How Material Performance of Building Façade Affect Urban Microclimate

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Abstract

The world has experienced extreme urban growth in the last and current centuries, since more than half of the world population living in urban areas. Cities are expanding toward megacities with higher densities and narrower urban canyon profiles with huge urban structures and building masses. The transformation of urban landscape to densified city blocks has created phenomenon known as urban heat island (UHI); where the temperature in cities in comparison to rural, records high differences during day and night. Within this respect, this study explores the urban canyon profile as microclimate, considering the thermal performance of the building façade, the heat exchange between the building and canyon surfaces as thermal masses. A parametric methodology implemented to study differentiation of six scenarios for façade material with different solar absorption, to narrow down between possible alternatives and find the optimized solution to have improved microclimate. Universal Thermal Climate index (UTCI) is being used to measure microclimate and outdoor comfort to monitor the temperature difference with combining air temperature, humidity, mean radiant temperature and wind speed in the urban canyon.

Keywords

Material Performance, Façade Materials, Urban Canyon, UHI, UTCI

1 INTRODUCTION

Due to rapid urbanization in most of the countries all over the world, environmental factors are getting more attention in cities. One of the main influential factors on environmental conditions in city scale is density of built environment. Achieving proper density is always a challenging question for city planners and urban designers, since there is a demand for high density to increase mobility and less energy consuming transportation. This vision will push toward denser urban fabrics. On the other hand densified cities are experiencing more urban heat island effect during the year, while the city cannot cool down during night. Urban Heat Island (UHI) is one of the most common manifestations on urban climate studies and since its advent by Luke Howard (1818), it is still the topic of researchers in different regions of the world. High levels of pollution in the atmosphere and the "cementification" of urban areas (an excess of asphalted, or "low albedo", areas relative to green areas) cause the UHI phenomenon resulting in the dramatic 2 to 8 degree Celsius temperature differences between cities and their surrounding suburban and rural areas (Taha, 1997). In urban scale, morphology of a city influence micro climate parameters such as direct and indirect solar radiations, air temperature, mean radiant temperature, humidity and wind. that is why built environments are known as one of the climate modifiers (Horrison & Amirtham, 2016). Urban geometry and thermal properties of canyon surfaces have been found to be two main influential parameters on urban micro climate (Arnfield, 2003; Oke, 1988). The ration between height of the buildings (H) and the distance between them (W) affects the amount of solar radiation being absorbed and reflected from the surfaces in the canyon; also this effects the direction and speed of wind. There is a direct relation between H/W ratio and sky view factor. If H/W increases, this will reduce SVF, as consequence the reflected outgoing long wave radiation decreases and ends up with higher UHI. Another important factor is the material of the building surfaces in the canyon, studies proved that high thermal capacity of the materials act as thermal mass and absorb large amount of radiation during the day and stores it, and sometimes could not be released until the night (Johnson et al., 1991a, 1991b). There are couple of other factors like anthropogenic heat released from vehicles and air-conditioning systems, as well as air pollution, which has small effect on the radiation but not directly on air temperatures, and these effects are usually proved to be small (Arnfield, 2003).

Studies show that form of the built environment and properties of the surface materials in urban canyons have physically strong effect on the micro climate of cities. Early stages of urban design could be promising area for addressing thermal comfort and outdoor comfort to have livable public spaces. However microclimate of the cities in design process has gained minimum importance in the planning of cities (Evans & Schiller, 1996). This lack is firstly because of having no proper and accurate tools for early stages of urban design in order to justify micro scale parameters, and secondly, complexity and time consuming simulation procedures made this process even more far from main decision making steps of design process. In recent years the necessity of focusing on micro scale in urban studies has achieved more popularity. Johansson (2006) investigated the influence of urban geometry on outdoor thermal comfort by comparing an extremely deep and a shallow street canyon in Fez, Morocco and concluded that, in hot dry climates a compact urban design with very deep canyons is preferable. Horrison and Amirtham (2016) quantified the impact of urban growth pattern characterized by orientation, ground cover, street geometry on variations in climate parameters and their study established a clear relationship between urban character and microclimate modifications. Ali-Toudert and Mayer (2006) contributed to aspect ratio and solar orientation, towards the development of a comfortable microclimate at street level for pedestrians. Within the existing research context, still there is a room for more research and practical study on detailed effect of built environment on outdoor comfort. This research aims to cast more light on material modification of building surfaces in urban canyons to monitor the behavior of changing parameters on mean radiant temperature and air temperature inside the canyon as well as outdoor comfort indices with coupling methodologies.

2 OUTDOOR COMFORT

In recent decades there is a quite well understanding of the link between microclimate and urban settlements. Improved outdoor thermal conditions are in direct connection with how people behave and use outdoor spaces, this reaction may be spontaneous but mankind knows how to get adapted to different climate conditions in urban spaces. Having a place with optimum comfort level will enhance the city in different direction such as: encouragement for cycling and walking, attracting more number of people to comfort zones in the city and turning this opportunity into business and tourist attractions to shift the area economically profitable (Nikolopoulou, Baker, & Steemers, 2001). Within this respect comfortable outdoor space could be achieved with set of strategies according to the context like, planting trees with the advantage of evaporative cooling plus shading effect or adding manmade canopies with local materials are some of the possible solutions. Being comfortable or feeling like having no thermal stress is dependent on several factors and parameters and at the same time it differs from each person to another one, but scientifically if the body reaches thermal equilibrium with the surroundings, then the feeling should be close to comfort zone. In urbanized regions the lowest part of the atmosphere is known as urban boundary layer (UBL), which is certainly affected by the nature of building typologies. The UBL is mainly divided into smaller sub layers according to its climatic considerations and fundamentals, and the lower part is where microclimate studies are being done. Figure 1 shows a conceptual sketch of effective parameters on outdoor comfort in urban canopy layer.

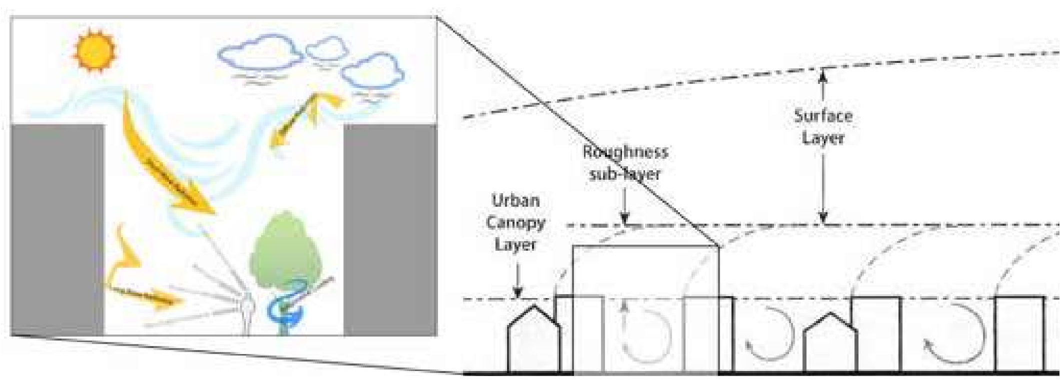


FIG. 1 Conceptual sketch of outdoor comfort and effective parameters

One of the sub layers of UBL is surface layer that goes up to about four or five times of average building height in urban areas. The effective parameters on this layer are known as three-dimensional geometry of the buildings and other attributes on the ground cover. This layer forms when the air has passed over a sufficient length of urban structures and attributes, including the heat generated within the city and rough sharp-edged structures (Erell, Pearlmutter, & Williamson, 2012). Below the surface layer and usually twice the average building height, the roughness sub-layer stands and it is highly variable because of different building heights, vegetation and open space variations. This zone is known as the transition layer between the highly vibrant urban surface and homogenous surface layer. The lower part of this roughness sub layer and urban atmosphere (UCL) starts from ground level and goes up to height of buildings, trees and other urban structures. In contrast to surface layer, the urban canopy layer is highly heterogenic since the conditions alter from point to point within the city boundaries. Corresponding to heterogenic essence of UCL, the necessity of establishing unique microclimate according to characteristics of each urban region such as; site parameters, vegetation, building typologies/systems, construction material and etc. is undoubtful. The relation between microclimate and architecture is reciprocal, in other words, the architectonic representation of the built environment impacts the outdoor thermal comfort, and on the other hand, the climate of the urban region impacts the building energy loads and consumptions. This research focuses on urban canopy layer to see the effect of built environment and surface materials on microclimate of city.

2.1 OUTDOOR COMFORT INDICES

Thermal comfort sensation in terms of outdoor perceived very differently from indoor comfort and people tend to accept a much wider range of thermal conditions outdoors than indoors. Based on conventional thermodynamic theories, comfort is steady state model which means the production of heat is equal to loss of it to the environment. This theory in reality is being adjusted by people themselves with modifying the clothing factor and the activities they do to decrease or increase the metabolic rate. Since the outdoor comfort is outcome of complex parameters, there have been very few attempts to define, scale and investigate outdoor comfort numerically. One of the most common indices is predicted mean vote (PMV) developed by Fanger (1973), the idea is based on the assumption that comfort is only reached and maintained at thermal equilibrium in the defined environment and boundary conditions. It is based on a steady-state heat balance model, empirically fitted to the sensation vote on a seven-point scale of a group of human test subjects exposed to static conditions in a controlled indoor environment. Standard effective temperature (SET) is another adjusted temperature scale meant to reflect the heat stress or cold felt by the occupant, and it is scaled in degree Celsius. In this model the total heat loss from the skin of an imaginary conditioned occupant is same with a person staying under the input conditions. Physiological Equivalent Temperature (PET) is another scale introduced by Mayer and (Höppe, 1999) and compares complex outdoor conditions to a typical steady-state indoor setting with the presets of MRT equal to Ta, wind speed of 0.1 m/s, Vapor Pressure of 12 hPa or RH=50% at Ta=20°C. The critical point among all of these indices and scales is that, using steady state models for assessment of outdoor comfort may not be correct solution since outdoor climate varies much more, temporally as well as spatially, values of the climate elements are usually very different from indoor values, and their relative influence can also be very different. Moreover, physiological adaptation of a person entering a climatically different environment takes some time and those models tend to overestimate discomfort values (Fiala, Lomas, & Stohrer, 2001). One of the recently developed indices for thermal comfort assessment is Universal Thermal Climate Index (UTCI) based on a dynamic physiological response model (Bröde, Jendritzky, Fiala, & Havenith, 2010). UTCI is this temperature of what the weather "feels like" and it takes into account radiant temperature (usually including solar radiation), relative humidity, wind speed and uses them in a human energy balance model to give a temperature value that is indicative of the heat stress or cold stress felt by the human body. For the calculations of Universal Thermal Climate Index the following simplified equation (UTCI) was applied (Błażejczyk, 2011).

$$UTCI = 3.21 + (0.872 \cdot t) + (0.2459 \cdot MRT) - (2.5078 \cdot V) - (0.0176 \cdot RH) \quad (1)$$

Where: t is air temperature (°C), MRT is Mean Radiant Temperature (°C), v is wind speed at 10 m above ground (m/s^{-1}), RH is Relative Humidity of air (%). Figure 2 shows different outdoor comfort indices scales in respective order.

PMV (INDOOR)	PET (GERMANY)	UTCI	SENSATION VOTE
	<4	<-40	Very cold
		-40--27	
-3	4-8	-27--13	Cold
-2	8-13	-13-0	Cool
-1	13-18	0-9	Slightly cool
0	18-23 (temp range for indoor comfort)	9-26	Comfortable/ neutral
1	23-29	26-32	Slightly warm
2	29-35	32-38	Warm
3	35-41	38-46	Hot
		>46	
	>41		Very hot

FIG. 2 Comparison of thermal indices PMV, PET and UTCI. (Pijpers-van Esch, 2015)

3 SURFACE MATERIAL PROPERTIES

Couple of studies already delivered on the effect of urban canyon material on outdoor comfort. Salata, Golasi, Vollaro, and Vollaro (2015) prove that the application of high albedo materials on vertical and horizontal faces of a canyon determines deterioration of thermal comfort especially in summer. This phenomenon could be handled by increasing the sky view factor of high albedo materials to limit the radiation reflection inside the canyon. In con-trast, high albedo materials usually improve microclimate during winter. This improvement is directly in connec-tion with the climate, because the improvement is not exactly equal to worsening that happens during the summer and most of the time it has less effect on winter. Dessì (2011) did an investigation considering performance of materials in terms of surface temperature to mitigate UHI effect. The research admits during the sunny day the surface temperature increases as the albedo decreases. Clear and smooth materials like marble have surface temperature simi-lar to air temperature and they behave as they are in shadow. It is believed that using clear materials is one of the popular strategies to reduce the UHI effect as they don't heat up that much and reflect solar radiation. Nevertheless, clear surfaces create problems such as visual discomfort inside the canyon. More severe problem is related to the thermal comfort and mean radiant temperature (MRT). The solar radiation reflected from clear materials, like the marble and glass surfaces, can be easily redirected into the canyon depending on the sky view factor. In the heat balance we have MRT with the whole radiation including direct and diffuse. It's true that the marble absorbs 20% of radiation and its surface temperature is always quite low, but we cannot ignore that the 80% reflects back to the canyon and can hit other urban surface on the space users.

4 METHODOLOGY

4.1 SELECTED STUDY AREA

The research concentrates on typical urban block located in Munich city center having mid-rise density surrounding with same height buildings. The urban canyon simulated with dimensions of 21 meters width, 75 meters length and buildings with 21 meters height (Fig. 3). Meteorological data (air temperature, relative humidity, wind speed, and wind direction) used for simulations gathered from the station in city center located near to study area(LMU Weather station), and selected period for study was typical hot summer day in last 10 years (12 August). Verification of surface materials is considered as concrete, brick and exterior insulation in order to measure different albedo and thermal mass effect.]

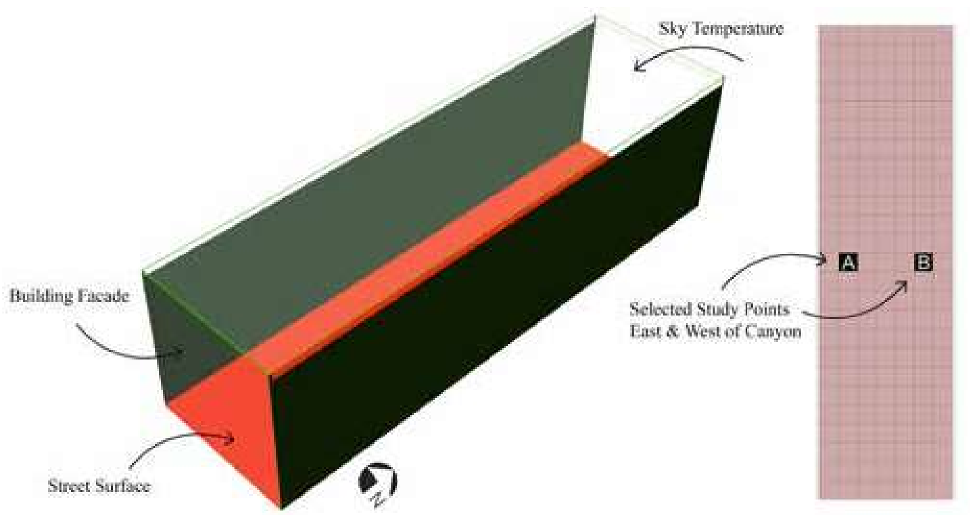


FIG. 3 3D model of urban canyon

4.2 SIMULATIONS

Each simulation tool has its own advantages and short comings, so coupling strategies implemented in order to maximize accuracy of results for each parameter. The process could be divided into three parts, firs part of the simulation is done with ENVI-met to calculate relative humidity and wind speed since ENVI-met is accurate in CFD modeling (De Maerschalck, Maiheu, Janssen, & Vankerkom, 2010). Second part is done with TRNSYS version 17.1 to simulate effect of different surface materials on mean radiant temperature and air temperature inside the canyon. For both simulations the same model implemented with same dimensions and properties. Last step was bringing results from two different simulation environments into one layer and overlap them to map outcomes. This was done with grasshopper as visual programming interface to read data from both simulations and map outdoor comfort visually as well as calculating values numerically (Fig. 4). Each simulation tool has certain boundary conditions, in case of TRNSYS: Weather data: try2010_13y_muehldorf.109, Analysis time span: 12th August 0-23hr, Ground Boundary Temperature: 20°C, Wall Boundary Temperature: Tamb, Wall Adjacent Temperature: 23°C, and Ceiling Boundary Temperature: Tsky.

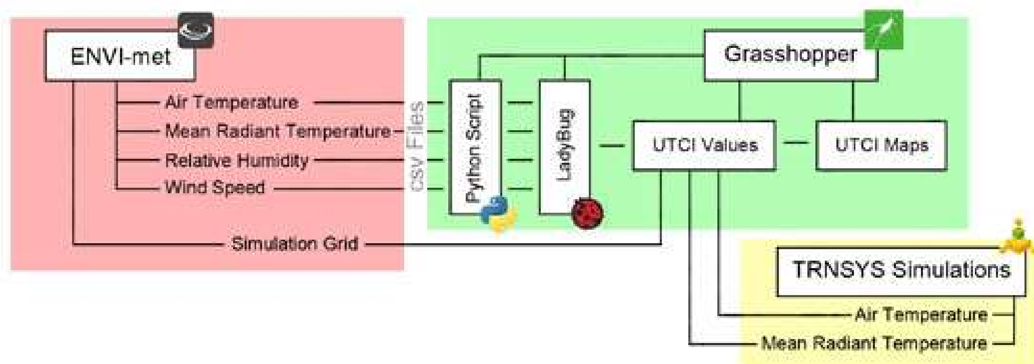


FIG. 4 Diagram of Coupling Methodology implemented tools

4.3 MATERIAL THERMAL PROPERTIES

Thermal simulations are dynamic in terms of material variation, for this reason there is possibility to evaluate different materials with varying solar absorption to see their impact on energy performance of urban space. This will help to select correct materials for building façade to have less impact on outdoor environment. Table 1 & 2 provide detailed information on material properties and construction variants for different simulations inputs. Six alternative materials are selected as input: Brick, Concrete and exterior insulation with plaster as finishing layer. The other variant was color of the materials with different solar absorption. For brick 35 and 68 percent, for concrete 30 and 80 percent, for wall with exterior insulation the color with 30 and 80 prevent solar absorption implemented for TRNSYS simulations.

MATERIAL	CONDUCTIVITY	CAPACITY	DENSITY
	kj/h.m.K	kj/kg.K	kg/m^3
Concrete	6.12	0.88	2300
Brick	2.88	0.84	1920
EPS	0.144	1.5	32
Plaster	0.72	1	849

TABLE 1 Material Properties of Surfaces

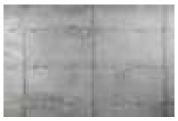
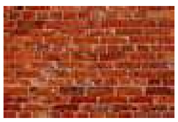
	Wall Variants	Walls	Floor	Solar Absorption
	Concrete	Concrete 30cm	Concrete 60cm	Light 30%
				Dark 80%
	Brick	Brick 30cm	Concrete 60cm	Glazed 35%
				Common Red 68%
	External Insulation	Plaster 2cm	Concrete 60cm	Light 30%
		EPS 20cm		Dark 80%
		Concrete 20cm		

TABLE 2 Surface Construction Variants

5 RESULTS

5.1 ENERGY PERFORMANCE OF MATERIALS

Simulation inputs are divided into six different variants, considering 3 materials (Brick, Concrete, and Exterior Insulation) with two different solar absorption values for each. In order to compare the effect of each component, two test points are selected in the canyon. The points are in the pedestrian height in both sidewalks. We name west point as 'A' and the East point as 'B'. The graphs are illustrated to compare brightness and darkness of same materials by means of varying solar absorption to see how they affect MRT on local points (Fig. 4). The comparison shows that dark materials end up in less mean radiant temperature values since they absorb most of the radiation as heat and reflect minor part of it into the canyon. Here the question could be the thermal mass effect during night, which we exclude from this paper since the topic is broad enough for a whole research paper and we focus just on day time effect of materials. The results values from two test points show that as the profile of the canyon has high walls with shadow casting effect, both points heat up almost in same pattern just with some hours of differentiation. During the evening west point cools down earlier and both points get close to equilibrium before sunset.

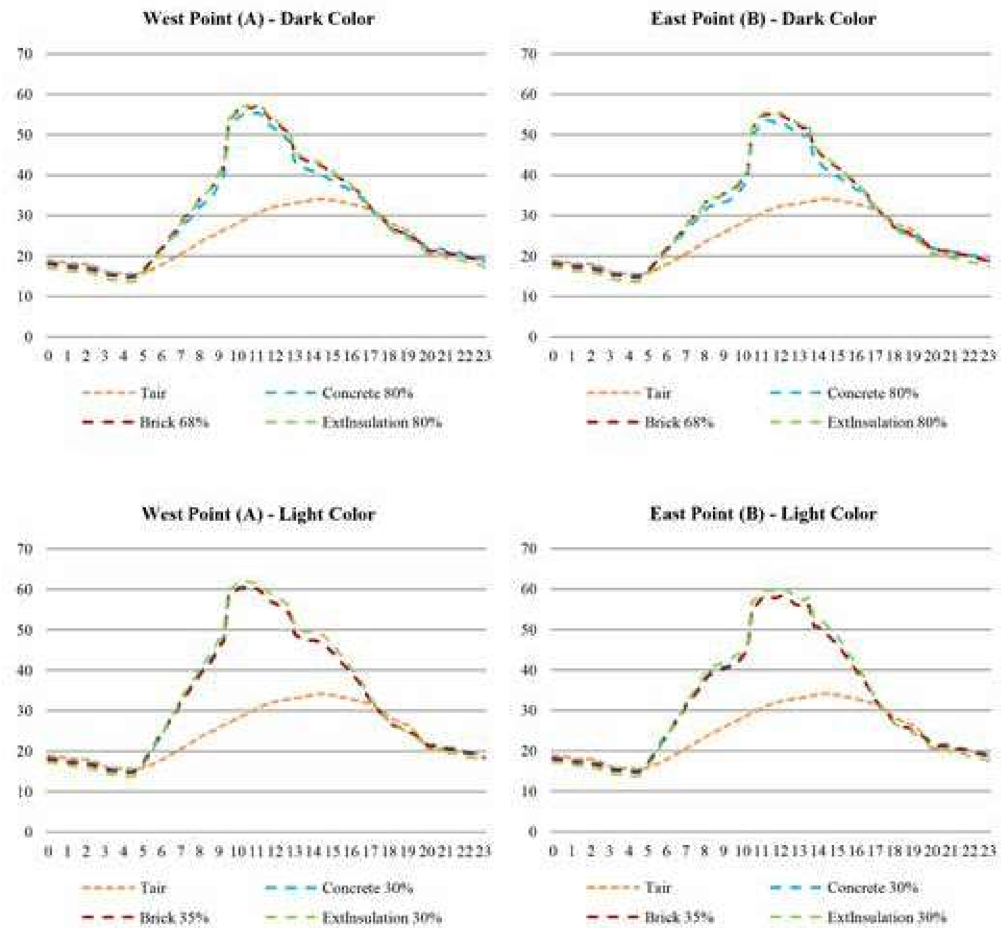


FIG. 5 MRT values for different material variants

We also monitor the highest MRT values for Exterior insulation case since the thermal mass effect of the material is minor and MRT during the day goes up to 61 °C which could be absorbed by ground and surrounding surfaces depending on sky view factor. This could be the main drive for heating the space during night time (Fig. 5). To compare the effect of material variation with different absorption values, we also map them in the canyon for 2pm. The most extreme case is with exterior Insulation with 30% solar absorption and the best case is brick wall with 68% absorption (Fig.6).

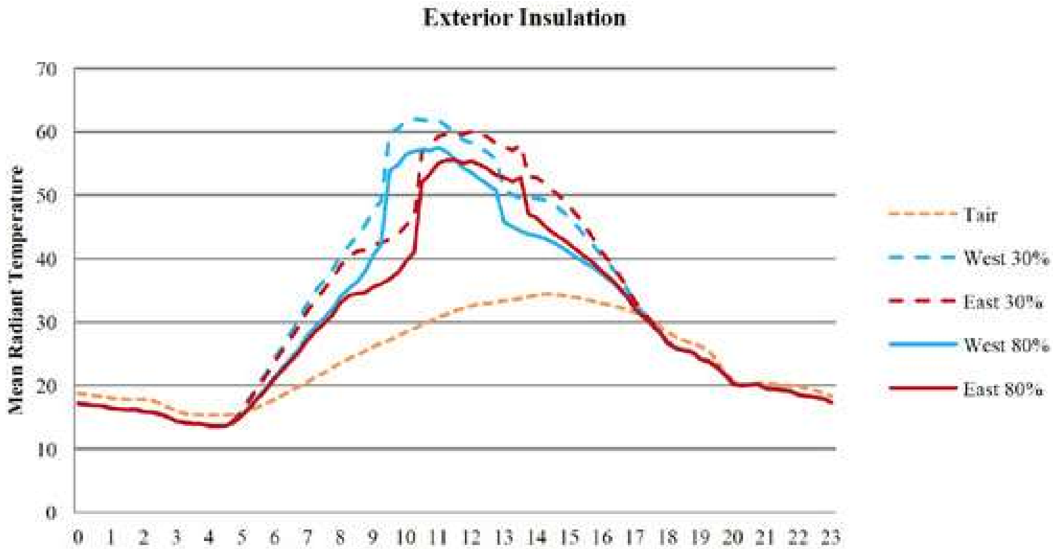


FIG. 6 Mean radiant temperature for Point A & B for Material with Exterior Insulation

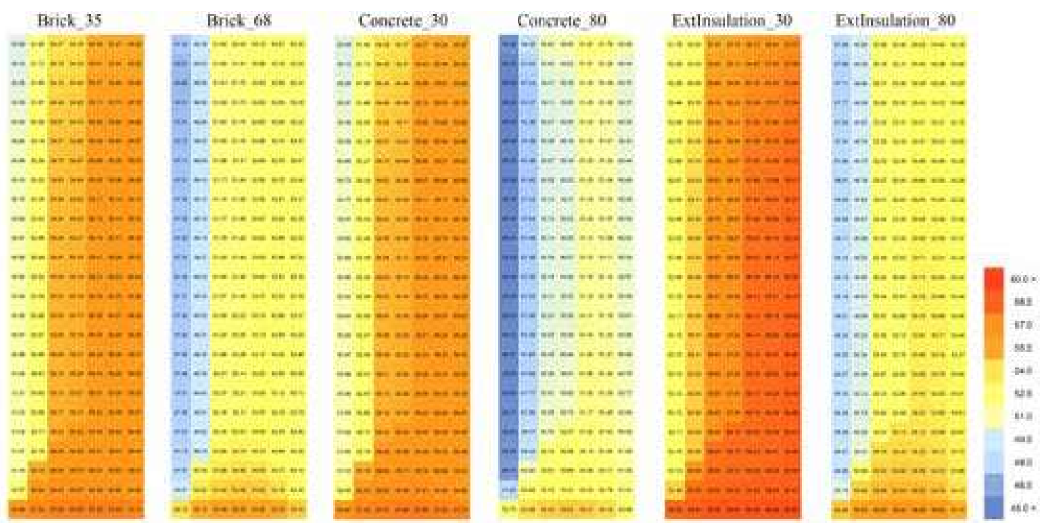


FIG. 7 Comparison of MRT values for Different facade materials

5.2 OUTDOOR COMFORT MAPPING (UTCI)

Final step was to get MRT values from TRNSYS and combine them with ENVI-met outputs to map outdoor comfort. It is also possible to get MRT directly from ENVI-met but there are some discussions going on the accuracy of the results in term of considering thermal mass of the material. Also in free version of the program there is no possibility to modify the façade material properties. That is why coupling methodology implemented by a script in Grasshopper to merge outputs of both simulations in UTCI map to define environmental performance and people well-being in urban canyon. The maps are produced for typical hot day at 2pm. Heat stress probability was calculated within UTCI values.
In all cases the values are between moderate heat stress and strong heat stress. Within the alternatives, concrete material with 80 percent of solar absorption has the least heat stress; in contrast the façade with exterior insulation and 30 percent solar absorption causes the most heat stress in the canyon.

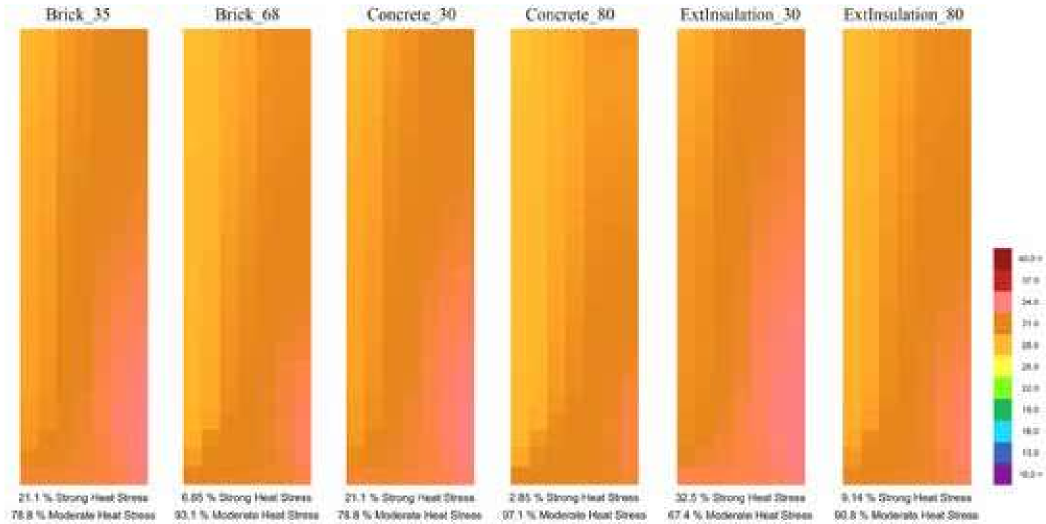


FIG. 8 Universal Thermal Climate Index for different Facade Materials

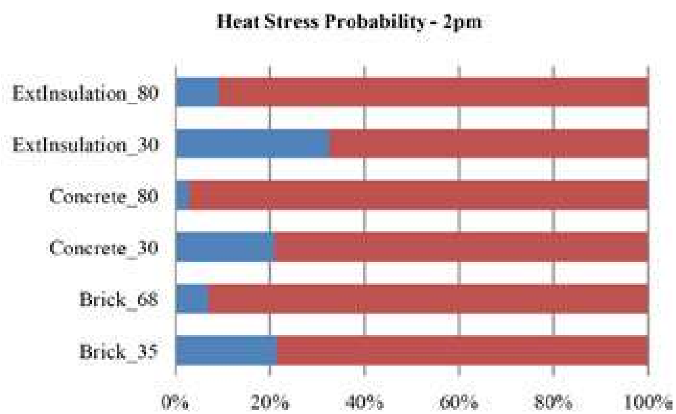


FIG. 9 Heat stress comparison of UTCI values

6 CONCLUSIONS

Material choice is one of the main role playing factors in terms of having less impact on environment. Each selection depends on where we are going to use the material. For example, high reflective materials can reduce temperature of urban surfaces like roofs and pavements as well as summer time building cooling energy demand. At the same time high albedo materials absorb less radiation and this increases MRT depending on sky view factor in day time. Studies find that reflected radiation from high-albedo pavements can increase the temperature of nearby walls and buildings, increasing the cooling load of the surrounding built environment and increasing the heat discomfort of pedestrians. Harmful reflected UV radiation and glare, unintended consequences of reflective pavements, need special consideration for human health (Yang, Wang, & Kaloush, 2013). Results and findings through this study reveal that:

- The solar absorption, surface temperature and mean radiant temperature have proportionally reverse relationship
- The results show that with higher solar absorption, less solar radiation is reflected directly into the space and causes the space to be cooler.
- The effect of different façade materials is significantly smaller than the impact of difference between solar absorption percentages on local mean radiant temperature values
- Higher solar absorption means higher surface temperature, but lower MRT, and vice versa.
- For the climate of Munich, the results show that light color walls with less solar absorption are worse than dark color walls in terms of outdoor comfort during hot periods.

The aim of this research was not just to investigate material variation; however the developed coupling methodology with different simulation tools gives an opportunity to have more accurate simulation result depending on the input parameters. Also the frame work could be used for future studies in order to have parametric exploration on the aspect ratio of the canyon (H/W) to monitor its effect on UHI based on varying SVF as well as material differentiation with different thermal mass capacities.

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