

How to Cool Down Dense Urban Environments? A Discussion on Site-Specific Urban Mitigating Strategies

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Abstract: For over a decade, the increasing effect of climate change patterns has become a global challenge to be considered and integrated on all levels into the planning of cities. Europe's extreme climate has continued to shatter heat records in the past ten years and is projected to worsen. The local heat islands in dense urban environments are affecting buildings' energy consumption and outdoor air quality, as well as increasingly influencing the health and well-being of the growing urban population, especially the elderly. Therefore, cities are a challenge when developing and adopting sustainable actions to mitigate the worsening urban thermal environment in upcoming years. The purpose of this research conducted under the supervision of Prof. Dr. Pia Fricker, Professorship for Computational Design in Landscape Architecture and Urbanism at Aalto University Finland, is to provide developed urban areas with a set of feasible and ecological outdoor thermal comfort mitigation solution strategies in respect to the changing climatic conditions of the future. The paper takes Helsinki as a pilot site, as it represents an average dense city with a high representative number of elderly citizens. Special focus is set on researching the performance of small-scale interventions which support the well-being of people living in affected urban areas. The applications fill an existing gap in urban services and infrastructure found in projected extreme climate change and engages citizens in the urban climate adaptation process.

Keywords: Heat environment, web-based application, sustainable urban design strategies, outdoor thermal comfort, dense urban environment

1 Introduction

1.1 General Introduction










Urbanization is a global trend, with 2.5 billion people expected to be residing in cities by 2050 (UN 2014). In the meantime, projected extreme weather events due to climate change will become more frequent and severe (EEA 2020). Heatwaves are the deadliest type of weather-related event, accounting for 68% of the 90,325 additional deaths throughout the whole of Europe during the period 1980 to 2017 (EEA 2020). Even in the Nordic countries, mortality rates due to heatwaves outstrip mortality rates caused by other extreme weather events (EEA 2017). Furthermore, the elderly, children, patients with pre-existing chronic illnesses, and groups in asthenic socioeconomic conditions are frequently listed as the most vulnerable communities among urban residents (KERAMITSOGLOU et al. 2017, SMID et al. 2019). In the urban context, urban structure and landcover contribute to the urban heat island (KLOK & ZWART 2012), which intensifies heat events locally. Variations in temperature range from 1 to 10 °C difference between densely urbanised areas and rural backgrounds (ULPIANI 2021), exacerbating the impact of heatwaves on human health (COFFEL 2018). Simultaneously, heatwave events increase energy consumption needed for cooling down and increases costs for construction and infrastructure maintenance (COFFEL 2018).

Even though Helsinki is commonly regarded as a city with moderate temperature, the increasing effects of heatwaves has had a noticeable impact. According to the FINNISH METEOROLOGICAL INSTITUTE (2019), the City of Helsinki counted 25 heatwaves in 2018, with these resulting in 380 fatal casualties. Even if emissions were controlled (RCP=4.5), the maximum and average summer temperature in Helsinki in 2100 will increase by 3 degrees compared to the present (MÄKELÄ 2016). In response to climate change, Helsinki has set up several sustainable development goals by locally implementing sustainable development responsibility (CITY OF HELSINKI 2019). However, Helsinki has not carried out relevant research on how to alleviate the urban thermal environment in the field of urban design or landscape architecture.

1.2 Outdoor Thermal Comfort Indices and Models

Outdoor thermal comfort research aims to ameliorate the worse effects of a heating urban environment, while human subjective perception is the direct method to evaluate it. Although the questionnaire survey method used in the initial stage here can immediately reflect the human body's subjective sensing, it requires mass human resources and large uncertainties (TSOKA 2018, ASGHARI 2019, THORSSON 2017). The outdoor thermal comfort approach proposes establishing a relationship between the external space and the human body's thermal sensation. These indicators assess the outside climate and predict heat perceptions with potential risks (BLAZEJCZYK 2012).

Table 1: The actual thermal perception represented by various thermal comfort indices values

	WGBT	HI	Humidex	SET	PMV	PET	PST	COMFA	UTCI
Unit	°C	°C	°C	°C		°C	°C	W/m ²	°C
Frosty 							<-36		<-27
Very cold 					<-3	<4	-36-16		-27-13
Cold 					-3--2	4-8	-16--4	<-150	-13-0
Cool 				<17	-2--1	8-18	4-14	-150-50	0-9
Comfortable 	<18		20-30	17-30	-1-1	18-23	14-24	-50-50	9-26
Warm 	18-24	27-32	30-40	30-34	1-2	23-35	24-34	50-150	26-32
Hot 	24-28	32-41	40-45	34-37	2-3	35-41	34-44	>150	32-48
Very hot 	28-30	41-54	45-55	>37	>3	>41	44-54		38-46
Sweltering 	>30	>54	>55				>54		>46

Indices in the early stage, such as the WetBulb Globe Temperature (WGBT) and Heat Index (HI), establish heat sensation judgments grounded on the relationship between meteorological parameters, such as air temperature and humidity, without considering the heat transfer model (BLAZEJCZYK 2012). Correcting from indoor thermal indicators, the outdoor indices, such as the Physiological Equivalent Temperature (PET) and the Standard Effective Tem-

perature (SET), import the steady heat transfer model into the heat sensation calculation, which includes the heat exchange between the human body and the environment (CHENG 2012, FANG 2019). Contrary to the steady heat transfer model's assumptions, the human thermal load continually changes in actual outdoor space. It takes a long time to reach a steady state in daily life while the human body is exposed outside for a short time (HÖPPE 2002). Thus, the current indices, such as the dynamic Physiological Equivalent Temperature (dPET) and Universal Thermal Climate Index (UTCI), are developed to describe the thermal sensation based on the dynamic heat transfer model (MAHGOUB 2019, BLAZEJCZYK 2013, FANG 2019). Despite the different calculation principles, Table 1 compares the perception interval of indices established in various stages. The PST and UTCI have a more reliable sensation calculation principle and comprehensive applicable temperature range. Therefore, PST and UTCI are adequate for outdoor thermal environment assessment.

A variety of software and platforms are certified to simulate the outdoor thermal comfort in an urban context effectively, with the most frequently used software listed as follows:

- Based on the grid level, the Envi-met computes the comfort indices through complex iterative operations of interactions between the urban context and meteorological aspects (TSOKA 2018, LATINI 2010, KÁNTOR 2018, ASGHARI 2019). On the one hand, the model includes the most comprehensive aspects, and the result can illustrate every single value in three-dimensional grids. On the other hand, it is impractical in the urban design process as elements are constructed in pixel units. Moreover, the software needs a high-capacity carrier where the process takes more than one day with a large-scale area.
- BUENO (2010) published Urban Weather Generator (UWG) on the grasshopper platform to analyse the UHI effect in urban canyon and its impact on architecture energy performance. The plugin is continuously under contribution. The UWG focus on neighbourhood-scale simulation of the urban canopy layer heat exchange produced by buildings. Unfortunately, the plugin lacks some environmental parameters, such as the effect of water evaporation.
- The Solar Longwave Environment Irradiance Geometry (SOLWEIG) model calculates radiant fluxes and MRT from Digital Surface Models (LINDBERG 2018, KÁNTOR 2018, THORSSON 2017). The model simplifies three-dimensional geometries into raster images with elevation information, which reduces the workflows and time-consumption. However, the SOLWEIG model only supports points-based PET and UTCI calculations in the newest version.
- Rayman software calculates the sunshine duration, shadow space, radiation flux, and thermal relevant indices assessment by inputting small meteorological data quantities (MATZARAKIS 2010, KÁNTOR 2018). Limitations exist due to incompatibility with low solar angles and the unexplainable shortwave radiation reflection.

For city level simulation, the Envi-met is more comprehensive, requiring a high-capacity carrier to process extensive information. The Grasshopper concentrates on building performance. The SOLWEIG model simplifies the complexity and time-consuming calculations compared to Envi-met.

1.3 A Survey of Current Urban Mitigating Strategies

Cities adopt diversiform strategies to mitigate the urban heat environment. According to action principles, research divides strategies into four categories: changing surface albedo, in-

tercepting solar radiation, enhancing air circulation, and direct cooling devices. Albedo, which means the ratio of the reflected solar radiation and the total received radiation by an object, determines ground surfaces' thermal behaviour (HULLEY 2012). The covering materials with higher albedos contribute more to UHI. Canoga Park in California has tested that a dark asphalt road with white paint coverings can lead to the 11 °C temperature difference on its surface (RIPPE 2017). TAKEBAYASHI (2009) has also proven that different parking paving can have 40 °C surface temperature differences at maximum. Vegetation has a similar albedo as brick and stone, whereas the interception of solar energy makes the vegetation play a prior role in mitigating the thermal environment. The surface covered with vertical green has a much lower temperature than non-organic materials such as concrete and wood (SCHRÖPFER 2020). The City of Phoenix initiated the Cool Urban Space project in 2014, which compared treeless and tree canopy covered communities. It turned out that tree canopy environments lead to a 4.3 °F temperature difference, and the grass-covered surfaces led to a 0.5 °F temperature reduction (MIDDEL 2014). Moreover, many cities use wind channels to mitigate intensified urban heat environments. Currently, cities such as Stuttgart, Tokyo, and Hong Kong have formulated relevant planning and design guidelines to optimize urban ventilation. Similar to an air conditioner's principle, many cooling devices have been developed for outdoor human body cooling through heat transferring. For instance, the outdoor cooling mechanism known as the Angels in Singapore provides an artificial breeze to pedestrians through the whale tail shape device. A 550 by 50 m² passive air conditioning system called Eco-boulevard in Madrid uses evapotranspiration to chill the nearby microclimate when the temperature is above 27 °C. Another frequently used piece of equipment is the outdoor misting system, where vents connected with water tanks or pipes spray liquid mist outside to cool the pedestrians physically. In summary, the strategies that have been implemented so far have been verified to alleviate the urban heat environment effectively. However, except for cooling devices, most strategies are investigated and targeted at cities rather than people living in cities themselves. The cooling devices usually need large space occupation to realize neighbourhood-scale air chilling, which is not suitable in the developed dense urban area.

2 Heat Environment in Helsinki

2.1 Simulation and Data Description

This current research aims to provide the developed dense urban area with a set of sustainable outdoor thermal comfort mitigation solutions directed towards the predicted severe climate situation of the future. Helsinki, as a good pilot area, represents an average dense city with a high representative number of elderly citizens. Currently, there is limited thermal environment research based on the Helsinki context which is also visible in a rather small amount of innovative data interaction (FRICKER et al. 2015). Therefore, the paper starts with an investigation of Helsinki's thermal environment and finds out the severe space.

From the city level, most of the population, including older adults (over 65 years old), are found in the city centre, which is also in poor green condition and paved with vast impermeable materials. The city centre of approximately 25 km² was chosen as the pilot area. Considering the spatial scale and calculation duration, the SOLWEIG model is most suitable. Overlaying the digital surface models (DSM) in a specific format with input meteorological data, the model will analyse longwave and shortwave radiation fluxes individually. The summarization of fluxes density will determine the mean radiant temperature (T_{mrt}) as the output

through the Stefan-Boltzmann law (LINDBERG 2018). The T_{mrt} index is the essential parameter of UTCI. The UTCI calculation in mathematical terms is as follows:

$$\begin{aligned} \text{UTCI} &= f(T_a; T_{mrt}; v_a; v_p) \\ &= T_a + \text{Offset}(T_a; T_{mrt}; v_a; v_p) \quad (\text{BLAZEJCZYK et al. 2013}) \end{aligned}$$

Currently, the latest SOLWEIG can only support the UTCI calculation in specified points. In order to overcome this, this research composes a script to calculate the UTCI in the whole region. When the T_{mrt} is computed, the generated raster images from the SOLWEIG will be transferred into a numerary array that records the value information. The script will read the array as a loop and do a mathematical calculation of the UTCI. Then, the calculated results will be returned as a new array and form a new raster dataset. The UTCI calculation formula refers to RAMSDEN (2015).

The input data consists of the city lidar dataset and the meteorological parameters. The research takes climate data from the Kaisaniemi weather station on the 15th July to simulate the outdoor heat environment. The lidar data is a three-dimensional point set scanned at 550m height in 2018. Dot density in the nadir was 21 points/m², and side coverage of queues is 50%. Due to the errors, the land use information is overlaid to reclassify the point attribute and repatch the blank area. The urban geographical information and digital model are derived from the reclassified lidar dataset.



Fig. 1: The Helsinki LIDAR set in 2018 transformed to Digital Elevation Map and sky view factor for thermal simulation (Data from Helsinki Map Service 2017)

2.2 A Description of Urban Heat Environment on Specific Date

The simulation studies the outdoor thermal environment in Helsinki on the 15th July 2018. Simulations describe the Helsinki thermal environment in 2m-by-2m grids at different periods (Fig. 2). The findings illustrate thermal pressure beginning to appear in the local central area, mainly during the morning. The thermal pressure continued until 17:00 when most of the area returned to an acceptable level. At 19:00, the whole area accomplished a thermally comfortable state. In general, wharves, open arterial roads, and public open spaces, such as squares and artificial parks, are the most thermally stressed areas due to lack of shelter from trees or buildings.

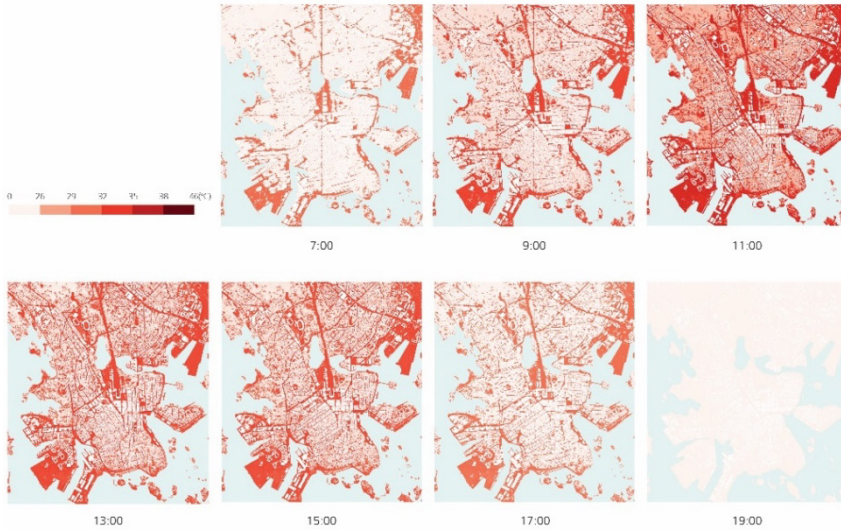


Fig. 2: Apparent temperature from 7:00 to 19:00 on 15th July 2018

Consistent with the analysis from LATINI (2010) and KÁNTOR (2018), green and construction shelters can effectively reduce heat perception. A plot under a tree or building shading can be 7 or 8 °C lower than the plot on the same landcover without shading. However, compared with other paving, grassland has an inconspicuous impact on thermal pressure relief with approximately 1 °C difference, which does not match the simulation results from LATINI (2010). Architecture is a contradiction to the thermal environment. On the one hand, the shadow of buildings reduces body temperature effectively. While, on the other hand, the space near the sunny side of the building will be about half a degree Celsius higher than the street temperature. In other words, whether the impact of the building on the ambient space is positive or negative depends on different times of the day.



Fig. 3: Apparent temperature in different spaces at 13:00 on 15th July 2018

3 Urban Cooling Strategies

3.1 Urban Cooling Strategies Based on Existing Context

It is easy to foresee that heatwaves in Finland will become more frequent in the future. Various outdoor spaces will become hazardous for citizens in these cases. To promote better outdoor quality and human well-being, multiple urban cooling strategies are conceived. Three kinds of cooling strategies for Helsinki to pursue a more resilient city were identified: adding green canopies, intelligent façades, and outdoor cooling mechanisms.

Shading is the most intuitive way to cool down pedestrian level thermal sensation, and trees have noticeable effects. Previous research and simulations have illustrated that different land coverings possess limited impacts on outdoor thermal comfort, whereas planting trees is a more efficient way. In Helsinki, there are many no tree-covered outer spaces. These areas are at high risk on heatwave occasions. The situation would be significantly improved if trees shaded these places. According to the different functions of outdoor spaces, experiments are taken to simulate woody plants' effects. The simulation areas are between 8,000 to 10,000 m², identified as the hot zone in the previous simulation. The trees are deciduous, with 8 meters in diameters and 15 meters in height (5 meters trunk zone). As a result, a single arbor with an approximate 50 m² canopy can produce approximately 84 m² shaded areas at 1 pm. For instance, in Kasarmitori, 30 deciduous can shade approximately 3000 m² squares in simulation (Fig. 4).

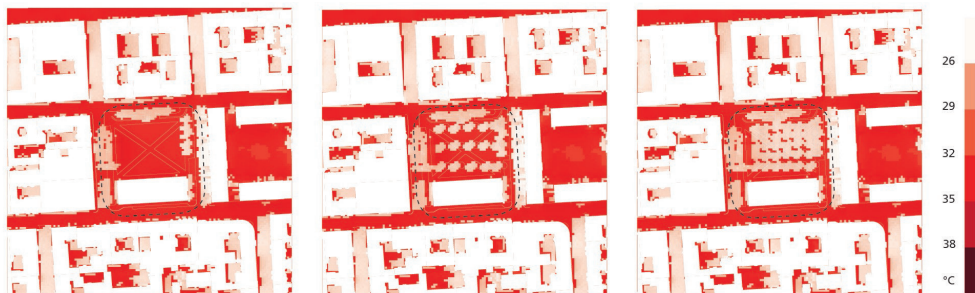


Fig. 4: Simulating the impact of 15 & 30 more trees in Kasarmitori

Façades, as the complicated interface protecting or regulating the building interior from the fluctuations of the outside environment, have an underlying impact on the surrounding microclimate (HOSSEINI 2019). Currently, intelligent façades focus on indoor ventilation and light volume. Besides enhancing the indoor ventilation, the dynamic façades can also extend the architecture's shadow range and reduce the reflected solar radiation to the sidewalk in summer, providing a delightful walking space for pedestrians.

Although there will be 2 °C temperature increase in the winter of 2050, extreme climate change means intense snowfall (> 10 cm/day) will be more common in Finland (FINNISH METEOROLOGICAL INSTITUTE 2019). Therefore, the research proposes a mechanical device that enables small area cooling in high-temperature weather. The mechanism, on the contrary, is an ecological response to the scorching climate through releasing the stored winter snow as cold air during heatwaves. The prototype of the mechanism consists of underground stor-

age part and the above-ground device part. In the winter, people can put accumulated snow into steel spaces through coarse filtering. The insulation materials ensure the long period storage of snow. When the heatwave comes, the sensor activates the pump to release the snow water outside. The mechanism can be combined with existing urban furniture for saving space.

3.2 Interactive Platform for Residents and Governors

Climate responses are considered governmental responsibilities in many countries, such as Australia, the United Kingdom, and India (SARZYNSKI 2015). It is difficult for citizens to participate effectively because the relevant technical knowledge is hard to understand and it is difficult to explain how global changes translate into local hazards (SARZYNSKI 2015). However, expectations of collaboration between authorities and citizens in climate change adaption are rising, and scholars are pursuing more efficient public engagement (KLEIN 2018). In Helmond, the Brainport Smart District is developed to embed smart technology and service in daily life, generate knowledge from residents, and enable development simultaneously (HOOP 2019). Helsinki's city council is also committed to using smart technology to strengthen citizens' participation and collaboration abilities (HÄMÄLÄINEN 2019).



Fig. 5: Digital services provide location-based information of heat perception, outdoor activity route, and cooling mechanism nearby

Therefore, this paper advocates an interactive platform to provide citizens with substantial services in the summer, put the responsibility back in the hands of residents, and train awareness of climate change simultaneously. As a carrier of thermal environment simulations and designs, the designed web-based platform interacts with residents and urban managers in a more intuitive and visual way. The designed application, as the output of the platform, consists of four primary services: Urban Heat Map, Feedback from Citizens, Outdoor Activity Guidance, and Integration of Snow House Mechanism in the Application. According to the GPS positions, the application will send the precise heat stress data of their place and provide users with a more suitable and site-specific proposal for outdoor activities. Users can also control the mechanism to cool down nearby areas on this platform (Fig. 5). Furthermore, the application allows public decision-makers to “listen” to citizens’ voices in a more focused

and site-specific manner, which would prevent authorities from investing in time-intensive research. Instead, concrete measures, such as planting trees, building intelligent façades, and installing cooling mechanisms, could be taken. Through this platform, residents can participate in these actions to ameliorate the worst effects of Helsinki's thermal environment and sense the city's improvements. Governors can also selectively intervene in urban space through feedback from users.

4 Conclusions and Discussion

Using Helsinki as a test case, this paper provides dense urban areas with a set of sustainable outdoor thermal comfort mitigation solutions (Fig. 8) to address the current severe climate situation. On the one hand, the design works to fill the existing gap in urban services and infrastructure embedded within the developing extreme climate situation. On the other hand, participating in the thermal environment confrontation will popularize sustainable awareness among urban residents. Unlike the traditional urban thermal environment design or planning, which emphasizes the planning of new urban districts, this research focuses on mitigating heat sensation within existing contexts. Therefore, the strategies put particular emphasis on the performance of small-scale interventions in dense urban areas and supporting the well-being of people living in affected areas. Strategies are based on the Helsinki context, but many other countries in similar situation can refer and adapt to their own local conditions.

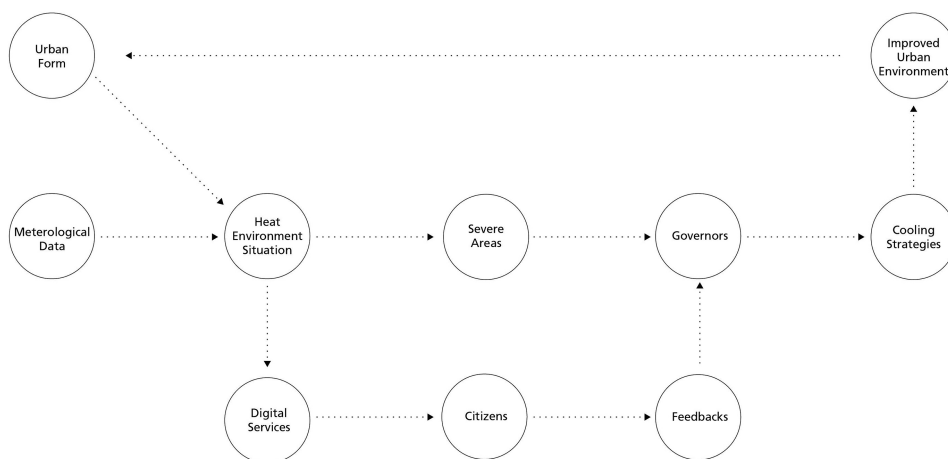


Fig. 6: Diagrammatic overview for developed heat environment mitigation model

Furthermore, the SOLWEIG model is used to evaluate the large-scale urban thermal environment effectively. As a result, shelters from trees or constructions are the most reliable urban elements to reduce thermal perceptions by 7 to 8 degrees. Different ground paving has limited contributions to the environment compared with trees. The paper also proposes that increasing the tree canopy can impact the different urban spaces positively in heatwave events. However, the SOLWEIG model currently does not consider energy consumption in the simulation, which means the influence of heat generated by human behaviour in buildings on the external environment needs to be studied.

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