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Models of Pedestrian Adaptive Behaviour in Hot Outdoor Public Spaces

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Abstract
Current studies of outdoor thermal comfort are limited to calculating thermal indices or interviewing people. The first method does not take into account the way people use this space, whereas the second one is limited to one particular study area. Simulating people's thermal perception along with their activities in public urban spaces will help architects and city planners to test their concepts and to design smarter and more liveable cities. In this paper, we propose an agent-based modelling approach to simulate people's adaptive behaviour in space. Two levels of pedestrian behaviour are considered: reactive and proactive, and three types of thermal adaptive behaviour of pedestrians are modelled with single-agent scenarios: speed adaptation, thermal attraction/repulsion and vision-motivated route alternation. An "accumulated heat stress" parameter of the agent is calculated during the simulation, and pedestrian behaviour is analysed in terms of its ability to reduce the accumulated heat stress. This work is the first step towards the "human component" in urban microclimate simulation systems. We use these simulations to drive the design of real-life experiments, which will help calibrating model parameters, such as the heat-speed response, thermal sensitivity and admissible turning angles.

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Keywords: outdoor thermal comfort, pedestrian dynamics, adaptive behaviour, urban heat island

1 Introduction

Two thirds of the world population are predicted to live in urban areas by 2050, adding more than 2.5 billion people living in cities. 90% of this growth is projected to be in Africa and Asia with tropical and subtropical (hot and humid) climate [1]. Outdoor thermal comfort is therefore critically important for urban studies. A prolonged exposure to the stressful heat is not just an uncomfortable experience, but a severe threat to human health and even life. One of the sad examples is the heat wave in Europe in 2003, which caused more than 70,000 deaths due to the heat-related causes like a stroke or acute hypertension [2]. This makes the governments and scientists all over the world to work

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on mitigation of the difference in temperatures between urban and surrounding rural areas, also known as "urban heat island" (UHI) [3]. This difference can reach 15 ºC (degree Celsius) in extreme weather and geographical locations like Athens [4].

Singapore is a highly-urbanized city-state situated in South East Asia, with very high annual average temperature of 27 ºC and humidity of 84% [5]. According to [6], the UHI in Singapore reaches 7 ºC in the season of south-west monsoons. Such an enormous amount of extra heat produced and captured by the city is a challenge in protecting people's health and lives, as well as in sustainable city development.

People's thermal comfort is more vulnerable in outdoor spaces, where they are exposed to solar and reflected radiation and have very few opportunities for cooling. Current research in Outdoor Thermal Comfort (OTC) investigates public spaces as an interaction of two components: climate and built environment. This is usually done by calculating the distribution of thermal comfort indices, such as PET (Physiologically Equivalent Temperature) [7] or UTCI (Universal Thermal Comfort Index) [8]. These indices use air temperature, humidity, wind speed and mean radiant temperature to calculate the OTC as a "feels-like" temperature in a reference indoor environment. Software packages such as RayMan [9] or Solweig [10] allow to perform simulations of urban spaces and calculation of these indices. There are very few studies though that analysed the influence of anthropogenic heat and urban design on microclimate and individual perception of thermal comfort, with the goal of developing the guidelines for designing more thermally comfortable urban spaces.

Some projects studied thermal comfort in urban spaces in different climates, including a Nordic city [11], hot and humid Taiwan [12], and Mediterranean [13]. Combining the measurements of climate parameters with interviews of people, these studies gained a good insight into the factors influencing thermal perception and behaviour. They analysed place usage and human behaviour based on discrete choice of actions, but did not create a generic simulation framework for modelling other places and testing different scenarios.

Several studies took into account real pedestrian flows, for example the authors of [14] proposed a data-driven navigation application for minimization of pedestrian exposure to stressful heat. It however does not model the climate or pedestrian behaviour in urban areas. In [15] the authors modelled pedestrian flows in Switzerland and Singapore, and investigated the impact of pollution on pedestrian health. However, thermal environmental parameters were not considered.

Our research is conducted within the Cooler Calmer Singapore project in ETH *Future Cities Laboratory*, aimed at providing the architects and urban planners with a design-simulation tool for assessing existing urban spaces and new urban designs in terms of outdoor thermal comfort, with the final goal of formulating the principles of thermally comfortable urban design.

The simulation platform includes three components: City, Climate, and People (see Figure 1). The detailed City and Climate models [16] take into account heat exhaust from air conditioners and vehicles to calculate precise distribution of climatic parameters in space and time. The third critical component, modelling people behaviour, is the topic of our research. It will allow us to analyse urban space as a place used, perceived and experienced by people. This modelling component takes into account the space function (e.g. sports, dining, or transit), travel demand, people movement, thermal perception and thermal adaptation in space. Finally, we will be able to formulate a measure of outdoor thermal comfort for public spaces as perceived by people.

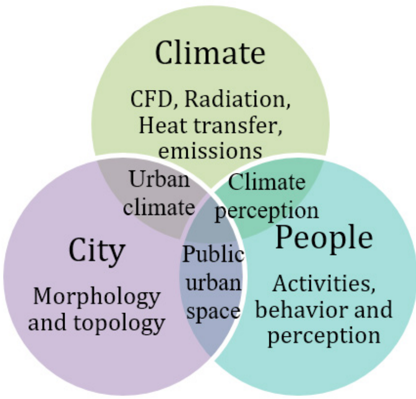

Figure 1. Components and models of the urban microclimate simulation platform of the *Cooler Calmer Singapore* project.

This paper describes the 'human' component of the urban microclimate simulation platform, the models of pedestrian adaptive behaviour in a hot urban space, and the