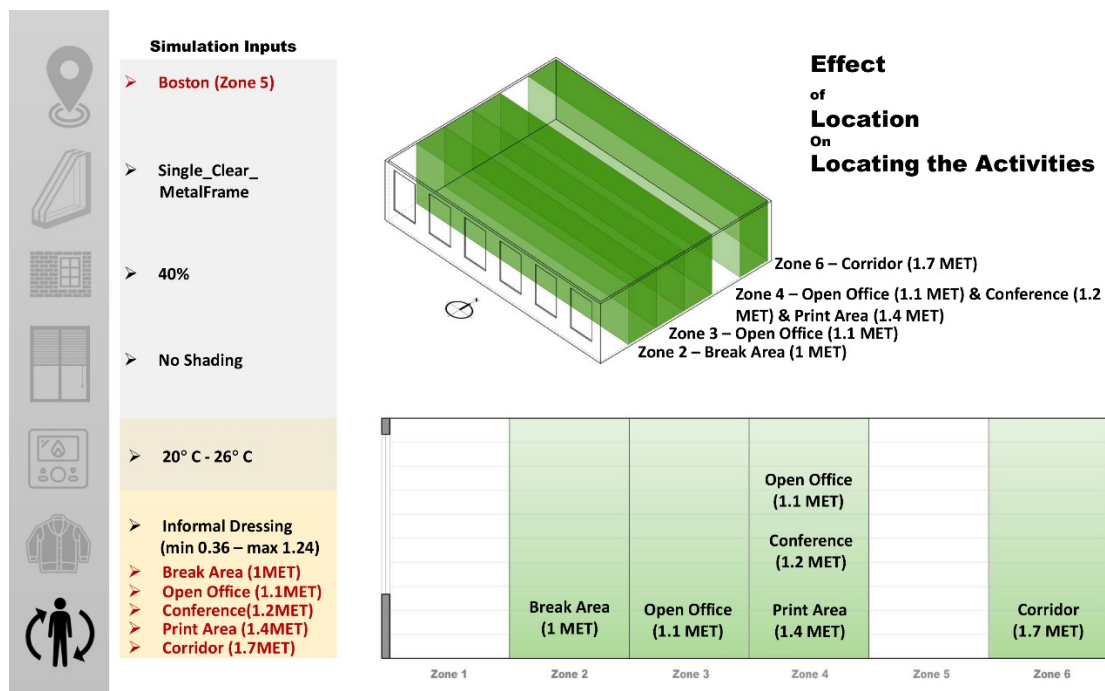


Figure 40. Effect of location - Comparing the results for Boston

4.1.4 *Effect of Window-to-Wall Ratio*

The following figures show the differences between 40% and 80% WWR. As can be seen, the comfort zone will be shifted back from the window with an increase of WWR.

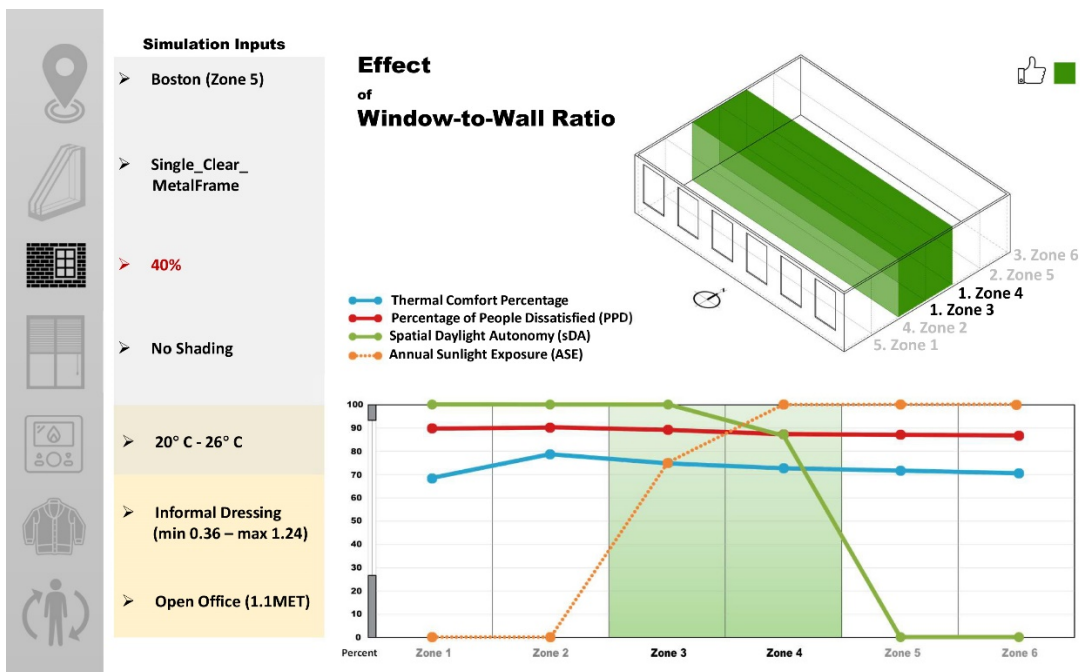


Figure 41. Simulation results for 40% WWR

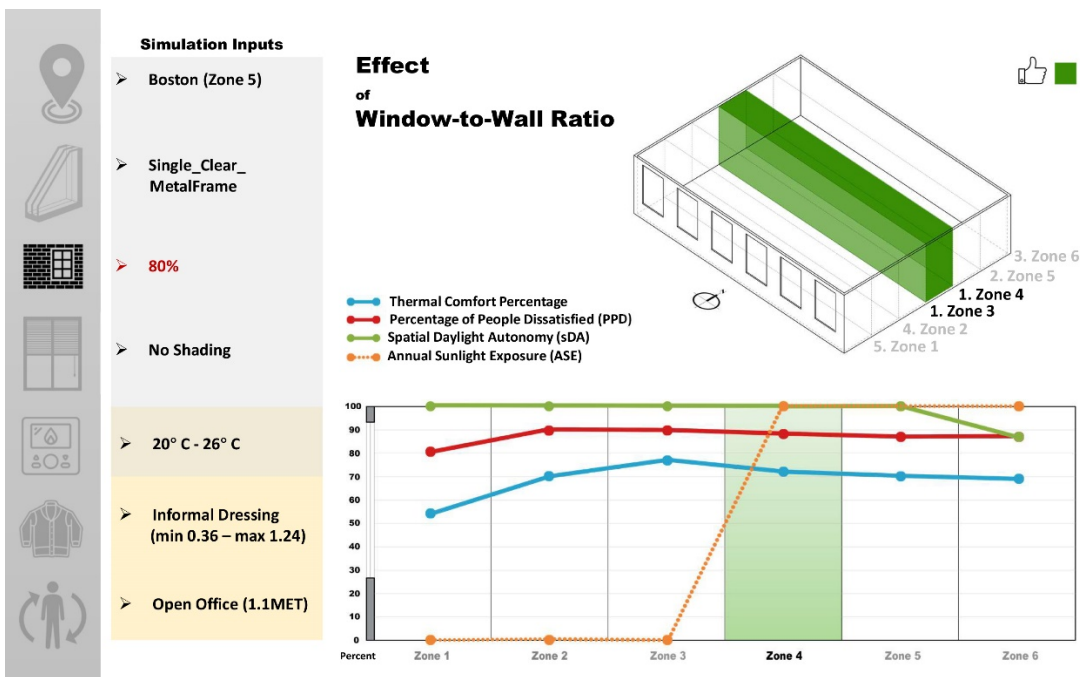


Figure 42. Simulation results for 80% WWR

4.1.5 Effect of Improvement

Other factors can improve indoor conditions. These factors are the glazing type, shading, and changing the heating and cooling set-points. As we can see, these factors have a significant effect on improving the indoor conditions, and even the areas close to the window become comfortable with these improvements.

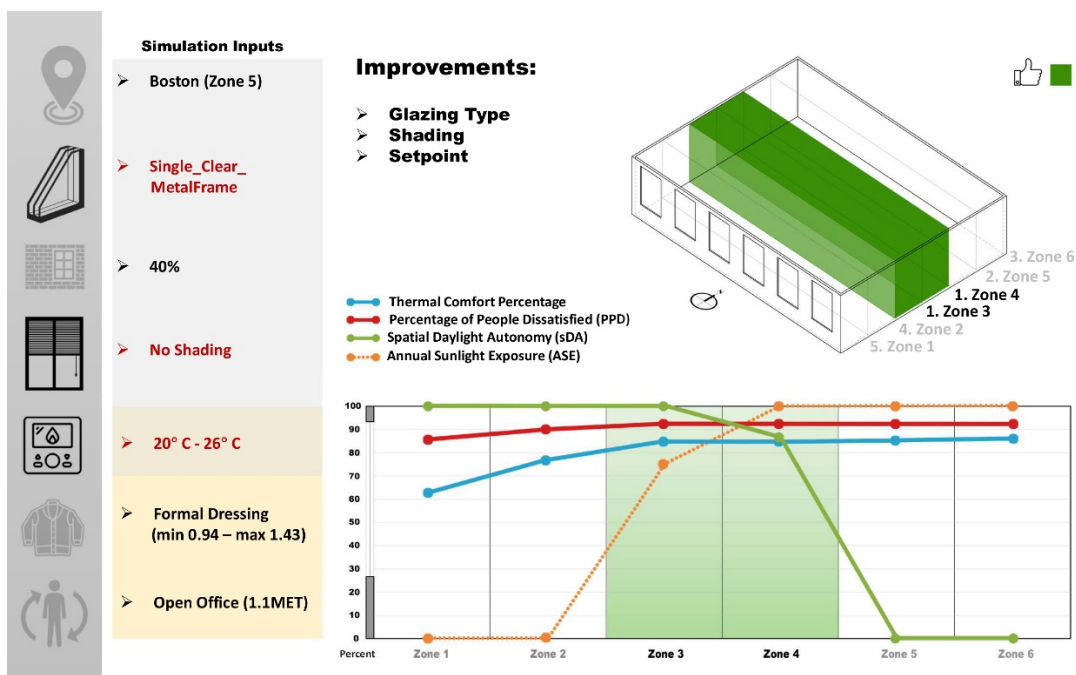


Figure 43. Simulation results for 40% WWR without improvements

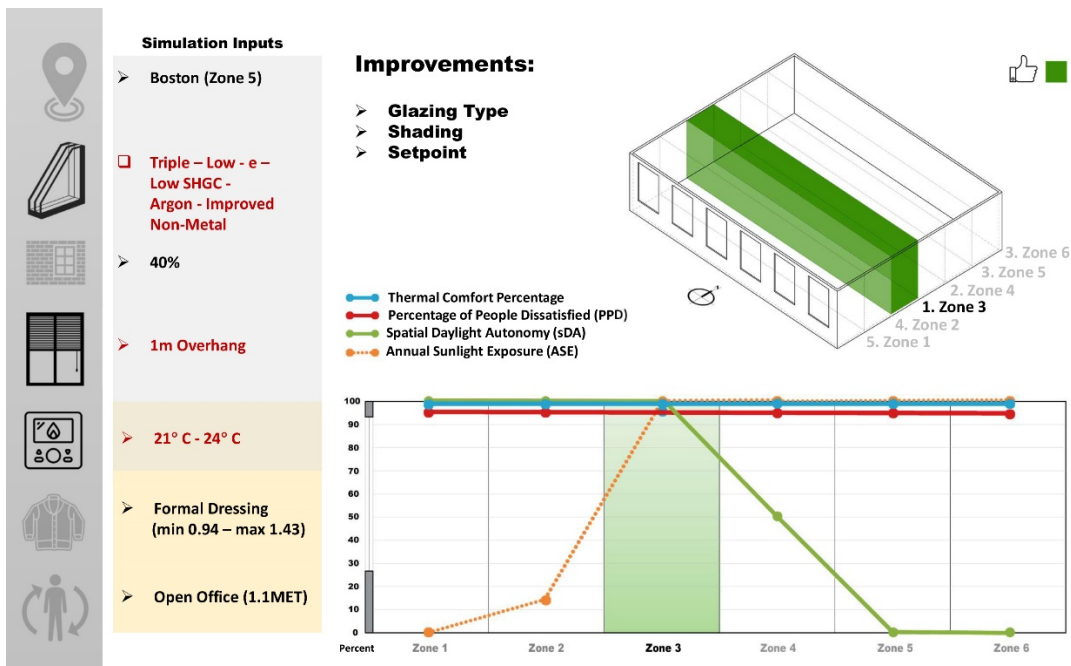


Figure 44. Simulation results for 40% WWR with improvements

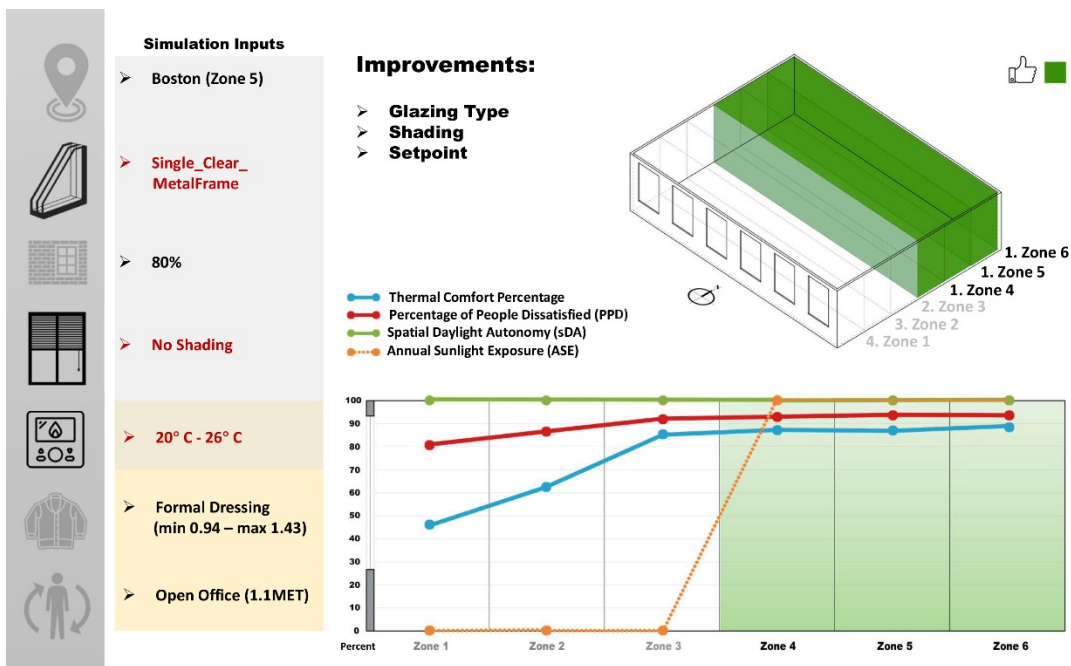


Figure 45. Simulation results for 80% WWR without improvements

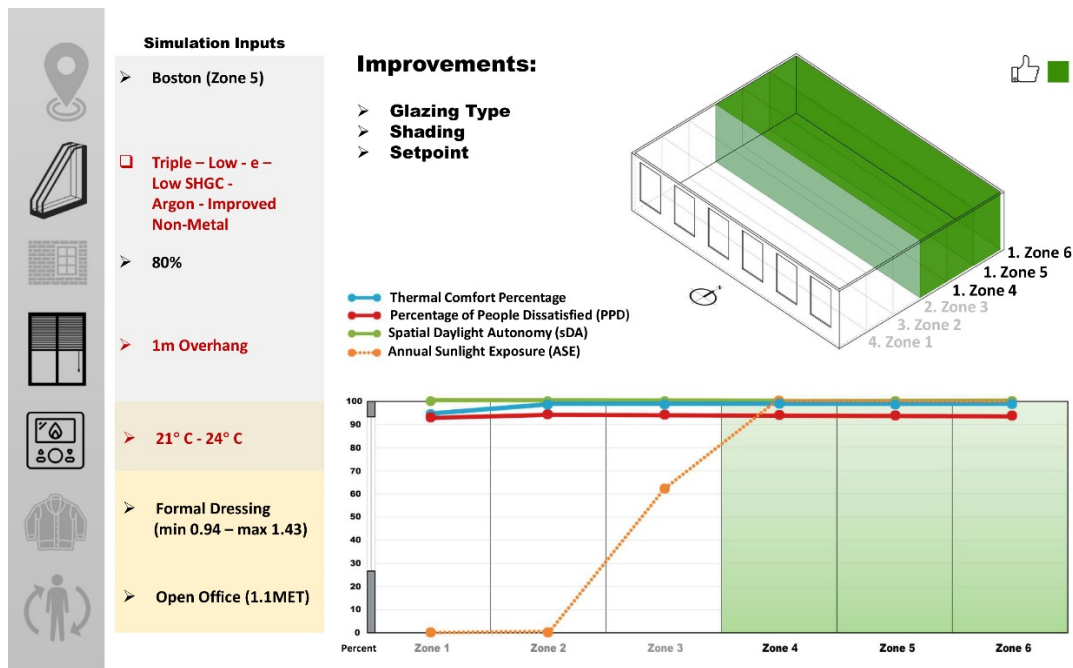


Figure 46. Simulation results for 80% WWR with improvements

4.2 GRID-BASED PROTOTYPE (X-MAPS)

The purpose of this prototype is to find the spatial location in the XY axis and the optimum direction for the desk to be facing. For grid-based simulation, as mentioned before, the divisions are as the following:

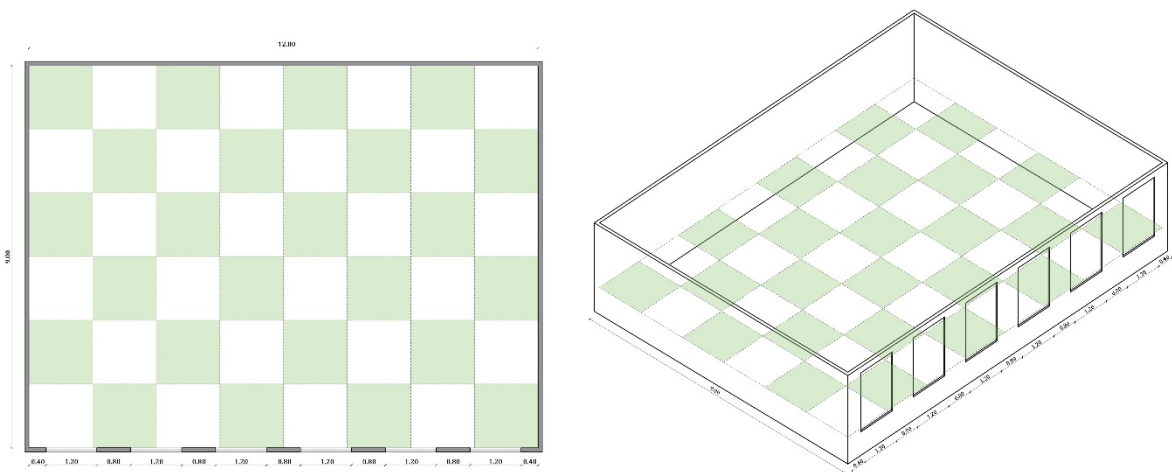


Figure 47. Grids for grid-based simulations

If the simulations are done in Boston with 40% WWR, Single-Clear- Metal Frame glazing, no shading, 20°C- 26°C set-points, and formal dressing for open office, the results for OTCP, DA, and ASE would be as the following:

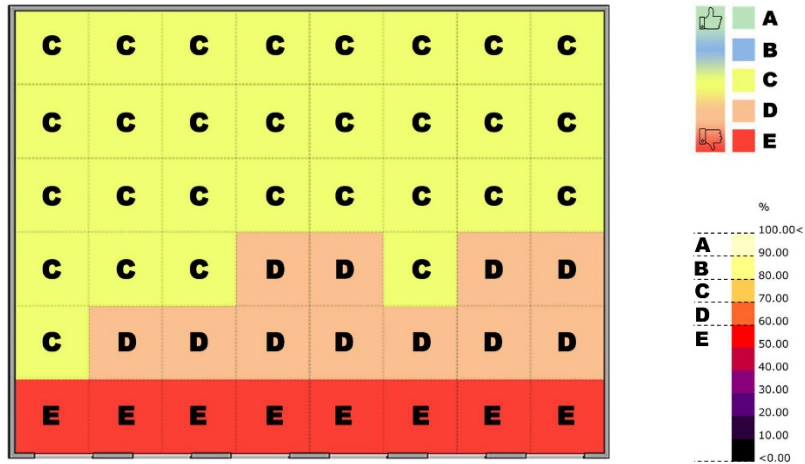


Figure 48. Occupied Thermal Comfort Percentage (OTCP)



Figure 49. Daylight Autonomy (DA)

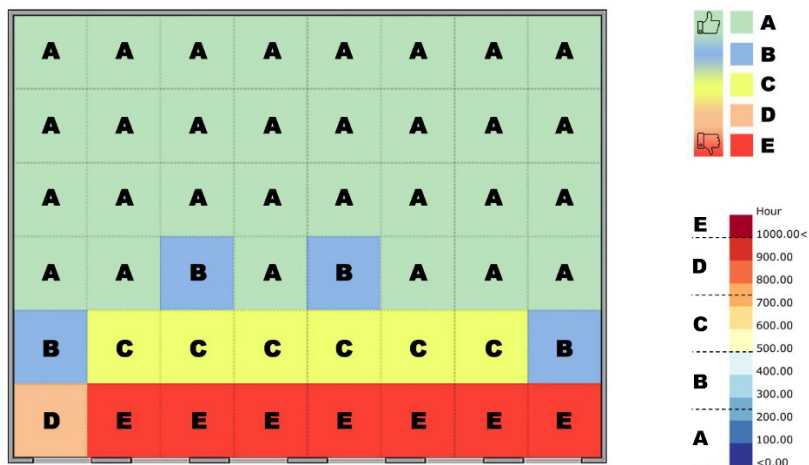


Figure 50. Annual Sunlight Exposure (ASE)

If the results for these three metrics are overlapped, it would be like the following figure:

The green is perfect; the blue and yellow are acceptable, the orange and red are visually and thermally uncomfortable respectively.

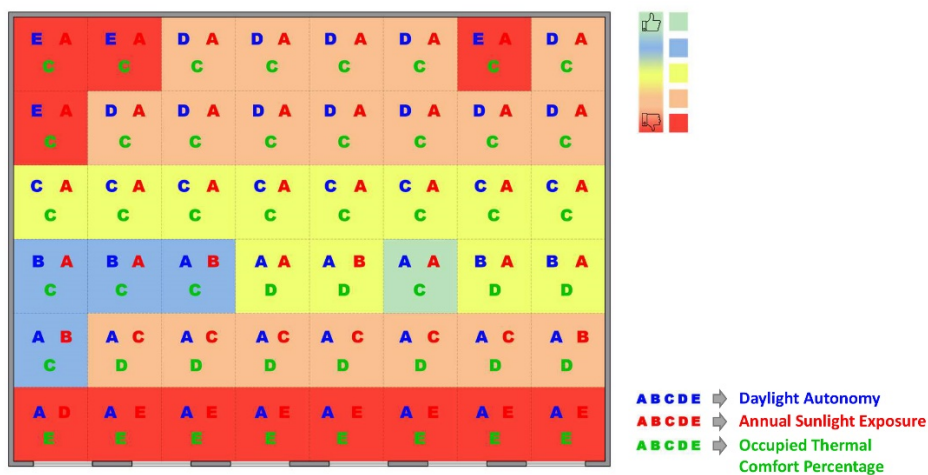


Figure 51. Integrated thermal and visual comfort

The next step for locating the workstation would be the desk orientation that is done based on the glare potential. January 21st at noon is selected for evaluating the glare results that is the worst time.

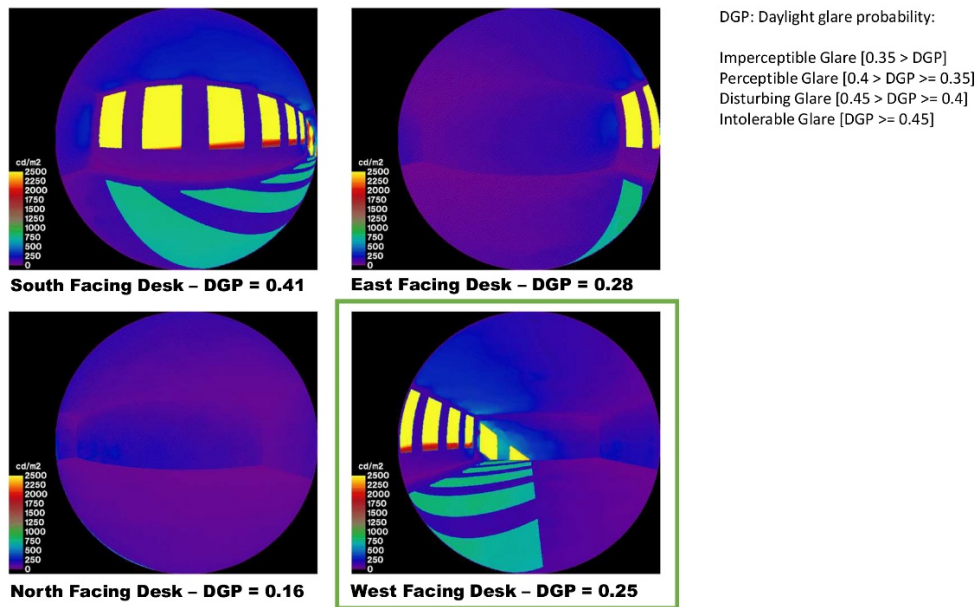


Figure 52. Glare analysis - Jan. 21st at noon

According to the results, the west facing desk show the best result for glare analysis at this point.

If DGP is calculated for each grid, the results are as the following:

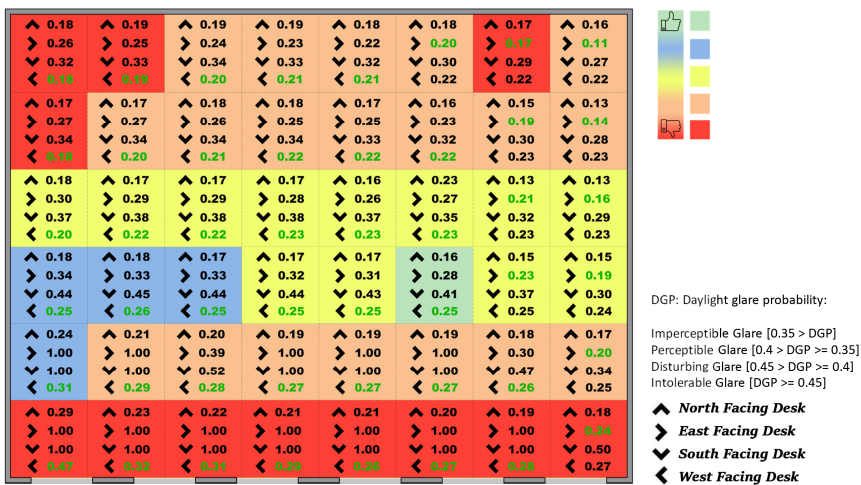


Figure 53. Glare analysis - Jan. 21st at noon for all grid points

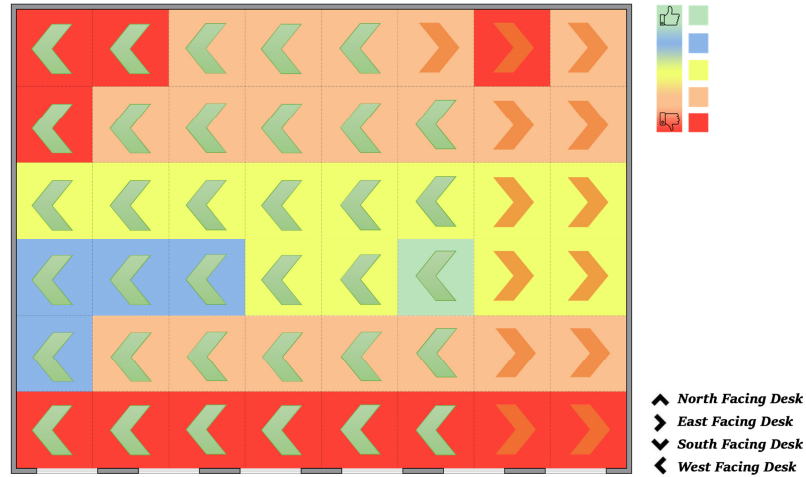


Figure 54. Orientation Results

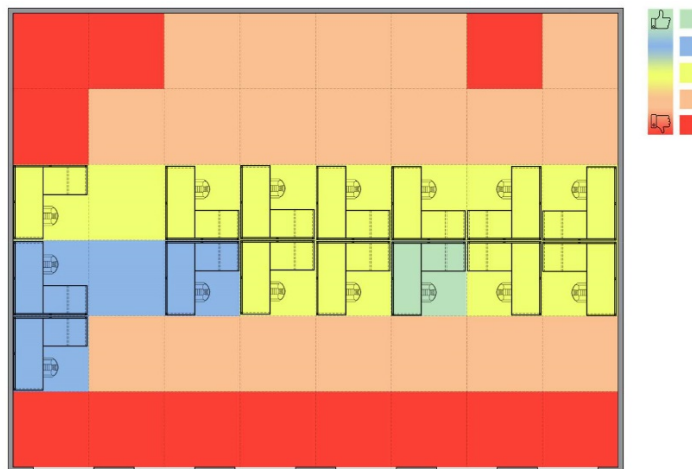


Figure 55. Locating sedentary areas

If the configurations are improved, and the simulations are done in Boston with 40% WWR, Triple – Low - e – Low SHGC - Argon - Improved Non-Metal glazing, 1meter overhang, 21°C-24°C set-points, and formal dressing for open office, the results for OTCP, DA, and ASE would be as the following:

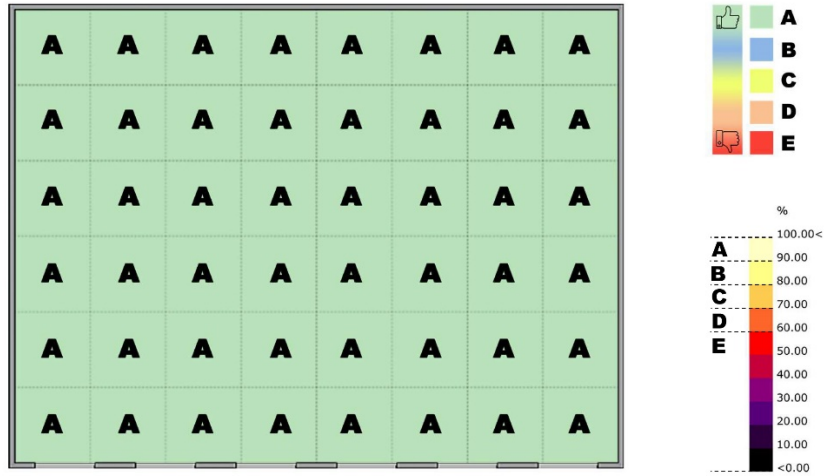


Figure 56. Occupied Thermal Comfort Percentage (OTCP) for improved configuration

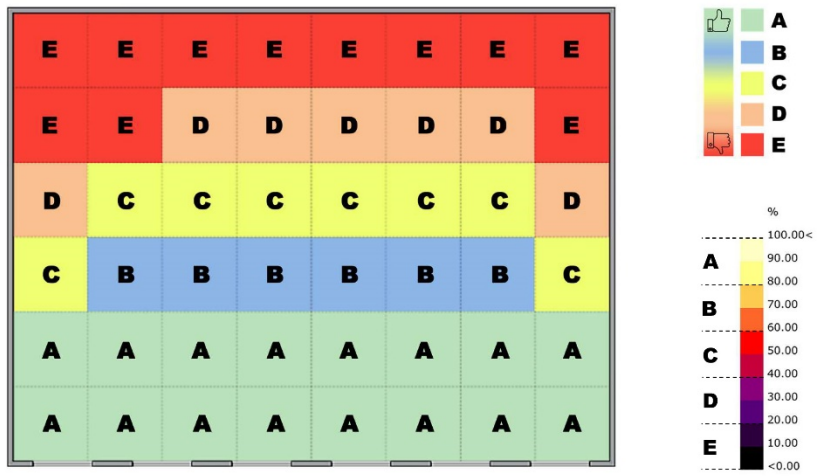


Figure 57. Daylight Autonomy (DA) for improved configuration

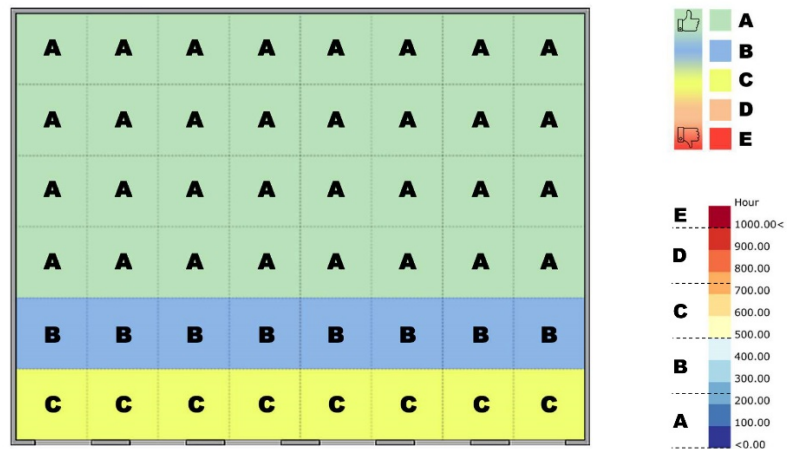


Figure 58. Annual Sunlight Exposure (ASE) for improved configuration

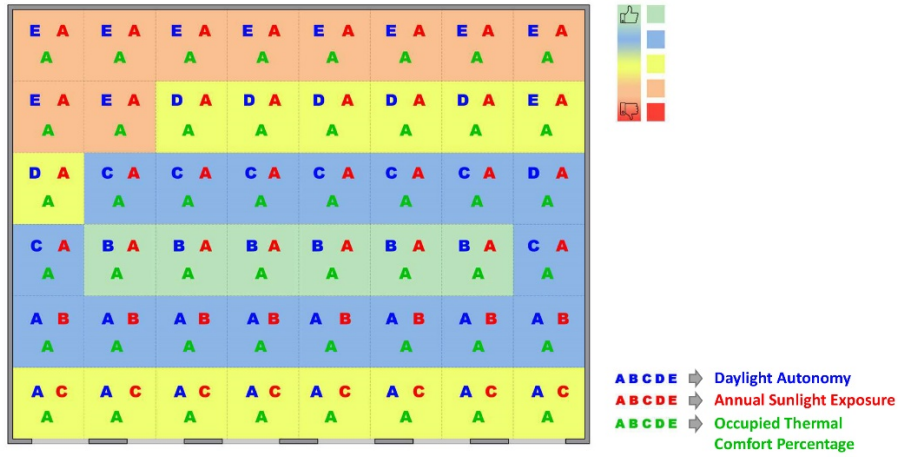


Figure 59. Integrated thermal and visual comfort for improved configuration

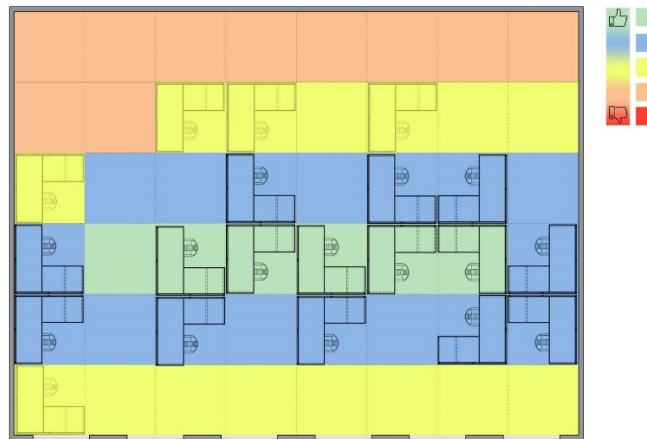


Figure 60. Locating sedentary areas for improved configuration

Chapter 5. CONCLUSION

Conventional practices come up with very similar solutions independent of location and condition. The reason is that traditional decision making is built around the convention, circulation, and adjacency without considering occupant's comfort related factors that are thermal, and visual comfort, and indoor air quality. When considering comfort aspects, designers often pay attention to just one comfort parameter without integrating multiple factors.

5.1 USE-CASES

The way that I can see this method is being used is in multiple design phases. Figure 61 shows the design phases in typical building construction.

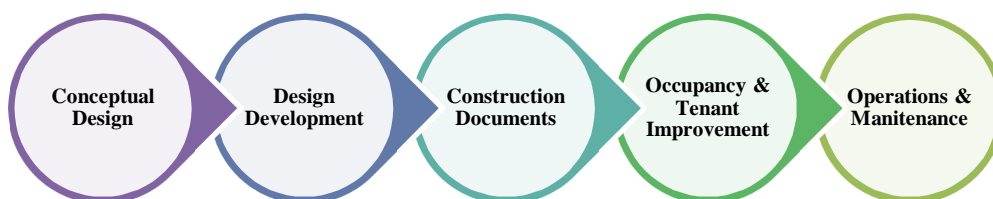


Figure 61. High-performance buildings design phases

5.1.1 *Conceptual Design*

The conceptual design phase is related to testing and comparing various design parameters and space-planning. One of the opportunities of the zone-based tool is to change the design parameters and compare the results in order to select the best configuration. In this phase, it would be worthwhile to have a tool that can change the parameters on a few clicks and pop up the time-consuming results in a second.

So, one of the other uses of this tool is to arrange the best configuration for the area. For a specific scenario, it would be possible to change the glazing type, WWR, cooling and heating set-points, and shading, considering the specific clothing and activity type and see what configuration shows the best result to be selected. In the following tables there are two scenarios to be compared with each other to see how the changes in glazing type, shading, and heating and cooling set-points can change the results for two types of WWR dramatically especially in the areas close to window and improve the performance of the building that directly affects the occupant's comfort and productivity. This tool can simplify the complicated process of overlapping different comfort factors and give the designers a broader perspective on space planning in a very short time.

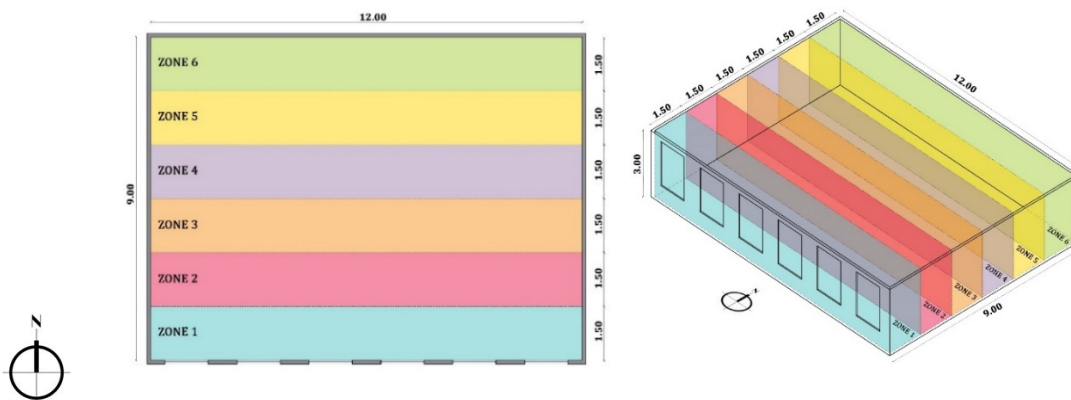


Figure 62. Different zones in the proposed 9m by 12m floor plan

Table 11. Result comparison for Case 1 with and without improvement

Scenario	Zone	TC	PPD (Rev.)	sDA	ASE (Rev.)
Baseline: <ul style="list-style-type: none"> • Boston (Zone 5) • 40% WWR • Single_Clear_Metal Frame • No Shading • 20° C - 26° C • Formal Dressing • Open Office (1.1 MET) 	No. 1	62.5	87.1	100	0
	No. 2	79.9	91	100	1.4
	No. 3	87.5	92.7	100	65.3
	No. 4	88.7	93.1	81.9	100
	No. 5	89.2	93.1	5.5	100
	No. 6	89.3	93.2	1.4	100
Scenario No. 1: <ul style="list-style-type: none"> • Boston (Zone 5) • 40% WWR • Triple_Low-e_Low SHGC_Argon_Improved Frame • 1 m Overhang Shading • 21° C - 24° C • Formal Dressing • Open Office (1.1 MET) 	No. 1	93.1	93.9	100	0
	No. 2	96.6	94.2	100	12.5
	No. 3	97.9	94.3	100	94.4
	No. 4	98.1	94.3	73.6	100
	No. 5	98.1	94.3	0	100
	No. 6	98.1	94.3	0	100

Table 12. Comparing the results of Scenario No. 1 and 2

	Number of improvements	Number of dis-improvements	Number of non-improvements
Scenario No. 1	14	3	7

By comparing the results, Scenario No. 1 provides a better configuration.

Table 13. Result comparison for Case 2 with and without improvement

Scenario	Zone	TC	PPD (Rev.)	sDA	ASE (Rev.)
Scenario No. 2: <ul style="list-style-type: none"> • Boston (Zone 5) • 80% WWR • Single_Clear_Metal Frame • No Shading • 20° C - 26° C • Formal Dressing • Open Office (1.1 MET) 	No. 1	46.4	76.9	100	0
	No. 2	62.5	87.4	100	0
	No. 3	85.6	92.2	100	6.9
	No. 4	88.6	93	100	100
	No. 5	89.5	93.2	100	100
	No. 6	90	93.3	93.1	100
Scenario No. 3: <ul style="list-style-type: none"> • Boston (Zone 5) • 80% WWR • Triple_Low-e_Low SHGC_Argon_Improved Frame • 1 m Overhang Shading • 21° C - 24° C • Formal Dressing • Open Office (1.1 MET) 	No. 1	87.1	93.2	100	0
	No. 2	94.9	94	100	0
	No. 3	97.9	94.3	100	54.2
	No. 4	98.5	94.3	100	100
	No. 5	98.5	94.3	97.2	100
	No. 6	98.6	94.3	86.1	100

Table 14. Comparing the results of Scenario No. 3 and 4

	Number of improvements	Number of dis-improvements	Number of non-improvements
Scenario No. 3	13	2	9

By comparing the results, Scenario No. 3 provides a better configuration.

5.1.2 Design Development

The conceptual design phase is focusing on details that are selected from the previous phase and includes the space layout, ventilation, thermal, and visual comfort, material choices such as glazing type, shading systems, and window configuration.

According to the results of the zone-based tool and through the development of zone-based “x-maps,” we can see spatial descriptions of a range of experiences that are shown in Figure 63.

By establishing clear thermal and visual comfort definitions and attributing them to various space-use types, patterns emerge that are informative to designers aiming to locate building uses within a floor plan appropriately

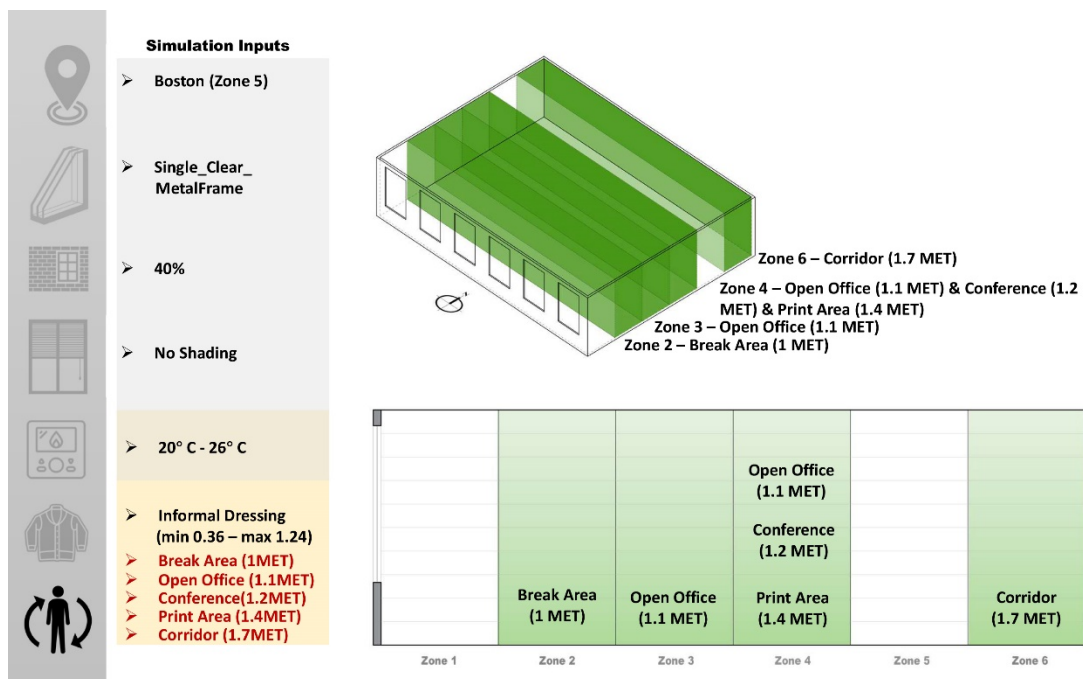


Figure 63. Spatial descriptions of a range of experiences

Also, the grid-based tool is valuable in this phase since it can optimize the space planning process based on occupants' comfort. In a traditional space planning process, the designer makes a layout for an open office in several ways.

Considering a blank 9m by 12m floor plan and using the conventional methods, there are typical layouts for arranging the desks that some of them can be seen in Figure 64. The determinant factor for these layout designs is aesthetics and shape, high density, privacy, distance from the window, and view. Besides these factors, building's performance and comfort is another determinant factor guiding the design process and bringing new ideas for the designers to simultaneously address all the factors mentioned above. It may be challenging to choose the best

solution for space planning among several choices that do not have a strong reason to support them. So, my purpose is to provide a comprehensive tool that overlaps several comfort factors in office buildings and can give designers an overall and broader perspective on space planning by comparing different zones inside the office from occupants' experience point of view based on conditions and locations. As explained before, one suggested layout for this 9m by 12m floor plan with specific scenario according to comfort factors can be seen in Figure 65. So, one of the applications of this method is space planning and creating new arrangements based on comfort and maximum performance.

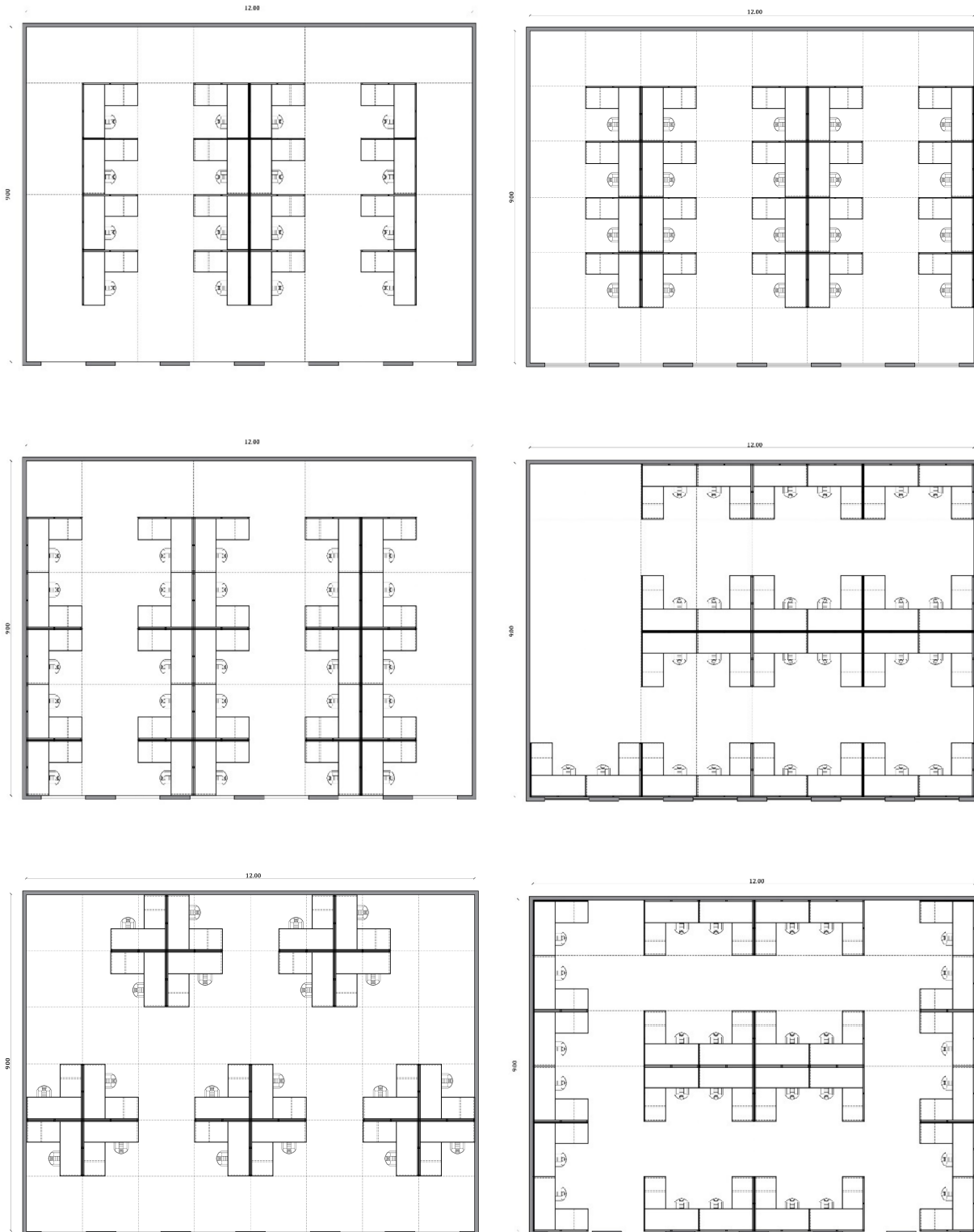


Figure 64. Different layouts for a 9m by 12m office plan

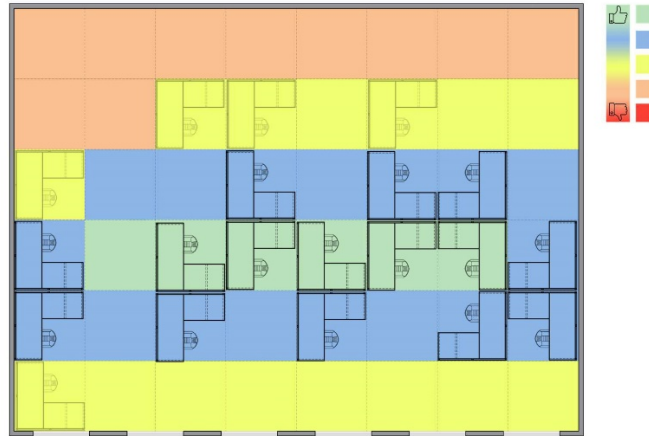


Figure 65. One suggested layout for this 9m by 12m floor plan with specific scenario according to comfort factors

5.1.3 *Post-Occupancy*

In occupied buildings, the tool can be used to help ameliorate occupant complaints, by identifying space planning modification options that would lead to improved comfort in situations where occupant dissatisfaction is regular and persistent. This process can be used to rearrange the desk locations in existing buildings and improve the interior conditions based on the occupants' need.

5.1.4 *Major Renovations*

In major renovation, the tool could be used to evaluate the impact of architectural improvements (e.g. window replacement or the addition of shading systems), or to align new space usage configurations or use-types with existing conditions that will remain.

5.2 OPPORTUNITIES

This study suggests two types of prototypes: one of them is zone-based, and the other is grid-based. The first one could give the designers an overall idea of comparing different zones based on the distance from the window and spatial descriptions of a range of experiences, while the second one

would go further to details and can give the designer the ideas for space planning and locating the workstations. So, these tools provide the opportunity to have better space planning method, improve the occupants' comfort, improve the existing buildings that are easy to use.

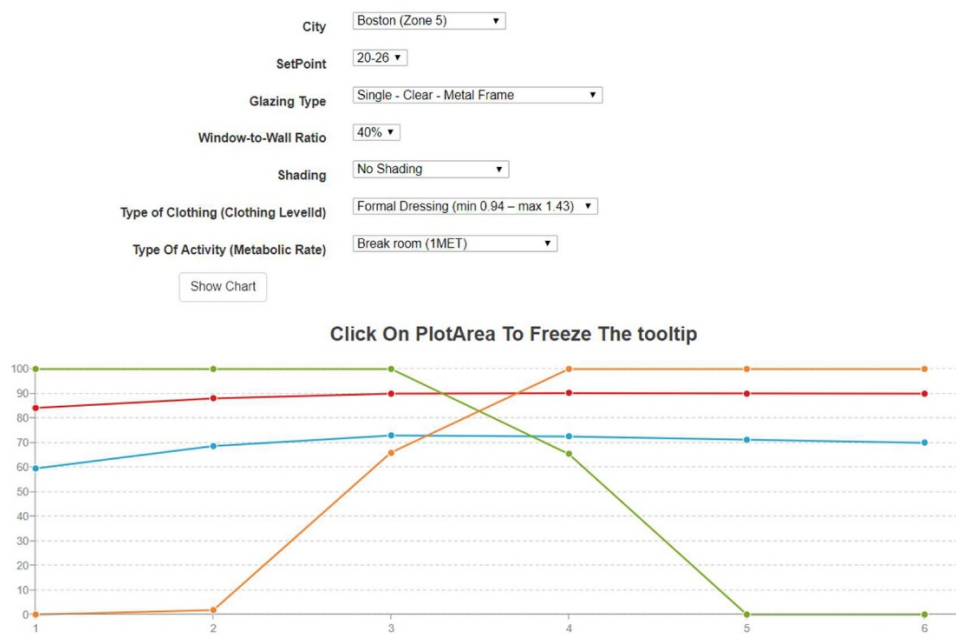


Figure 66. Prototype Zone-based Tool Demo

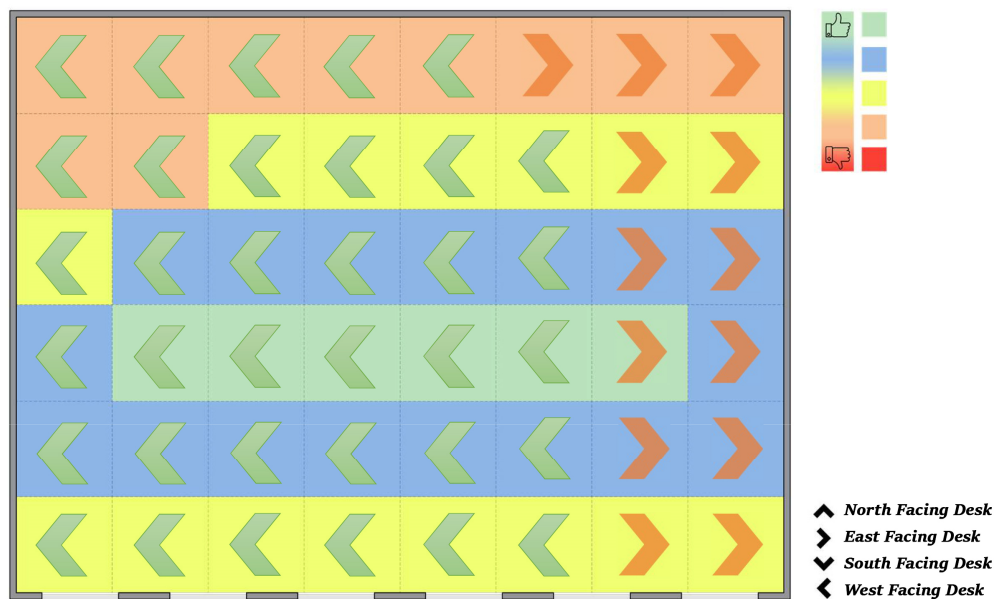


Figure 67. Prototype Grid-based tool

5.3 CHALLENGES

This tool is based on the simulation results extracted from the Grasshopper scripts and reflected in charts to be used easily by the designers, but it is still a custom process. There is no need for the user of this tool to fully understand criteria for thermal and visual comfort but for the other cases that are not included in this tool; there is a need for a guide to educate the user in order to use the grasshopper scripts and change the inputs and see the results.

5.4 FUTURE DEVELOPMENT

One of the future opportunities for this tool is to create a spatial room designation plugin for the most used software programs such as Revit and Rhino that have these criteria attached to it. One other is to create a library of standard multi-variate criteria for shared spaces.

Chapter 6. BIBLIOGRAPHY

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