

## OPTIMIZED STREET DESIGN TO BALANCE OUTDOOR THERMAL COMFORT AND INDOOR DAYLIGHTING PERFORMANCE WITHIN LARGE SCALE URBAN SETTINGS IN HOT ARID CLIMATES

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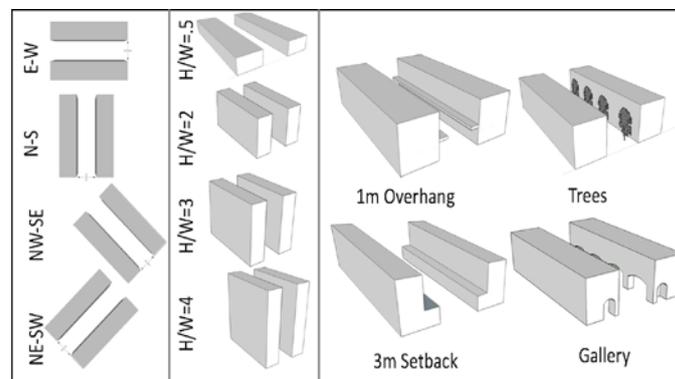


Figure 1. Three groups of four different street configurations.

WHICH ARE YOUR ARCHITECTURAL (R) SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL, AND ECONOMIC CHALLENGES OF TODAY?

### Research summary

Due to rapid urbanization in developing countries, achieving better outdoor thermal comfort has gained an elevated level of attention, especially within urban settings in hot climates. Although many research studies have focused on improving outdoor thermal comfort in urban settings and many researchers have discussed the influence of a building's geometry on the availability of daylighting in indoor spaces, there has been very little focus on street design as a means of improving both outdoor thermal comfort and indoor daylighting. This research study examines street design within urban settings in order to find a balanced design that could lead to better day-lit indoor environments and improve pedestrian thermal comfort. A series of quantitative simulations of various street configurations - such as street orientation and the ratio of building height to street width – have been performed. In order to find a balanced street configuration that achieves a comfortable outdoor environment and better day-lit indoor environment, the simulation results have been plotted and compared. The results show that the use of overhangs and galleries could achieve the desired balanced result.

**Keywords:** Daylighting, outdoor thermal comfort, urban daylighting

## 1. Introduction

The Department of Energy (DOE) reported that the residential sector's lighting use in 2010 was 9.6% of the country's total energy consumption. In terms of energy, this amount is about 23.8 billion kWh in one year alone. In other words, in 2010 the lighting in residential buildings produced about 137 billion tons of carbon dioxide. When it comes to the commercial sector, the same report shows even larger numbers. The commercial sector's lighting use in 2010 was estimated to be 17.1% of the country's total energy consumption, which is equal to 29.1 billion kWh and 183.6 tons of carbon dioxide in one year (DOE, 2011). A significant amount of energy can be saved by using daylight to light buildings. This reduces artificial lighting consumption, thereby lowering heating and cooling costs. Daylighting not only saves energy, it also increases worker productivity by elevating moods which, in turn, increases the overall economic value of the space (Rea, Figueiro, & Bullough, 2002).

The United Nations projects that over the next two decades, we will need to plan, design, and build new homes for 1.7 billion people (U.N., 2002). Adding such a large number of structures to the overall built environment is problematic. As such, there is a rising need for solutions that lead to more sustainable urban growth.

The external environment has a substantial impact on how people live, and is influenced by many factors such as building density, vegetation, and shading elements (Klemm, Marks, & Klemm, 2000). For decades, research has focused on improving outdoor thermal comfort, with only one research study suggesting that street design and orientation, as well as other factors such as overhangs, galleries, building materials, and trees, could have a significant impact on improving outdoor

thermal comfort (Ali-Toudert, 2005). However, this study focuses on examining street design in large scale urban settings with the goal of achieving both maximized indoor illumination and optimized outdoor thermal comfort.

This research endeavours to establish street design guidelines for use in hot arid climates in order to achieve an optimal balance between pedestrian outdoor thermal comfort and optimized indoor daylighting performance. The research methodology allowed for different street design scenarios to be modelled and simulated in order to match and compare the trade-offs among street width, street orientation, and street-to-building height ratio; these comparisons were made in order to assess the overall levels of pedestrian thermal comfort using the Physiological Equivalent Temperature (PET).

Other variables considered were building setbacks, overhangs and galleries, and trees. Below, after discussing my findings with regards to these variables, I analyse the various correlations between them and the balance between optimum thermal comfort and indoor daylighting performance.

This research study then proposes a set of recommendations and guidelines, based on the simulation results, which are designed to improve both balanced indoor daylighting illumination and outdoor thermal comfort in urban developments. Additionally, potential energy savings resulting from the application of these recommendations are presented.

## 2. Method

### 2.1 Location

For this research study, Cairo, Egypt was selected as the location for testing the thermal comfort and daylighting simulations. According to Köppen's climate classification system,

Egypt has a hot desert arid climate with generally clear skies and direct solar radiation (Peel, Finlayson, & McMahon, 2007). Cairo's latitude and longitude are 30.0500° N, and 31.2333° E, respectively.

About 95% of Egypt's 85-million inhabitants live near the River Nile, which occupies only 5.5% of Egypt's total area. This disproportion in population distribution has resulted in severe social and economic challenges, such as an increased rate of unemployment and generally low living standards. Since the 1980s, the Egyptian government has announced plans to rectify those problems by re-distributing the population through urban expansion into the desert areas (Shalaby & Tateishi, 2007). The government's plans have resulted in an on-going and rapid urban sprawl. Over the last two decades dozens of mega-cities have been built and occupied, most lying close to Cairo. As a result, there is an urgent need to establish sustainable street design guidelines that will help achieve a comfortable outdoor setting without compromising the quantity of daylight available to indoor spaces. Such daylight ultimately will lead to significant energy savings that are much appreciated, especially in Egypt; a recent study has shown that the country's demand for electricity is estimated to increase significantly, at a rate of 8% over the next few years (Hanna, 2011).

## 2.2 Thermal comfort and daylighting indices

The thermo-physiological assessment index called PET (the Physiologically Equivalent Temperature) was used in this research study to determine the level of thermal comfort in the examined street configurations. PET has frequently been adapted by researchers to assess thermal comfort in an urban context (Hwang, Lin, & Matzarakis, 2011; Cohen, Potchter, & Matzarakis, 2012; Ng & Cheng,

2012). The PET index is determined by the following meteorological variables: air temperature, vapour pressure, wind speed, and mean radiant temperature.

Continuous Daylight Autonomy (cDA) was adopted in this research study to determine the availability of daylighting in the examined indoor spaces. Continuous Daylight Autonomy is a climate-based metric derived from Daylight Autonomy (DA), which represents the percentage of annual daytime hours that a given point in space is above a specified illumination level; cDA awards partial credit or points to values below the user-defined luminance threshold.

## 2.3 Simulation engines

Urban Daylight is a plug-in for Rhinoceros, a 3D modelling tool used in this research study to analyse daylighting availability. The tool was developed in 2012 by a team of researchers from the Massachusetts Institute of Technology (MIT) (Dogan, Reinhart, & Michalatos, 2012).

ENVI-met was used to measure thermal comfort. Envi-met is a numerical tool used to simulate surface-plant-air interactions. Envi-met is also able to calculate bio-meteorological indices such as Mean Radiant Temperature (MRT), Predicted Mean Vote (PMV), and Predicted Percentage of Dissatisfied (PPD) (Huttner & Bruse, 2009). Finally, Rayman was used to calculate the PET index; it used the following four values obtained from the Envi-met simulations: MRT, wind speed, relative humidity, and air temperature (Matzarakis, Rutz, & Mayer, 2007).

## 2.4 Simulation scenarios and parameters

Cairo's climate is characterised by clear skies, which leads to a high level of solar radiation in the daytime; global horizontal radiation can reach up to 980 wh/sq.m. All simulations were performed on July 30<sup>th</sup>, and the simulation time was set to 7:00 am. The simulations were performed for a 24-hr period, at one-hour intervals. The street width was kept constant at 9m, and black asphalt was used for the street material. Building façades, roofs, and overhangs were assigned a concrete material. Floor height was fixed at 3m and a 0.4 window to wall ratio was used for the south and west buildings facades; 0.8 was used for the north and east facades.

Three sets of street configurations were modelled in both Rhinoceros and Envi-met. The first set contained multiple street orientations: north-south, east-west, north east-south west, and north east-south west. The second set of street designs contained four variations of the ratio of building height to street width (H/W): H/W= 0.5, 1, 2, 3 and 4. Finally, the third set of street configurations contained unique settings such as building overhangs, building galleries, building setbacks, and tall trees (see Figure 1). The overhang width was 1m, and the gallery's width was 9m. The tree height was 8m, which was modelled in Envi-met. A sycamore tree, which is native to Egypt, was chosen for this simulation. The Envi-met spatial resolution used was 1m horizontally, and 2m vertically. The average wind speed was set to 3mph, which is typical for Cairo. A vertical section was placed in the middle of the street for further climate studies. Air temperature (Ta) and Mean Radiant Temperature (MRT) were calculated at the following different height levels: 0.2m, 0.6m, 1m, 1.4m, 1.8m, 3m, 5m, 7m, 9m, 11m, 13m, 15m, 19m. The PET values were measured at 1.2m high. All three sets of street configurations were analysed in Envi-met; a

typical 24 hour simulation took between six and ten hours to complete. The different street configurations were then modelled a second time in Rhinoceros for further daylighting analysis in urban daylight. The daylight availability threshold was set to 500 lux for the internal building perimeter and 300 lux for the core of the building.

### 3. Results and design potential

To better analyse the simulations, the air temperature at a sensor point 1.2m high and in the centre of each street was plotted for a period of time between 01:00 and 17:00 (See Figure 2). Additionally, the PET values were calculated at the same sensor location for the same period of time (see Figure 3). Finally, the average cDA was measured for all of the floors inside the buildings and on both sides of each building; these values are recorded in Table 1. Better outdoor thermal comfort was accomplished by using galleries, overhangs, and trees where the PET values were the lowest: 33-52, 30-50, and 30-48, respectively. However, some of these configurations showed decreases in cDA. For example, the average cDA for all floors in the buildings on both sides of the street when a building setback was used was 90%. This value decreased by 2%, 20%, and 22%, respectively, when galleries, overhangs, and trees were used for shading. Although street orientation had little effect on daylighting availability, the orientation variations had average cDAs from 73.5% to 75%, and had considerable effect on thermal comfort. Streets oriented east to west had PET values of 32-60°C and air temperatures between 25-40°C, while streets oriented north to south had PET values of 30-48°C and air temperatures between 20-34°C. Finally, using different H/W ratios caused an inverse relationship between both daylighting

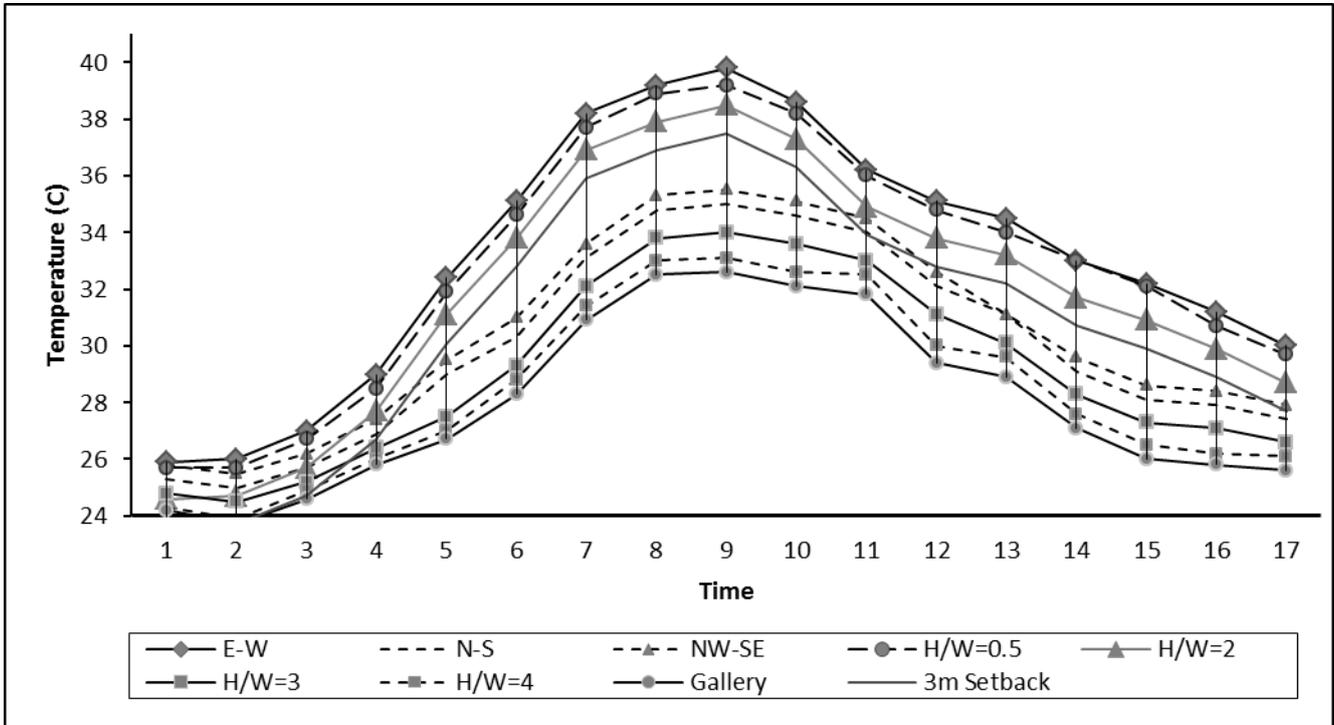


Figure 2. Air Temperature (Ta) measured at 1.2 m height for nine street configurations.

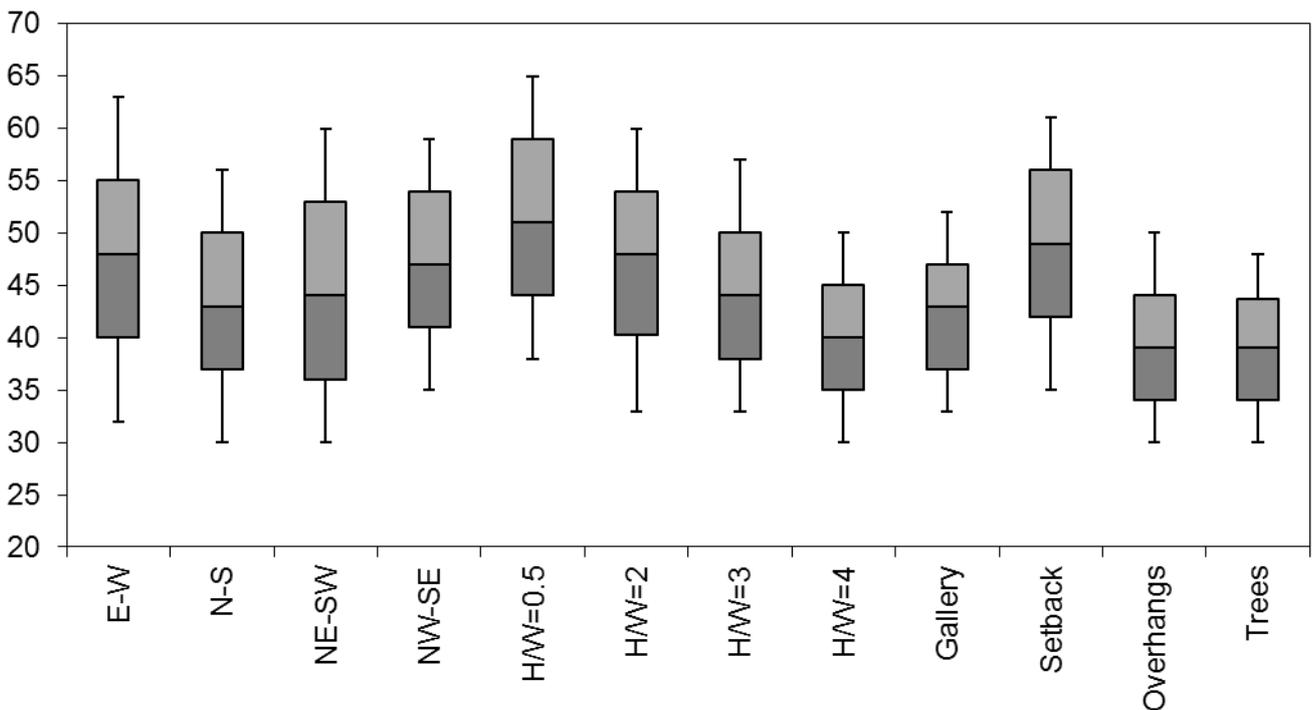


Figure 3. Boxplot graph showing PET values of for various street configurations (time 01:00 to 17:00).

and thermal comfort. A street with a H/W ratio of 0.5 caused an increase in daylighting (average cDA = 88.5%) and a decrease in thermal comfort (PET = 38-65°C), while a street with a H/W ratio of 4 caused a substantial decrease in daylighting (average cDA = 64.5%) and an increase in thermal comfort (PET = 30-50°C).

Table 1. cDA and PET Values

Street setting	Bldg1 cDA (%)	Bldg2 cDA (%)	PET value (°C)
E-W	73	74	32-62
N-S	73	77	30-48
NE-SW	73	74	30-55
NW-SE	73	75	35-59
H/W= 0.5	89	88	38-65
H/W= 2	72	66	33-60
H/W= 3	62	71	33-57
H/w= 4	60	69	30-50
Gallery	88	86	33-52
Setback	90	90	35-61
Overhangs	72	72	30-50
Trees	70	68	30-48

#### 4. Future implementation

The use of a parametric modelling environment could be a highly efficient means of street design due to the large number of variables that can be used to produce various street configurations. It is very difficult to examine large numbers of street configurations using the method introduced in this research study. Additionally, optimizing more than one objective in order to find the optimum configuration is problematic if large numbers of street configurations are being examined. Therefore, utilizing the Multi-Objective Optimization (MOO) tools that exist for most parametric modelling environments will

substantially reduce the time and effort required to find an optimized street configuration that is also based on multiple objectives such as pedestrian outdoor thermal comfort, daylighting availability, indoor thermal comfort, and walkability score. Several research studies have confirmed that integrating performance simulation engines with MOO tools within a parametric environment can be highly beneficial in assessing the performance and environmental impact of buildings in urban settings (Labib, 2015; Lin & Gerber, 2014; Aly & Nassar, 2013). Recently, several tools have been developed for use in conjunction with parametric modelling and MOO methods to measure urban building performances. However, there currently are no available tools that can calculate the PET index when analysing outdoor thermal comfort.

Considering the benefits of analysing performance using MOO methods in parametric environments, future development of work-frames to assess outdoor thermal comfort in such modelling environments would be greatly beneficial for both architects and planners.

#### 5. Conclusions

The results of this study confirm that it is possible to create a street design that can balance between outdoor thermal comfort and indoor daylight availability. The use of galleries, overhangs, and trees for shading provided comfortable outdoor environments had a trivial effect on daylighting in the lower floors. The use of a building setback provided plenty of daylight to the indoor spaces and tremendously increased the outdoor air temperatures. Street height to width ratios had the most significant effect on both daylight

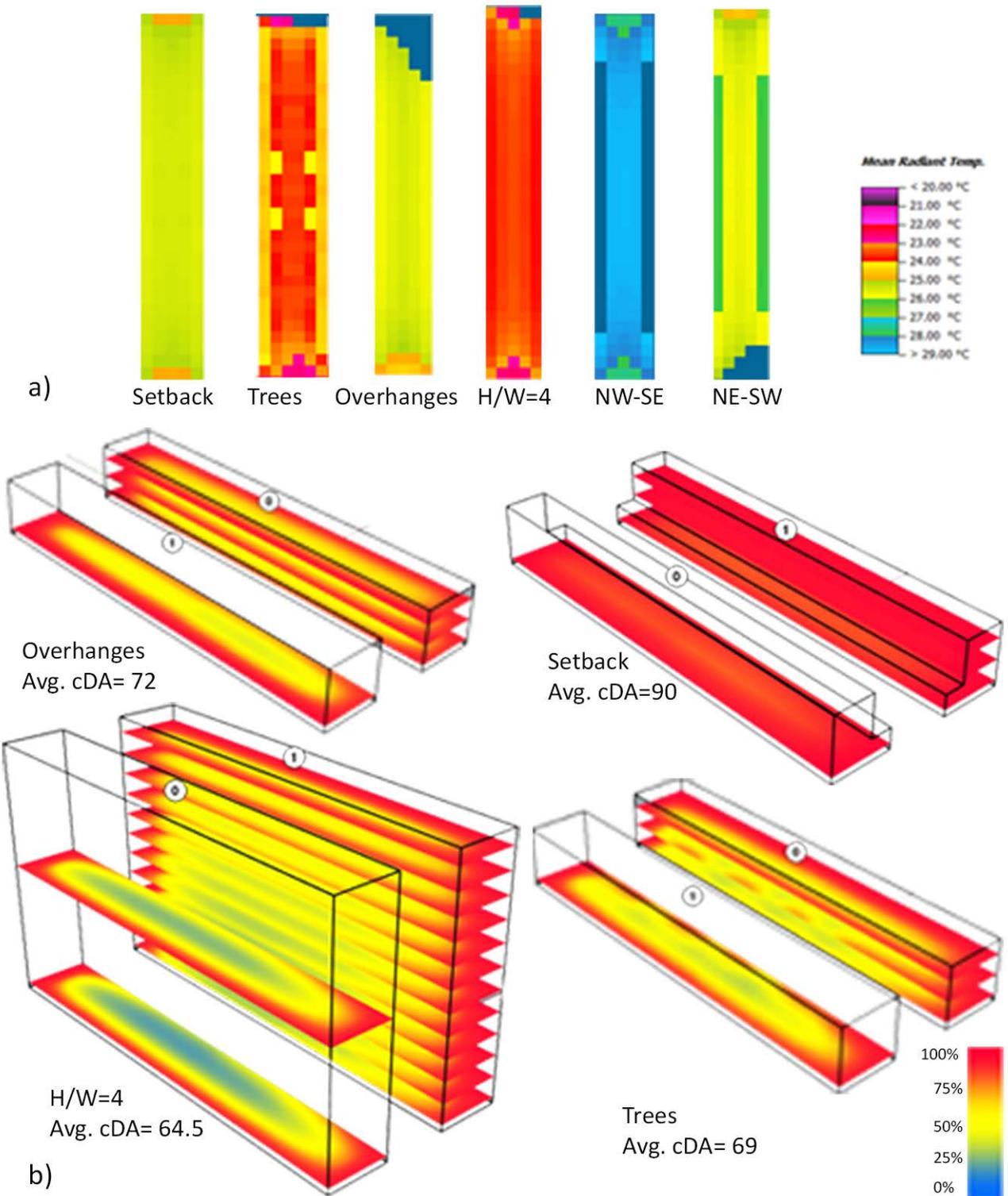


Figure 4. a) Mean Radiant Temperature (MRT) maps of different street settings. b) cDA analysis grids for different street configurations.

availability and outdoor temperatures, causing an inverse relationship between daylighting in the indoor spaces and thermal comfort in the outdoor spaces.

## 7. Acknowledgments

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