

# Simulating human thermal comfort and resulting usage patterns of urban open spaces with a Multi-Agent System

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**ABSTRACT:** Attractive public open spaces can serve as key design elements for enhancing life quality in urban areas and to diminish the negative effects of urbanisation. In order to fulfil this task, open spaces must meet the expectation of potential users and offer the right mix of environmental, economic and social conditions. It is well known that the local microclimate belongs to the main factors driving the individual perception and assessment of an outdoor environment. In order to simulate the thermal comfort of pedestrians in urban open spaces, the method of Multi-Agent Systems (MAS) is used. In which each agent represents a virtual pedestrian with individual physiological properties and different routes through the model environment. While walking through the domain, these agents are virtually exposed to different climate conditions. The impact of these climate environments on the individual thermal comfort are simulated using a dynamic model of the human thermoregulatory system. Depending on their individual thermal comfort level, the agents can adjust their routing decisions and also consider using optional facilities such as benches or restaurant chairs. Using the simulation results from a few thousand virtual pedestrians, it is then possible to generate different kinds of comfort or frequentation maps not only representing the local microclimate conditions, but also considering the space-time links that establish through pedestrian motion and individual decisions.

**Keywords:** Thermal comfort, Urban open spaces, Urban microclimate, Multi-Agent Simulation

## 1. INTRODUCTION

Unattractive urban areas are one of the main reasons why people prefer to live in the outskirts of cities rather than in their centre. As an effect, a continuous expansion of the urbanized areas known as urban sprawl can be observed. There are many environmental and economical drawbacks associated with this sprawl effect, from which land consumption and traffic generation are probably the most obvious. In order to counteract this effect, urban planners wish to bring life back into the cities and attract more people to live inside the city core.

One of the key planning tools for enhancing urban life quality is to design attractive public open spaces that act as vital and pulsating oases, attracting people for all kinds of business or leisure activities.

Without doubt, designing public spaces that are accepted and used by pedestrians is a challenging task for urban planners as it addresses a multitude of different architectural, technical and social aspects. One of the key factors determining whether an open space establishes as a component of urban life or remains a stone desert is the environmental quality offered by the area. The right mix of sun and shade, the presence of windy and calm areas: the local microclimate conditions are indisputably one of the main factors that drive the users perception of an

outdoor space and influence their decision whether to stay or leave (compare [1]).

In urban areas, the average regional climate conditions are often replaced by heterogeneous and small scale local microclimate environments whose characteristics depend to a huge extend on the environmental design of the surrounding area. The magnitude of different materials used in the urban fabric and the arrangement of buildings, trees and other urban objects modify the larger scale climate conditions and can produce typical microscale meteorological effects such as wind speed decrease, local jet effects and increased thermal loads. Hence, environmental design can be used as a tool to improve the local microclimate to create agreeable conditions for the potential users of the open spaces. On the other hand, careless compilation of urban elements can easily create uncomfortable climate conditions and, in return, produce dissatisfied pedestrians or deserted urban areas.

In the context of urban microclimate, thermal comfort is the key indicator to describe the comfort of the users of open spaces as it summarizes the impact of sun, wind, air temperature and humidity on the human climate perception. If the human body is not able to compensate hot or cold environmental conditions through thermoregulation, thermal



Using this model, the simulation system can predict for any agent at any location and at any time step the main thermophysiological parameters of the body such as the actual skin and core temperature ( $T_{sk}$  and  $T_{core}$ ), the skin wetness or the different energy fluxes at the body surface.

There are several methods how to aggregate the high-resolution data from the individual agents in order to generate two-dimensional maps of the domain. The simplest method which is used in this paper is to calculate an average value of the analysed parameter over all agents visiting the associated grid cell. To simplify the interpretation of the resulting map, gaps in the 2D data where no agents have been passing are linearly interpolated within a 5 m distance and the resulting data structure is smoothed with a 3 x 3 averaging filter.

## 2.2 Assessment of the microclimate conditions: The F-A-ST Model

The individual assessment of the microclimate conditions is a crucial factor when analysing the environmental quality offered by a location. The question whether a certain location is regarded as pleasant or not depends not only on the location itself but on two factors: the thermal state of the individual pedestrian and the microclimate conditions at the respective location. For example, a sunny location with calm winds might be assessed as comfortable and pleasant by a person coming out of a shady street but the same spot may be considered as too hot by someone entering from a sunny open space.

As both thermal state of the pedestrian and microclimate conditions cannot be clearly classified by using sharp class ranges (at what temperature does the microclimate change from "warm" to "hot"?), a Fuzzy-Logic [15] based assessment system is used in BOTworld.

The assessment system used in BOTworld is called "F-A-ST model" in which the **F** stands for the environmental factor to be assessed (e.g. solar radiation, "external parameter" in Fig. 1) while **ST** ("internal state" in Fig. 1) represents the associated thermal state of the agent which has an impact on the assessment of **F**.

Finally, **A** is the resulting assessment value which ranges from -1 to +1, where -1 is the worst possible assessment and +1 the best one. An **A** value around 0 indicates a neutral assessment of the analysed situation.

The main decision logic of the F-A-ST system is based on four rules, which decide how the two parameters **F** and **ST** interact with each other and how the value final assessment **A** should be:

- **IF** (F is high) AND (ST is high)  
     **THEN** A is negative (A=-1)
- **IF** (F is low) AND (ST is low)  
     **THEN** A is negative (A=-1)
- **IF** (F is high) AND (ST is low)

- THEN** A is positive (A=+1)
- **IF** (F is low) AND (ST is high)  
     **THEN** A is positive (A=+1)

A typical example for such a combination is **F**= "solar radiation" and **ST**= "skin temperature": If the agent has a high skin temperature, he will consider locations with a high solar input as uncomfortable.

Contrary to classical Boolean logic in which a statement can be either TRUE or FALSE, but nothing between, Fuzzy logic allows a smooth transition between TRUE (1) and FALSE (0). Depending on the level of truthness of the IF-statement, the corresponding conclusion (THEN statement) will also only be applied to a certain level. If, for example the statement

IF (F is high and ST is low)

is "True" for only 70%, the conclusion "A is negative (A=-1)" will also be only fulfilled for 70%, which means **A** will be assigned -0.7 rather than -1.

The assessment of a location is not only an informative parameter, but is also used in BOTworld to trigger the behaviour of the agents. If sections of a path towards a target are considered as "uncomfortable", the virtual length (or "felt distance") of this segment is increased. Hence, uncomfortable routes will appear longer compared to more comfortable alternatives even if they are equal in real distance. As the agents are programmed to select the virtually shortest path, they will try to avoid uncomfortable route segments if possible. Also, the selection and usage of optional locations such as benches or restaurant chairs is controlled by the assessment value **A**. This will be described more in detail in the case study example.

## 3. A CASER STUDY: REDESIGNING AN URBAN OPEN SPACE

### 3.1 Overview

In order to demonstrate some typical model results, we will analyse a simple urban open space with the size 200 m x 200 m including four 150 m long connecting streets. As the BOTworld system is a grid based system, the model domain is horizontally resolved into 2 m x 2m grid cells. This resolution is relatively coarse for analysing pedestrian traffic flows but sufficient for microclimate analysis. In this example, we will compare two different design scenarios: The "bare" scenario represents an open space without any greening but with a small water pond in the center of the place (see Figure 2 left). The "green" re-design scenario (Figure 2 right) represents a new layout of the open space with a number of newly planted trees plus a structure of hedges in the centre of the place.

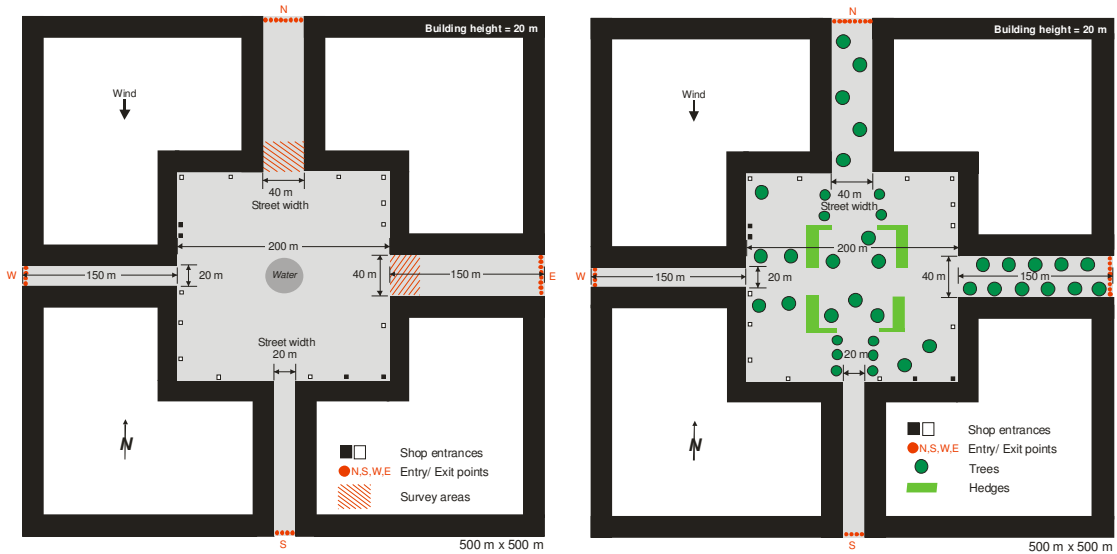


Figure 2: Layout of the case study seen from the top. Left: Old design without greening (“bare” scenario), Right: New design with additional trees and hedges (“green” scenario)

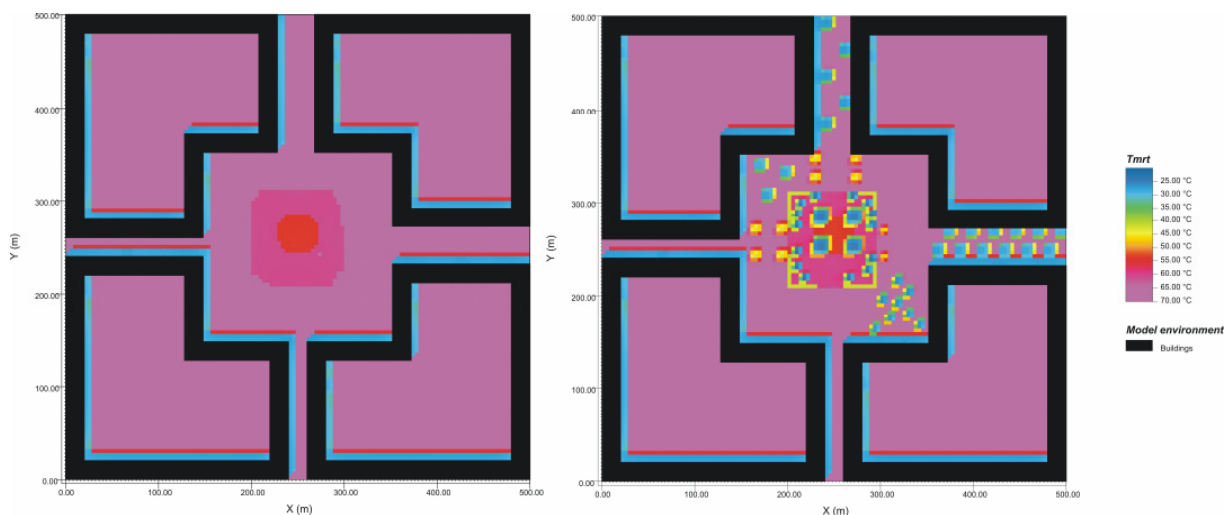


Figure 3: Spatial distribution of Mean Radiant Temperature  $T_{mrt}$  at 14:00 LST in 1.6 above ground. Left: “bare” scenario, Right: “Green” scenario

The red dots in Figure 2 are the entry and exit interfaces of the model, where the agents enter and leave the model world. The black and white squares are the so called “internal targets” (e.g. shop entrances) which are visited by the agents. In order to generate virtual pedestrian traffic in the model, each agent selects a number of these internal targets based on predefined frequentation data plus some random component.

After all targets have been visited, the agent leaves the model domain, his (or her) data are stored and the computer storage place is released. In the BOTworld version used here, 350 agents can be controlled simultaneously.

In order to calculate thermal comfort, the relevant meteorological parameters (air temperature, wind speed and direction, mean radiant temperature and

air humidity) are required for all grid cells of the model domain. In general, it is not relevant from which source these data come as long as they are complete over the entire model area and fit with the structure of the urban morphology. For this study, the microclimate model ENVI-met [16] has been used to simulate the required input data for both scenarios.

The microclimate situations used in this paper represent the simulated conditions for 14:00 local solar time (LST) on a clear sky and moderate northern winds. The air temperature is around 25 °C with small variations inside the model domain.

Figure 3 shows the Mean Radiant Temperature ( $T_{mrt}$ ) distribution inside the model environment. The  $T_{mrt}$  value is a synthetically calculated value summarizing the different solar and infrared energy fluxes received by the human body in terms of a

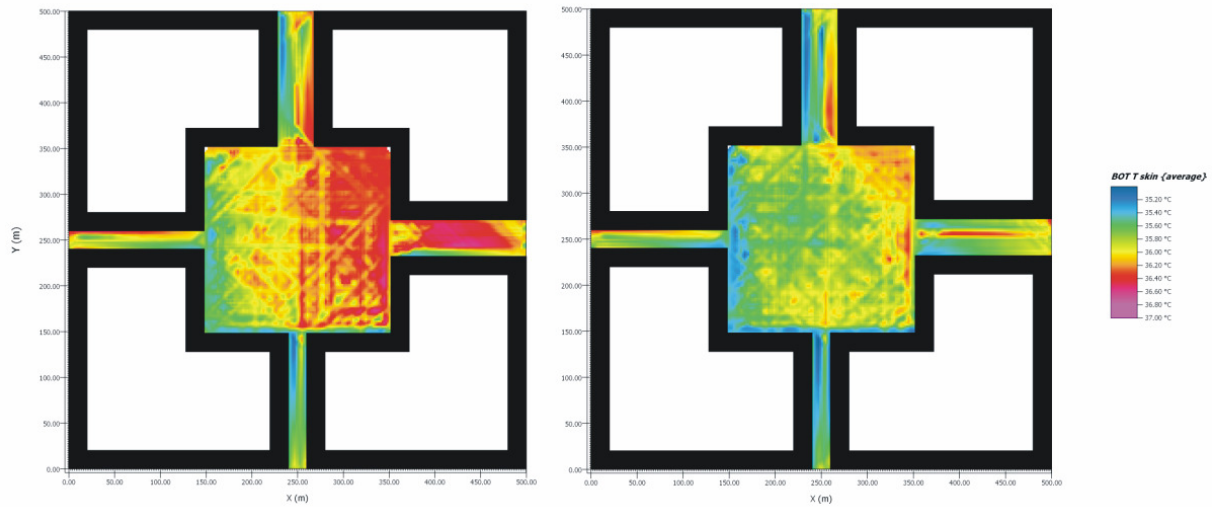


Figure 4: Distribution of average skin temperature calculated over 2300 (“bare” scenario, left) and 2000 (“green” scenario, right) different agents

temperature value. While air temperature and humidity normally do not vary much over a short distance, the Mean Radiant Temperature is, along with the wind speed, the most important microclimatic factor when assessing the thermal conditions.

Figure 3 shows very clearly the difference between areas in the shade (blue colors,  $T_{mrt}$  values around 25°C) and those in the sun (cyan colors,  $T_{mrt}$  values around 70°C). The yellow and red areas in the “green” scenario (Fig. 3, right) are those areas in the half-shade of the less dense trees with  $T_{mrt}$  values between full sun and full shade.

The example simulation shown here was executed over 1,5 hours of model time. During this time, the meteorological situation did not progress. Hence, the total simulation time has only an impact on the number of analyzed agents in the area. In our case, 2000 (“green” scenario) to 2300 (“bare” scenario) agents have been analysed.

### 3.2 The thermal comfort situation in the “bare” case

From the number of different parameters and indices that can be used to describe the human thermal state, we have chosen the average skin temperature ( $T_{sk}$ ) to demonstrate the model results. The main advantage of the skin temperature is that this value is directly provided by the biometeorological model in BOTworld and no other helper parameters are required. On negative side it must be admitted, that the absolute value of the skin temperature is not an indicator which most of the people can directly associate with a thermal impression.

Figure 4 illustrates the spatial distribution of the skin temperature averaged over all agents entering the respective grid cell (between 20 and 50 agents for most cells of the area).

Different to the spatial distribution of the microclimate (especially of the Mean Radiant

Temperature), the Multi-Agent simulation generates a structured pattern of thermal conditions over the complete open space with hotter areas in the eastern parts of the open space and in the eastern street. This mainly due to the fact, that the northern and eastern connection streets are wider than their western and southern counterparts. Hence, more parts of these streets are in the sun (see Fig. 4) and, as a consequence, more people using these streets are exposed to the sun. When those people enter the open space, their thermal load is higher compared to people coming from the narrower and more shaded streets. This results in a higher skin temperature level observable in those areas of the open space directly connected with the wider streets. Also, not even a small band of shade along the building facades can be found in the eastern half of the place.

### 3.3 Assessment of the thermal situation

In order to assess the impact of the proposed design changes on the users’ thermal perception, we have defined a Fuzzy F-A-ST assessment rule based on the Mean Radiant Temperature ( $F$ ) and the skin temperature ( $ST$ ). The only further required definitions are the extreme minimum and maximum values for both  $F$  and  $ST$ . These are the value where it is 100% sure ( $\mu=1$ ) that  $F$  or  $ST$  are “high” or “low” respectively.

Figure 5 shows the GUI provided by the BOTworld software with the used F-A-ST set and the associated values use in the simulation. These settings were used to generate the simulation results discussed in the following sections

Figure 6 presents the results of the assessment processes averaged over all agents. The range of assessment values observed in this case study is between -0.5 and +0.5 which is acceptable for this demonstration case. However, when analyzing a real situation, the definition range of the Fuzzy Sets needs to be adjusted to the analysed situation to fit

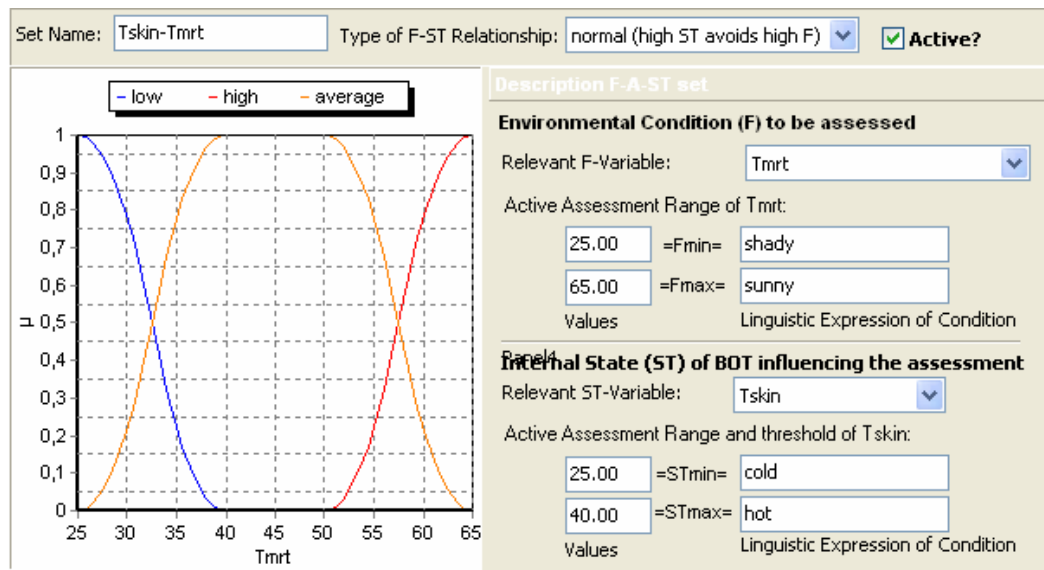


Figure 5: Definition of the Tskin-Tmrt F-A-ST set in the BOTworld software. The chart shows the bounds of the low, average and high Fuzzy sets for Tmrt

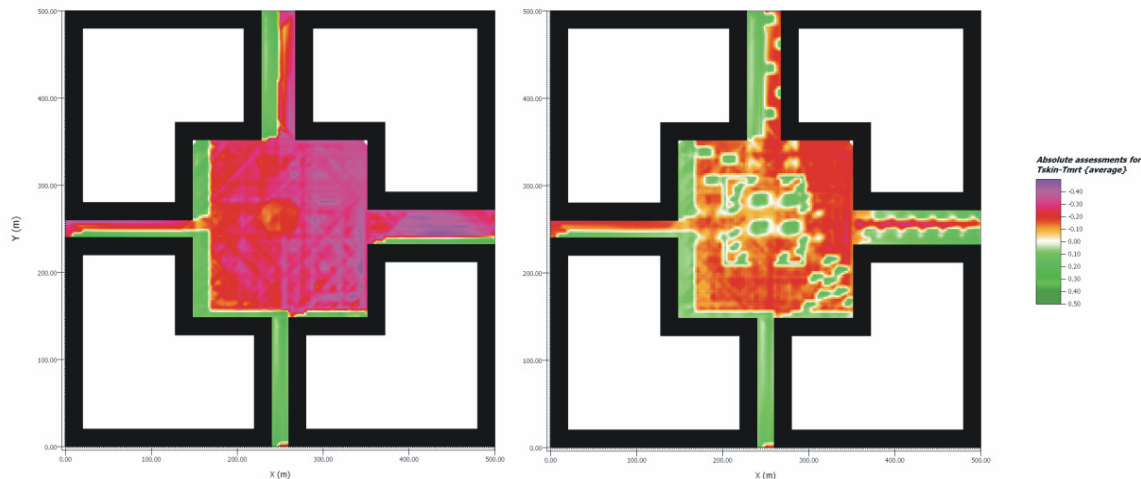


Figure 6: Distribution of average assessment value for the F-A-ST set “Tsk - Tmrt” calculated over 2300 (“bare” scenario, left) and 2000 (“green” scenario, right) different agents

the users perception of the microclimate and to include cultural or seasonal biases as well.

From Figure 6 (left) we see, that in the “bare” scenario most parts of the open space plus the sunny sides of the streets get negative assessment values of -0.30 down to -0.50. Only the shaded areas indicate positive values of +0.15 to +0.20.

However, comparing the spatial structure of the positively assessed areas in the “bare” scenario with the structure of the shade (Fig. 3 left), we can see that the two are not identical. For example, the southern street is assessed completely positive while the Tmrt distribution shows that the right side of the street is in the sun. This effect shows the impact of the movement of the agents combined with the

simple fact, that heat stress needs some time to build up before it becomes a negative experience.

Looking at the influence of the additional trees and hedges (Fig. 6 right) the assessment structure has changed fundamentally. The shaded areas below the trees show assessment values around +0.15 while the shaded sections of the streets and the open space now indicate assessment values around +0.10. It is important to see, that the impact of the shading devices is not only restricted to area they actually shade, which would have been the result if a static indicator such as PMV would be used.

Through the additional trees, the complete assessment of the open space - including those

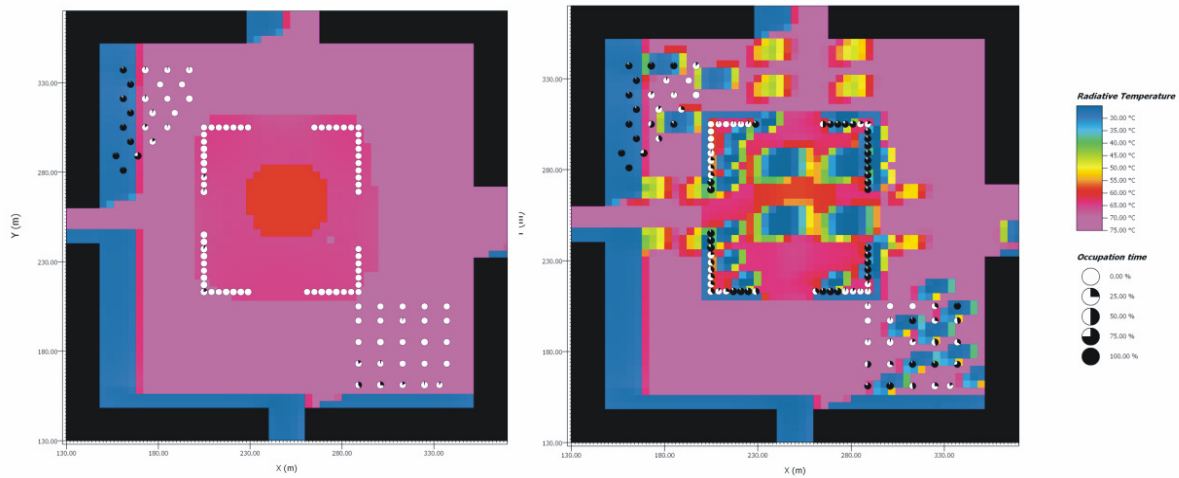


Figure 7: Distribution of Mean Radiant Temperature and relative occupation time of optional targets for the main center place (left: “bare” scenario, right: “green” scenario), Simulation for 14:00 local solar time

parts not directly affected by the trees’ shade - has improved. For example the north-eastern corner was assessed with values around -0.35 in the “bare” case and is evaluated with values around -0.20 in the “green” scenario while the microclimate conditions have not changed in this part of the place.

#### 3.4 Impact of microclimate on open space usage

Planners are usually interested to know and to understand which impact the environmental design and the resulting microclimate has on the usage of the open space and the frequentation of areas.

As mentioned earlier, there is a certain feedback between the thermal comfort and the route choice of the agents. However, pedestrian normally detest making deviations from the direct and shortest path and the impact of microclimate on their routing choice is only traceable if the “climate-optimized” route is only slightly longer than the shortest possible one or under extreme climate conditions.

But, if we think of an urban open space as a location that offers more options than just traffic distribution, the impact of microclimate can become much larger and visible. For example, the selection and usage of benches or the frequentation of restaurant tables is much more sensitive to the local climate than the routing choice.

To investigate this phenomenon, BOTworld offers the possibility to define “Optional Targets” inside the model domain. These targets are not a part of the initial and purposeful walking plan of the agents, but might be spontaneously inserted in their activity schedule if the right conditions apply. In BOTworld, these “right” conditions are:

- at least neutral assessment of the location there the optional target is located ( $A \geq 0$ )
- proximity of the target to the agents purposed walking route (here: max. distance 20 m)
- a random factor, finally deciding whether the agent is willing to use an optional target or not

To analyse the usage patterns in the example domain discussed here, three groups of optional targets have been distributed over the open space as shown by the circles in Figure 7.

The targets in the center of the place represent some benches with a typical duration time of 10 min while the targets in the upper left and lower right are restaurant tables with a typical stay of about 20 min.

If the right conditions as given above apply and an agent decides to use the optional target, an expected duration time based on a user-given average value for this target plus a random time component is assigned. Then, the agent “uses” the target and stops moving. If at any time during the stay the agent begins to feel uncomfortable and actual the assessment of the location falls below - 0.2, the agent leaves the location.

Figure 7 shows the distribution of the Mean Radiant Temperature and the relative occupation time of the optional targets for the center place. The relative occupation time is defined as the occupation time of a target relatively to the total time of simulation.

In the “bare” scenario (Fig. 7 left) the benches in the center of the place are completely unused during the simulation time as they are exposed to the bare sun and therefore do not offer an adequate microclimate environment. Only the restaurant tables in the upper left which are in the shade are well used with frequentation rate approaching 100%.

In case of the “green” scenario (Fig. 7 right) the frequentation of benches and restaurant chairs has increased significantly. It also has to be notified that although the assessment of the open space has improved all over the area (compare Fig. 7 right), the usage of benches and tables is still basically limited to the shaded or half-shaded locations.

#### 4. CONCLUSIONS

The microclimate offered by an urban open space has a strong impact on the thermal comfort of visiting pedestrians and consequently on the perception and the usage of the open space. The technique of Multi-Agent simulations (MAS) allows investigating the impact of the microclimate conditions on human thermal comfort on the level of the individual pedestrian. As pedestrians move through the urban environment, they are exposed to different microclimate conditions over a short time. With MAS it is possible to analyse the impact of such dynamically changing conditions on the thermal state of the simulated pedestrian and to make assumption on the resulting usage patterns of urban open spaces.

However, while the biometeorological model of the human thermoregulatory system is physically based, the rules used for the behaviour simulations are not. Therefore they must be calibrated to the specific situation in order to reproduce realistic results. Hence, the simulated usage patterns should be interpreted as prediction maps of potential frequentation rather than crisp pedestrian counts.

The application of a MAS like BOTworld to analyse a situation should be seen as "play" with different scenarios like in a Decision Support System. The outcomes are based on some general assumptions how the design options can influence human behaviour. These results are only as good as the implemented rules are.

On the other hand, the final conclusion, which strategy is the best for a successful urban design is always based on some general rules of thumb and coarse assumptions. If not applied using a computer, the urban planners will make these final decision steps based on their personal experience. In these cases, the final conclusion is much more subjective and discussable compared to a computer assessment system like BOTworld where at least all the assumptions and rules must be explicitly defined and they are applied strictly to all situations. This ensures consistency and neutrality of the assessment rules.

#### ACKNOWLEDGEMENT

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