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Computational models of human response to urban heat

From physiology to behaviour

Melnikov, V.

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Chapter 3

Models of pedestrian adaptive behaviour in hot outdoor spaces

Thermal perception is the level of human response in-between physiology and behaviour. It plays the central role in the process of OTC, as comfort is a perceptual concept. It also drives the response at the behavioural level and in the end, overall human response to thermal environments is determined by the level of perceived thermal comfort. Influenced by physiology, but also by environmental and personal psychological parameters, thermal perception is a complex and currently poorly understood process. In this chapter we suggest the use of an instantaneous thermophysiological index, which can be calculated with our physiological model, to approximate the level of comfort. The deviation of this dynamic index from comfortable range is then proposed as a driver of behavioural adaptation. We use this driver to formulate several models of pedestrian adaptive behaviour. Two of these behaviours are experimentally and computationally studied in subsequent chapters. This chapter plays an important role in connecting individual levels of human response to thermal environments into coordinated multi-level response.

This chapter is based on Melnikov, V., Krzhizhanovskaya, V. V., & Sloot, P. M. A. (2017). Models of pedestrian adaptive behaviour in hot outdoor public spaces. *Procedia Computer Science*, 108, 185-194.

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 the urban 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 chapter, 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 used simulations to drive the design of real-life experiments, which will help calibrating model parameters, such as the heat-speed response, thermal sensitivity and perceived cost of walking under the sun.

3.1 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 [3]. 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 [123]. This makes the governments and scientists all over the world to work on mitigation of the difference in temperatures between urban and surrounding rural areas, also known as "urban heat island" (UHI)

[33]. This difference can reach 15 °C (degree Celsius) in extreme weather and geographical locations like Athens [124].

Singapore is a highly-urbanised city-state situated in South East Asia, with very high annual average temperature of 27 °C and humidity of 84% [125]. According to [126], the UHI in Singapore reaches 7 °C 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) [71] or UTCI (Universal Thermal Comfort Index) [72]. 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 [67] or Solweig [66] 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 [127], hot and humid Taiwan [128], and Mediterranean [129]. 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 space use 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 [130] proposed a data-driven navigation application for minimisation of pedestrian exposure to stressful heat. It however does not model the climate or pedestrian behaviour in urban areas. In [131] the authors modelled pedestrian flows in Switzerland and Singapore, and investigated the impact

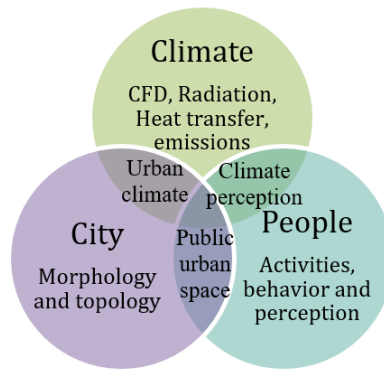


FIGURE 3.1: Components and models of the urban microclimate simulation platform of the Cooler Calmer Singapore project.

of pollution on pedestrian health. However, thermal environmental parameters were not considered. This chapter aims to formulate human component of the design-simulation framework for assessing existing urban spaces and new urban designs in terms of outdoor thermal comfort. The ultimate goal of such framework is to assist architects and urban planners in formulating the principles of thermally comfortable urban design. The OTC simulation platform would include three components: City, Climate, and People (see Figure 3.1). The detailed City and Climate models [68] take into account heat exhaust from air conditioners and vehicles, and calculate precise distribution of all climatic parameters in space and time. The third critical component, modelling human response, is the topic of our research. This component 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 physiology, perception and behaviour in space. Finally, we will be able to formulate a measure of outdoor thermal comfort for public spaces as perceived by people. This builds a connection between physiological and behavioural levels of response to thermal environments through thermal perception. Here we consider perception of instantaneous thermophysiological state (i.e. level of thermal comfort) as a driver of thermoregulatory behaviour of pedestrians. We hypothesise several types of such behaviour and use the thermal perception driver to formulate the models for these behaviours, and demonstrate the

first simulation results in three single-agent scenarios. The chapter is organised as follows: Section 3.2 reviews the basic principles of thermal adaptation and levels of human behaviour, Section 3.3 describes our models of thermal adaptive human behaviour, Section 3.4 demonstrates simulation results, and Section 3.5 concludes the chapter.

3.2 Adaptive behaviour overview

An adaptation of people to the environment is found everywhere. The most obvious is navigation in space: obstacles and collision avoidance. Other examples of people's adaptive behaviour are hiding from the rain under the trees or going to the green parks on a sunny day. In this chapter, we consider thermal adaptation of people in hot and wet climate, i.e. adjustments made by the people in their normal outdoors behaviour to reduce exposure to heat.

3.2.1 Thermal adaptation

People can adapt to the thermal environment in many different ways, which are usually classified into physical adaptation (implying change in behaviour) and physiological adaptation (implying change in physiological thermoregulation [86]). Adaptive behaviour is therefore a physical adaptation, which can be reactive (adapting to the environment) and interactive (adaptation of the environment). Interactive adaptation is almost absent in outdoor environments, unlike indoors, because urban environment rarely allows modification. Clothing and physiological metabolic adaptation to heat are not considered here, because these types of adaptation are inherent to the climate and are restricted in variation while people perform their activities in a particular space. The remaining type of physical adaptation is spatial variation, which therefore is the main objective of this study.

Authors of [86, 87] demonstrate that psychological adaptation of people to outdoor spaces influences significantly their thermal perception of space and is governed by such factors as naturalness, expectations, time of exposure and perceived control. In the studies of outdoor spaces in Cambridge, it was found that the percentage of dissatisfied people was 7 times less than predicted by

the Predicted Mean Vote technique (13% found versus 91% predicted). That tells that psychological factors shall be taken into account in assessing thermal comfort in outdoor environments.

3.2.2 Levels and models of pedestrian behaviour

Pedestrian behaviour is usually classified in 3 levels: strategic, tactical and operational [132]. In the strategic level, pedestrians decide on their goals and activities. In the tactical level, they plan locations and schedule activities. In the operational level, they perform the actual transition between locations. According to this classification, our study is considering pedestrian behaviour on operational level, assuming that the selected goals and schedules bring pedestrians into the studied urban areas. Assessment of public spaces in terms of their thermal comfort for activities different from walking, i.e. implementation of strategic and tactical behaviour levels is the topic of our future work.

We distinguish between two sub-levels within the operational level: the reactive and proactive level, similar to those from the general classification of animal behaviour [133]. Reactive behaviour (also known as steering behaviour [134]) responds to the movement in space, while complying with a set of rules, such as path following, collision avoidance, cohesion, alignment, etc. The proactive level is responsible for planning and motivated travel decisions. In this chapter, it is restricted to the route choice. Table 3.1 describes the levels of pedestrian behaviour we consider and the models traditionally used to simulate this behaviour.

3.3 Models of pedestrian thermal adaptive behaviour

We model three hypothesised ways of pedestrian thermal adaptation: speed adaptation, thermal attraction/repulsion and vision-motivated route alternation. These models are based on general knowledge of human behaviour and on experimentally observed effects. Here we assume that instantaneous value of the thermophysiological index (such as PET [71]) is calculated (e.g. with physiological model reported in Chapter 2) for an agent. We then model the

TABLE 3.1: Levels of pedestrian behaviour and corresponding models.

Behaviour level	Behaviour activities	Models
Proactive	Route choice and dynamic update (negotiating obstacles, cost minimisation)	Path finding algorithms (Dijkstra, A*) with custom cost functions and heuristics Vision models
Reactive	Path following Collision avoidance	Rule based [134, 135], Social Force Model [136], Reciprocal Velocity Obstacles (RVO) [137]

perceptual response to thermophysiological state as a deviation of this index from the range of values perceived as comfortable by a particular agent. We leave the determination of individualised comfortable ranges of thermophysiological index outside the scope of this thesis due to inability of currently limited knowledge of thermal perception to inform the computational models. Our perceptual model reflects the amount of thermal discomfort, which is driving the behaviour proposed in the following subsections. These behavioural models are then incorporated into the agent-based simulations, where we used the Reciprocal Velocity Obstacles (RVO) model for agent navigation and collision avoidance [137]. The RVO2 library was employed, as it allows velocity vector updates at every time step. The behavioural model rules are therefore used to re-calculate the agent's velocity vector, which is then passed on to the RVO simulation engine.

3.3.1 Speed adaptation model

Walking speed is affected by several factors of the environment, such as crowd density, surface slope, gender, age and even music playing in the person's earphones [138]. According to an extensive study of walking speed factors [139], an increase of speed was observed not only while people go down the slope but also up the slope, which brings us to conclusion that people speed up to pass the stressing/disrupting areas faster. This conclusion is supported by a study performed in Canada [140], where significantly higher walking speeds

were observed at -15°C , compared to those observed at 15°C (1.43 m/s versus 1.23 m/s). For temperatures above 15°C , the speed slightly increased again, to 1.28 m/s at 25°C . People walk faster at temperatures outside their comfortable range, to escape the uncomfortable area as soon as possible. The exact values of mean and variance of walking speeds in Singapore are reported in Chapter 4. Here we assume the following values: $V_{\text{comf}} = 1.2$ m/s (4.3 km/hour), $V_{\text{max}} = 1.65$ m/s (5.9 km/hour). The upper bound of comfortable feels-like temperature $\text{PET}_{\text{comf}} = 28^{\circ}\text{C}$.

We define an adaptive walking speed as a function of experienced PET, where the speed linearly grows from V_{comf} to V_{max} as PET exceeds the comfortable value PET_{comf} . In this study, only hot climate is modelled, therefore cold temperatures are not considered. To avoid unrealistically high accelerations, the acceleration/deceleration rates are restricted to 0.1 m/s^2 per time step.

$$V_{\text{adapt}}(\text{PET}) = V_{\text{comf}} + \delta_{\text{PET}}(V_{\text{max}} - V_{\text{comf}}) \quad , \text{ where} \quad (3.1)$$

$$\delta_{\text{PET}} = \begin{cases} \frac{\text{PET} - \text{PET}_{\text{comf}}}{\text{PET}_{\text{max}} - \text{PET}_{\text{comf}}}, & \text{if } \text{PET} > \text{PET}_{\text{comf}} \\ 0, & \text{otherwise} \end{cases}$$

3.3.2 Reactive thermal attraction model

Perceived air temperature can vary in space with no obvious visual signals, such as shade, trees or water bodies. It may be due to the winds, drafts or air-conditioning (both cool air and hot exhausts from the cooling units). People sense temperature by their skin receptors and accurately estimate spatial gradients (e.g. it is cooler to the left). This ability to perceive temperature difference is surprisingly precise: as shown in [141], humans can sense a difference of 0.005°C by arm, and even smaller difference by forehead. This perceived difference can motivate pedestrians to deviate from a straight pathway towards a cooler area. This will result in a curved path, different from the shortest line. The shape of this curve is governed by 4 parameters: sensitivity for thermal stimulus, current thermal comfort, admissible deviation angle, and sensation radius (approximately a half of the shoulder width). To implement

this reactive thermal attraction, we assume that pedestrians can sense PET by their arms at the side of the body, or 0.4 m to the left and to the right from the agent movement direction (PET_{left} and PET_{right}). The agent then compares it to the currently experienced PET in the centre and deviates from the direct trajectory by an angle $\alpha(t)$ according to a stimulus value $\beta_{\text{PET}}(t)$ and sensitivity to the thermal stimulus θ :

$$\alpha(t) = \alpha_{\max} \frac{\beta_{\text{PET}}(t)}{\theta} \quad , \text{ where}$$

$$\beta_{\text{PET}}(t) = \begin{cases} -\beta_{\text{right}}, & \text{if } \beta_{\text{right}} > \beta_{\text{left}} \text{ and } \beta_{\text{PET}}(t) \leq \theta \\ \beta_{\text{left}}, & \text{otherwise} \end{cases}$$

$$\beta_{\text{left}} = \begin{cases} PET(t) - PET_{\text{left}}, & \text{if } PET(t) > PET_{\text{comf}} \text{ and } PET(t) \geq PET_{\text{left}} \\ 0, & \text{otherwise} \end{cases}$$

$$\beta_{\text{right}} = \begin{cases} PET(t) - PET_{\text{right}}, & \text{if } PET(t) > PET_{\text{comf}} \text{ and } PET(t) \geq PET_{\text{right}} \\ 0, & \text{otherwise} \end{cases}$$
(3.2)

3.3.3 Proactive vision-motivated route planning model

At the proactive level, pedestrians may recalculate the cost of possible future paths based on the new factors encountered [142]. These factors influencing the travel cost are obstacles, crowdedness or even attractive shops [143]. From different studies [144] it follows that visible thermal properties of space, such as sun/shade or greenery, are factors taken into account by pedestrians while evaluating the path attractiveness. Parameters governing the choice of a modified route are the current thermal comfort, expected thermal stress costs of travelling along the shortest but hot path, and expected travel time/distance cost of a detour from the shortest path along a more attractive route. We model this type of behaviour as vision-based cost estimation. Given the current goal, an agent looks to the left and right within a certain angle ω (see Figure 3.2). This angle depends on the current thermal comfort (or how urgent it is to cool down). Then the region of possible paths is processed by the agent and alternative paths are weighted according to the personal cost function. This function depends on path length, ratios of route parts of certain

type (e.g. sun, shade, grass) and coefficients relating the cost of walking in this type of environment to the cost of walking in some reference conditions (e.g. shade). In case of only two types of visible thermal zones, e.g. sun and shade, we define g to be the cost function dependent on path length l , ratio of a shady path α_{shade} , and the cost multiplier of travelling a unit distance in the sun compared to travelling in shade, c_{sun} . Finally, an alternative path minimising the cost is selected and a new trajectory is planned.

$$g(\alpha_{\text{shade}}, c_{\text{sun}}, l) = l \cdot [\alpha_{\text{shade}} + c_{\text{sun}}(1 - \alpha_{\text{shade}})] \quad (3.3)$$

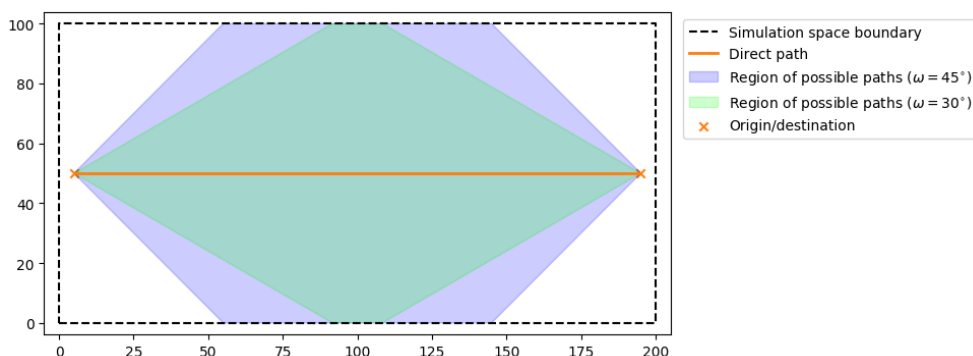


FIGURE 3.2: Proactive path planning: regions of searching for an optimal path at two different angles of vision ω .

3.3.4 Experience-motivated route alternation model

In our daily life, we are continuously gaining experience that helps us avoid discomfort in the future. In addition to the simple vision-motivated decisions, people are building more complex decision chains based on their intelligence and memory. For example, if we need to go around a half of a building in a sunny day then we can easily predict which side of the building is shady before we actually see it. Or we may remember that one side can offer a nice tree canopy above the pathway. Or in the end of the day, after the sunset, we can calculate which side has been shady for the past few hours and is therefore cooler. To model this in the future, we will need also extra agent properties

(age, heat resistance, etc.) and date and time to calculate the sun position and shady areas.

3.3.5 Heat stress accumulation model

To assess the effect of each type of adaptation we use two measures of "heat stress": the accumulated amount of heat stress $\langle h_s \rangle$ and the average stress h_s over the travel time t_{tr} :

$$h_s = \int_{t_{start}}^{t_{end}} h(t) dt \quad , \text{ where} \quad (3.4)$$

$$h(t) = \begin{cases} \text{PET}(t) - \text{PET}_{\text{comf}}, & \text{if } \text{PET}(t) > \text{PET}_{\text{comf}} \\ 0, & \text{otherwise} \end{cases}$$

$$\langle h_s \rangle = \frac{h_s}{t_{tr}} \quad (3.5)$$

3.4 Simulation results

To test the implementation of thermal adaptive behaviour rules integrated into the general walking behaviour, we designed 3 simple scenarios: reactive speed adaptation and thermal attraction, and proactive vision-motivated route planning.

3.4.1 Speed adaptation simulation results

For demonstration of the speed variation behaviour, we used a quasi-one-dimensional strip of 200 meters with 5 zones of different length with a varying value of PET. The agent is travelling from left to right, crossing these different thermal zones (see Figure 3.3). Agent's PET thermal perception is updated to a new value instantaneously, i.e. the change from one value of PET to another is a step function. The results of speed adaptation are shown in Figure 3.3. The table inset shows that speed adaptation reduced the amount of accumulated heat stress by 20%, and the average is reduced only by 8% (because travel time reduced with the speed increase in hot areas).

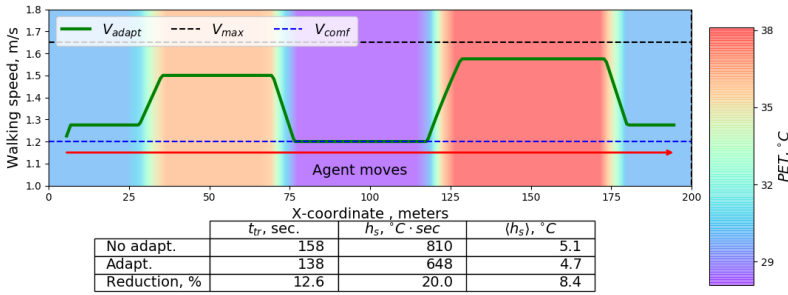


FIGURE 3.3: Simulation result of pedestrian speed adaptation in hot areas. The agent moves straight through five areas with different "feels-like" temperatures (PET), increasing the speed in hot regions to get to the comfortably cool area faster.

3.4.2 Reactive thermal attraction simulation results

To demonstrate reactive adaptive behaviour, the following simulation setup is used: a two-dimensional area 200 m by 50 m, where PET increases linearly from 26 °C to 36 °C along the Y-direction (see Figure 3.4). Several agents are travelling from left to right from the same origin to the same destination (the shortest path would be parallel to X-axis). Agents feel the temperature 0.4 metre to the left and to the right and adjust their direction towards a cooler area. Parameters governing the resulting trajectory of agents are the maximum angle of deviation from direct path (α_{max} , degrees) and sensitivity to the cooling stimuli (θ). Figure 3.4 shows how these parameters affect the curvature of the path. The longest path is taken by the agent with the largest deviation angle and highest sensitivity (smallest θ). The table inset in Figure 3.4 shows that the accumulated heat stress of the agent with $\alpha_{max} = 14^\circ$ and $\theta = 0.05^\circ\text{C}$, is 83% lower than that of walking straight through the hot area. Adding speed adaptation to the direction change, further reduce the heat stress. As the agent deviates to a cooler place it uses less speed adaptation, thus contribution of speed adaptation in heat stress reduction is much less while combining two adaptive behaviours. Agents are responsive to cool stimulus only when they are experiencing temperature higher than comfortable; we can see that the red trajectory becomes parallel to X-axis once the agent reaches a comfortable $PET_{comf} = 28^\circ\text{C}$. This trajectory also demonstrates the agent's perception of heat: he is not returning to the destination until the very last moment, to minimise the heat stress.

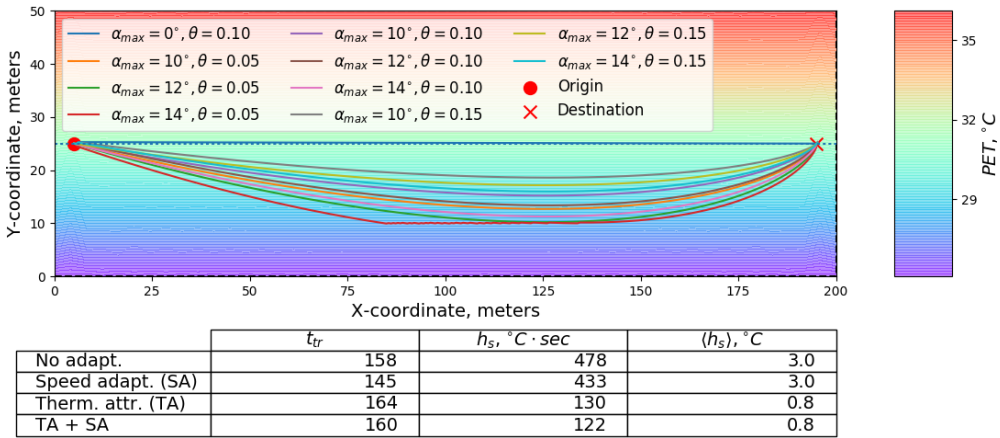


FIGURE 3.4: Simulated thermal attraction behaviour of pedestrians with different sets of parameters.

3.4.3 Proactive route planning simulation results

Simulation of vision-motivated proactive path planning was performed in a rectangular environment of 200m by 100m. There are 3 shaded regions. For simplicity we assume that these shades are produced by sun screens installed in many pedestrian zones in Singapore. The rest is heated by the scorching sun. There are no obstacles, so the agents are free to choose any trajectory they consider optimal. Figure 3.5 demonstrates the pathways of agents with a plan to go from side to side (Figure 3.5, left) and from corner to corner (right). The smartest tactic is to go directly to the shade and move in it for as long as possible (that is, while it still lies within the region of possible paths). While building alternative paths, the agents consider each shaded region in their vision and calculate an optimal path within this shade. Then all possible combinations of up to 3 shades are evaluated by minimising the cost function. Finally, a path with the minimal cost is selected. Figure 3.5 demonstrates that for different origin-destination pairs as well as cost functions, different alternatives will be chosen. People in real life tend to keep some clearance from the edge of shade. This is taken into account in the model, and all alternative paths go with a 3-meter margin from the edge of shade. This parameter can be set different for individual pedestrians to create more variation in paths and to make them more realistic.

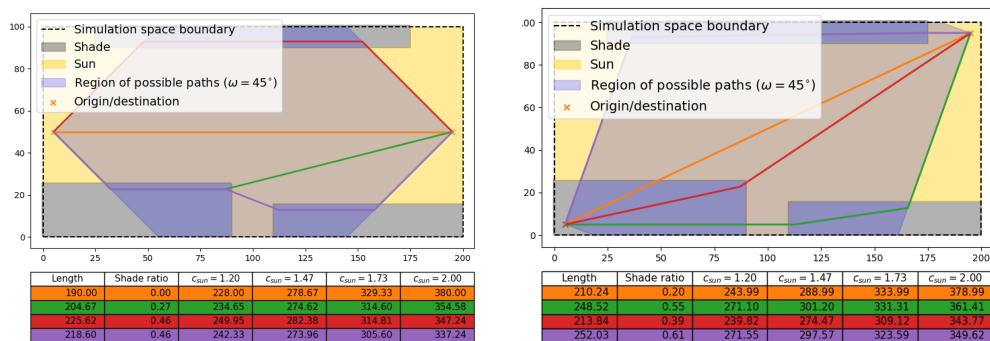


FIGURE 3.5: Simulation of vision-motivated route alternation: alternatives and their costs for different goals and cost coefficients c_{sun} penalising the time of being exposed to the sun.

3.5 Conclusions and future work

Thermal comfort of outdoor environments should be analysed from the perspective of individual users of space, able to perceive environment thermally and to adapt to it both reactively and proactively. In this chapter we proposed four models of thermal adaptive behaviour of pedestrians driven by the instantaneous value of a thermophysiological index, which approximates thermal perception. Three of these adaptive strategies with various model parameters have been studied and evaluated in terms of the accumulated and average heat stresses. These numerical studies helped to design real-life experiments of human behaviour reported in Chapters 4 and 5

The usage of the dynamic value of the thermophysiological index for each individual agent allows to obtain more realistic measure of thermal (dis)comfort (i.e. perception) of people, which in turn drives behavioural response. This measure accounts for individual characteristics like height, weight, metabolic rate, time of exposure and thermal history of that person. Integration of the thermophysiological model allows to formulate measure of accumulated heat stress and helps developing more precise behavioural models, e.g. taking into account the fact that speeding up increases internal heat production due to the higher metabolic energy production (see Chapter 4).

After coupling the pedestrian simulation engine with the other components of the design-simulation-loop tool, city planners can evaluate urban

spaces in terms of thermal comfort of people using those environments.