

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 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 conflict with each other, and most studies have focused on just one aspect of comfort in isolation. 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 comfort parameters based on occupants' preference is of great importance. There are also factors that are not defined by standards, but by culture and climate, such as occupants' characteristics such as metabolic rate and clothing insulation, building's characteristics, and climate building's physical location and orientation. Conventional practices often produce very similar solutions for different locations and conditions without considering the factors mentioned above. So, the objective of this study is to provide a comprehensive tool that overlaps multiple 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 a comfort point of view based on 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. 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.

1.1. 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.

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). Several environmental conditions, such as visual, thermal, acoustic, and air quality can influence occupants' indoor comfort. Most building regulations and guidelines consider just one aspect of comfort since overlapping several aspects and parameters can be confusing and time-consuming.

Many previous studies indicate the relationship 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 a 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 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 and Tahsildoost 2017). According to a literature review by Atzeri, et al. (2014), some studies (Tsikaloudaki, et al. 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, et al. 2015) (Soori and Vishwas 2013) or thermal comfort (Ruppa, Vásquezb and 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)

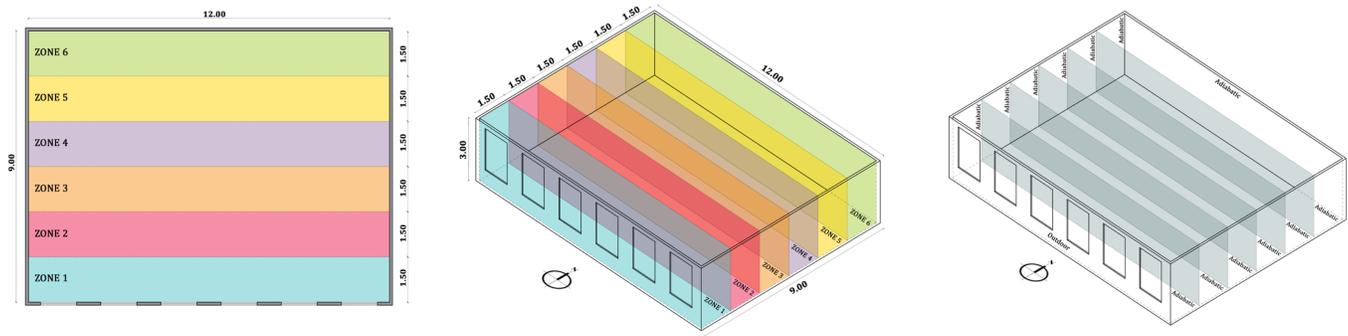


Figure 1. Floor Plan and Zone Divisions

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, et al. 2014) (Zomorodian and 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 study 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 the office interior space planning process to provide comfortable indoor conditions.

2. 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, it is well-known that the indoor environment affects occupants' well-being in both the short and long term.

The focus of this study is physical aspects of comfort that directly affect the office indoor environmental quality. There are seven 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 acoustics, 6) biophilia and views, 7) look and feel. 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. Also, some of these factors such as noise and acoustics, biophilia and views, and "look and feel" are not in the scope of this study and they possibly could be included in the future studies. The first four parameters can be used as simulation inputs.

2.1. 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, et al. 2016). Because of the shift from private office layout to modern open-plan in recent years (Kim and Dear 2013), higher attitude, and capability to provide more satisfaction and productivity for occupants, an open-plan office is selected in this study. 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. A 12m by 9m floor plan with south facing windows is selected to test the simulations.

Moreover, most office workstations are approximately 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. All the vertical walls, floor and roof are designated as adiabatic except the glazing wall exposed to outdoor conditions because this floor plan is conceptualized as a part of a larger floor plan and selected to show the simulation results. ASHRAE defines 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 zones smaller than overall floor plate to be evaluated independently and in isolation.

2.2. INDOOR AIR QUALITY AND VENTILATION

One strategy for improved indoor air quality is the use of natural ventilation which can have better impacts on occupants as compared with air conditioning systems, but is dependent on the location of the building (Al horr, et al. 2016). In this study, window natural ventilation is considered in all simulations to

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

Table 1. Metabolic rate for different activities in office building according to ASHRAE

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

Table 2. Minimum and maximum Clo for formal and informal clothing calculated by CBE thermal comfort tool

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 3. Default settings for the thermostat in most of energy simulation software protocols.

incorporate the impact of climate location on thermal comfort performance. Half of each window is defined as an operable single sliding window opening with insect screen (discharge coefficient of 0.17).

2.3. THERMAL COMFORT

According to the 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.” Thermal comfort can be affected by all the factors influencing the heat exchange between the human body and its surrounding.

For thermal comfort, there are personal parameters, related to expected or known characteristics specific to the anticipated user group, including clothing insulation (clothing level), and metabolic rate (activity level). There are also ambient parameters, related to the building location, that include: air temperature, mean radiant temperature, relative humidity, and airspeed. These parameters constitute the simulation inputs that are location-based and are exported from the weather file assigned to the simulation.

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 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 (Croitoru, et al. 2015).

The “adaptive comfort model” based on the body’s ability to adapt physiologically, is another model. 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.

The *X-map* method uses the PMV model that is related to physical aspects of comfort.

METABOLIC RATE

Metabolic rate is “the heat generated within the body” and one of the most critical comfort parameters and is expressed in the unit MET (1 kcal/kg/hour) (Luo, et al. 2018).

To establish the MET, different activities and their related metabolic rate are considered. Using the ASHRAE table for different activities, the metabolic rates indicated in Table 1 have been selected.

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, et al. 2018). According to ASHRAE standard 55, clothing insulation is expressed in clo value.

The clothing insulation is different for formal and casual dress and can affect the simulation results significantly. Two types of clothing insulation are selected in order to see the impact on results. There are min and max values for clothing factor in simulations that are calculated with the CBE thermal comfort calculation tool (Hoyt, et al. 2019) and are shown in Table 2.

HEATING AND COOLING SET-POINT

Since the PMV model was developed for conditioned spaces, critical variables for assessment are the heating and cooling set-points. The following table shows typical thermostat set-points used for energy simulation software protocols (Parker and Florida Solar Energy Center 2013).

According to table 3, two types of set-points are considered for simulations. A conventional arrangement is 21°C (72° F) for the heating set-point and 24°C (75° F) for the cooling set-point. In some cases, and as an energy savings strategy, an “expanded comfort zone” is used. This allows for a broader

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
Single - Clear - Metal Frame	7.32	0.73	0.69

Table 4. Glazing Characteristics (EWC, 2012)

range of temperatures and adaptive comfort by maintaining a lower heating set point and higher cooling set-point. Usually the expanded comfort zone is in the range of 20°C (68° F) for the heating set-point and 26°C (78° F) for the cooling set-point.

2.4. 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 physical characteristics of the visual environment are primarily used in order to evaluate its quality (Frontczak and Wargocki 2011). Reinhart, Mardaljevic, and Rogers (2006) considered Daylight Factor (DF), view to the outside, and avoidance-of-direct-sunlight as static daylight metrics and found limitations with them. To address some of these limitations, a number of dynamic metrics for daylight performance have been developed, such as Daylight Autonomy (DA) (Reinhart, Mardaljevic and Rogers 2006), spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic 2005), and Annual Sunlight Exposure (ASE) for climate-based measurement.

2.5. OTHER PARAMETERS

There are some parameters that 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 to highlight performance differences between individual zones and specific design alternatives.

For glazing type, since the intent is to look at the variety of comfort conditions, the single pane glass is selected based on the presumption that it will be the most comfortable. Conversely, triple glass is assumed to be much more comfortable and thermally resistant. These glazing characteristics are mentioned in table 4.

Likewise since the purpose is to look at the extremes of different comfort ranges, a window-to-wall ratio of 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 contemporary office buildings fall within this range.

Additionally, the simulations are done with either no window shading or with a 1-meter overhang.

Since the thermal and visual comfort metrics used are location-based or weather-file based, it is essential to define the physical building location for simulations.

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

Boston (Longitude: -71.03, Latitude: 42.37) is in Zone 5 that is defined as a cold climate by Building America

Phoenix (Longitude: -112.02, Latitude: 33.43) is in Zone 2 that is defined as a hot-humid climate by Building America.

San Francisco (Longitude: -122.38, Latitude: 37.62) is in Zone 3 that is defined as a marine climate by Building America (Pacific Northwest National Laboratory & Oak Ridge National Laboratory, 2010).

So, there are several inputs for simulations to be changed that can be categorized, as shown in Chart 1.

The simulations are done for an open-plan office with natural ventilation. Air temperature, mean radiant temperature (MRT), relative humidity (RH), and air speed are each time and location-based and extracted from the hourly weather data file. Ultimately, there are seven different factors with defined variables for each design alternative that is considered. This results in 480 permutations as described in Chart 2.

2.6. SIMULATION TOOLS AND THEIR OUTPUTS

There are several dynamic metrics for thermal and visual comfort. These evaluate a space on a point-by-point or a zonal basis using data from a typical meteorological year. These metrics provide annualized climate-dependent percentage of time-based metrics that can help a designer understand the percentage of time that space is comfortable.

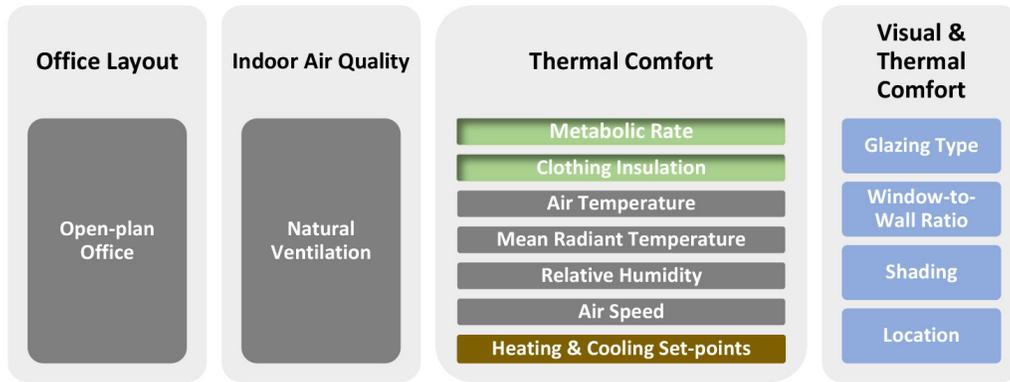


Chart 1. Factors affecting comfort and productivity in office buildings

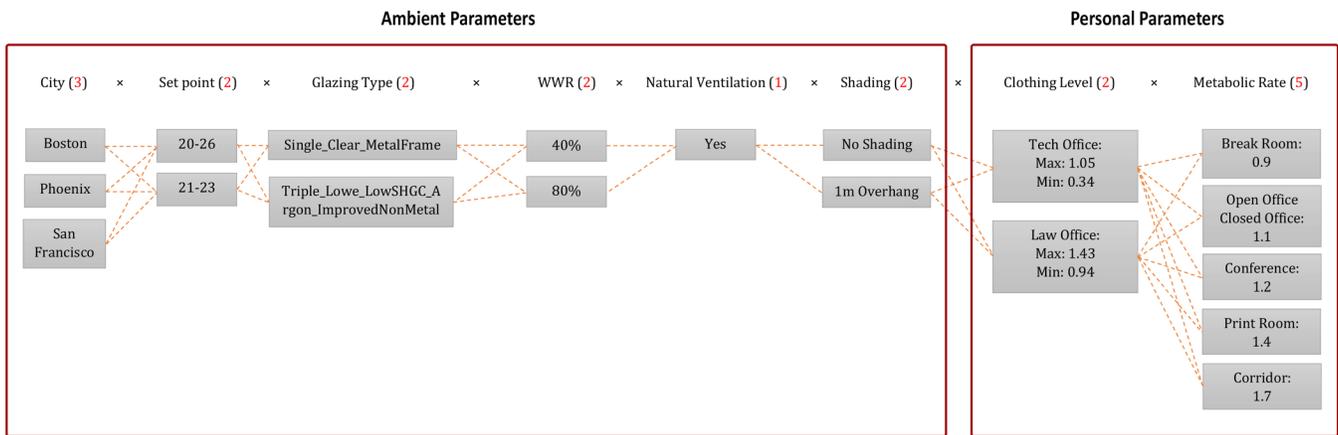


Chart 2. Simulation inputs

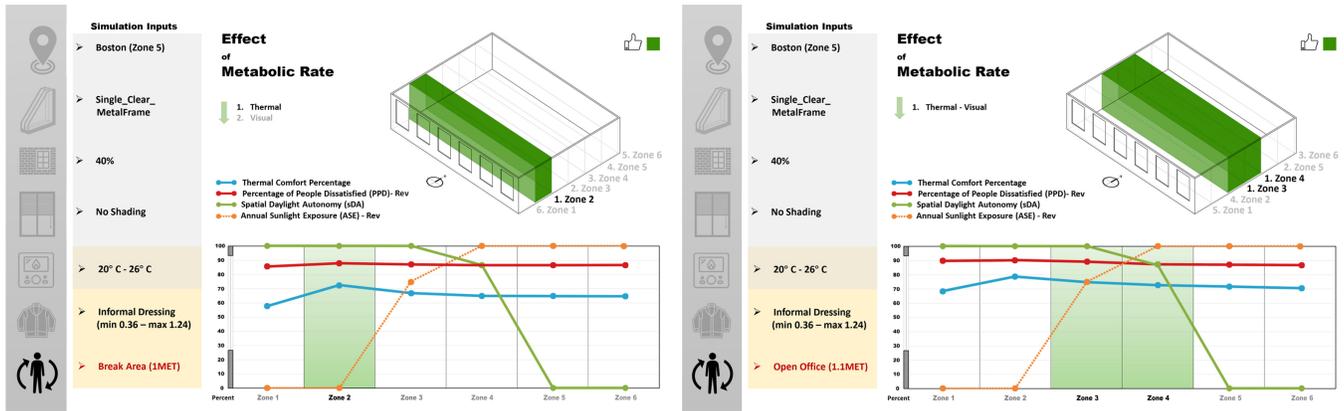
For thermal comfort, TC (Percentage of Time Comfortable) is a comprehensive metric that recognizes the percent of time under which the occupant is comfortable under the simulated input conditions. Taken together with PPD (Predicted Percentage of Dissatisfied), a relatively holistic picture of thermal comfort can be evaluated.

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 and Tahsildoost 2017). To simplify the process, Grasshopper (Grasshopper 2007) plugins such as Ladybug, Honeybee, and EnergyPlus which can provide more straightforward spatial thermal analysis are used since they are open source, no-cost, and more broadly accessible to designers.

For choosing daylight metrics, the appropriate IESNA (IESNA 1979) recommended illuminance levels for office spaces are used for daylight illuminance thresholds. The Spatial Daylight Autonomy (sDA) metric, which 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) is used for calculating daylight sufficiency. 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, Annual Sun Exposure (ASE) (IES 2012) is used as a companion metric to sDA and describes the amount of space with too much direct sunlight as a proxy for glare assessment. “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) (Wienold & Christoffersen, 2006) is selected for annual glare analysis.

Since the goal is to provide simultaneous thermal and visual comfort, it is less complex and more efficient to do thermal and daylighting simulations using the same software and simulation process. For this reason, the Honeybee plugin for Grasshopper is used for spatial daylighting simulation so both thermal and daylighting simulations can be done simultaneously.



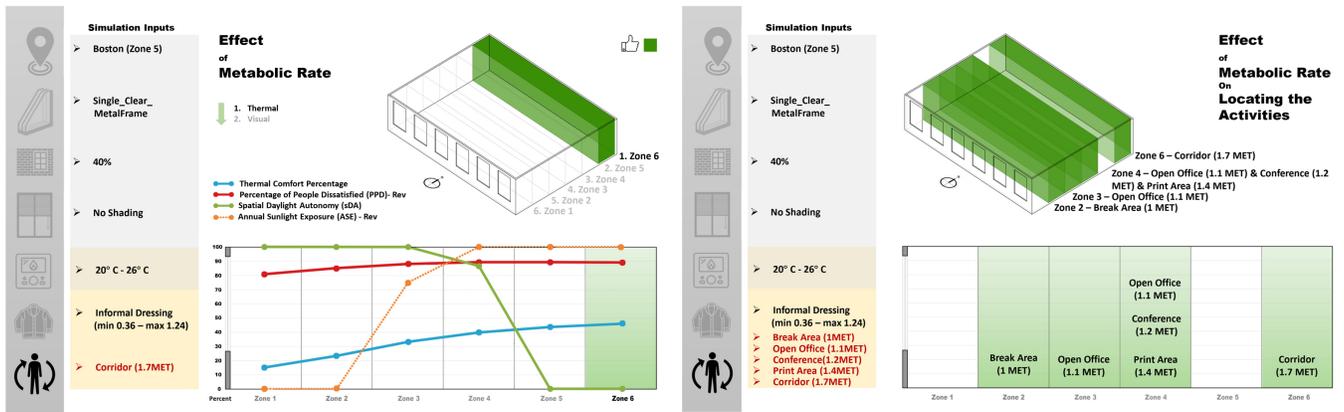
Simulation results for break area

Simulation results for open office



Simulation results for conference

Simulation results for print area



Simulation results for corridor

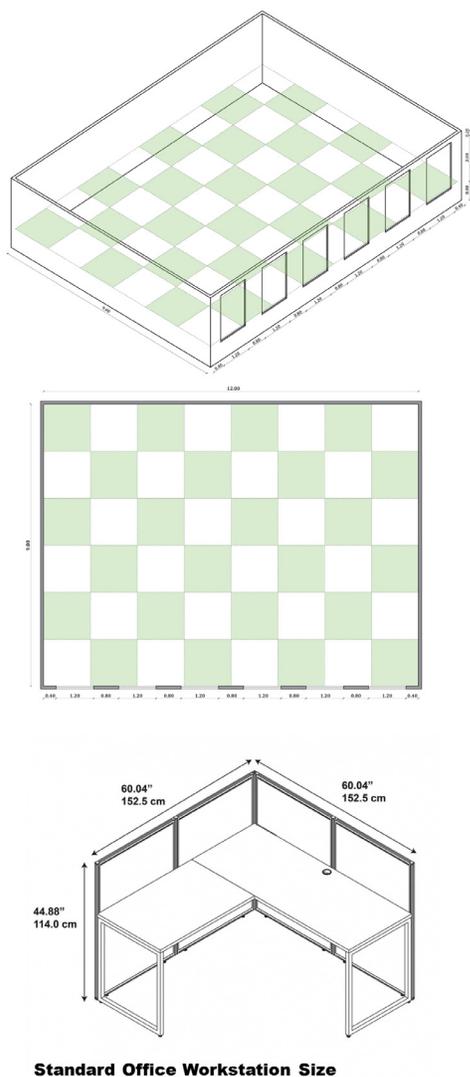
Comparing the best zone for each activity

Figure 2. Effect of metabolic rate

Once all of the simulations are complete and data is retrieved for each metric, the next challenge is to assemble it in a way that can provide design feedback that incorporates all of the experiential metrics in a singular manner that can provide clear feedback to the designer for interpretation and design decision-making. This is the central goal of the *X-map* and is covered in the following sections:

3. Prototypes

In this study, there are two types of analytical approaches to test out the *X-map* methodology: zone-based and grid-based. Two prototype model have been developed to test each method.



Standard Office Workstation Size

Figure 3. Grids for grid-based simulations

3.1. Zone-based Prototype

To test the methodology by evaluating comfort criteria relative to distance to the window, a prototype model was created with zones parallel to the window (Y-axis on the floor grid). For the zone-based simulation, there are six different zones and the percentage of time thermally comfortable, PPD, sDA, and ASE are calculated for each of them. The results are imported into pre-created charts and organized 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 independently, yet presented in a as a combined suite of evaluations.

3.1.1. Effect of Activity Level and Metabolic Rate

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

Figure 2 illustrates 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 four trend lines 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 so that improved performance is always at the top of the display.

As can be seen, in Figure 2. each simulation result provides different visual and thermal experiences which can be matched to corresponding programmatic activities. So, the activity type and its related metabolic rate have a significant effect on comfort results in office buildings. Since conventional design methods generally use the same value for all the activities inside the building, similar design solutions are often used for spaces with significantly differing experiential goals. As the simulation results show dramatic differences in results, using the same value for all of them leads to sub-optimal space planning and increased levels of potential discomfort.

3.2. Grid-based Prototype

The purpose of the grid-based prototype is to find the best-match spatial location for a given set of criteria within a defined floor area (both the X and Y on the floor grid) and the optimum direction for the desk to be facing. The divisions are as described below in Figure 3.

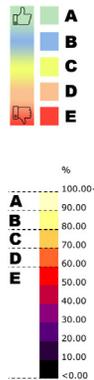
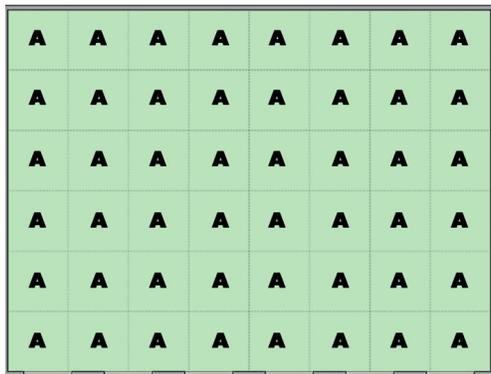
As an example, a simulation case is presented in Figure 4. Here the simulations are done in Boston with 40% WWR, Triple – Low - e – Low SHGC - Argon - Improved Non-Metal glazing, 1meter overhang, 21°C- 24°C set-points, and formal dress for open office. The results for Occupied Thermal Comfort Percentage (OTCP) , DA, and ASE are provided below in Figure 4 with each spatial zone within the floor place given a grade of best to worst from A-E for each experiential parameter (with “A” being best).

Green represents a perfect fit; blue and yellow are acceptable; the orange and red are visually and thermally uncomfortable respectively.

The next step is to identify the best-fit location for a task or activity area and to identify the best orientation (for a desk if appropriate), which is done using glare potential. This would be dependent on orientation and would require the designer to guess at the worst-case scenario. This process can be seen in

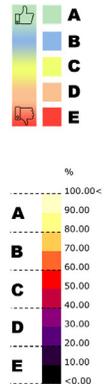
Occupied Thermal Comfort Percentage (OTCP)

□ 1.5m x 1.5m Grids



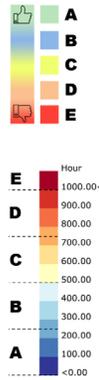
Daylight Autonomy (DA)

□ 1.5m x 1.5m Grids

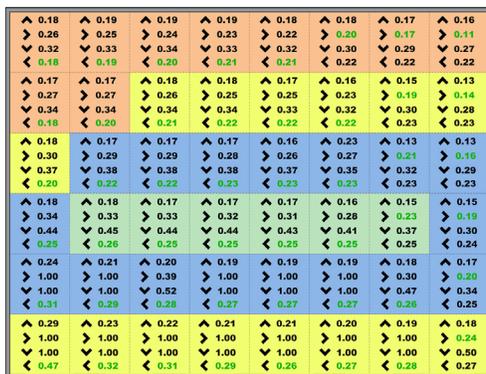
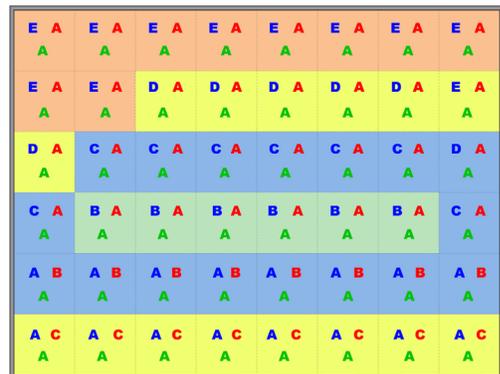


Annual Sunlight Exposure (ASE)

□ 1.5m x 1.5m Grids



Integrated Thermal and Visual Comfort



DGP: Daylight glare probability:
 Imperceptible Glare [0.35 > DGP]
 Perceptible Glare [0.4 > DGP ≥ 0.35]
 Disturbing Glare [0.45 > DGP ≥ 0.4]
 Intolerable Glare [DGP ≥ 0.45]

▲ North Facing Des
 ▼ East Facing Desk
 ▼ South Facing Des
 ◀ West Facing Desk



Figure 4. Grid-based prototype results and locating the sedentary areas



Figure 5. Prototype Zone-based Tool Demo

4. Conclusion

This study suggests two methodologies for generating experience maps (*X-maps*). One of them is zone-based, and the other is grid-based. The first one is intended to give 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 increases the granularity of analysis and is intended to add guidance for space planning and locating the workstations. These tools provide the opportunity to have improved experiential input in the space planning process and to improve the occupants' comfort in new construction or in re-configuring existing buildings.

One of the opportunities of the zone-based tool is to modify the design parameters and compare the results in order to select the best configuration and to provide sensitivity analysis relative to changes in projected thermal and visual comfort. It is targeted toward decision making during the conceptual design phases when it is possible to change the glazing type, WWR, cooling and heating set-points, to provide shading, and to include the specific clothing and activity type; and to evaluate what configuration shows the best result to be selected. 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. 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. In particular, the grid-based tool is valuable in new construction or tenant improvements to optimize occupants' comfort during the space planning process.

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.

1.1. Challenges

This tool is based on 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. In most cases, there is no need for the user of this tool to fully understand criteria for thermal and visual comfort, however it could be valuable to provide a guide to educate and assist users who would like to use the grasshopper scripts, and change the inputs, and customize the results.

1.2. 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 pre-defined space type, visual comfort, and thermal comfort criteria attached to it. Additionally, it could be valuable to establish a library of standard multi-variate criteria for shared spaces.

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