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A review study**

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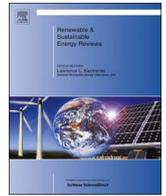
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## Urban measures for hot weather conditions in a temperate climate condition: A review study



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Thermal comfort  
Hot weather

### ABSTRACT

This paper discusses the effects of urban design and meteorological parameters on thermal comfort for pedestrians at street level. A comparison of different urban modifications allows an objective assessment of the effectiveness of climate adaptation measures. Because, these results are based on different measurement and modelling methods, they are given in various comfort indicators and studied in a specific urban context, climate and weather condition. This study presents the relative effects of design measures based on identical input parameters and one simulation method using the high resolution three-dimensional model ENVI-met and the thermal comfort index physiological equivalent temperature (PET).

### 1. Introduction

Climate change will lead to an increase in warm and hot days in many parts of the world [1,2]. It has been established that climate variations resulting in changes in temperature and rainfall in particular, have a large impact on human comfort and health, especially in cities. In anticipation of future climate conditions, stakeholders can be proactive when redeveloping or building new urban areas with the aim of making them less vulnerable to climate change. Although there is an increasing interest in the urban microclimate, there seems to be a lack of knowledge about which climate adaptation measures perform better in terms of summer comfort. Planners and policy makers need to know more about the potential cooling effect of a measure. For example, the choice between stimulating wind or changing pavement materials depends highly on the potential cooling effect of these measures.

The city climate has some generic characteristics and processes [3], these processes have many weather and context dependencies which result in a large variability within a city. Many adaptation measures have been tested in specific contexts or locations across the world [4–6]. However, for the temperate climate zones only few studies and simulations have been conducted in this field [7]. Various studies that have focussed on similar climatic conditions give an idea of the effect of some measures within a specific urban context [8] or a specific measure [9–12]. However, a straightforward comparison of the effects of adaptation measures can lead to ambivalent results because the effects on thermal comfort are highly context dependent. Moreover, a comparison is practically impossible with all the different weather

and climate conditions, the numerous methods to measure or simulate and the many different comfort indicators.

Therefore, this study aims to comprehensively review and gain insight in the effects on thermal comfort within comparable conditions on a hot summer situation. The research question is two-fold. Firstly, do all measures result in the same cooling range? And if not, the second question is whether there are significant differences between measures? An answer to the first question may reveal many possibilities for adaptation strategies while the second might suggest measures that should be studied in more detail and applied more often. This leads to the question of which measures require more research and which could be implemented more frequently. This paper therefore focusses on a mix of parameters: influence of buildings, orientation, wind direction and wind speed, pavement versus grass, trees and hedges. In addition we look at the influence on results of changes in model grid size.

All the different measures are assessed with the thermal comfort indicator PET (Physiological Equivalent Temperature). Often effects of climate adaptation measures are assessed based on air temperature, neglecting the effects of wind, radiation and humidity. PET links these important climate aspects to the physiology of the human body. Finally, this paper additionally aims to evaluate the simulation results with the microclimate model ENVI-met with field measurements and other available studies.

### 2. Methods

The research methods used in this study, the sequence and relations

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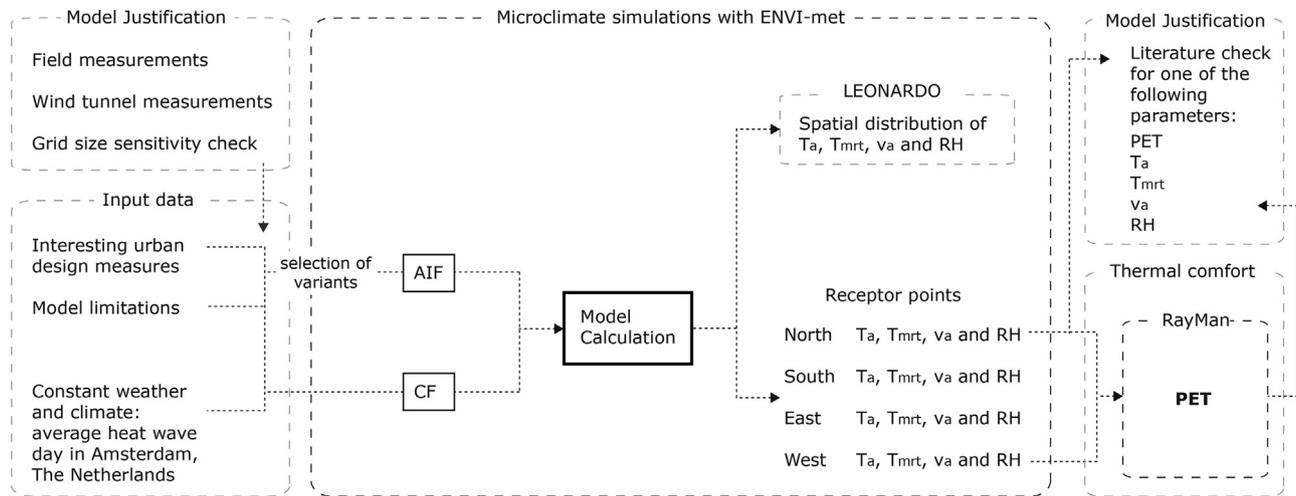


Fig. 1. Research schema.

between them, are described in this section and presented schematically in Fig. 1.

### 2.1. Comparable results

Comparing results from other studies can be challenging because they are often placed in a different context, in various climates and weather conditions. Their measurement methods or simulation models may also vary and present results in a different way. The context plays an important role in the effect urban measures have. For instance, adding a tree in an empty street has a different effect than adding a tree in a street that already has trees. The climate and weather conditions on a specific location also influence the effect of urban measures, e.g., close to the equator shadow devices or narrow streets increase thermal comfort during much of the year, while in regions further away from the equator narrow streets are too dark and cold in winter because of the lower sun angle. Measurement methods may be inconsistent in type of equipment, stationary measurements, traverse measurements or satellite imagery, the height and location of the measurements and the number of measurement points. Another factor making comparisons more complex is caused by the availability of many different thermal comfort indicators: air temperature, mean radiant temperature or a comfort indicator such as Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET) or Predicted Mean Vote (PMV). And furthermore, as Shashua-Bar et al. [13] observed, even though most researchers indicate effects of adaptation measures in air temperature, the effect of vegetation on air temperature is negligible while the effect of vegetation on thermal comfort is substantial.

Together, all these methodological variables do not allow for an objective comparison of effects of urban measures. To achieve a comparable set of measures the in- and output parameters need to be of the same kind. In addition, significant variations in urban geometries obstruct a comparative approach. This study therefore starts out from the most basic form: a building block in an open field. The analysis of the influence of urban measures is based on changing parameters within the same plot.

### 2.2. Variants description

A set of variants is analysed on the basis of mutual differences in air temperature and thermal comfort. The selection of urban design- and meteorological parameters in this study is mainly based on the capacity of the simulation program ENVI-met and the practical value they can have for urban development. Apart from the variants chosen for this study, many other relevant variants could have been included. However, the number of simulation variants is limited for reasons of

time and to keep the analysis manageable. Furthermore, the simulations presented in this paper cover different urban settings compared to previous studies with a focus on the urban canopy layer [14,15].

Fig. 2 gives an overview of the variants that are simulated. In sets A through I a total of 35 variants are studied. The first variant is an open field with different land-surface covers: brick pavement, grass and a combination of these two. The same land surface cover is used for the other simulation variants. In set B, a single 8 m tall building is studied. Set C shows the effects of changes in wind direction (North, South, East, West, North-East and South-West) and set D concerns the effects of wind speeds (1.0, 1.5, 3, and 6 m/s). The path of the sun from East to West causes changes in up heating when grass and brick pavement sides change orientation in set E. In set F differences in building height for a single building are studied. The effects of adding a building of the same height (8 m) is studied in set G. Set H contains trees in different positions and different tree-coverage ranging from 3 trees in a row to the whole area planted with trees. Finally, in set I the accuracy of results in relation to different grid sizes is tested, comparing a grid of 0.5\*0.5 m, 1\*1 m, 2\*2 m and 5\*5 m.

## 3. Calculation

### 3.1. Microclimate model ENVI-met

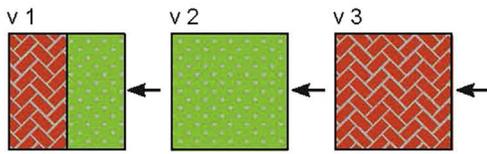
The comparative study uses the microclimate model ENVI-met. The main advantage of ENVI-met is that it calculates the microclimatic process in a daily cycle and allows for the inclusion of various building shapes and heights as well as vegetation. The program provides an accurate insight of the microclimate at street level. ENVI-met is a three-dimensional non-hydrostatic numerical simulation model that calculates exchange processes in, on and between urban elements with a high spatial (0.5–10 m) and temporal (10 s) resolution [16]. In a description of the model ENVI-met 3.0, which is the version used in the presented study, the used formulae and numerical aspects are documented, including: main wind flow, temperature, humidity, turbulence, radiation fluxes and individual soil properties such as thermodynamic and hydraulic conductivity or albedo [17]. This simulation model seeks to reproduce the main processes in the atmosphere that affect the microclimate on a well-founded physical basis [14].

The basic concept to describe three-dimensional turbulent flow is given by the non-hydrostatic incompressible Navier Stokes equations in the Boussinesq- approximated form (1.1)–(1.3):

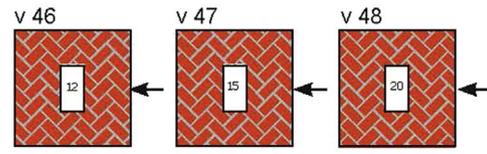
$$\frac{\partial u}{\partial t} + u_i \frac{\partial u}{\partial x_i} = -\frac{\partial p'}{\partial x} + K_m \left( \frac{\partial^2 u}{\partial x_i^2} \right) + f(v - v_g) - S_u \quad (1.1)$$

Variants overview

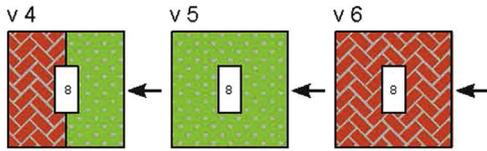
A. Pavement versus grass



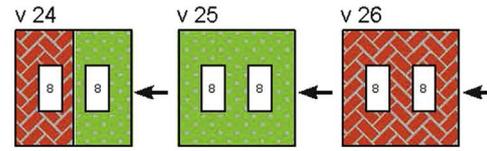
F. Single building with different heights



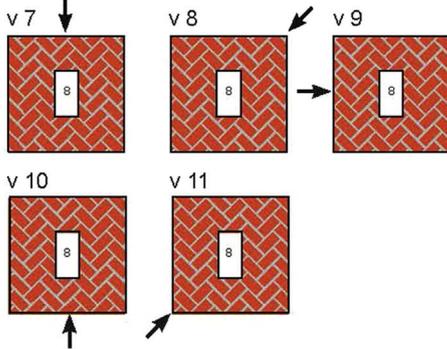
B. Single building



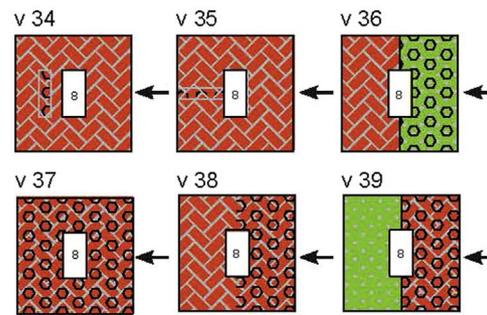
G. Two buildings



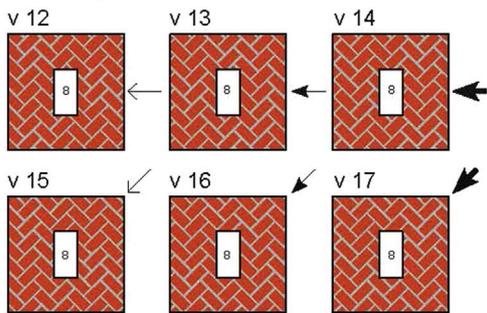
C. Wind direction



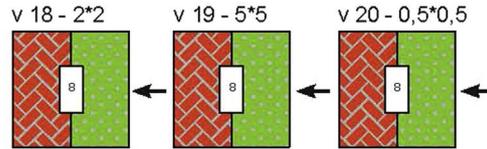
H. Trees



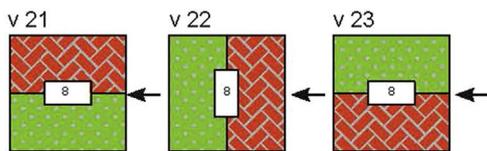
D. Wind speed



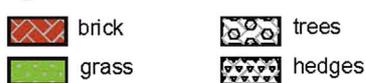
I. Grid size



E. Area rotation



Legend



Windspeed at 10 meter height

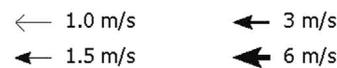


Fig. 2. Overview of the simulated variants.

$$\frac{\partial v}{\partial t} + u_i \frac{\partial v}{\partial x_i} = -\frac{\partial p'}{\partial y} + K_m \left( \frac{\partial^2 v}{\partial x_i^2} \right) - f(v - u_g) - S_v \quad (1.2)$$

$$\frac{\partial w}{\partial t} + u_i \frac{\partial w}{\partial x_i} = -\frac{\partial p'}{\partial z} + K_m \left( \frac{\partial^2 w}{\partial x_i^2} \right) + g \frac{\Theta(z)}{\Theta_{ref}(z)} - S_w \quad (1.3)$$

With  $u_i=(u, v, w)$ ,  $x_i=(x, y, z)$  for  $i=1,2,3$

As the flow is incompressible in ENVI-met,  $\rho$  does not change for any fluid parcel, and  $\frac{D\rho}{Dt}=0$ . Therefore, the Continuity equation is reduced to:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

Where, PO.

$f$  ( $=10^4 \text{ s}^{-1}$ ) is the Coriolis parameter,  
 $p'$  is the local pressure perturbation, and  
 $\Theta$  is the potential temperature at level  $z$ .

A one-dimensional reference model is used for the inflow wind profile at the boundary, a zero-gradient Neumann condition is used for the lateral and outflow boundary conditions for wind.

Compared to other models and methods to calculate urban microclimate conditions, the ENVI-met model is the most appropriate for the calculation of human comfort on street level. Other models that can be used to calculate outdoor conditions are for example: SOLWEIG, ANSYS Fluent (CFD) and RayMan. The SOLWEIG model is a radiation model that is very accurate in predicting the  $T_{mrt}$ . The model is developed by Göteborg University [18]. A measurement and modelling study shows that both, SOLWEIG and ENVI-met give an accurate prediction of the  $T_{mrt}$  within a range of 4 °C [19]. However, SOLWEIG does not calculate air flow. The computational fluid dynamics (CFD) models such as, ANSYS Fluent, are developed to predict air flow and turbulence. The models can be extended with a radiation and heat balance and an evaporation module [20]. Modelling with Fluent is very precise and used to test the aerodynamics of, for example, vehicles or to calculate flow in indoor spaces. The simulation output would give an unnecessary high detail level for this study. The RayMan model, in contrast with CFD modelling, has a very short running time. Like the SOLWEIG model, RayMan calculates radiation and generates the  $T_{mrt}$ , however does not include multiple reflections between buildings. A large advantage of the model is the possibility to generate output in common thermal comfort indexes like the PET and PMV [21].

### 3.2. Simulation input

Two files need to be created to set the conditions for the simulation in ENVI-met: the Area Input File provides the model information and the Configuration File the climatic conditions.

The location is the same for all simulations and is positioned in the temperate climate zone of the Netherlands, in Amsterdam, with latitude 52.22 and longitude 4.53. The Area Input File (AIF) has 120\*120\*20 ( $x*y*z$ ) grid cells with a grid size of 1\*1\*2 m ( $x*y*z$ ), thus a domain size of 120\*120\*40 m ( $x*y*z$ ) for all variants except for set M where the grid size varies from 5 m to 0.5 m. The reference building height is 8 m. The specific properties of the buildings, pavement and vegetation used for the simulations in this study are given in Table 1. Most of the properties are pre-sets in the ENVI-met program.

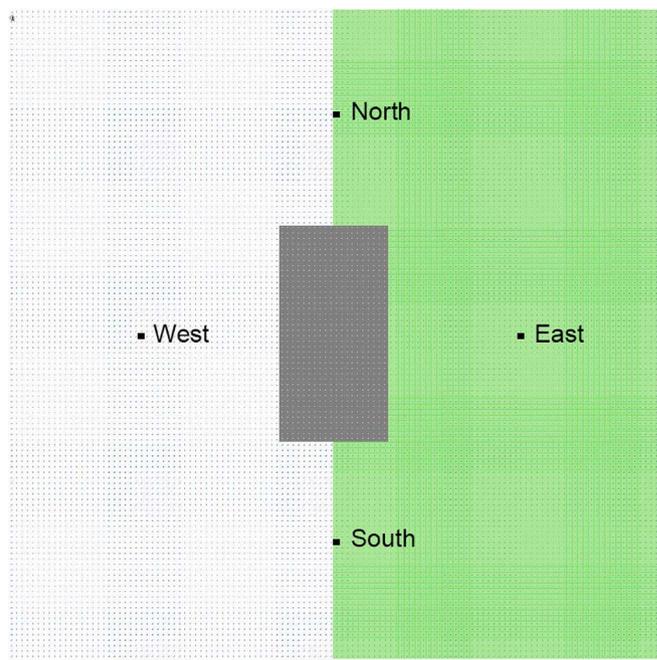
In ENVI-met data can be retrieved in so-called ‘receptor points’. These function as measurement points where data can be extracted for every  $z$  grid. In Fig. 3 the location of the receptors placed at the North, South, East and West side of the area is shown.

The meteorological input data for the simulations in ENVI-met do not correspond directly to one particular date. To be able to look at

**Table 1**

Pre-sets and chosen properties for materialization in ENVI-met.

Material/vegetation	Value	Unit
Albedo Brick pavement	0.3	
Grass xx	0.5	m (height)
Hedges dense	2	m (height)
T2 < tree 15 m very dense, leafless base	15	m (height)
Albedo walls	0.2	
Albedo roofs	0.3	
Heat transmission walls	2.5	W/m <sup>2</sup> °C
Heat transmission roofs	3.3	W/m <sup>2</sup> °C



**Fig. 3.** The Area Input File with the four receptor points at the North, South, East and West side of the area.

changes in wind direction, wind speed and initial temperature a more standardized situation is needed. The values for the reference situation are chosen based on the average circumstances during a heat wave day in the period 1950 through 2011 in the Netherlands, De Bilt [22]. The chosen date in the AIF is 21-06-2005 because this is the longest day of the year with the highest sun angle. In Table 2 the input data is given.

### 3.3. Simulation output

The thermal comfort indicator PET is the main evaluation index used for this study because it fits outdoor conditions and the temperate climate zone [23]. The PET is a well-known comfort indicator in the field of urban meteorology and has been used in multiple studies [15,24–27]. The PET links micrometeorological factors such as air temperature, radiation, wind and humidity to the physiology of the human body and is expressed in the common temperature scale Celsius, therefore, many can empathise with this indicator (Table 3). The choice for this comfort indicator is in agreement with other research groups that are connected to this study within the *Climate Proof Cities* project [28].

The basis for the PET calculation is the basic heat balance Eq (3) for the human body [23]:

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \tag{3}$$

**Table 2**

Configuration File input parameters in ENVI-met.

Input	Value	Unit
Start Simulation at Day	21.06.2005	DD.MM.YYYY
Start Simulation at Time	5:00:00	HH:MM:SS
Total Simulation Time	24.00	Hours
Save Model State	60	min
Wind Speed in 10 m ab. Ground	3	m/s
Wind Direction (0:N,90:E,180:S,270:W)	90	
Roughness Length $z_0$ at Reference Point	0.1	
Initial Temperature Atmosphere	296 (23)	K (°C)
Specific Humidity in 2500 m	7	g Water/kg air
Relative Humidity in 2 m	65	%
Database Plants	[input]/Plants.dat	

**Table 3**

Ranges of the thermal index physiological equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo [20].

PET (°C)	Thermal perception	Grade of physiological stress
4	Very cold	Extreme cold stress
	Cold	Strong cold stress
8	Cool	Moderate cold stress
	Slightly cool	Slight cold stress
23	Slightly warm	Slight heat stress
	Warm	Moderate heat stress
35	Hot	Strong heat stress
	Very hot	Extreme heat stress

$M$ =metabolic rate

$W$ =physical work output

$R$ =net radiation of the body

$C$ =convective heat flow

$ED$ =latent heat flow to evaporate water into water vapour diffusing through the skin

$ERe$ =sum of heat flows for heating and humidifying the inspired air

$ESw$ =heat flow due to evaporation of sweat

$S$ =storage heat flow for heating or cooling the body mass

The data from the four receptor points in Fig. 3 can be loaded separately in any other data processing program. The four main parameters air temperature ( $T_a$ ), mean radiant temperature ( $T_{mrt}$ ), airspeed ( $v_a$ ) and relative humidity (RH) are selected and converted in PET. For the conversion of the output data from ENVI-met in PET the RayMan program is used [21] already mentioned in Section 3.1.

Although PET is a common human thermal comfort indicator, most studies of the effectiveness of cooling measures give their results in air temperature. Therefore, the comparison of results from this study with other studies is also based on the average air temperature from the four receptors. In the following section the simulation results are presented in average PET and air temperature. A more detailed insight into the influencing factors for the PET is shown with the PET per receptor point and, if necessary, the basic data from which the PET is generated. Zooming into the basic data like this helps to explain why an urban measure leads to up-heating or cooling. The basic data can be analysed through the visualisation model LEONARDO. The colourful images of the separate parameters give a quick overview of the spatial distribution pattern of the air temperature (Fig. 4), wind speed (Appendix A.1), mean radiant temperature (Appendix A.2) and relative humidity (Appendix A.3).

### 3.4. Justification of ENVI-met

In this section several methods are used to show that the accuracy of ENVI-met results is appropriate for the comparison of different urban forms. In the first section a validation of ENVI-met is done by comparing field measurements of different paving materials with simulation results of different paving materials. The second section makes use of wind tunnel measurements with comparable urban compositions. Followed by, the explanation of the justification and clarification of results, through comparing them with results found by others in literature. Finally, a computational grid size sensitivity check is done.

#### 3.4.1. Field measurements versus simulation

In this section the ENVI-met model is validated through a comparison of measurements and simulations results of the two paving materials grass and brick, both on a winter day. The measurements were done in two courtyards of buildings on the campus of the Delft University of Technology, Delft, the Netherlands: the Science Centre with grass (Fig. 5a) and the Chem Tech building with brick pavement (Fig. 5b). Two Escort Junior data loggers (Fig. 5c) were used to measure air temperature with an interval of 30 min. The sensor for air temperature was protected by a bin with aluminium cover (Fig. 5d) to minimise the effect of radiation.

For the measurement and simulations a sunny day was chosen, the 19th of December 2013, to avoid discrepancies between measurement and simulation results due to cloudiness. To do these simulations an ENVI-met Area Input File (AIF) and a Configuration File are needed, as explained in Sections 3.2 and 3.3 respectively. The simulation input data for the 19th of December 2013 are presented in Table 4. The simulation results are collected in so called receptor points. For the validation we looked at the average of the four receptor points.

The measured and simulated air temperatures are shown in Fig. 6. Here it becomes clear that the difference in air temperature between the measured and the simulated data do not differ more than 2 °C. The root-mean-square deviation (RMSD) is calculated to indicate the accuracy of the simulated data on a winter day for the Netherlands. The RMSD is a frequently used measure of the differences between values predicted by a model and the values actually observed. The RMSD between measured air temperature and simulated air temperature in the performed field study is 0.94 °C for brick and 0.74 °C for grass. The maximum difference between measured and observed data is 1.8 °C for brick and 1.6 °C for grass. The hourly fluctuations in the measurement data are not found in the simulation results because the model calculates with starting values, and these are not forced into another direction because of a change of weather.

#### 3.4.2. Validation with wind tunnel measurements

Wind is one of the four main thermal comfort indicators, and therefore, a main parameter in the PET.

In this study the simulation results are compared to wind tunnel measurements by Beranek [29,30]. This is a very extensive wind tunnel study that shows wind patterns for different forms of buildings and various wind directions. These wind tunnel results can be used to validate simulation results, as it is already done in a study about the typical wind flow pattern around buildings and its influence on pedestrian level [31].

In Beranek's wind tunnel study a scour technique is used to analyse the wind pattern at pedestrian level. The scour technique consists of two parts. First, dry sand is sprinkled over the turntable in a uniform layer, and wind speed is increased in steps until all the sand has been blown away. In the second part, the same uniform sand layer is created and the same steps of wind speed are now performed with a building on the turntable. The sand erosion that occurs with each step of wind speed is photographed after it has reached a steady state. The total wind pattern at ground level is visualised by combining the erosion patterns of all the steps. In this study ENVI-met results in wind speed are compared with results measured in a wind tunnel study in set C and F, Section 4.3 and 4.6 respectively.

#### 3.4.3. Computational grid size sensitivity check

The influence of grid size is important in the evaluation of thermal comfort with computer models. Grid size determines how detailed buildings, the site layout and other objects can be modelled and what the distance is between the points that are calculated. In practise the minimum and maximum grid size in ENVI-met is 0.5\*0.5 and 10\*10 m respectively. Depending on the detail level of information one may need to retrieve, the grid size can be chosen. In an earlier study the grid size of 5\*5 m turned out to be too coarse to give insight in the effect of

Variants overview - output in air temperature

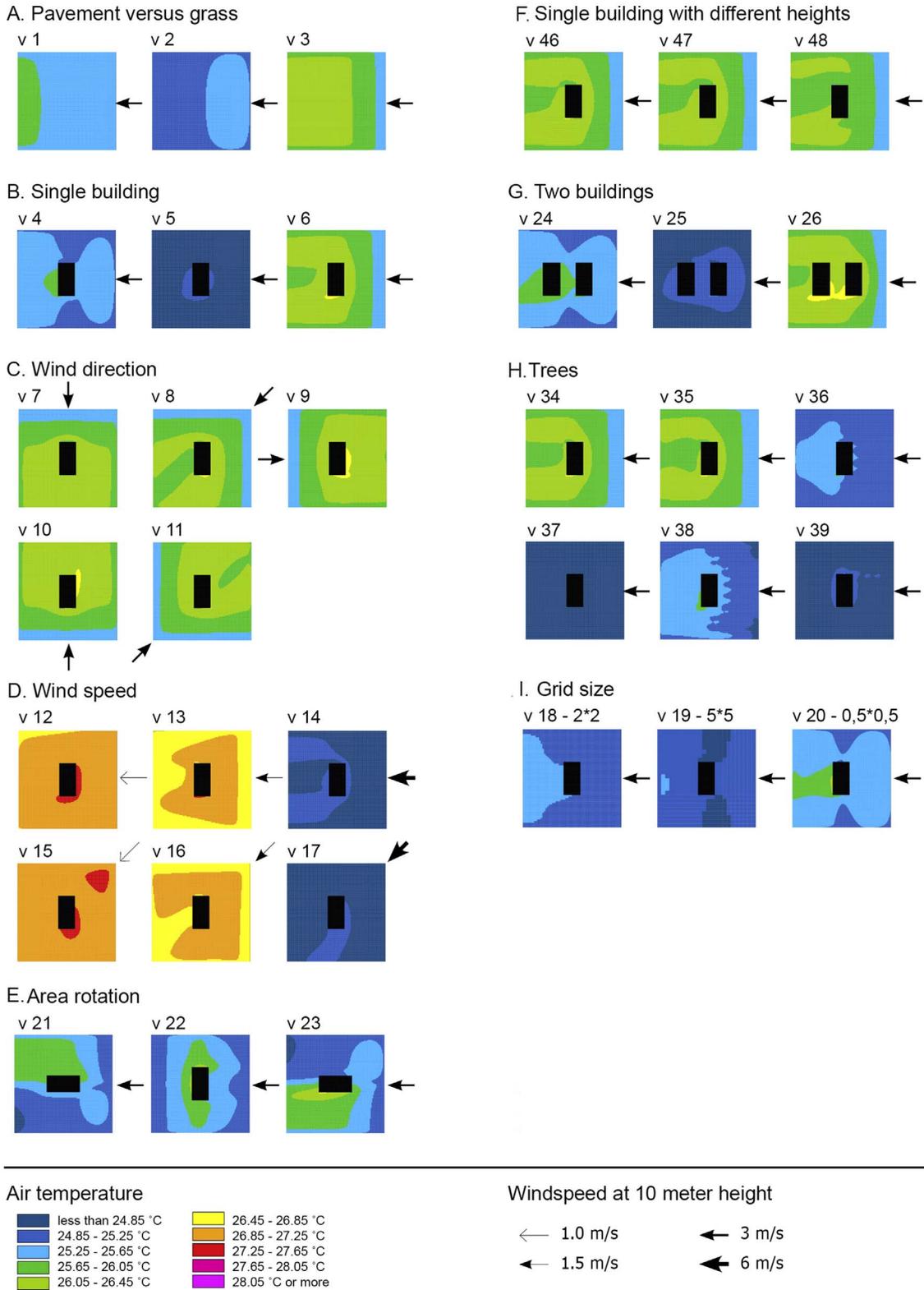
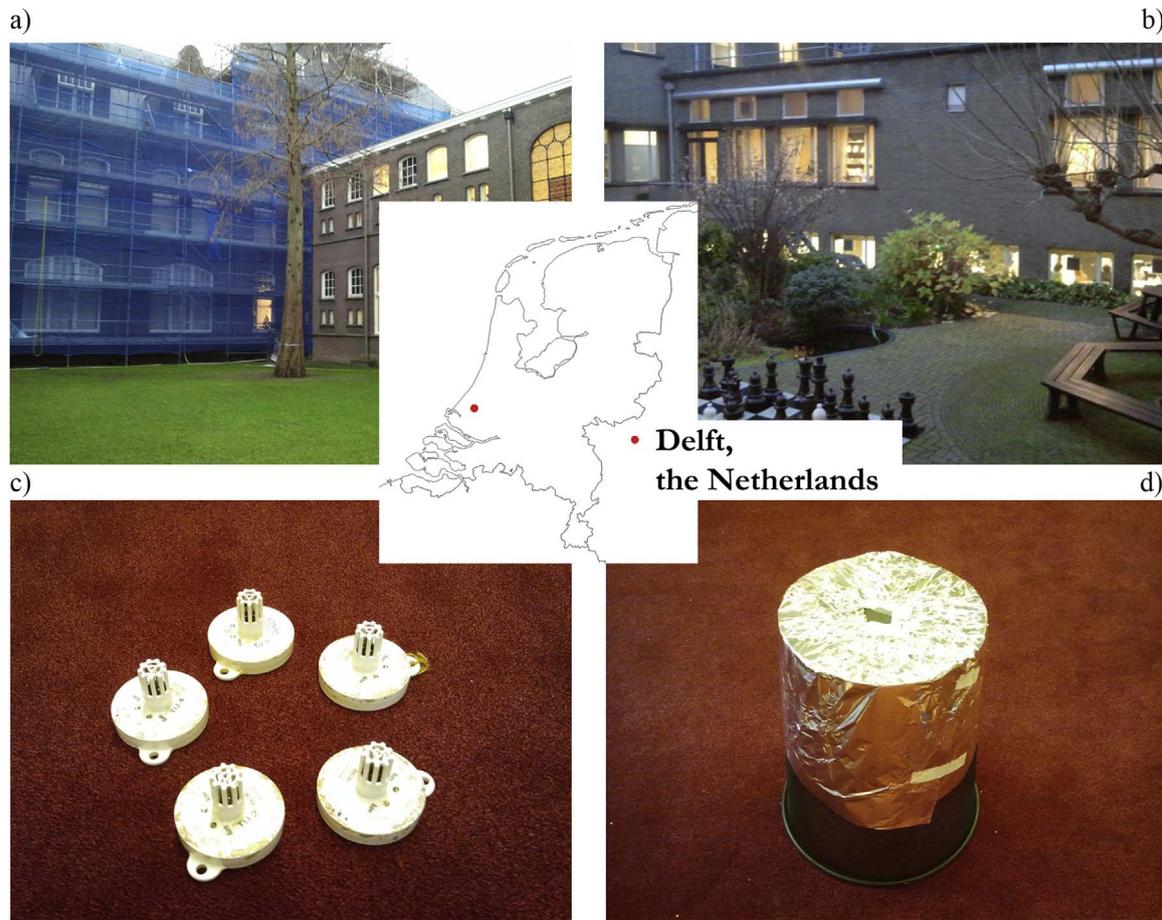


Fig. 4. The air temperature at 13:00 h at 1 m height by the graphic program LEONARDO.

climate adaptation measures within a street profile or neighbourhood square [32].

The influence of grid size is studied in set M with four different grid sizes: 0.5\*0.5 m (v20), 1\*1 m (v4), 2\*2 m (v18) and 5\*5 m (v19). In the average PET of the four receptor points a larger grid size results in a

lower PET. The average PET decreases by increase of grid size with: 36.9 °C; 37.8 °C; 36.6 °C and 35.9 °C for respectively 0.5\*0.5; 1\*1; 2\*2 and 5\*5 m. The grid size step from 1\*1 to 0.5\*0.5 results in a difference of less than 1 °C. While the grid size step from 2\*2 to 1\*1 results in 1.2 °C in PET. We consider a deviation of 1 °C in PET the threshold for



**Fig. 5.** a) the measurement location for the grass field at the Science centre and the location Delft as the place of validation; b) the measurement location for the brick pavement; c) Escort Junior data loggers used for the measurements; d) a bin with aluminium cover to shield the data loggers.

**Table 4**  
Configuration File input parameters in ENVI-met for the 19th of December 2013.

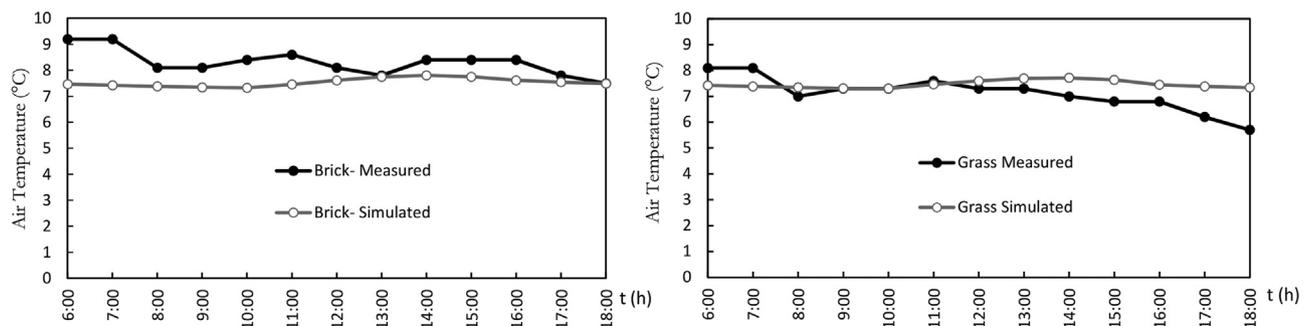
Input	Value	Unit
Start Simulation at Day	18.12.2013	DD.MM.YYYY
Start Simulation at Time	5:00:00	HH:MM:SS
Total Simulation Time	37.00	Hours
Save Model State	60	min
Wind Speed in 10 m ab. Ground	5.7	m/s
Wind Direction (0:N,90:E,180:S,270:W)	208	
Roughness Length z0 at Reference Point	0.1	
Initial Temperature Atmosphere	280 (7)	K (°C)
Specific Humidity in 2500 m	7	g Water/kg air
Relative Humidity in 2 m	86	%
Database Plants	[input]/Plants.dat	

deviations caused by the grid size. Therefore we use a grid of 1\*1 in this study.

The difference caused by grid size in air temperature is smaller than in PET. Fig. 7, clearly shows that a grid size of 0.5\*0.5 instead of 1\*1 m does not make a lot of difference in air temperature prediction. In less than 10% of the area the air temperature increases with a maximum of 0.4 °C. However, with a grid size of 2\*2 instead of 5\*5 m the air temperature changes in about 50% of the area with a maximum of 0.4 °C. Both results, in PET and air temperature require a grid size of 1\*1 m or smaller.

**3.4.4. Justification and clarification with measurements and simulations from literature**

Next to the validation of the ENVI-met results with field measurements and wind tunnel studies, the simulation results are compared to



**Fig. 6.** Simulation results with the ENVI-met model and field measurements at the campus of the Delft University of Technology on the 19th of December 2013, with on the left results for the brick pavement and on the right for the grass field.

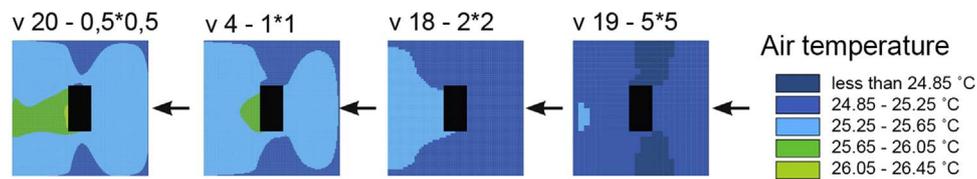


Fig. 7. The air temperature at 13:00 h at 1 m height for the grid size variants (from left to right) 20, 4, 18 and 19 by ENVI-met.

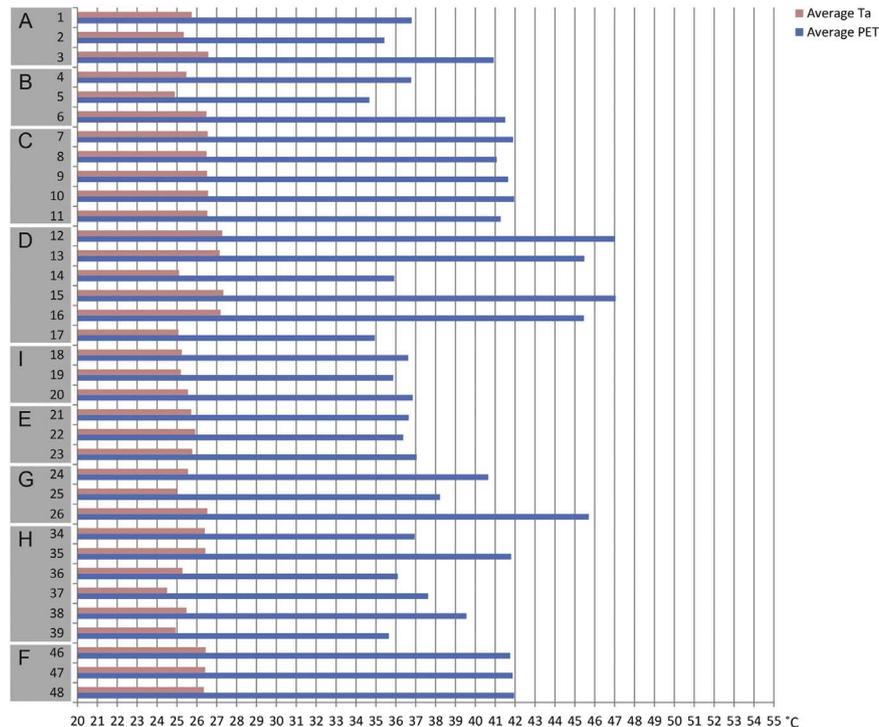


Fig. 8. The average PET and air temperature on 13:00 h at 1 m height.

results found in literature. Depending on the parameter(s) changed in the variant study, the effects are analysed in PET, air temperature, mean radiant temperature, wind speed or relative humidity. To clarify or justify the effects calculated with the ENVI-met model, the results are compared with field measurements or simulations by others and theoretical principles in sets A, B, D, E, G, H, I and J.

### 3.4.5. Discussion on reliability of ENVI-met

Due to the complexity of modelling the microclimate, some processes in ENVI-met are simplified and standardised. Model limitations, for example, are the overestimation of daytime temperature because the heat storage in building surfaces is not calculated [33], the global radiation is somewhat overestimated, and at night the missing heat storage in building surfaces leads to an underestimation [16]. Also the meteorological inputs at the boundary conditions are limited [34] this makes it difficult to approach measurement series done in the field. This functionality will be included in the new version ENVI-met 4.0 [35] which is in development. In a study of the ‘Stadtgarten’ in Essen, Germany, the differences between modelled data and observed data are in the range of +1.5 to -1.0 °C [36]. A study in Singapore also concludes that the ENVI-met simulation supports the data generated from the field measurement [37]. ENVI-met is less suitable to reproduce exact temperatures for a specific day, but gives insight in the micrometeorological processes in urban environments. The simulation model makes it possible to compare and analyse temperature differences as well as the temperature distribution for different urban situations [38]. The accuracy of calculations depends heavily on grid size, details in the model and input parameters.

The validation with field measurements in Delft, the Netherlands,

as described in Section 3.4.1 and by Taleghani, Tenpierik [39], indicates that the influence of different urban materials on air temperature can be calculated with an accuracy of about 80% and with an average deviation between 0.74 and 0.94 °C by the ENVI-met model. However, this does not give hundred percent confidence in the accurateness of other microclimate parameters. Therefore, the use of ENVI-met is justified in this study with several additional methods: with wind tunnel measurements from literature; a computational grid size sensitivity check; and with measurements and simulations described in literature with results in air temperature, surface temperature and wind speed. The direction of the effect - cooling or up-heating -, and the magnitude of the effect in relation to the other urban changes are accurate for the type of conclusions in this paper. It would take a different approach to validate the absolute value of the outcomes by ENVI-met. In any case, basic knowledge about the urban microclimate and experience with modelling programs is still required to interpret simulation outcomes.

In the chosen application the effects of urban measures can be compared objectively. Real-time weather influences or differences in climate do not occur because the same input parameters are used for all simulations. To test the influence of differences in wind speed and wind direction set C and D have slightly different input parameters.

## 4. Results and clarification

The variants are analysed at three different points in time, at 13:00, 21:00 and 04:00 h. The PET temperature at 21:00 ranges from 15 to 23 °C and at 04:00 h from 12 to 20 °C, both have a difference of 8 °C from minimum to maximum temperature. At 13 o'clock the difference

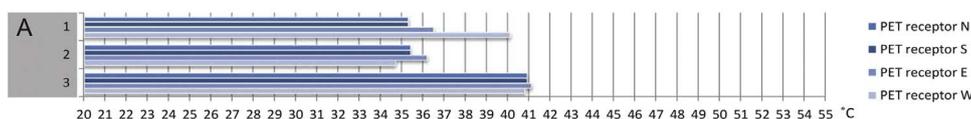


Fig. 9. The PET for pavement versus grass in variant 1, 2 and 3 in set A at 13:00 h at 1 m height.

in PET is larger, 21 °C, ranging from 34 to 55 °C. The wider range shows more detail and enables a more precise comparison between the variants. Therefore, the results will be compared based on the values at 13:00 h. This moment of the day is also representative for the accumulation of heat in urban configurations. Fig. 8 shows the average PET for the four receptor points at 1 m height together with the average air temperature. In the following paragraphs the results are analysed for the different sets of adaptation measures A till M.

#### 4.1. Set A: Pavement versus grass

The simulation results for the variants in set A (Fig. 9) show that the brick pavement (variant 3) feels 6 °C warmer than the grass surface (variant 2). The bricks give a homogenous PET distribution across the area, while the grass variant has a slight PET increase on the East side and a slight decrease on the West side. The expectation is that grass lowers the wind speed which would result in a PET increase at the West side instead of the East side. The simulations indeed show a decrease in wind speed at the West side but also a drop in humidity and air temperature relative to the East side, resulting in an overall decrease in the PET temperature on the West side.

Variant 1 combines grass at the East side and brick pavement at the West side. The 50% grass coverage causes a PET decrease of 3.5 °C within the same area. The presence of the grass also lowers the PET for people who are at the brick (West) side. The difference is almost 1 °C compared to the brick variant without grass (variant 3). The effect of the 50% grass on the East side (variant 1) results in the same low PET in the North and South receptor as the variant with 100% grass coverage (variant 2). Thus, a 6 °C cooling effect is measured in comparison with the brick variant (3). This implies that with only half the amount of grass, more than half of the area has an effectively lower PET.

To compare the simulation output from ENVI-met in set A with results by others a different indicator than PET or air temperature is needed since there are no studies about surface materials that give their result in one of these two indicators. Luckily, there are studies that analyse the effect of pavement and grass by the surface temperature. In a study by Onishi et al. [40] a multivariate linear regression model is used to compare a parking lot with 100% concrete or asphalt pavement versus 100% grass coverage and showed a significant decrease of the surface temperature. The maximum cooling of the maximum daily surface temperature due to grass is 8 °C, while the average decrease of the whole area surface temperature is 0.3 °C [40]. Another study that simulated surface temperatures for different land-covers indicates a maximum cooling effect of tall grass compared to concrete of 22 °C [41]. Here the simulation model was built up with surface heat transfer equations and a numerical approximation of the 1-D unsteady heat diffusion equation. Finally, a study done in Manchester measured a maximum cooling effect of 24 °C by a grass surface instead of concrete pavement [42].

ENVI-met makes it possible to generate a spatial map of the surface temperature so we can compare the results from the studies described above with the simulation results. The surface temperature calculated by ENVI-met is around 29 °C for grass and 41 °C for brick pavement, as shown in Fig. 10. This means that the simulations show a difference in surface temperature of around 12 °C between grass and brick. The surface temperature per material is dependent on external factors like the air temperature, wind speed and solar intensity and on material properties such as conductivity, thermal capacity and moisture within

the material or permeability of the pavement. The high variability of external factors explains the large range of the surface temperature differences of 8 and 24 °C found by other studies comparing grass and brick pavement. The simulated difference of 12 °C in ENVI-met lies within this range.

#### 4.2. Set B: Single building

When a single building of 8 m tall is placed in the middle of the area in set B (Fig. 11) the effect of brick pavement and grass is similar to the situation without building. The difference in PET between brick pavement (variant 6) and grass surface (variant 5) ranges from 6 °C at the North, South and East side to 8 °C at the West side. The building blocks the wind and therefore increases the PET at the leeward side of the building. The West side of variants 4, 5 and 6, is 1–3 °C warmer compared to the variants 1, 2 and 3 without a building. The North and South side of the area is 1–1.5 °C cooler with building than without building. This decrease in PET can be explained by the acceleration of airflow at the sides of the building as shown in Fig. A.1.

Another parameter that can be studied in this context is the influence of a single building on thermal comfort. The average PET is 1 °C cooler with building than without for a situation with grass, as shown in Fig. 8. For the situation with brick the average PET is 0.5 °C warmer with building than without. As can be expected, the receptor points show a higher variability per receptor compared to the average value. Looking at the PET difference per receptor that is caused by a building, this is 1–3.5 °C warmer and 1–1.5 °C cooler. The influence of urban geometry is usually measured or simulated within an existing urban context or a standardised canopy profile [36,43,44]. There are many studies specifically focused on the airflow around a single building. The effect of buildings on the wind pattern is studied in detail in set C and F, Section 4.3 and 4.6 respectively.

Besides the effect buildings have on wind, they also affect the mean radiant temperature ( $T_{mrt}$ ) in the direct surrounding of the building. The reflectivity of the façade influences the amount of shortwave radiation that is reflected. The more radiation is reflected, the higher the  $T_{mrt}$  in the surroundings of the building. Apart from increased reflectivity, a building also casts a shadow which leads to a decrease of the  $T_{mrt}$  in the shadow location. The simulation results in Fig. A.2 show that with a facade albedo of 0.2 the building increases the  $T_{mrt}$  up to 1 °C when the building is surrounded by pavement (variant 6). When the building is surrounded by grass the building does not increase the  $T_{mrt}$  within its surrounding. Looking at the average PET the same trend is visible in Fig. 8: the PET increases with 0.5 °C when a building is placed in the brick pavement variant and the PET decreases with 0.7 °C when it is placed in the grass variant. Thus, a building can cool, and also heat up the pedestrian area, depending on the location and the wind direction, sun orientation, building properties and the materialization and greening of the surrounding. More research is needed to know the effects on the PET with alternative albedo values and building heights.

From set B with a single building the effect of grass can be analysed more thoroughly. Variants 1 and 4 show the effect of grass when it is situated at the windward side of the area. In both variants the stony leeward side (West) shows a higher PET than the grass at the windward side (East). Is this still the case when the grass is situated at the opposite leeward side? In this case the leeward side has a 50% grass coverage, as in variant 22. The PET at the North and South side in variant 22 is the same as for variant 4. The expectation is that the West

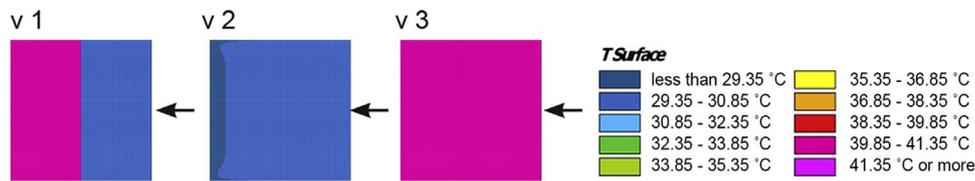


Fig. 10. The surface temperature of the pavement and grass variants in set A at 13:00 h by ENVI-met.

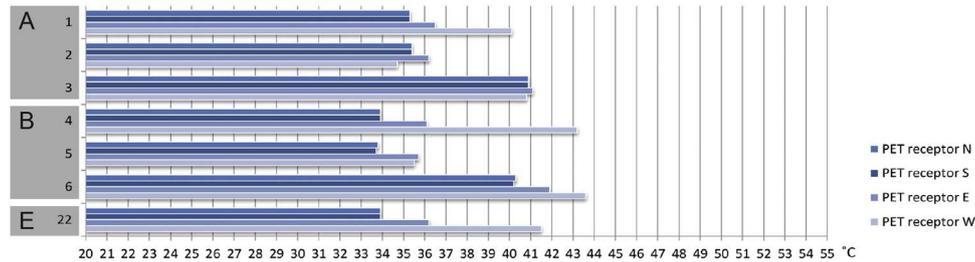


Fig. 11. The PET for a single building in variant 1–6 and 22 in set B at 13:00 h at 1 m height.

side of variant 22 is cooler than in variant 4 because of the grass and the East side is warmer due to the brick pavement. The results meet this expectation: the West side (grass) is 1.7 °C cooler and the East side (brick) is 0.1 °C warmer. We can conclude that grass is cooler than brick, regardless the East or West orientation or the wind direction.

The results above show that grass gives a lower comfort temperature compared to brick pavement in all cases: in an open field, in combination with a building and at both the leeward and windward side. Grass even lowers the temperature of the surrounding paved area with 1 °C. The PET between grass and brick pavement ranges from 0.1 to 8 °C.

### 4.3. Set C: Wind direction

The next set of variants look into the effect of the difference in wind direction in set C (Fig. 12). A general conclusion from these simulations is that the leeward side of the building is 1.5–3 °C warmer when the wind direction is perpendicular to the building. When the wind arrives at the building at an angle (variants 8 and 11) instead of perpendicular to the facade, the temperature distribution around the building is more equal and results on average in the coolest situation, as presented in Fig. 4. The difference in the average PET goes up to 0.9 °C. When the wind arrives at the short side of the building, as in variant 7 and 10, the PET increases most. The highest PET arises at the leeward side of the building.

As explained in the method Section 3.4.2 simulation results in wind pattern and wind speed are compared to wind tunnel measurements. In Fig. 13 the result of the wind tunnel study by Beranek is placed next to and is combined with the simulation output from ENVI-met for a comparable building and wind angle. Building variant 8 and wind tunnel test a4both have a width of 20 m and length of 40 m, only the height of the buildings differs from each other: in ENVI-met the modelled building is 20 m high (due to model limitations) and the wind tunnel scale model (scale 1:300) is 70 m high. The wind tunnel experiments are done with a wind hinder parameter  $\gamma=2.0-1.8-1.6-$

1.4–1.2–1.0–0.8. These are visualised with lines and the increase is shown in light- to dark grey.

The wind tunnel result and the ENVI-met simulation outcome can first be compared to the kinds of changes in wind pattern caused by a building. Both show a wake field on the windward and the leeward side of the building. The other important correspondence between the two is the high-pressure field on the windward corners of the building.

The next element of comparison would be the magnitude and form of the wind patterns. However, a problem arises because the models do not show the same information exactly. The different grey shades in the wind tunnel tests correspond to a sand pattern formed with a certain wind speed, while the ENVI-met outcome shows the steady state situation after 8 h of calculation starting with an incoming wind speed of 3 m/s on 10 m height. The wake field behind and in front of the building are larger for the wind tunnel test than for the simulation outcome. The same goes for the high-pressure area around the corner which is larger for the wind tunnel test. This difference is clearly a result of the difference in building height shown in Fig. 14. The size of the pressure area typical of a building of 25 m high is very similar to the size of the pressure area typical of the building of 20 m high in the ENVI-met simulation.

### 4.4. Set D: Wind speed

In set D the effect of wind speed is simulated, as shown in Fig. 15. The variants 12, 13, 6 and 14 have wind from the East and a speed of 1, 1.5, 3 and 6 m/s at 10 m respectively above the ground. And the variants 15, 16, 8 and 17 have wind from the North-East and the same speed of 1, 1.5, 3 and 6 m/s respectively. A higher wind speed results in a lower PET for the tested wind speeds from 1.0 up to 6 m/s. The range of the temperature effect is similar for both wind directions from the East and the North-East. The effect on the PET in relation to the wind speed is shown in Table 5.

It is now interesting to verify whether the temperature changes correspond with the theory. In Fig. 16 Victor Olgyay shows the wind

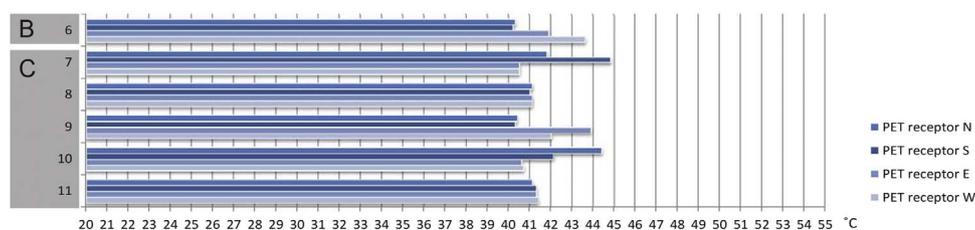


Fig. 12. The PET for the wind direction in variant 6–11 in set C at 13:00 h at 1 m height.

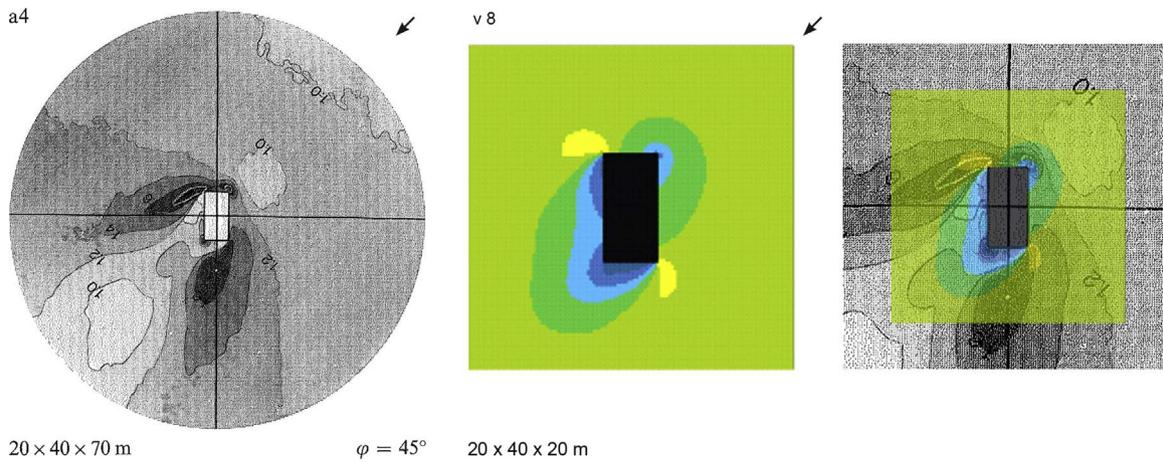


Fig. 13. The influence of a rectangular building on the wind speed on the ground floor. On the left (a4) the result from the wind tunnel study [22] for a building size of 20\*40\*70 (w\*l\*h), in the middle (v8) the result from the ENVI-met simulation at 13:00 h for a building size of 20\*40\*20 (w\*l\*h), and on the right the two outcomes combined.

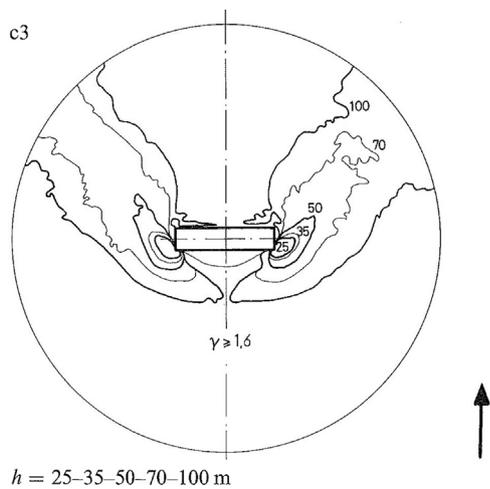


Fig. 14. The influence of a rectangular building - 20\*80 (w\*l) - on the wind speed on the ground floor for the building heights 25, 35, 50, 70 and 100 m tested in a wind tunnel [22].

velocity theoretically needed to restore comfort when temperatures and relative humidities are out of the comfort zone [45]. An increase in wind speed from 1 to 1.5 m/s and from 1.5 to 3 m/s theoretically results in cooling effects of respectively 0.67 °C and 1.22 °C. This is a lower cooling effect than predicted by ENVI-met. The larger temperature drop given in Table 5 can mean that ENVI-met overestimates the effect of wind speed on air temperature and humidity. Moreover, the wind speed at the receptor points is lower than the wind speed at 10 m above the ground, which should theoretically result in an even smaller temperature drop.

Studies of wind speeds are generally focussed on the cold winter situation where higher wind speeds cause discomfort from 5 m/s or more and danger from 15 m/s [29,46]. Therefore, the effect on the cold winter situation should always be considered when considering higher

Table 5  
Effect of wind speed on PET in °C.

Wind speed:	East	North-East
from 1 to 1.5 m/s	-1.6 °C	-1.7 °C
from 1.5 to 3 m/s	-4 °C	-4.5 °C
from 3 to 6 m/s	-5.6 °C	-6.1 °C

wind speeds to increase comfort in hot weather conditions.

#### 4.5. Set E: Area rotation

The rotation of the area results in a different wind angle in combination with a different sun angle. The average PET of the four receptor points does not vary more than 0.6 °C between the variants 4 and 21–23, presented in Fig. 8. The separate PET per receptor point varies more, from 0 to 3.2 °C. The separate receptors only differ from each other in the North and South receptor, which is a coherent output because the northern and southern half switch from grass to brick. Variant 4 and 22 have been discussed in Section 4.2 where grass resulted in a lower PET compared to brick.

Grass can improve the comfort sensation and even eliminate discomfort sensation hours when combined with trees [13]. From this study it can be concluded that the influence of vegetation on air temperature is negligible on the small scale of the building block, while the contribution on thermal comfort is substantial. However, on the large scale, vegetation does affect air temperature significantly [5]. The radiant exchange is usually the dominant factor in human thermal comfort sensation.

Another study that looked into the cooling effect of grass calculated the difference in sensible heat flux between grass and asphalt [47]. The reduction was 100–150 W m<sup>-2</sup> during the day and around 50 W m<sup>-2</sup> at night. Even though there is a significant effect of grass cover on the sensible heat flux, the effect on air temperature was estimated on

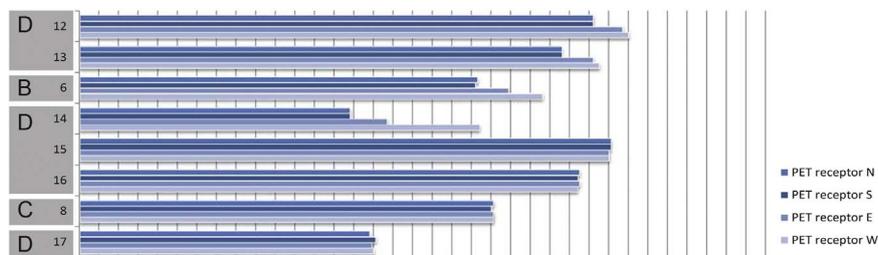


Fig. 15. The PET for the wind speed in variant 12, 13, 6, 14, 15, 16, 8 and 17 in set D at 13:00 h at 1 m height.

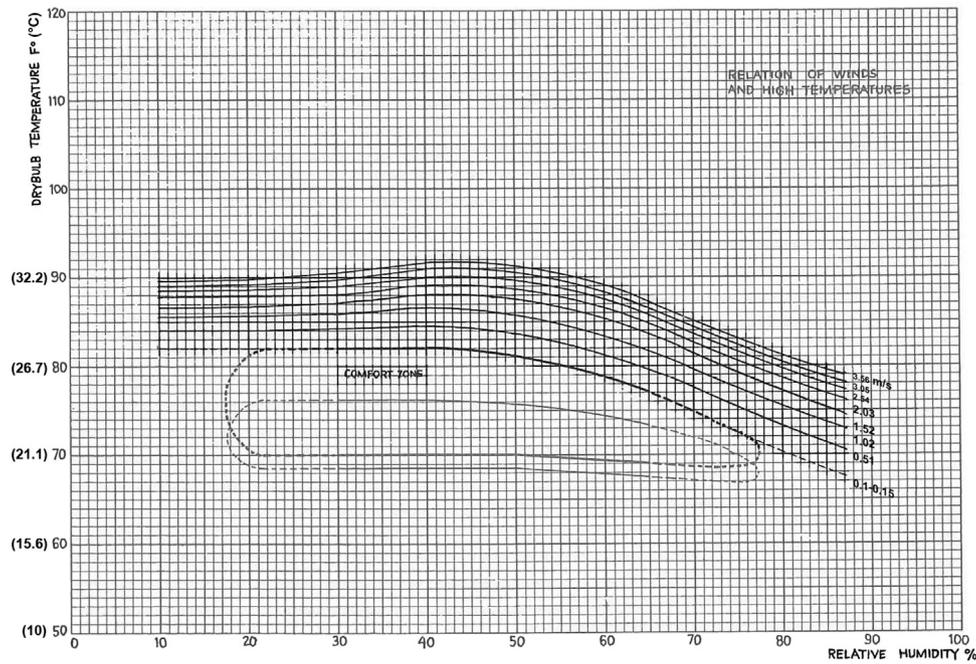


Fig. 16. Relation of winds and high temperatures [39].

0.1 °C. This corresponds to the small effect on the air temperature of 0.0 °C and 0.17 °C calculated by ENVI-met.

4.6. Set F: Single building with different heights

In set M a single building with different heights is simulated: 8 m (v6), 12 m (v46), 15 m (v47) and 20 m (v48). The results in Fig. 17 clearly show that the most important parameter for the PET, influenced by building height, is the wind speed. The wind speed decreases at the East and West side and increases at the North and South side. This is a common known effect. The air temperature decreases at all receptor points with increasing building height. But this is overruled in the PET by the change in air speed. The average PET given in Fig. 8 shows a slight increase of the PET with increasing building height 41.5–41.8–41.9–42.0 °C. The locality of the effects of wind must be taken into account: the lee- and windward side of buildings have a higher PET with increasing building height due to wake fields and at the corners of the building the PET is lowered because wind speed increases at these points.

As explained in Section 3.4.2 and elaborated in Section 4.3 the outcome of the simulations can be compared with Beranek's wind tunnel study [29]. In Fig. 18 the result of this wind tunnel study is placed next to and is combined with the simulation output from ENVI-met for a comparable building. Building variant 48 approaches the wind tunnel test the best. Both have a width of 20 m and length of 40 m, only the height of the buildings is different: in ENVI-met the modelled building is 20 m tall and the wind tunnel scale model (scale 1:300) is 25 m tall.

As described in Section 4.3, the wind tunnel result and the ENVI-met simulation outcome can first be compared for the direction of the effect. In this case, both show a wake field on the windward and the leeward side of the building. And both show the high-pressure field on

the windward corners of the building.

The next element of comparison, the magnitude and form of the wind patterns, show a correspondence between the wind tunnel and simulation outcome. The wake fields behind the building have the same size and a very similar form; the same goes for the high-pressure fields on the windward corners of the building. The wake field in front of the building shows a different form in the wind tunnel and simulation outcome. The wind tunnel result is not symmetrical due to local and temporal turbulence, while the simulation outcome shows a symmetric wind pattern. The other difference between the two is a somewhat higher-pressure area in front of the building with a thin layer of a low-pressure area directly at the building wall, and a low-pressure area at some more distance from the building. The simulation outcome does not show such an area with increased pressure in front of the building.

The discussion above directs to the conclusion that ENVI-met has an accurate prediction of wind behaviour concerning the location of the effects on changing wind flow around a building. It is more difficult to conclude whether the magnitude and form of the wind patterns are accurate, the comparisons in this study indicate that ENVI-met gives an adequate prediction to estimate the PET.

4.7. Set G: Two buildings

In set G the effect of two buildings, both 8 m tall, is simulated in the variants 24, 25 and 26. The results from these variants can be compared with the variants 4, 5 and 6 which have a single building. Fig. 19 shows the effect on the PET. The PET values at the North and South side do not change with two buildings instead of one. But, at the East and West side the PET is significantly higher for the variants with two buildings. In the case of two buildings the PET at the western receptor increases with 7.7–10.1 °C compared to the corresponding variants with a single building. The eastern receptor shows an increase

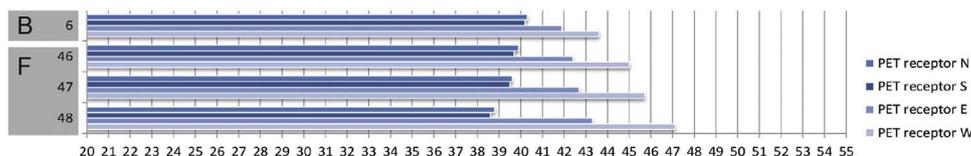
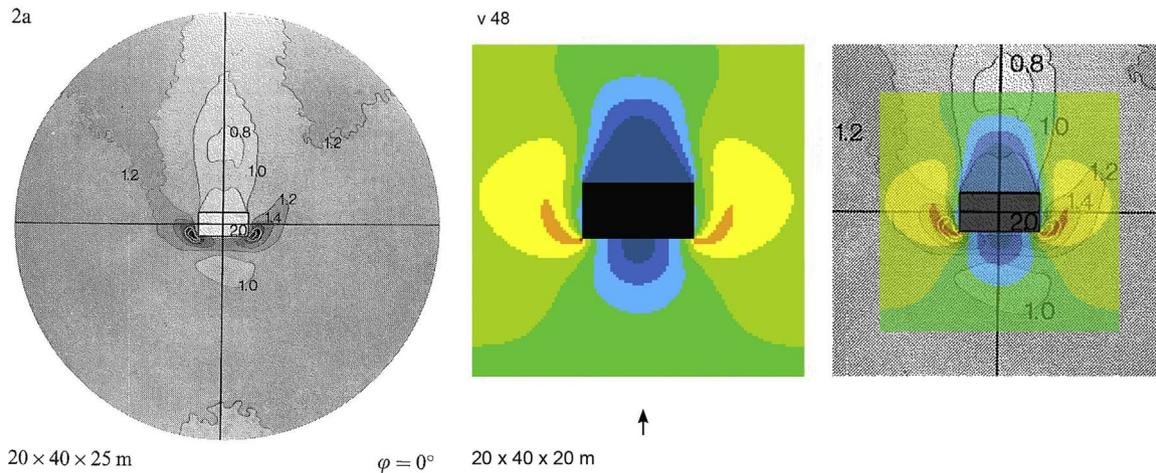


Fig. 17. The PET for a single building with different heights in variant 6 and 46–48 in set F at 13:00 h at 1 m height.



**Fig. 18.** The influence of a rectangular building on the wind speed on the ground floor. On the left (2a) the result from the wind tunnel study [22] for a building size of 20\*40\*25 (w\*h), in the middle (v48) the result from the ENVI-met simulation at 13:00 o'clock for a building size of 20\*40\*20 (w\*h) and on the right the two outcomes combined.

of 4.9–6.4 °C. The main responsible parameter is the wind speed that is lowered drastically at the East and West receptors because the receptor points are closer to the building façade. Because of the smaller distance to the façade, the radiation also increased slightly due to multiple reflection of shortwave radiation and long wave radiation from the building façade. In this case, the addition of buildings results in extra up heating at 13:00 h because of the decreased wind speed and the additional reflection from facades. Especially the space in between buildings is changed substantially with additional radiation and a lower wind speed, as shown in Figs A.1 and A.2.

Although the addition of buildings can lead to a lower wind speed and increase radiation on street level, they also cast shadow and high buildings can bend airflows downwards and increase wind speed at street level. The two latter principles will lower human thermal comfort. These principles, together with heat storage in hard surfaces, result in a cooler city in the morning compared to the surroundings of the city. Still in the afternoon and at night, cities are warmer than their surroundings.

4.8. Set H: Trees

Simulations of the overall effect, different positions, amount of trees, and different contexts are analysed in set H. The overall effect of trees during daytime is predominantly a cooling effect. The average PET of the four receptor points is given in Table 6. The variants with trees are 1.9–5.8 °C cooler, except for variant 35 with three trees perpendicular to the building façade which has an up heating effect of 0.3 °C.

All variants with a grid of trees on the East side (variant 36–39) have a significant cooler PET at the East receptor. The result is a PET between 22 and 32 °C as shown in Table 7. Thus, the trees result in the cooling of the PET of 10–20 °C compared to the PET of variant 6 without green. In all variants the trees cause a lower air temperature and especially a lower radiant temperature. The varying wind speed is also related to the presence or absence of grass. However, in this case

**Table 6**

The average PET from the four receptor points for the variants 6, 36, 37, 38 and 39.

	Average PET (°C)
Variant 6	41.5
Variant 34 parallel	37.0
Variant 35 perpendicular	41.8
Variant 36	36.1
Variant 37	37.6
Variant 38	39.6
Variant 39	35.7

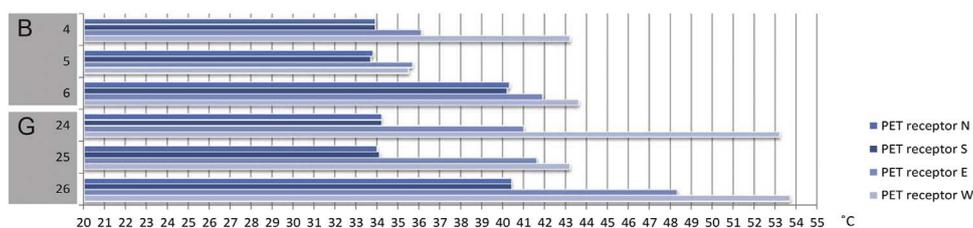
**Table 7**

The four parameters that influence the PET at the East receptor for the variants 6 and 36–39.

East receptor	PET (°C)	temp (°C)	RH (%)	Wind (m/s)	Radiation (°C)
Variant 6	41.9	26,58	66,67	1,79	69,37
Variant 36	29.4	25,24	80,29	1,52	42,18
Variant 37	29.9	24,30	76,05	2,44	50,76
Variant 38	31.7	25,42	74,88	2,33	51,64
Variant 39	21.9	24,78	66,69	1,58	24,27

the lower wind speed does not overrule the cooling effect of the air and radiant temperature on the PET.

Different positions of trees in relation to a façade are analysed in variants 34 and 35: a row of three trees on the leeward side of a single building, respectively parallel and perpendicular to the façade. The average PET of the four receptor points show a difference of 4.8 °C between variant 34 and 35 in Table 6. The receptor on the West side is responsible for this large difference, as shown in Fig. 20. When the trees are placed parallel to the building, the receptor on the West side indicates a PET of 26 °C. If the trees are placed perpendicular to the building, the PET increases with almost 10 °C to a PET of more than 45 °C. The latter situation even results in a higher PET than in variant 6 where no trees are present.



**Fig. 19.** The PET for two buildings in variant 4–6 and 24–26 in set G at 13:00 h at 1 m height.

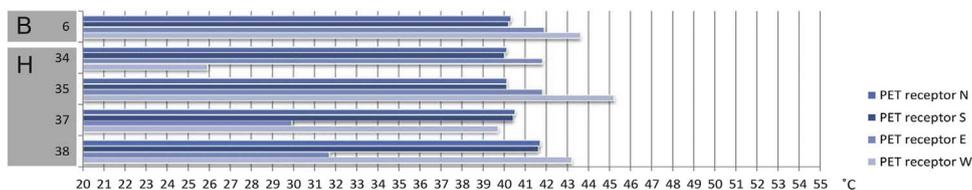


Fig. 20. The PET for trees in variant 6, 34, 35, 37 and 38 in set H at 13:00 h at 1 m height.

Table 8

The four parameters that influence the PET at the West receptor for the variants 6, 34 and 35.

West receptor	Temp (°C)	RH (%)	Wind (m/s)	Radiation (°C)
Variant 6	26,19	62,31	1,27	69,66
Variant 34 Parallel	26,09	63,45	0,75	28,68
Variant 35 perpendicular	26,21	62,89	0,94	69,69

Table 9

The maximum effect on the PET measured at one of the receptor points and the average effect in PET of the four receptor points for the set of variants A to D and G to M.

	Maximum ΔPET for a single receptor point (°C)	Average ΔPET (°C)
A. Pavement versus grass	-8	-5.5
B. Single building versus empty field	-8	-0.6–0.7
C. Wind direction change (North, South, East, West, North-East and South-West)	3	0.0–0.9
D. Wind speed: 1 m/s versus 6 m/s	-12.4	-11.6
E. Area rotation		
F. Single building with different heights: 8 m versus 20 m	-1.5 and 3.5	0.5
G. One building versus two buildings	10	3.5–4.2
H. Single building without trees versus with trees	-20	-5.8–0.3
I. Grid size		

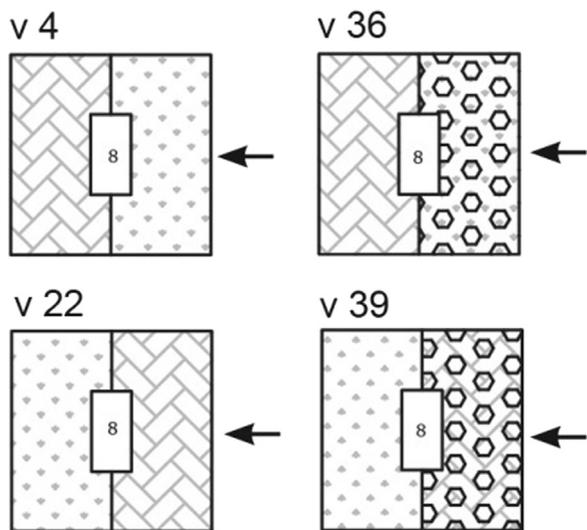


Fig. 21. Variant 4 with grass on the East side, variant 36 has additional trees on the East side, variant 22 has grass on the opposite West side and variant 39 has additional trees on the East side.

Zooming into the PET components given in Table 8, it is clear that the large difference in the West receptor between variant 34 and 35 is caused by the difference in radiation. In variant 34 the receptor is most likely shaded by one of the trees resulting in a decrease of the radiant temperature of 41 °C. The trees also reduce wind speed, which has a counter-effect and causes a slight up heating. Variant 6 without trees has a higher wind speed and therefore a cooler PET of more than 1 °C compared to variant 35.

The amount of trees is analysed by placing only three trees in variants 34 and 35, a grid of trees (45 trees) covering half of the area in variants 36, 38 and 39 and a grid of trees covering the whole area in variant 37 (81 trees). In Table 6 the average PET per variant indicates that more trees do not necessarily lead to a lower thermal comfort sensation. For example, variant 37, with a grid of trees covering the whole area, is not the coolest. The lowest average PET is achieved in variant 39 with trees at the windward side.

The effect of trees can be different depending on the context they

are placed in. In this set of variants the different contexts are: trees placed in a grass field (variant 36) or in pavement (variant 39). Comparing the variants in Fig. 21 that have grass at the opposite side with and without trees we can see the effects of these parameters applied together. In Fig. 22 the simulation outcome per receptor is given. The North and South receptors show a higher PET of 2–6 °C for the variants with trees (36 and 39) compared to the variants without trees (4 and 22). The receptor at the East side shows a lower PET of 6–14 °C for the variants with trees (36 and 39) compared to the variants without trees (4 and 22). The trees have a local cooling effect because they do not lead to a cooler PET at the other receptor points, they even increase the PET at the leeward side of the trees because of a lower wind speed. The average cooling result of trees planted at the East side is given in Fig. 8 and is about 1 °C. The receptor at the West side shows a higher PET of 2–4 °C for the variants with grass at this side (22 and 39).

The analysis of these simulations with trees shows that the measurements at the receptor points are highly influenced by the exact location. Thermal comfort can be increased on a hot day in the shade of a tree, while the same tree could decrease comfort when the person stays, simultaneously, under the sun and in the wake of the tree. The large variation within a small distance from a tree gives people a choice where they feel most comfortable in relation to their kind of activity. Other studies confirm that trees can locally improve comfort significantly by shading [13,42,48,49]. Also the evaporative cooling effect of trees can be significant for thermal comfort sensation and is highly dependent on the availability of water [50].

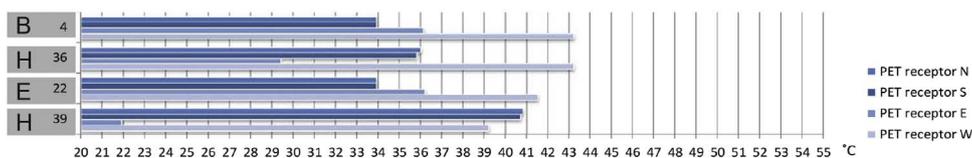


Fig. 22. The PET for trees in variant 4, 36, 22 and 39 in set H on 13:00 o'clock at 1 m height.

## 5. Discussion and conclusion

In this paper effects of changes in the urban context and weather on thermal comfort are compared based on the PET (Physiological Equivalent Temperature). The simulations start with very simple situations and increase complexity step by step. The higher the complexity, the more difficult it is to predict the effect on thermal comfort at a specific location. This is in accordance with the findings of a study by Gulyás, Unger [19/26], which states that: “complex urban environments can result in very different and often extreme comfort sensations even within short distances”. Most simulation results we found can be explained by known effects about wind flow around buildings and trees and by looking at the changes in air temperature, humidity, wind speed, and mean radiant temperature.

The method used in this study allows a comparison between the effects of urban changes on thermal comfort because the simulations are all based on the same model and have the same input and output parameters. It is the first time such an extended comparison is done for the temperate climate. In addition, the detailed analyses show the underlying principles of some microclimatic effects. One finding from the simulations is that the type of pavement can have a significant effect for the whole area, while the effect of trees depends highly on the position of the tree and the receptor (measurement) point. Multiple receptor points are used to get an overview of the effect within the area. The more points there are, the better the effect can be estimated and evaluated. The average PET of the receptor points gives the overall effect in an area. However, a rationale is important to determine whether you need improved thermal comfort in the whole area or perhaps only on a few spots. A recommendation is to place the measurement points in places where the designer/researcher wants people to feel comfortable. Thus the focus will be on getting the best results at these specific locations.

The methodology chapter 2 gives a description of the limitations in the ENVI-met model. Differences in urban situations can be compared accurately with the model which is based on sound and proven formulae. A summary of the simulation results are presented in Table 9.

Below, the main findings from the summary in Table 9 are discussed and the effects are described separately in the sections that follow. Vegetation shows to be the most effective in cooling, as many other studies have also indicated. The maximum cooling effect found in this study with trees is 20 °C and with grass 8 °C. Interestingly, the average cooling effect considering a whole area leads to a different order of effectiveness, which especially indicates the significance of wind speed on the PET, where an increase of wind speeds results in a lower PET. Also the addition of buildings can have a significant effect, but is very depended on the surrounding context, whether it leads to up heating or not. Building form and height seem to have a smaller significance compared to vegetation, wind speed and amount of buildings.

The comparison of grass with pavement shows that grass gives a lower comfort temperature compared to brick pavement in the following cases: in an open field, in combination with a building and at both the leeward and windward side. Grass even lowers the surrounding paved area with 1 °C. The difference in PET between grass and brick pavement ranges from 0.1 to 8 °C, with an average of 6 °C.

The influence of a single building can lead to cooling, but can also increase the PET at pedestrian level, depending on the location in combination with the wind direction, sun orientation, building properties and the materialization and greening of the surrounding. In this study the effect of a building placed on a grass field leads to cooling, while when placed on brick pavement the building leads to an increase

of the PET. More research is needed to know the effects on the PET of various albedo values and building heights.

The direction of the wind caused a difference in the average PET (from four receptor points) around the single building up to 0.9 °C. The leeward side of the building is 1.5–3 °C warmer when the wind direction is perpendicular to the building. The effect of a higher wind speed results in a lower PET. For the tested wind speeds from 1 m/s to 1.5 up to 6 m/s the PET at the windward side decreases between 1.6 and 6.1 °C.

By turning the area, situations are studied in which the wind does not blow across grass and then brick pavement but only across one of these materials. In this case the grass side does not show a cooler PET than the brick side, as was the case in the variants described in the second paragraph of this section. The parameter responsible for this contradicting effect is a decrease in wind speed caused by the grass.

The addition of buildings creates cooler and warmer areas because of their impact on shadow pattern, wind speed, and long- and short-wave radiation. In general, buildings provide a cooler direct environment in the morning and a warmer afternoon and evening.

Trees and other vegetation cause a lot of variation within an area. Thermal comfort can be increased on a hot day in the shade of a tree, while the same tree could decrease comfort when the person is in the sun and in the wake of the tree. The large variation within a small distance from a tree gives people a choice where they feel most comfortable in relation to their kind of activity.

Note that the conclusions given above, apply to the specific simulation variants chosen for this study. In a different urban context, another climate or with deviating input parameters, urban changes might lead to another outcome in terms of thermal comfort. Many more variants are interesting to analyse in the same manner, especially the amount and position of vegetation, higher buildings, different building configurations and the effect of the albedo of roofs and facades on thermal comfort. This is part of follow-up studies.

The general conclusion from this study is that large temperature effects can be achieved with measures that influence wind speed and mean radiant temperature. Yet these effects remain local. Measures that influence air temperature and humidity are more effective on a wider scale. A shadow device, for example, that protects people waiting for the bus normally does not contribute much to thermal comfort in the rest of the street, in contrast to a tree that offers shade and also cools the air actively by evaporating water, and therefore, has a wider range of influence. In the case of a bus stop more properties are important to consider, such as: protection from rain, space for the bus lane and aesthetics. In the design of a bus stop the best of both worlds could mean the integration of a grass roof or climbing plants which have both a large local effect as well as a small effect on the city climate. The answer to the question from the introduction: ‘which measures require more research or should be implemented more frequently?’ is described above and is related to the desired effect. Thermal comfort in the outdoor environment is not a static situation, but depends on people's activities, clothing, age and acclimatization. Always consider the broader perspective when designing within the urban microclimate.

## Acknowledgements

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**Appendix A**

See Appendix Figs. A1–A3.

In Appendix A the simulation results in addition to the air temperature results in Fig. 4 are represented graphically in wind speed (Fig. A.1), mean radiant temperature (Fig. A.2) and humidity (Fig. A.3).

Variants overview - output in wind speed

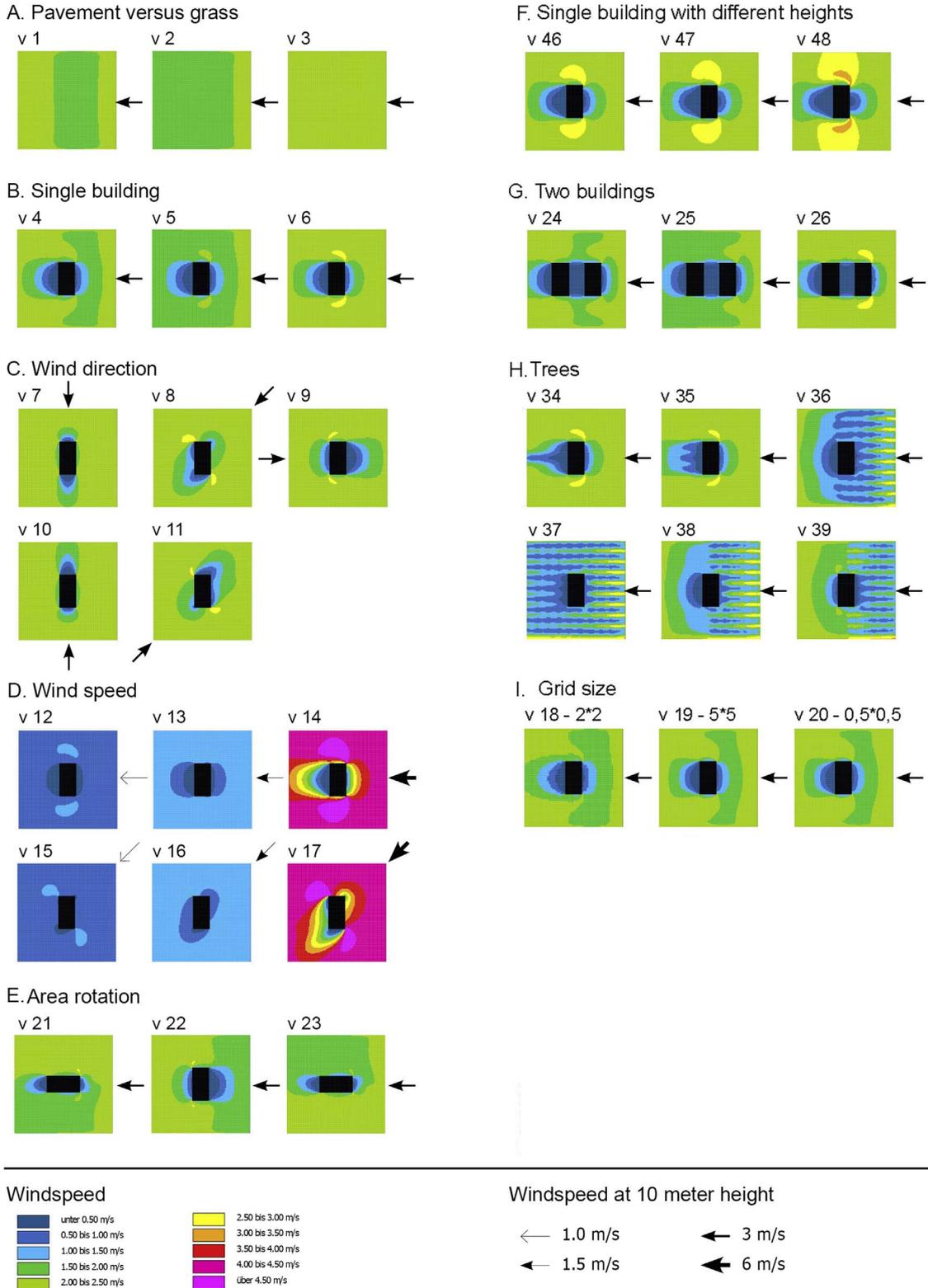
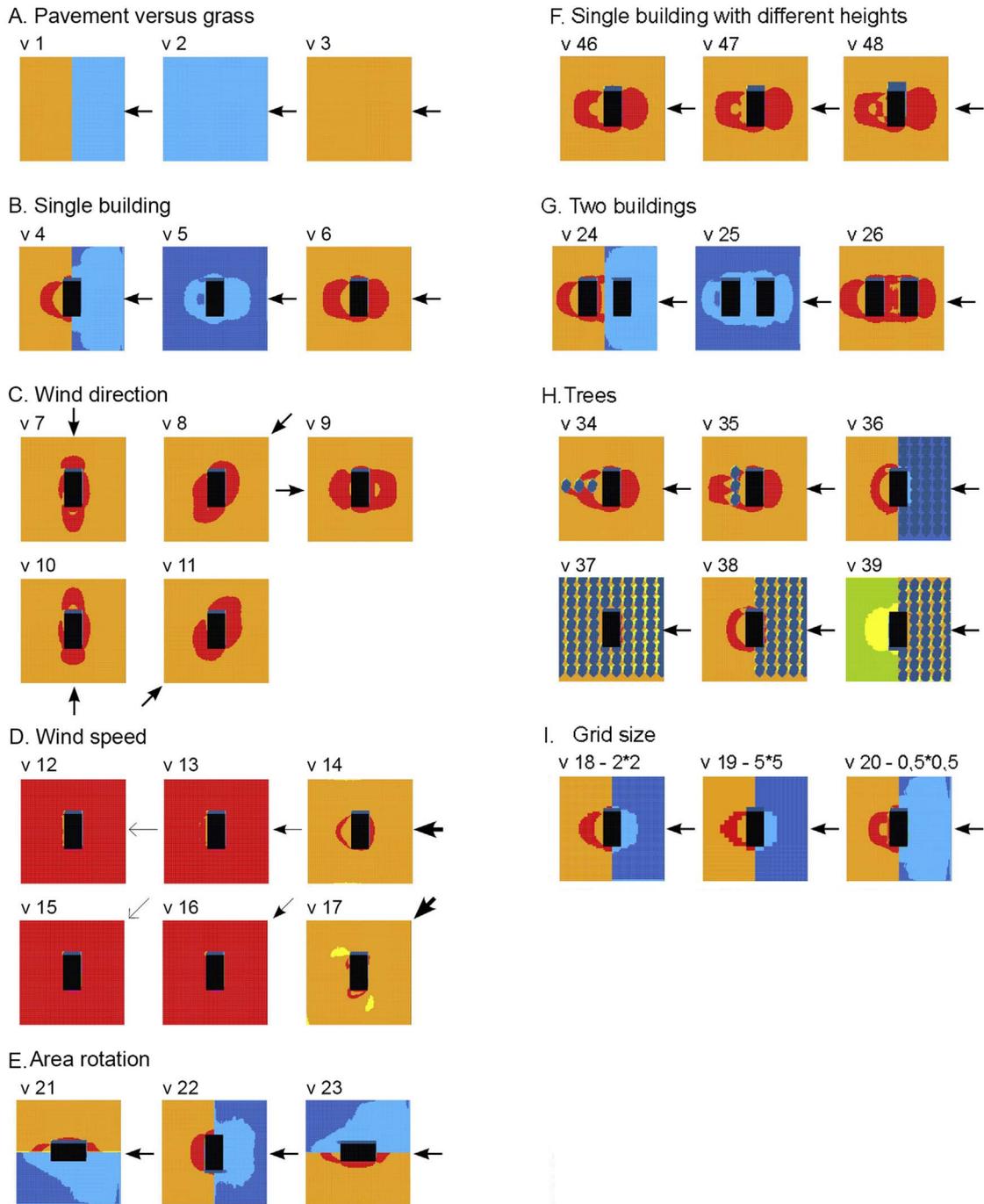
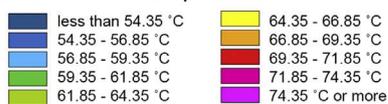


Fig. A.1. The wind speed on 13:00 o'clock at 1 m height by the graphic program LEONARDO.

Variants overview - output in mean radiant temperature



Mean radiant temperature



Windspeed at 10 meter height



Fig. A.2. The mean radiant temperature on 13:00 o'clock at 1 m height by the graphic program LEONARDO.

Variants overview - output in relative humidity

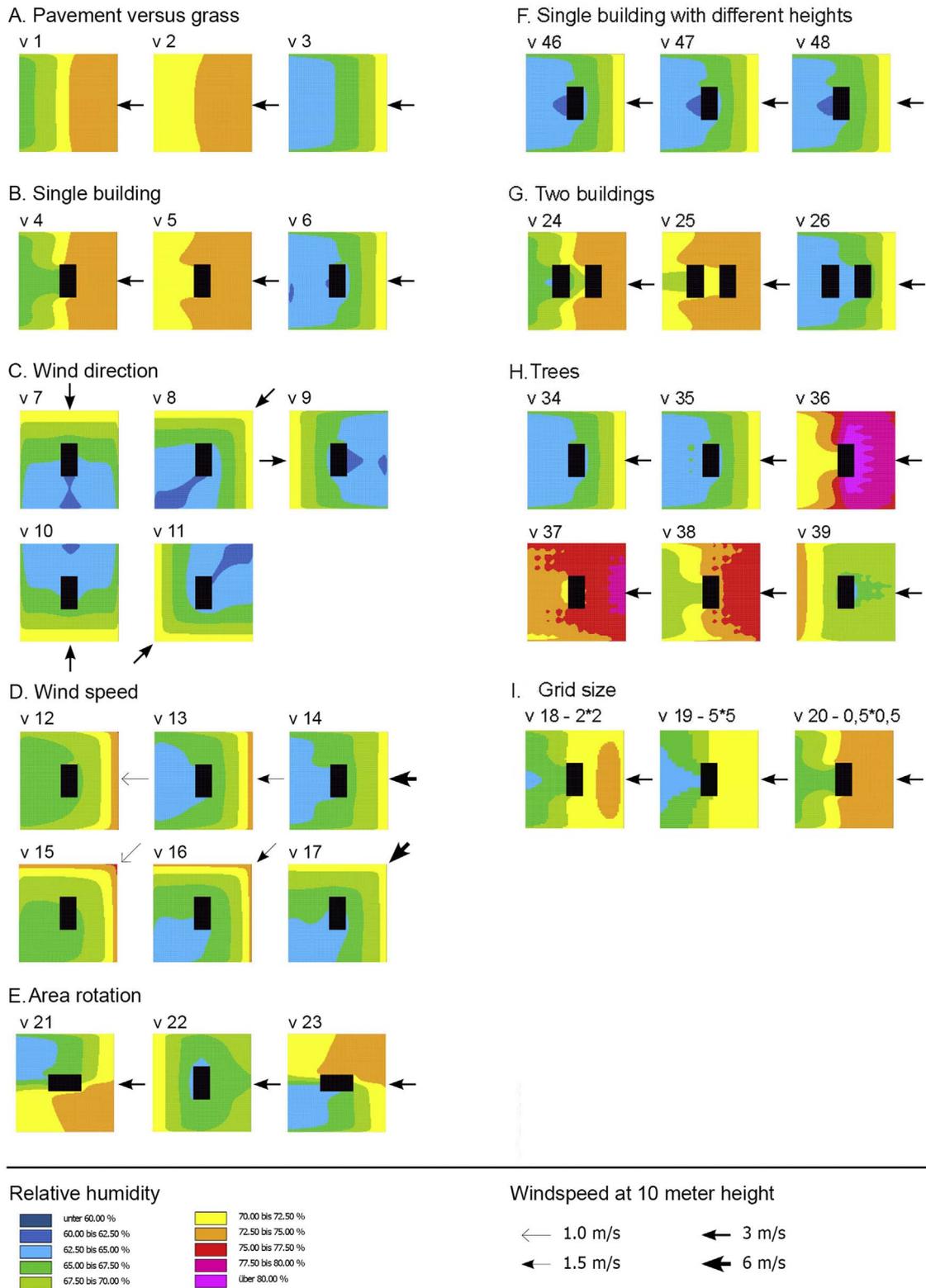


Fig. A.3. The humidity on 13:00 o'clock at 1 m height by the graphic program LEONARDO.

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