THE POTENTIAL OF VENTILATION CORRIDORS TO MITIGATE URBAN HEAT ISLAND EFFECT

- CASE STUDY BUDAPEST -

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THE POTENTIAL OF VENTILATION CORRIDORS TO MITIGATE URBAN HEAT ISLAND EFFECT
- CASE STUDY BUDAPEST -

FOCUS WORK
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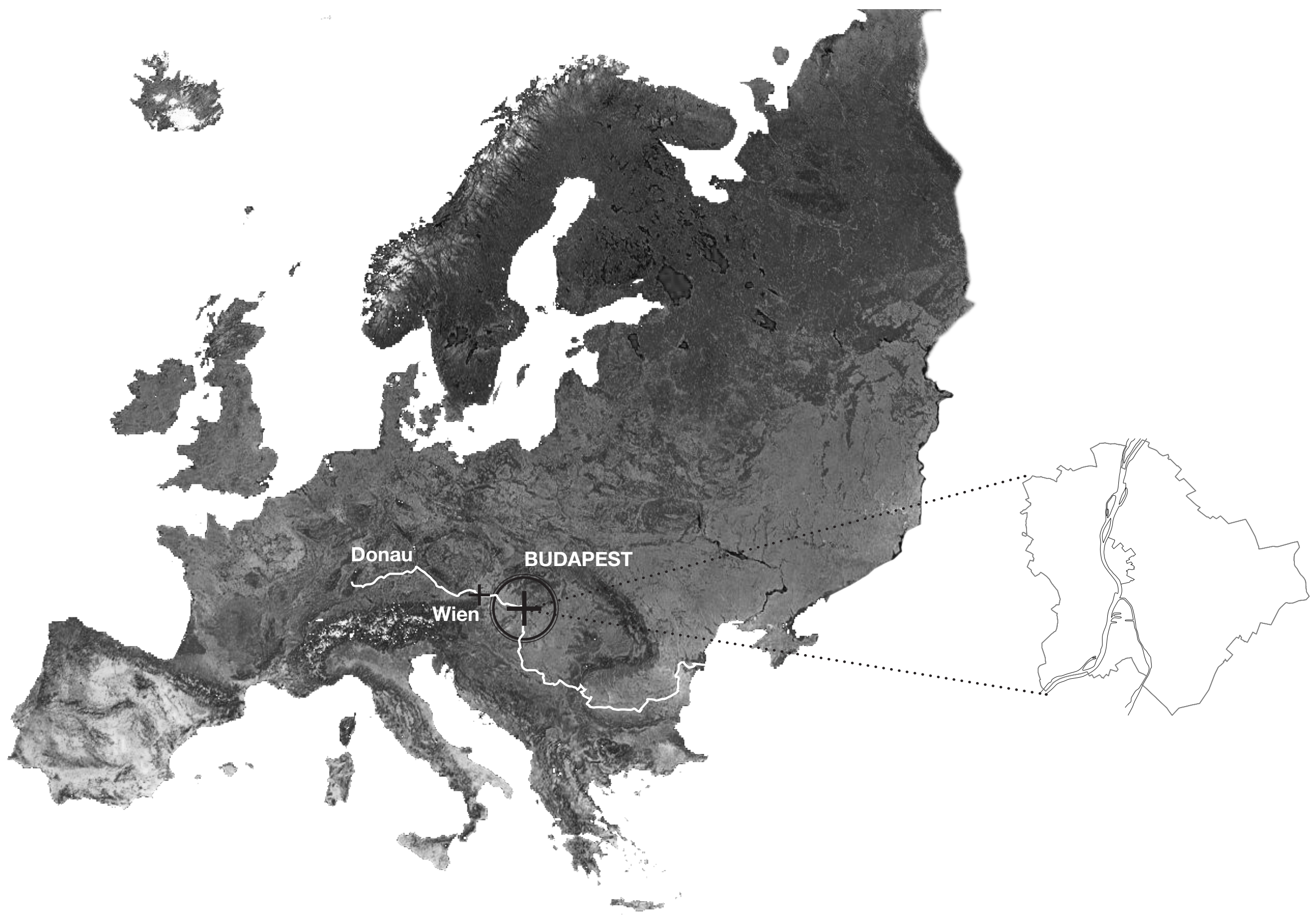


FIG.1: SITE: BUDAPEST

1. INTRODUCTION

Global warming is unquestionably one of the biggest challenges of our time. Facing unbearable heat, Qatar has begun to air-condition outdoor spaces (Mufson, 2019) , Swiss residents wrap glaciers in blankets to prevent them from disappearing (Schlanger, 2018), there are even concepts to pump artificial snow on the Antarctic to slow down its melting process (Green, 2019). Whether these ideas are the most intelligent or effective solutions for these questions remains unanswered. Nonetheless, it shows that there seems to be a beginning of a new era in urbanistic and territorial planning when humans not only predict and try to mitigate the process of global changes, but desperately attempt to counteract them with direct actions on urban/territorial scale.

There is a need for real actions and new urban spatial concepts which demand a theoretical foundation in urban physics. As such, the interdisciplinary field between urban physics and urban planning will probably gain an enormous importance. This work targets precisely this field and will focus on the possibilities for the mitigation of urban heat island effect (UHI). Half of the world's population lives in cities, where the impact of global warming even increases due to the urban heat island effect. Unsurprisingly, the problem of UHI has become one of the most significant concerns of contemporary urban planners and designers. Still, cities have very little knowledge and idea on how to mitigate urban air temperature (HSIEH, 2016). Scientific discussions of the last decade pointed out that establishing urban wind corridors could be one of the main mitigation strategies for UHI (CHANG, 2018). Enhanced wind velocity can reduce air temperature by evaporative cooling, leading not only to comfortable outdoor temperatures but also helping to clean the air from pollutants. However, these processes depend on the climatic profile of the city. The study area of this current work is the city of Budapest. It is a capital with 2 million inhabitants and has a typical continental climate, therefore, it is extremely exposed to the effect of UHI. The climate is hot in summer, air temperature often goes up to around 40 °C, and at the same time it is also quite dry with very little precipitation. Nevertheless, this combination of high air temperature and low relative humidity provides the perfect condition and opportunity to develop concepts using evaporative cooling. As such, an urban concept of ventilation corridors offers a real promise to the city.

This semester project explores various urban climate and air flow tools to evaluate their suitability for climate driven urban planning at the example of Budapest. Recently released digital tools, including free online plugins, enable architects and urban planners to involve quantitative climate knowledge into their planning. The idea that architects and urban planners can involve more specified analysis into a holistic understanding could lead towards a new way of thinking and facilitate a more interdisciplinary approach in urban planning. Thus, especially the combination of quantitative and qualitative analysis is in the focus of this study.

After a brief literature review and method overview, this research includes four kinds of studies: an urban structure analysis, a climate analysis, a thermal map analysis and CFD analyses. The purpose of this project is to identify the mesoscale ventilation corridors of Budapest with the combination of these different analyses.

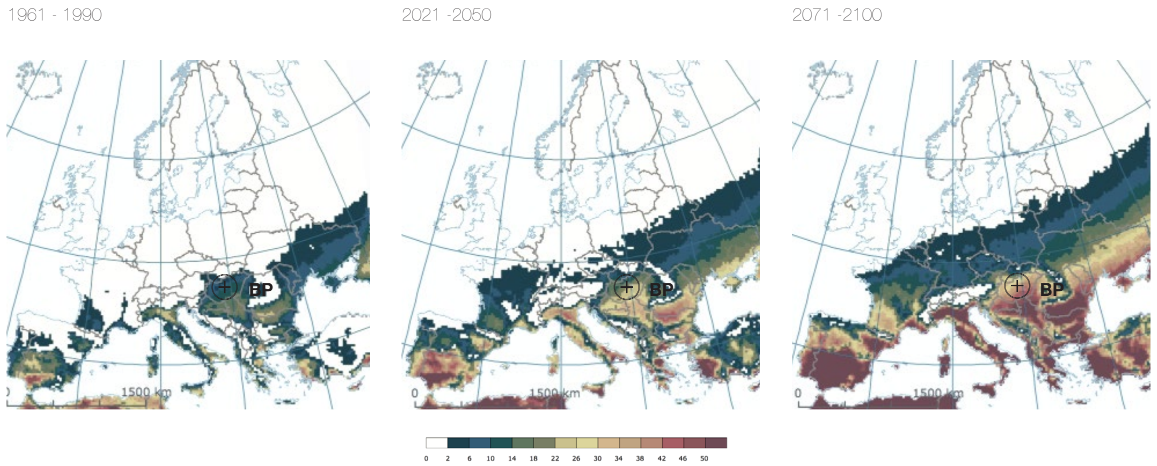
This document is designed as a storyboard relying majorily on images and figures, hence allowing an accessible presentation of the topic to architects and urban designers. Therefore, it may serve as a general guideline and introduction to the topic and hopefully stimulating further projects in climate informed urban planning studies for other cities and regions.

2. LITERATURE REVIEW

The literature review contains in the first part some quantifications about global warming and its predictable effect in Europe and especially in Budapest. In the second part, it creates a brief overview regarding the urban boundary layer (UBL) and meso and localscale ventilation simulations.

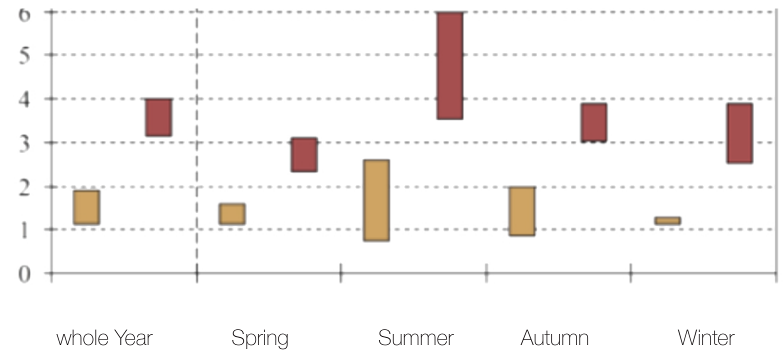
2. LITERATURE REVIEW

2.1. GLOBAL WARMING / EFFECT ON BUDAPEST

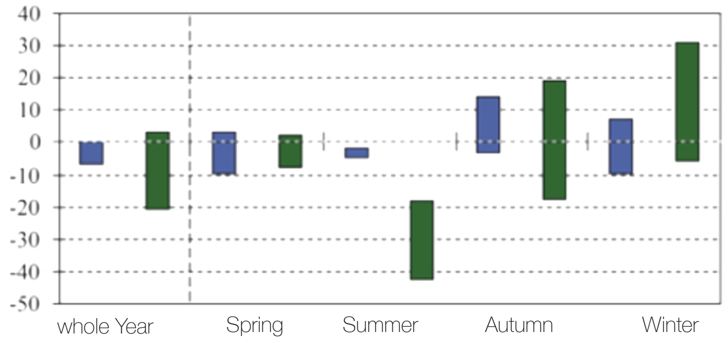


Number of combined tropical nights (>20°C) and hot days (>35°C)
(EEA, 2012)

FIG. 2: GLOBAL WARMING IN EUROPE IN THE NEXT 100 YEARS
For the site I have chosen Budapest, on the one hand, because I come from there, and on the other hand, because it is a large European city that is already struggling with extreme heat waves. Its climate will be enormously affected by global warming. As we see from these forecasts, that the climate zones will also shift in Europe, and scientists predict that in 50 years e.g., Budapest's air temperature in summer will be on the level which North Africa had in the 90's.



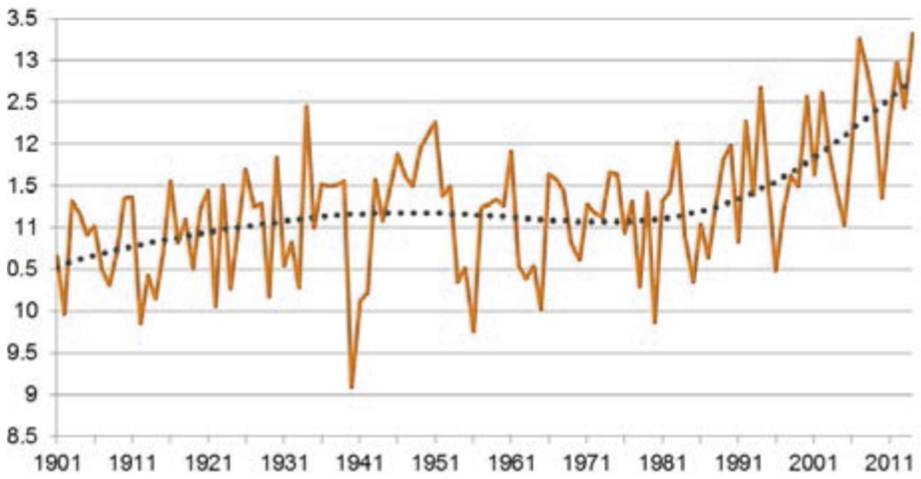
The likely change in average temperature (°C) between 2020-2050 (brown columns) and 2070-2100 (red dark columns)
(BFÖ, 2018)



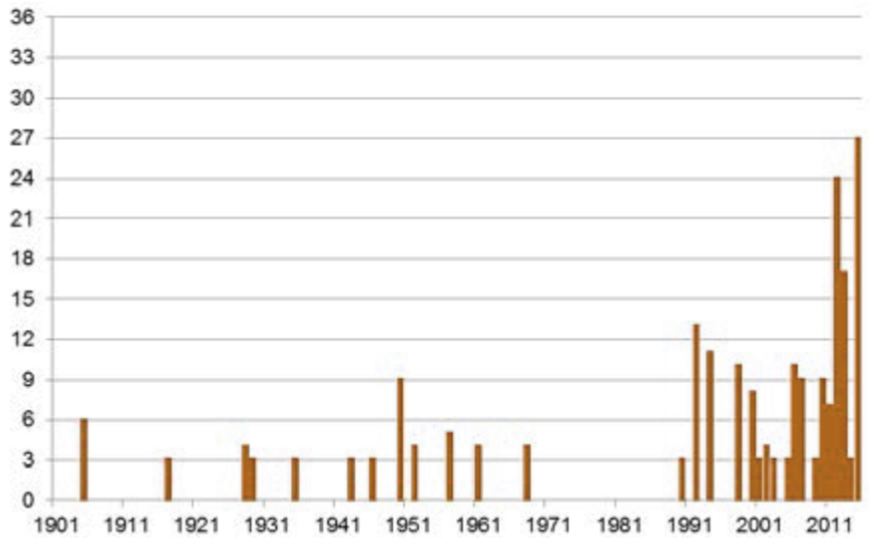
The likely change in average precipitation (%) between 2020-2050 (blue columns) and 2070-2100 (green columns) (BFÖ, 2018)

FIG. 3: THE PREDICTION OF THE CHANGE IN TEMPERATURE AND RAINFALL IN THE 21ST CENTURY.
In Budapest, one third of the summer days are already considered as hot. (see also Fig. 14) Moreover, the summer case is changing more rapidly than the winter and in 70 years will be up to 6 degrees warmer on average. At the same time, precipitation will predictably decrease.

2.1. GLOBAL WARMING / EFFECT ON BUDAPEST



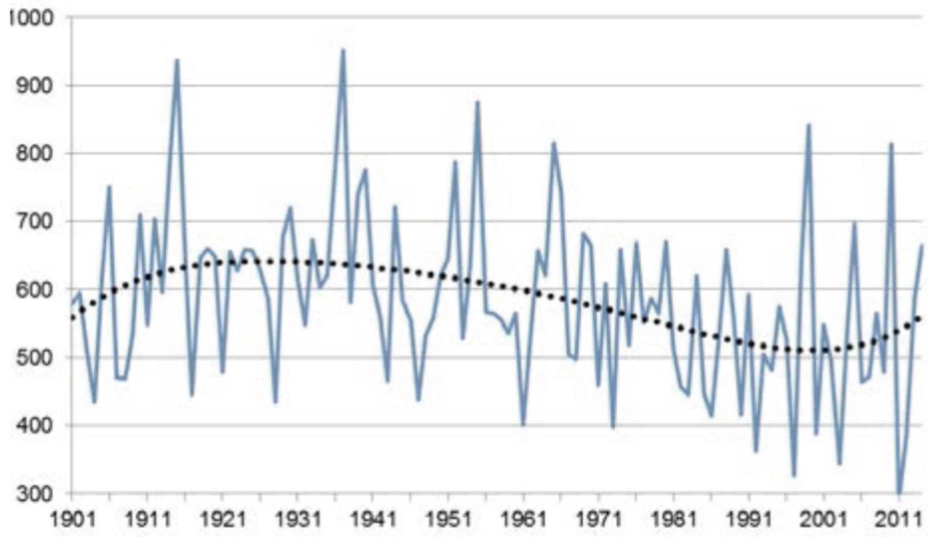
Average annual outdoor temperature (°C) (BFÖ, 2015)



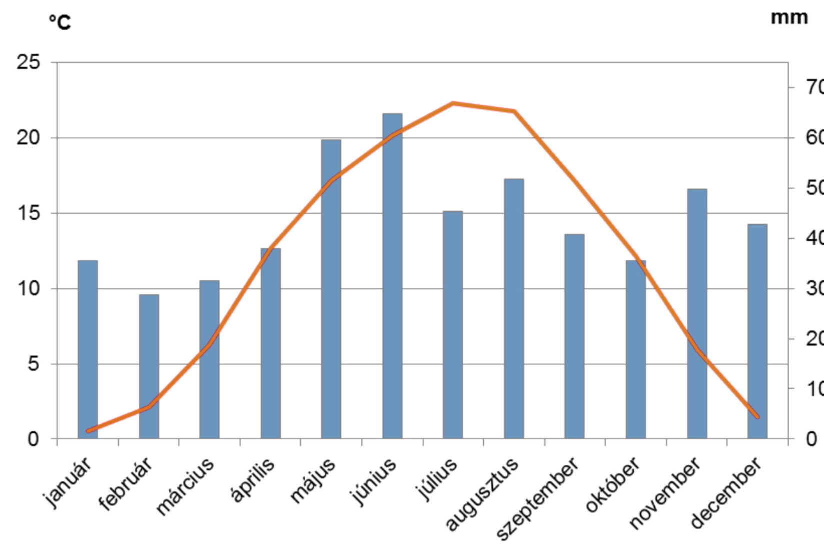
Number of days which were at least above 27°C, Budapest (BFÖ, 2015)

FIG. 4: DRY BULB TEMPERATURE:IT'S GETTING WARMER

In Budapest, one third of the summer days are already considered as hot. Not only the annual average outdoor temperatures are rising, but the number of hot days as well.



Average annual rainwater (mm) (BFÖ, 2015)



Average monthly rainwater (BFÖ, 2015)

FIG. 5: RAINWATER

The average monthly rainwater is today half of that of Zürich. As shown before, there is even a greater rainwater shortage to be excepted which will definetly increase the climate crisis in Budapest in the future.

2.2. THE URBAN BOUNDARY LAYER, URBAN CANOPY LAYER AND MESOSCALE VENTILATION SIMULATIONS

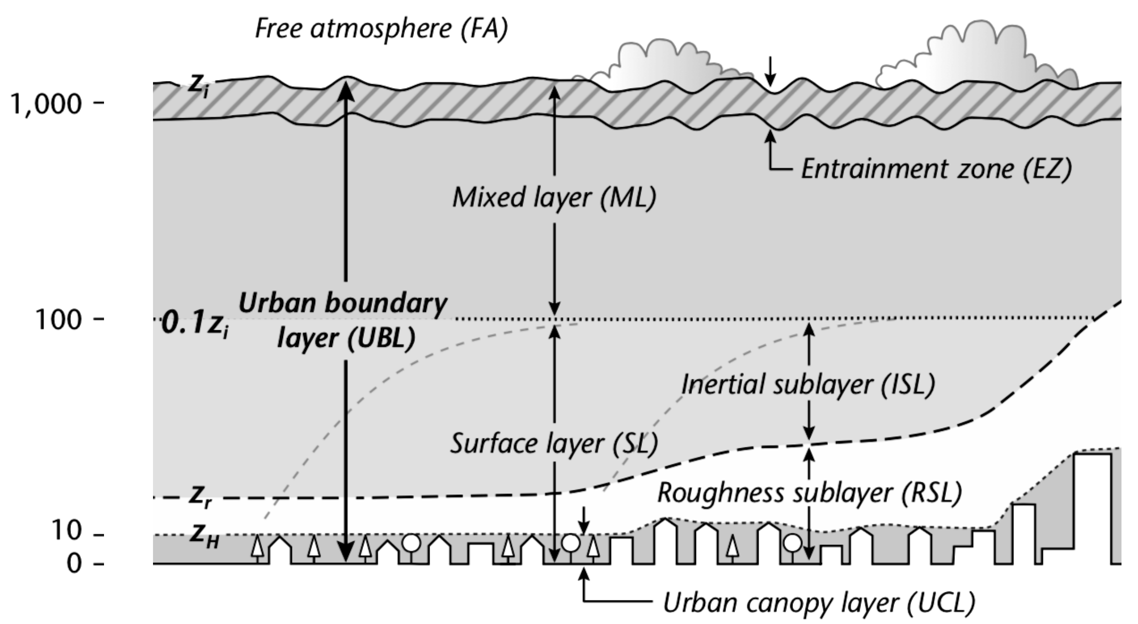


FIG. 6: ATMOSPHERIC BOUNDARY LAYERS DURING THE DAY
(OKE et. al., 2017)
"The urban boundary layer (UBL) is the part of the atmosphere in which most of the planet's population now lives, and is one of the most complex and least understood microclimates. Given potential climate change impacts and the requirement to develop cities sustainably, the need for sound modelling and observational tools becomes pressing." (Barlow, 2014, p.1)

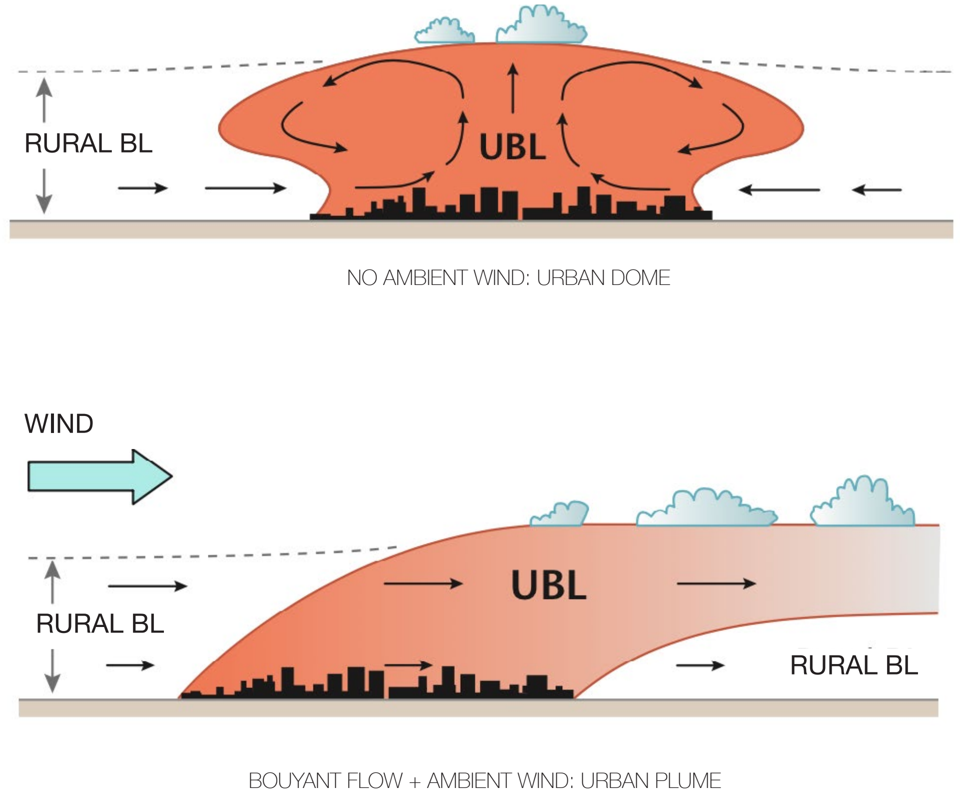
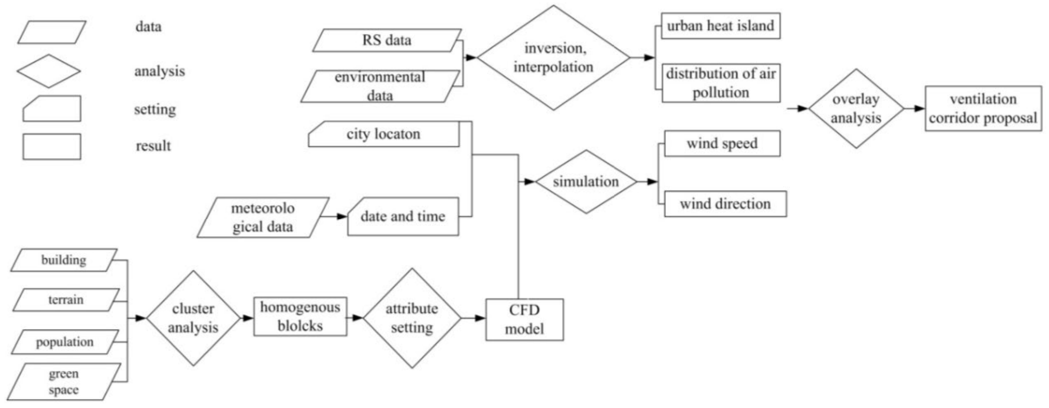


FIG. 7: THE COMBINATION OF WIND AND THERMAL DRIVEN FLOW: URBAN DOME AND URBAN PLUME
(OKE et. al., 2017)
"Typical overall form of urban boundary layers at the mesoscale: (a) urban 'dome' when regional flow is nearly calm, and (b) urban internal boundary layer and downwind 'plume' in moderate regional airflow." (OKE et. al., 2017, p.30)

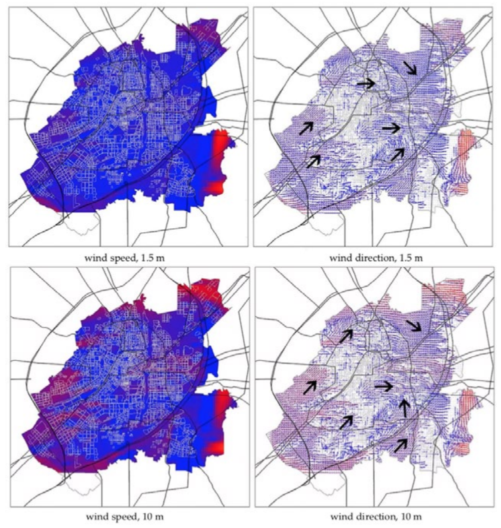
2.2. THE URBAN BOUNDARY LAYER, URBAN CANOPY LAYER AND MESOSCALE VENTILATION SIMULATIONS

SCALE	MESOSCALE/ MACROSCALE (over 10*10 km / some 100 kilometers)	MICROSCALE / LOCAL SCALE (some 100 meters / some kilometers)
METHOD	- diverse - finite difference method FDM	- CFD models - finite volume method FVM
ADVANTAGE	- large areas and interrelations	- accurately resolve the urban roughness sublayer (RSL), urban canopy layer (UCL) - information about ventilation corridors in RSL +UCL
DISADVANTAGE	- not capable of resolving geometrically urban heterogeneous structures - low spatial resolution (1 km2* 5m) > based on assumption of a horizontal homogeneity	- limited scale

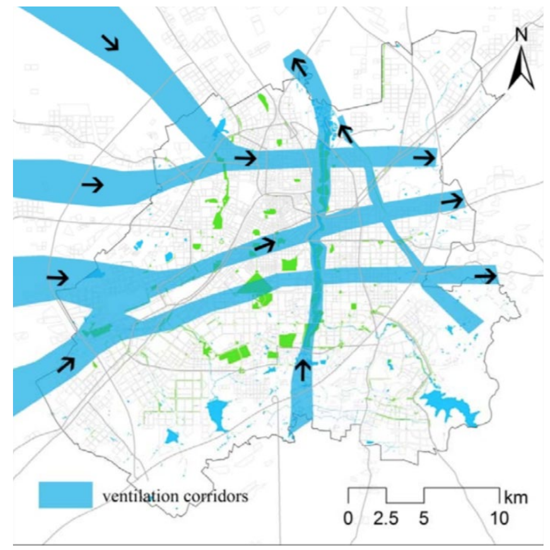
FIG. 8: MESOSCALE VENTILATION SIMULATION
Mesoscale ventilation simulations are especially challenging because of the complexity of the UBL (seen before Fig. 6-7). According to the conclusions of Piroozmand and Oke et. al. the advantages and disadvantages both meso/macroscale and micro/local scale simulations were collected.
(Piroozmand et. al., 2020, Oke et. al., 2017)



Method



CFD Analysis

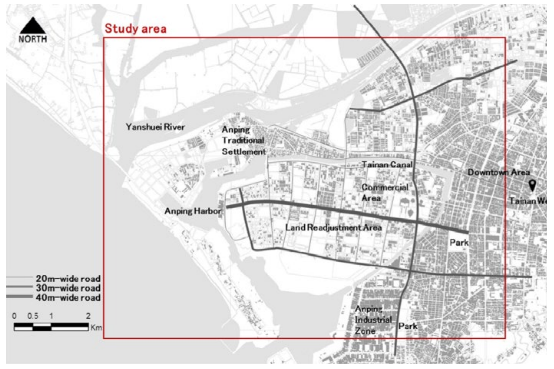


Ventilation corridors

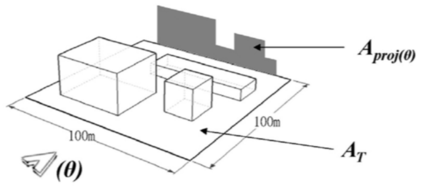
> GIS (spatial analysis - homogenous blocks) + CFD
> LOCAL / MESO SCALE: 30*30 km
> for two winddirections (summer and winter prevalent wind, different heights)
> Changchun City, China

FIG. 9: MESOSCALE CFD ANALYSIS
(CHANG et. al., 2018)
Mesoscale CFD analysis is still a seemingly impossible task because of its computational demand. Therefore, scientist creatively use a combination of different methods. Chang et al. combined a GIS analysis with CFD analysis of homogenous blocks to predict the ventilation corridors of Changchun City in China. According to them, they used the advantages of both analysis: "Computational fluid dynamics (CFD) has advantages in the fine assessment of wind environment, and a geographic information system (GIS) has excellent performance in spatial analysis." (CHANG et. al., 2018) The idea and logic of the use of small scale CFD models with a combination of large scale analysis was also the base of my own method.

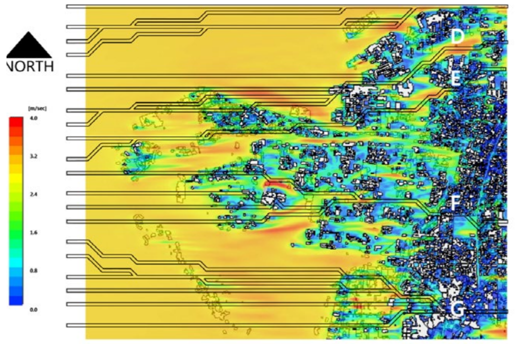
2.2. THE URBAN BOUNDARY LAYER, URBAN CANOPY LAYER AND MESOSCALE VENTILATION SIMULATIONS



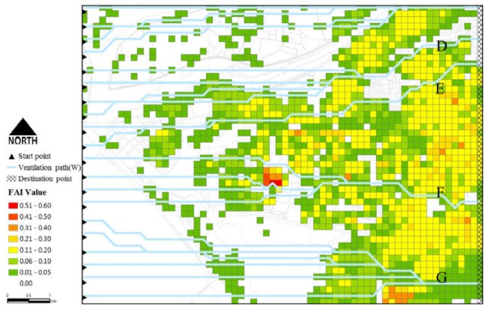
Site: Taiwan

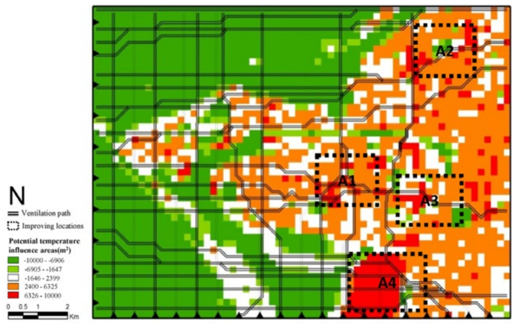


Geometry simplification - Grid



CFD Analysis - wind speed, Direction: West

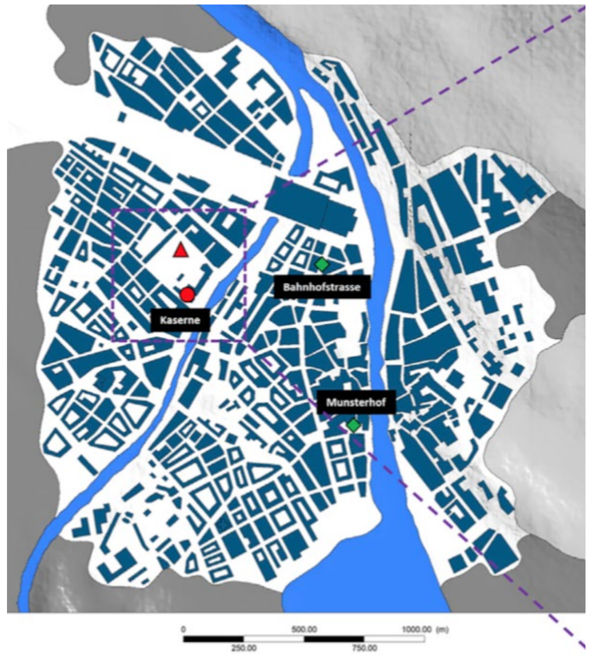




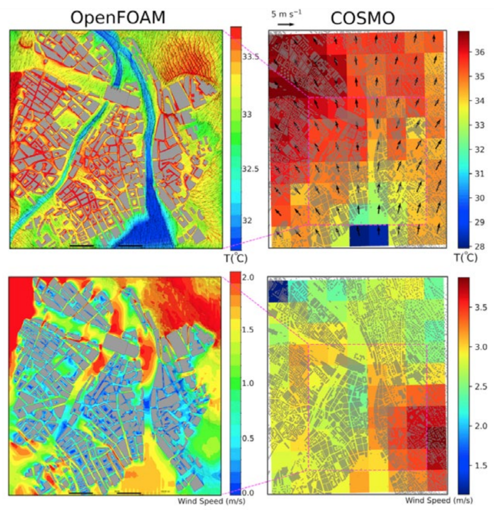
Least cost path (LCP) wind corridor for Western wind (GIS) Improvement locations of selected study area

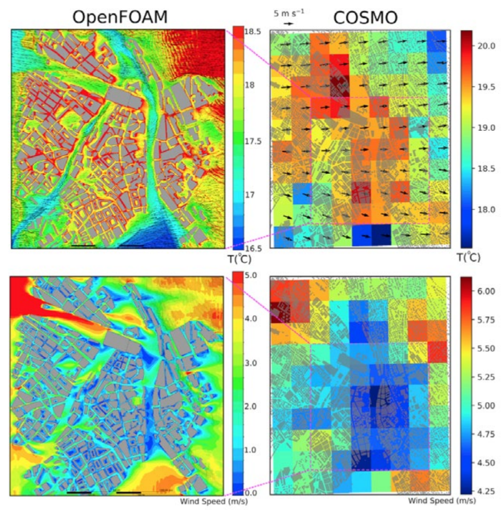
> OpenFOAM (CFD) model is superimposed to the LCP GIS model (least cost path)
> LOCAL SCALE: 6,4 km * 4,8 km
> for 2 wind directions
> Site: Anping Harbor in Tainan City, Taiwan.

FIG. 10: LOCAL SCALE CFD ANALYSIS
(HSIEH et. al., 2016)
"This study maps out ventilation paths that are expected to draw in breezes from suburban areas and the sea to mitigate the urban heat island effect in Tainan City. Wind corridors are estimated based on the concept that wind moves along paths of low urban roughness, as defined by the frontal area index (FAI) and the least cost path (LCP) methodology followed in this study." (Hsieh et. al., 2016) The idea that if we are able to define the urban roughness and define where the wind will be blocked (frontal area index) was inspirational for my own study.



Site: Zürich





July 2, 2015, between 12 and 1 pm.   June 23, 2015, at 12 and 1 pm.

> OpenFOAM (CFD) model is coupled to the COSMO (regional atmospheric model)
> LOCAL SCALE: 2,5 km * 2,5 km
> for 2 SPECIFIC TIME OF THE YEAR 2015
> Site: Zürich, Switzerland

FIG. 11: LOCAL SCALE CFD ANALYSIS
(PIROOZMAND et. al., 2020)
In this study the OpenFOAM model is coupled to the regional atmospheric model COSMO in order to provide boundary conditions for atmospheric variables. The effort to integrate the regional atmospheric movements can help to capture the complexity of the processes of the UBL. (Piroozmand et. al., 2020) However, at the same time the study analyses two specific hour of the year and therefore it takes away the holistic level of the approach.

3. RESEARCH METHOD

My research question is to find out where the ventilation corridors of Budapest are. In addition, to identify blockages and areas that should or could be improved. I conducted a variety of analyses and combined quantitative and qualitative methods with the help of various Grasshopper plugins, summarized in Fig. 12. As pointed out in the literature review, the challenge of the mesoscale analysis is both the complexity of the processes (most importantly, the impact of buoyant flow on the wind-driven flow) and the scale of the analysis area as well as its computational demand. Therefore, the basic idea of the method is, on the one hand, to divide thermally driven and wind-driven flow in order to reduce the complexity and computational demand of the simulation. On the other hand, to combine the quantitative and qualitative method. CFD simulations will be conducted only for smaller blocks of homogenous urban structure (Local Climate Zones) and the results will be qualitatively upscaled to the level of the entire city. This approach is based on the study of Chang et. al (2018).

Therefore, in the first step, in the Ladybug analysis, I tried to understand when synoptic effects and when thermal effects influence the flow. As has been shown before, without ambient wind the flow creates an urban dome. The combination of wind driven flow and thermal effects create an urban plume. The ambient flow dominates, if buoyant processes are negligible. The idea is that, with the help of a ladybug analysis, I can predict when or how often the wind is blowing and from which direction it is coming, and so that when there is an urban dome, an urban plume or just absolutely wind-driven flow. In this way, I can divide the different cases methodologically. In the case of the synoptic/wind-driven flow, I also divided the analysis spatially. I did a complete CFD only for the dense downtown area. In the outskirts, I was looking for possibilities for a combination of quantitative qualitative analysis. I have defined the local climate zones, in particular the areas that are open and allow the wind to blow through and the areas that block the ventilation. For each local climate zone, a CFD analysis was conducted. From this result, I qualitatively defined the wind-driven ventilation of the outskirts.

From the Landsat images, I discovered the hot and cool areas of the city, so it was possible to predict qualitatively the thermal-driven flow and the combination of thermal-driven and wind-driven flow. For each relevant wind direction (conclusion of Ladybug wind analysis), each quantitative (CFD) and qualitative flow analysis should be carried out. In this study, analyses were conducted only in one direction to demonstrate the logic of the method.

3. RESEARCH METHOD

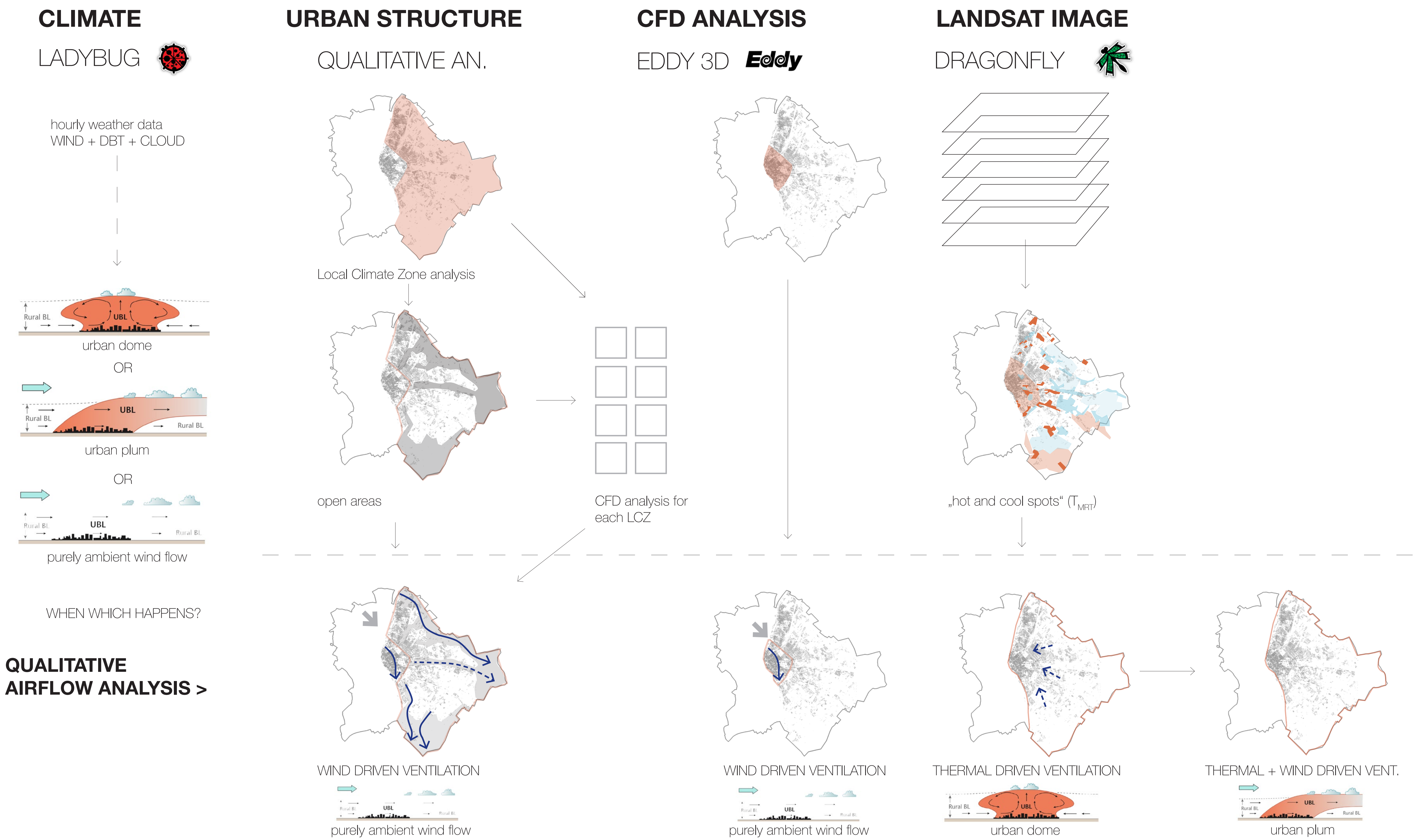


FIG. 12: OVERALL RESEARCH METHOD

4. URBAN STRUCTURE OF BUDAPEST

The Danube divides the two sides of the city, Buda and Pest. The hilly (mountainous) Buda has large forests, low rise and low-density area and therefore a very high green area ratio. (s. Fig. 13 to 14) The opposite is observable in the case of Pest, it is almost completely flat. It has a very urban character, a high density downtown with 4-5 story buildings and a very low green area ratio. The downtown of Pest is comprised by the so called “transition area” consisting a mixture of underused brownfields, industrial areas and areas which that have already been transformed. (s. Fig. 13 to 14) These areas could play a very important role in the development of the ventilation corridors of Budapest, because these industrial / brownfield areas are often the thermal hot spots of the city but at the same time, they have the potential of a largescale transformation. The dense urban areas, the high rises and the industrial areas of Pest make this side of the city much more affected by the urban heat island effect. That was the reason why this analysis focuses only on the ventilation corridors of Pest.

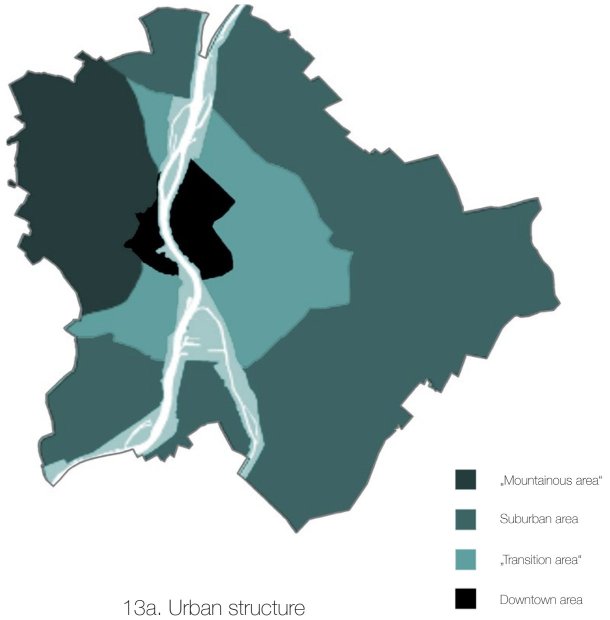
The urban structure analysis consists of three subchapters: the base maps, the local climate zone analysis and the street orientation analysis. The analysis of the general urban structure / base maps (chapter 4.1.) serves two objectives. First, it gives a background knowledge about the city, how it is structured, how does its terrain and urban tissue look like, where are the main roads, what are the uses of the areas and how is its green area ratio changes in the different urban zones. Second, from the conclusion of the analysis of the thermal maps I identified the thermal hot and cool spots of the city. The comparison of these spots with the urban structure reveals the reason behind why these spots are hotter and cooler.

The local climate zone analysis (Chapter 4.2.) has a central significance for the entire study, because it creates the base of the qualitative analysis for the identification of the ventillation corridors of the city. (s. Fig. 17-18 of open and closed areas and chapter 7.)

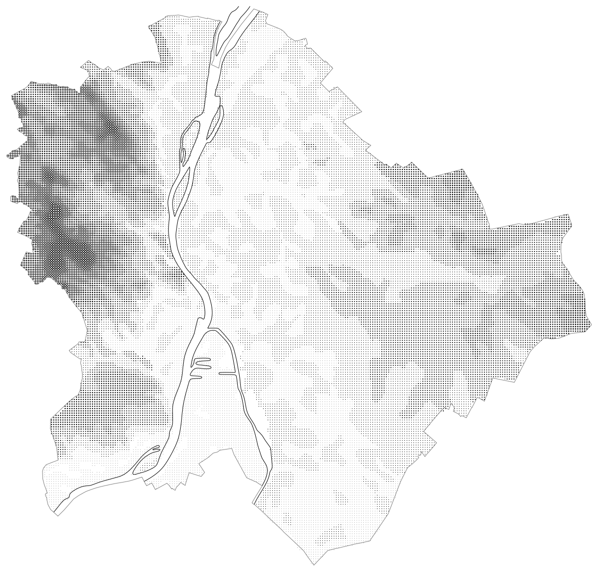
The street orientation map (chapter 4.3.) is not strictly part of the method, but it is also a qualitative analysis of the street structure that can give a quick and effective impression as to whether the city is well ventilated or not. The method and results are described in more detail in chapter 4.3.

4. URBAN STRUCTURE OF BUDAPEST

4.1. BASE MAPS

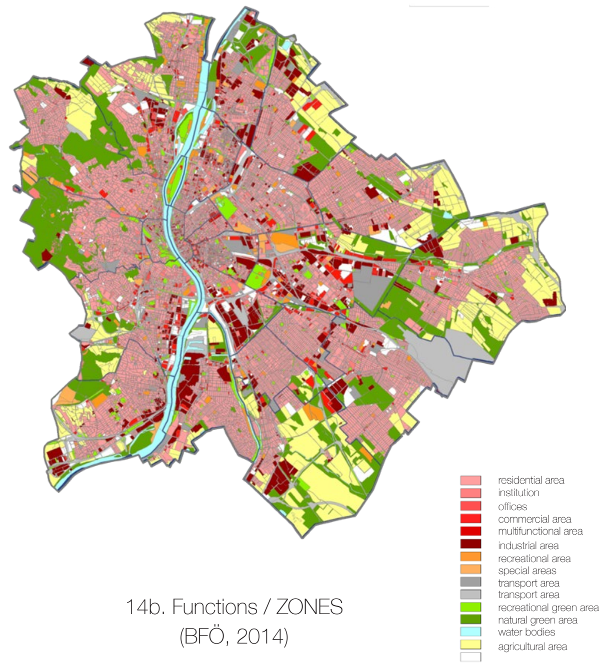


13a. Urban structure
(TATAI, 2018)

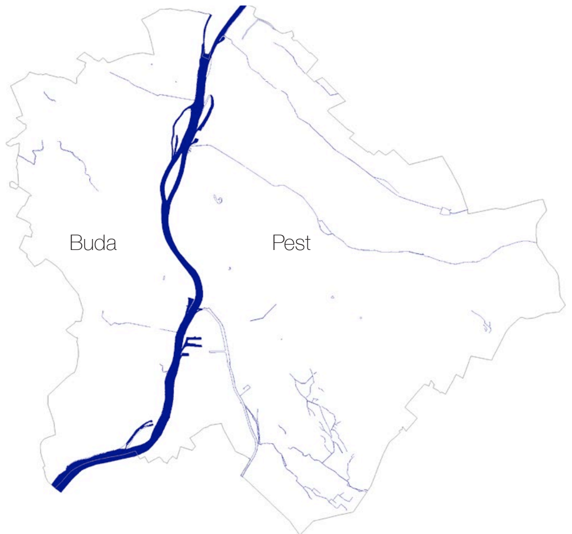


13b. Topography
(Content acc. BFÖ, 2018, own graphic)

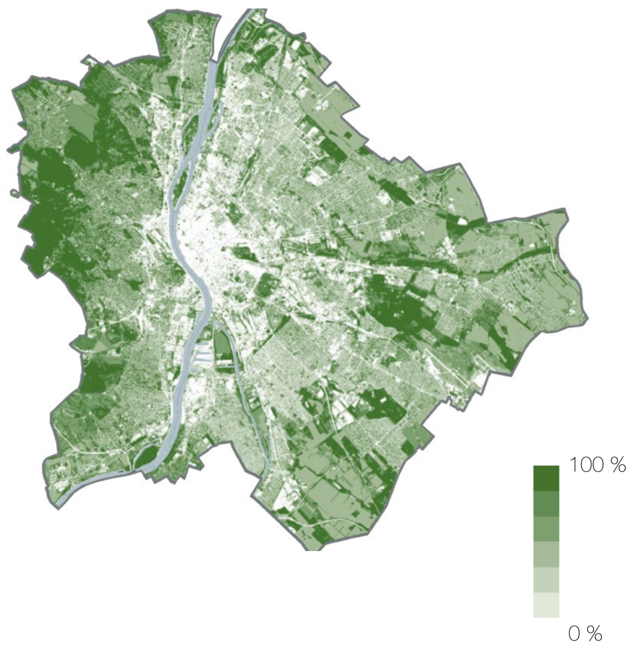
14a. Street network hierachy
(own graphic, data from CADMAPPER, 2020)



14b. Functions / ZONES
(BFÖ, 2014)

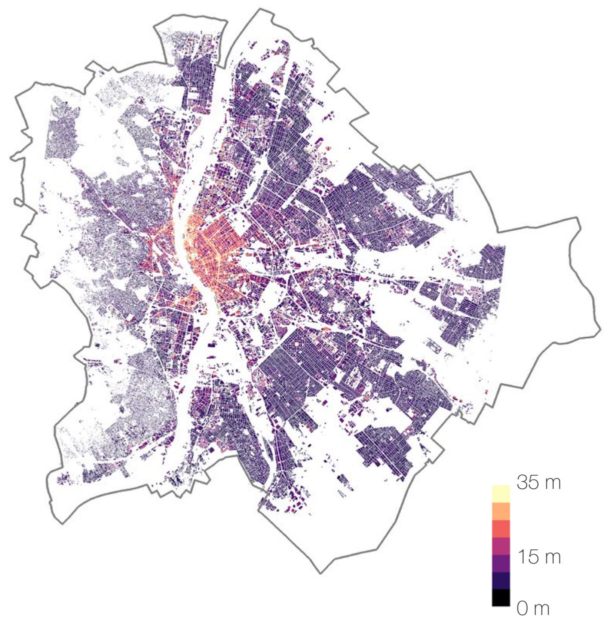


13c. Water bodies
(own graphic, data from CADMAPPER, 2020)



13d. Green area ratio
(S.JOMBACH In: TATAI, 2018)

14c. Buildings
(own graphic, data from CGTRADER, 2020)



14d. Building height
(DEMUZERE et. al.,2019)

FIG. 13: NATURAL ELEMENTS OF THE URBAN STRUCTURE
(Description s. Chapter 4.1.)

FIG. 14: ARTIFICAL ELEMENTS OF THE URBAN STRUCTURE
(Description s. Chapter 4.1.)

4. URBAN STRUCTURE OF BUDAPEST

4.2. LOCAL CLIMATE ZONE ANALYSIS

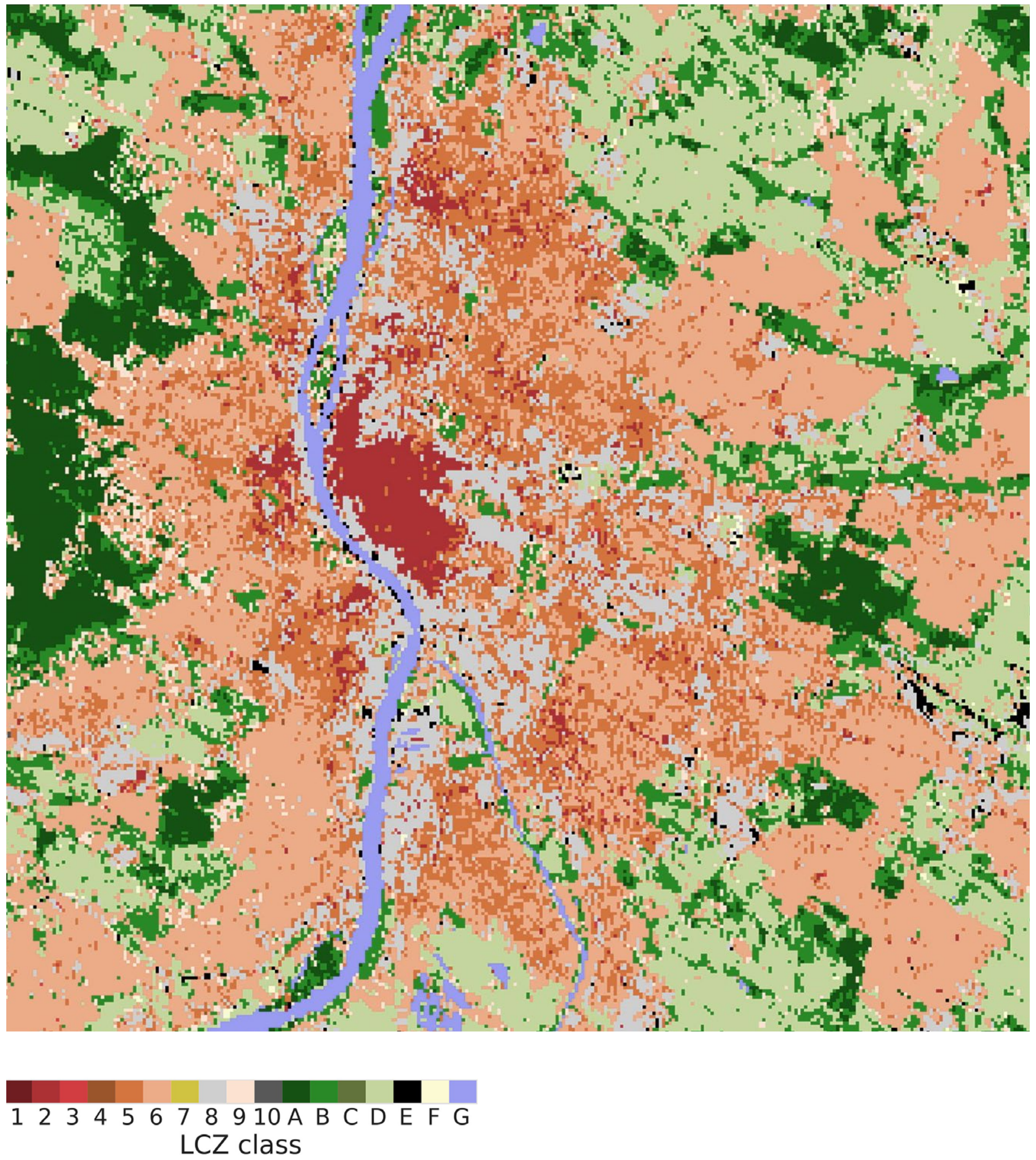


FIG. 15: LOCAL CLIMATE ZONES OF BUDAPEST
(DEMUZERE et. al.,2019)
"The Local Climate Zone (LCZ) typology has been adopted as a baseline description of cities as it categorises distinct landscapes at a scale of about 1 km² into recognisable types that can be linked to important surface parameters (known as urban canopy parameters)." (DEMUZERE et. al.,2019, p.2)
Above, we can see that Budapest has a relatively clear typological distribution, which I have also studied in detail.

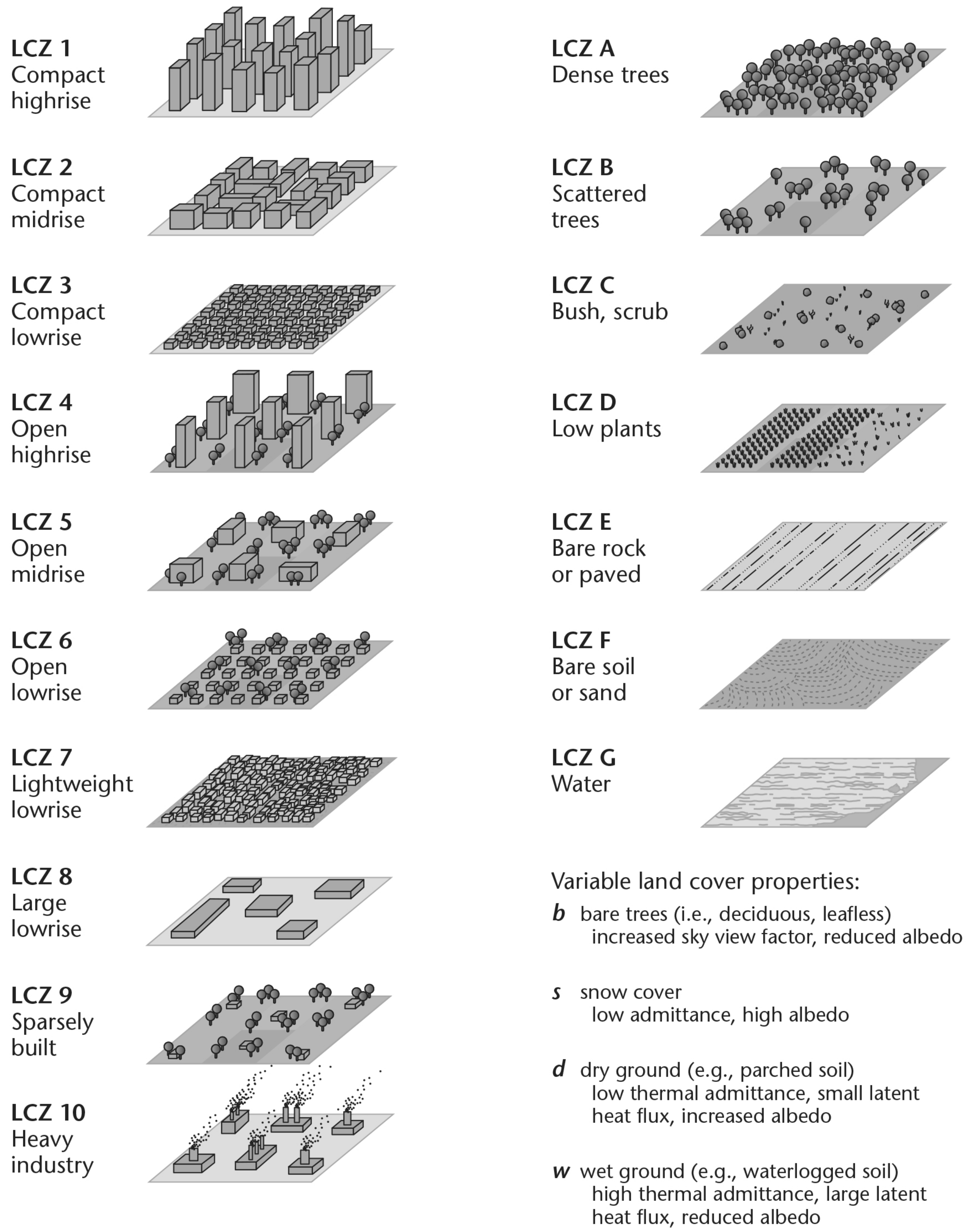


FIG. 16: CLASSIFICATION OF LOCAL CLIMATE ZONES
(OKE et. al., 2017)
"The criteria on which the classification is based are known to exert control on aspects of micro- and local climates (wind, temperature and moisture). The LCZ are clustered by their approximate ability to modify local surface climates due to their typical fabric, land cover, structure and metabolism." (OKE et. al., 2017, p.25)

4.2. LOCAL CLIMATE ZONE ANALYSIS

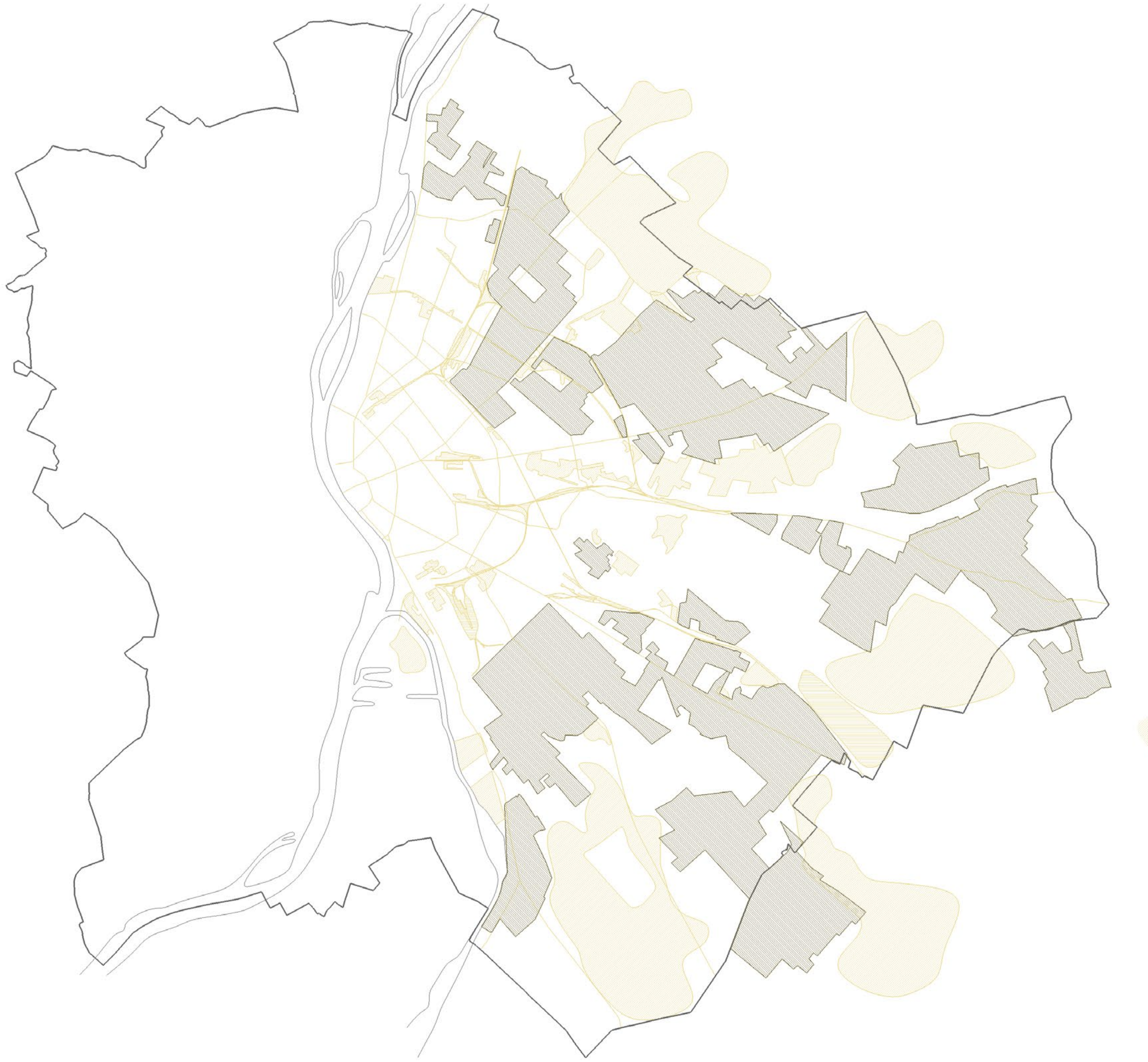


FIG. 17: OPEN AREAS // LCZ D, LCZ E
(own analysis)

In my own LCZ research, I have focused on identifying open areas that are possible airflow corridors and closed or higher typological areas that obstruct the wind. I found LCZ E (low plants), LCZ D (paved) areas to be open areas. LCZ 6 (open low rise) does not significantly block airflow over 10 metres. Note that higher radiation will give rise to a strong buoyant flow over large paved areas. Therefore, in hot, non-cloudy summer days, LCZ E can also block its ventilation corridors. At the same time, this means that the change in the albedo of these paved areas could be very significant in order to maintain the ventilation corridors.

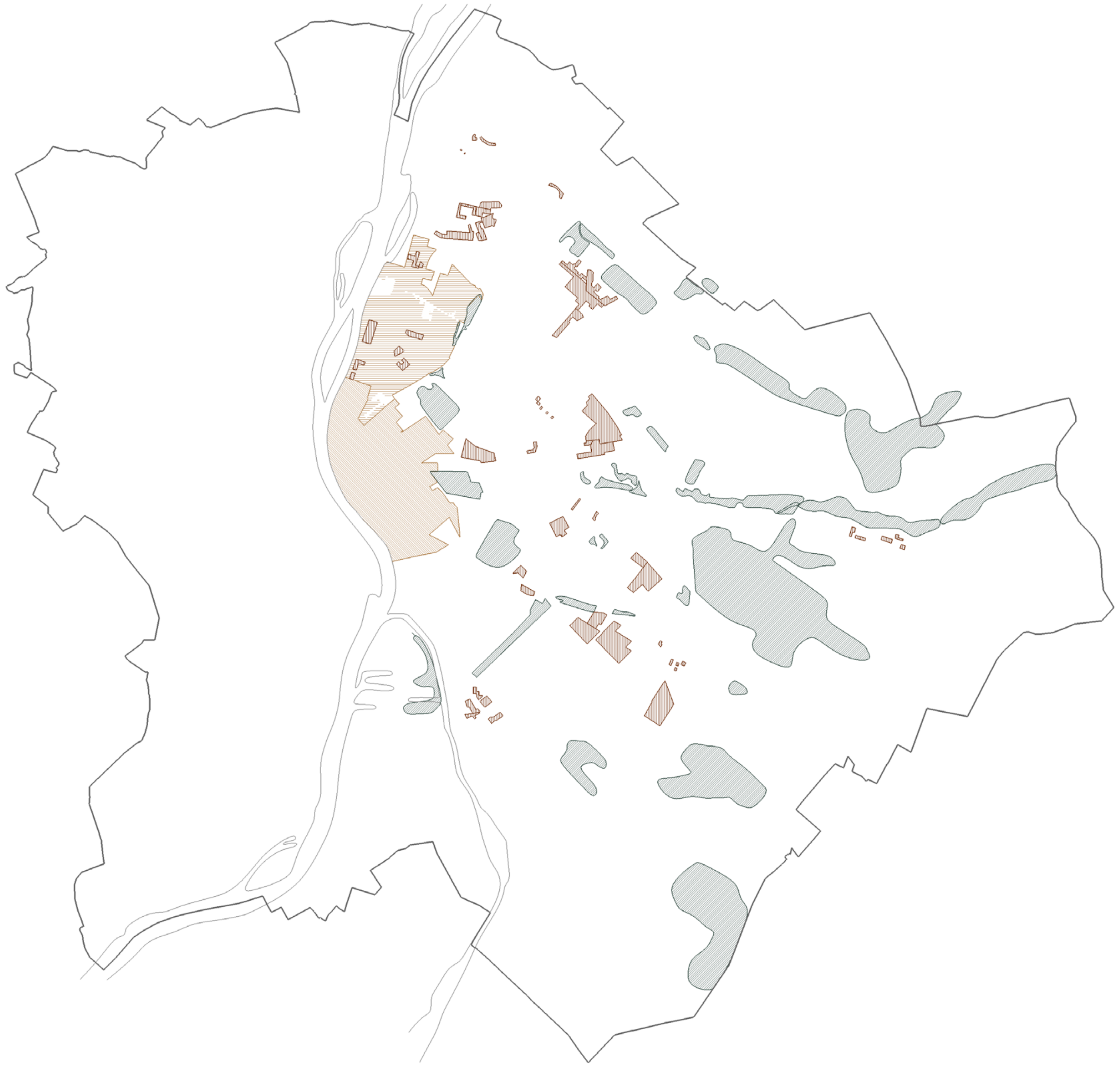


FIG. 18: BLOCKING AREAS // LCZ 4, LCZ11, LCZ A/ LCZB
(own analysis)

High and compact typologies can block ventilation corridors significantly. These typologies are especially the LCZ 4 (open high rise), LCZ 11 (large highrise like stadiums), LCZ 2 (compact midrise), partly LCZ 5 (open midrise). However, forest cause a cooler local microclimate, from the point of view of the ventilation corridors, its position in the urban tissue can be still disadvantageous.

4. URBAN STRUCTURE OF BUDAPEST

4.3. STREET ORIENTATION MAP

The street orientation map is a detour to this study, as it is not strictly part of the method as shown in Fig. 12 p. 24. The street orientation map divides the streets by their orientation. The magnitude of the length of the street in each direction was shown in a circular graph.

This type of analysis was first conducted by Seth Kadish in 2014. Later, Geoff Boeing, a Berkley urban planner, innovated the idea by releasing a free Python script tool. (Montgomery, 2018) (Xie, 2014) He describes the objective of his tool as follows:

"These street networks organize all the human activity and circulation in the city," "I think these visuals can help make otherwise dry or technical city planning concepts more salient and approachable for laypersons. You can easily see and comprehend your own city and how it relates to others' patterns." (Montgomery, 2018)

My analysis has made a contribution to this subject in two ways that have not yet been addressed by Boeing or Kadish. First, this analysis can be a very powerful first analysis of the city's ventilation. The comparison of street orientation analysis- or how I call it the "street-rose" with the wind rose of the city can already give a quick and effective first glimpse of its ventilation characteristics, especially in the dense urban downtown.

Second, the chart is not the only result of the analysis. My own Grasshopper script also colours the streets according to their orientation. As such, it will be immediately visible which areas of the city have a simple oriented street network and which are constantly changing. This latter would immediately mean that a ventilation corridor may not be built in this area.

4.3.1 METHOD

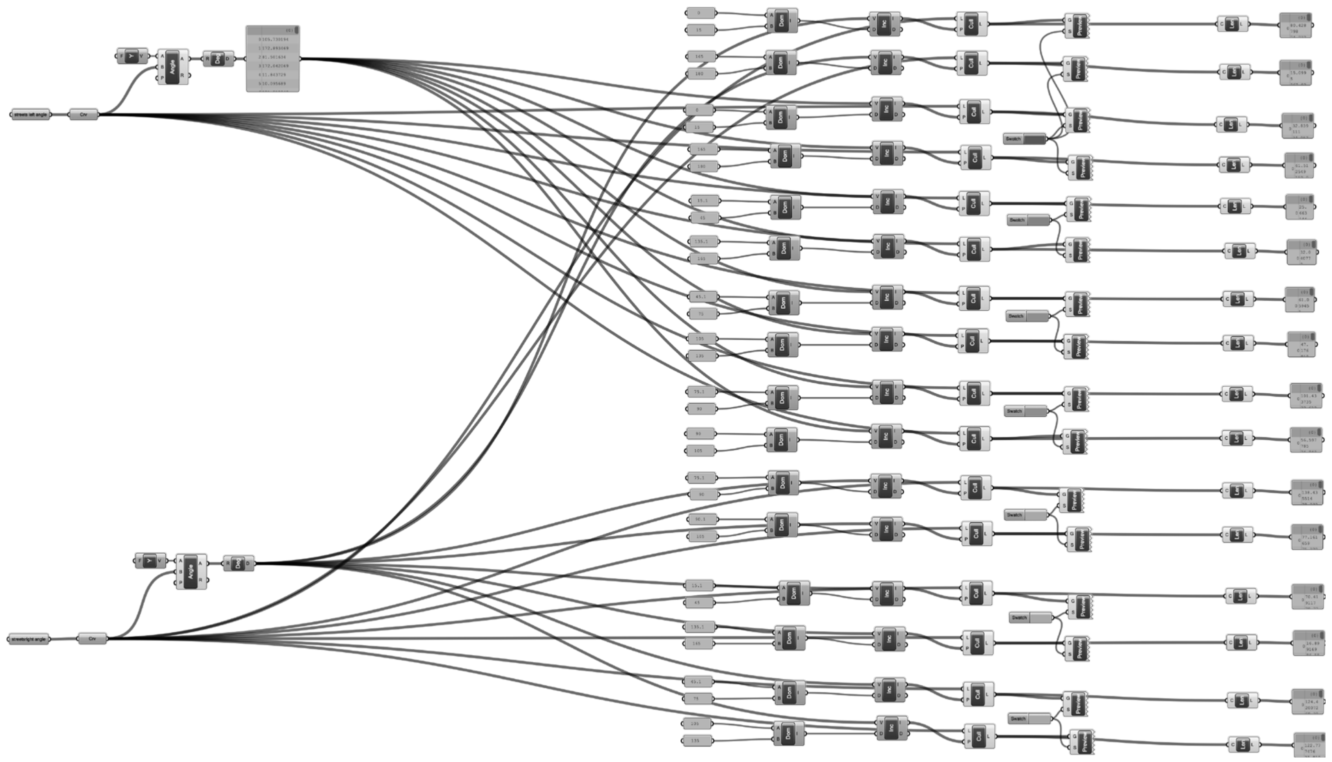


FIG. 19: GRASSHOPPER SCRIPT
(own analysis with grasshopper)
The street orientation map shows the streets according to their orientation. This can be defined in Grasshopper in such a way that the angle of each segment of the street line is measured. The list of lines is separated by a "cull pattern" for every 15° angle.

4. URBAN STRUCTURE OF BUDAPEST

4.3. STREET ORIENTATION MAP

4.3.2. RESULTS & CONCLUSIONS

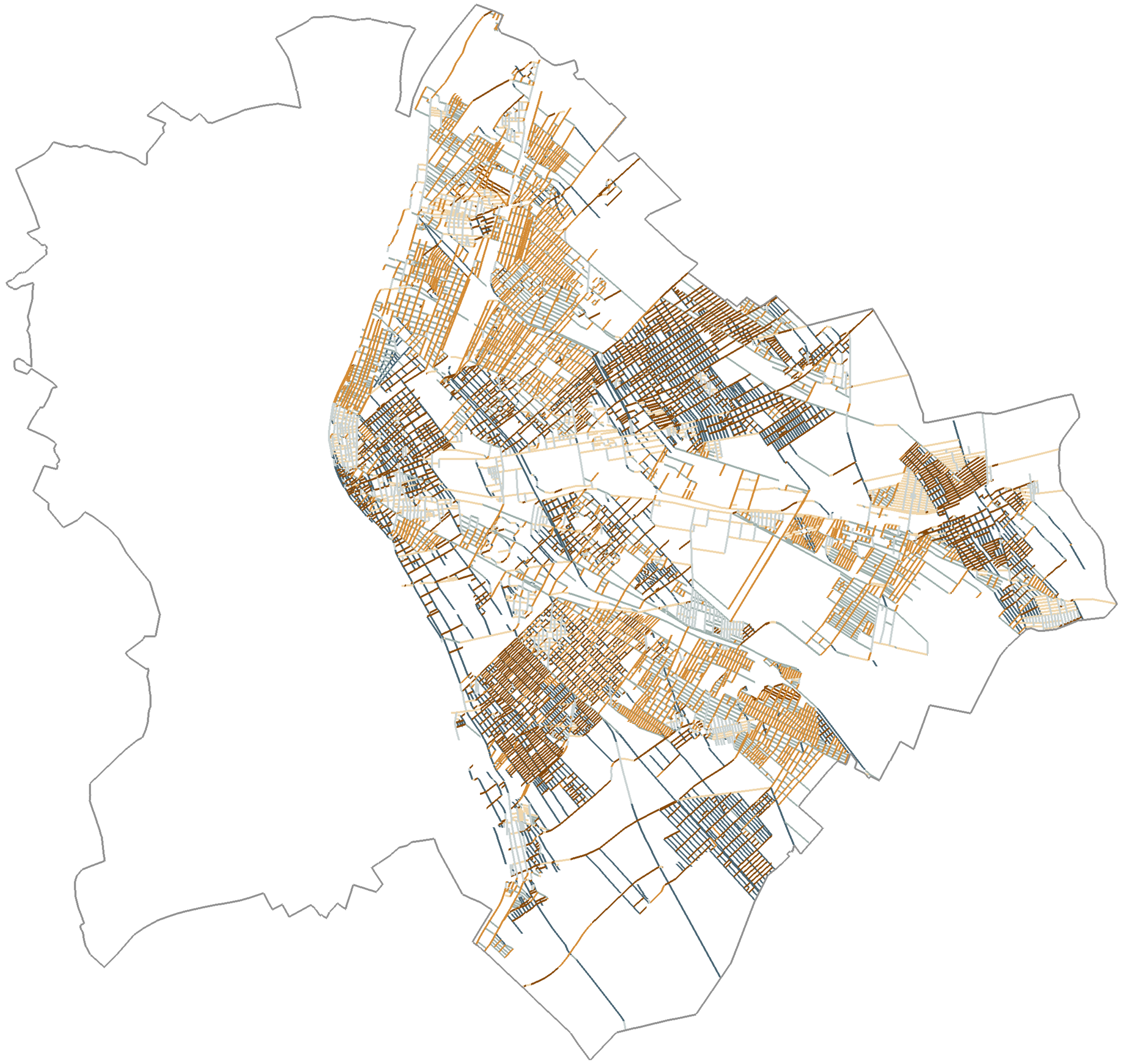
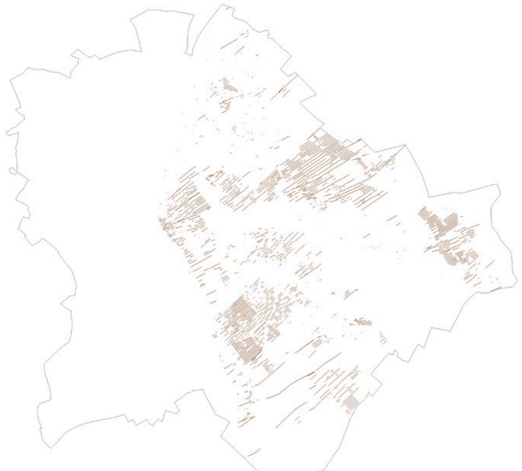


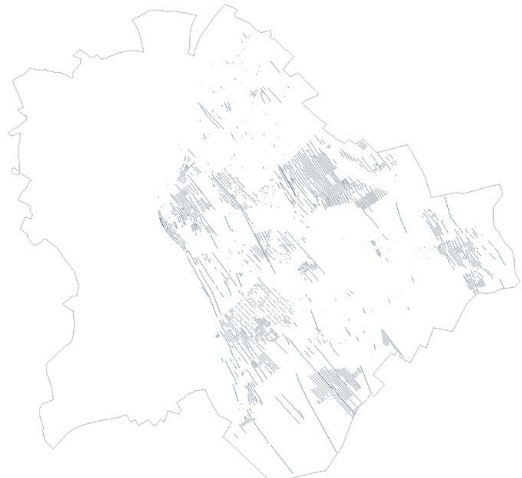
FIG. 20: WIND // STREET ORIENTATION ANALYSIS
(own analysis with Grasshopper)
The complex morphology of the city results in streets with constantly changing direction. Without any simulation it is visible that with higher probability the wind cannot pass through the urban fabric (especially in the downtown).

NE-SW // 345-15° / 165-195°
521'353 m

NW - SE // 105-135° / 245 - 275°
520'636 m



NE - SW // 15-45° / 195 - 215°
557'804 m



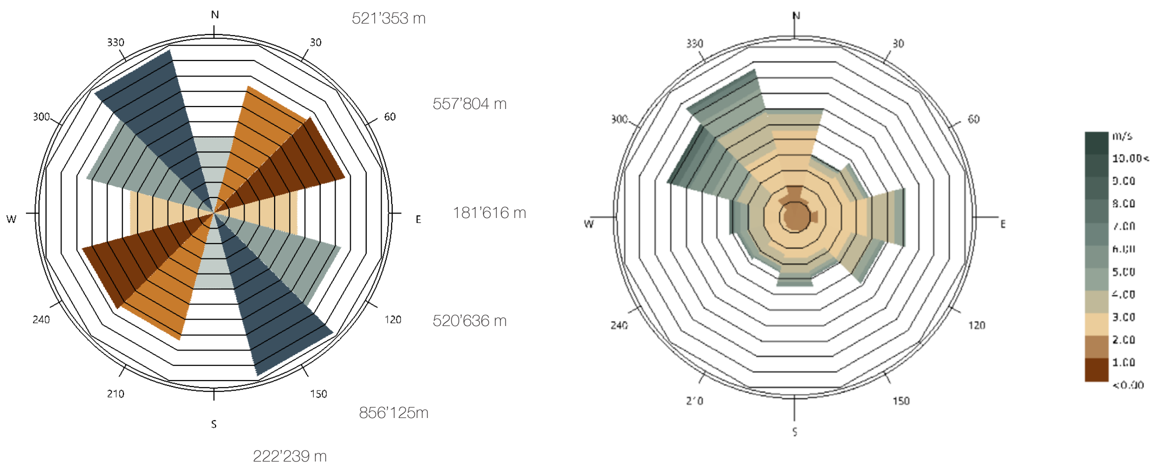
NW - SE // 135-165° / 275 - 315°
856'125m

W - E // 45-75° / 215 - 245°
181'616 m

N - S // 75-105° / 315 - 15°
222'239 m

FIG. 21: WIND // STREET ORIENTATION ANALYSIS
(own analysis with Grasshopper)

4.3. STREET ORIENTATION MAP
4.3.2. RESULTS & CONCLUSIONS



Street Rose of Pest

Wind Rose (2019 Jan-Dec)
of Pest

FIG. 22: WIND // STREET ORIENTATION ANALYSIS // WIND ROSE - STREET ROSE
(own analysis with Grasshopper)
The street-rose shows the street orientations. The magnitude of each hatch represents the magnitude of street length in this orientation. Most streets are in the prevalent wind direction wich is the Northwest. However the Northern and Western wind is still considerable, there are very few steets in the direction.

The complex morphology of the city results in streets with constantly changing direction, especially in the downtown, therefore the wind cannot pass through. The urban structure can block or favour the ventilation corridors. In the densely built-up inner city, the wind is blocked even more. This reduces the ventilation capabilities of the city and possibly amplifies summer heat waves.

By the comparing the wind-rose with the street network orientation ("street-rose") it becomes clear that they do not match each other, which means that the ventilation of the city is already hindered by the urban structure.

This method is also a small invention. This approach could help to get a first estimation about whether the city is well ventilated or not. Hence, correlations might be established between street orientations and city specific urban heat island effects.

5. CLIMATE ANALYSIS
5.1. METHOD

The ladybug climate analysis serves two purposes. First, the general analysis describes the basic climatic characteristics and gives us an understanding of why the city's evaporative cooling and ventilation corridors have a high significance in order to mitigate the city's summer heat waves.

Second, a detailed wind analysis is used to understand when synoptic effects (winddriven wind) and thermal effects influence the flow. With the help of a ladybug analysis, I can predict when, how often and from which direction the wind is blowing and whether there is an urban dome (no ambient wind), an urban plume (environmental wind + buoyant flow) or simply a wind-driven flow. In this way, I can divide the various cases methodologically.

DATA ACQUISITION:

- Energyplus
- METEOBLUE - historical forecast data
- OPENWEATHER - data of weather stations
- WORLDWEATHERONLINE etc.

Energyplus weather data:

- .epw data of Energyplus contains only a one year dataset. This is often merged together from different datasets. Therefore it seems to be statistically incorrect.

Openweather weather data :

- dataset since 1979 onwards (data of ca. 400'000 hours)
- for Budapest data of 3 stations and their averaged value are available
- this work uses the averaged dataset of Budapest
- data about: dry bulb temperature, atmospheric pressure, relative humidity, wind direction, windspeed, cloud cover, rain
- information about precipiation / rain seem to be false
- dataset contains „feels like temperature„
- does not contain any information about the solar radiation

METHOD:

1. Converting the .csv data into .xlsx:

- There are several coverters available online:

www.zamzar.com

convertio.co

2. Creating a musterfile as .xlsx

- The easiest way to rearrange the data is to take an existing .epw file and convert it into .csv master file with the help of the

Energyplus converter.

Then one converts this data into .xlsx. One can delete the specific data from this file and keep the headlines.

- Energyyplus converter can be downloaded from the website of Energyplus.

- One can fill up the data column by column.

- Note. Openweather data did not consist dew point temperature. Dew point temperature was calculated from dry bulb temperature and relative humidity: TDP = T- (100-RH)/5 (This approach is accurate to within about ±1 °C as long as the relative humidity is above 50%, which is in Budapest mostly the case.)

3. Editing / Filling up .xlsx data

- One can fill up the data column by column.

- Note: Openweather data does not contain dew point temperature. Dew point temperature was calculated from dry bulb temperature and relative humidity: T_{DP} = T- (100-RH)/5 (This approach is accurate to within about ±1 °C as long as the relative humidity is above 50%, which is mostly the case in Budapest)

4. Convert .xlsx into .csv (with the help of the online converters)

5. Corrections of the .csv file

- During the conversion some special characters (",* etc.) may appear in the data which should be deleted

- One should ensure that the date is in the same format as in the master file

5. Convert .csv into .epw file

- .csv data can be converted into .epw data with the help of Energyplus. Too big dataset can lead to an error.

- Another way to convert .csv data into .epw data is that one opens the .csv data in Notepad. Besides one should open another master file in Notepad to compare both. After that one should change some characters (like date etc.) by using the function replace to create a file with the same appearance as the master file. One can replace the data in the original .epw file by inserting the corrected data. One saves it as a new file.

- I have created 3 different datasets (.epw): 2019 annual hourly data; 1980-1989 averaged annual hourly data; 2009-2019 averaged annual hourly data. By the calculation the author used the arithmetic mean. Note that the leap days have been deleted.

Common mistakes:

- Data of 4 decades means over 400'000 rows of data. By converting from .csv into xlsx, one should make sure using .xlsx, instead of .xls which is not able to handle this amount of data.

- Openweather data contains duplicate rows which can cause shift in the chart or may lead to error. These duplicates should be deleted. (This can be easily managed in the Excel file.)

- The .csv file needs to be in absolutely the same format regarding spacing attributes, commas etc. as the master file

- Energyplus is not able to convert larger files than around 8'000 rows which corresponds to one year annual hourly dataset

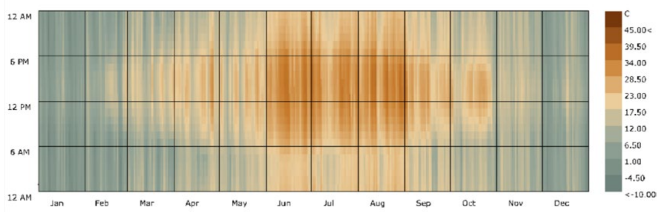
Limitations:

- The data does not consist data regarding solar irradiation

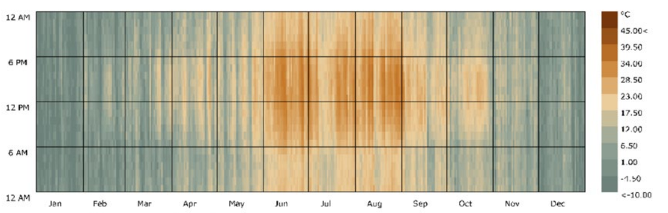
- I used the dataset of the last relevant year for this study (2019). Therefore, statistically, the values are not entirely correct. The use of the TMY (Typical Meterological Year) would be the correct approach to the establishment of a data set to work with. The creation of this data set would go beyond the scope of the current study.

5. CLIMATE ANALYSIS

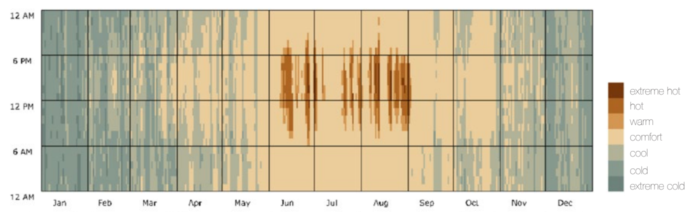
5.2. RESULTS



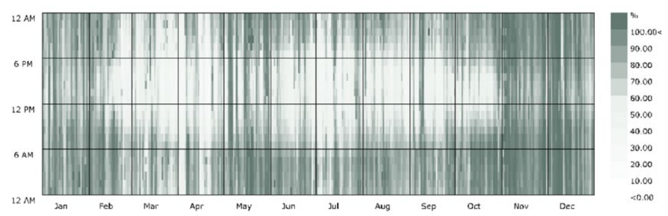
Annual hourly outdoor temperature (2019)



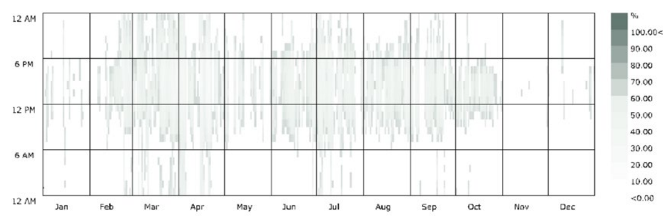
Annual hourly UTCI Universal Thermal Climate - Perceived outdoor temperature (2019)



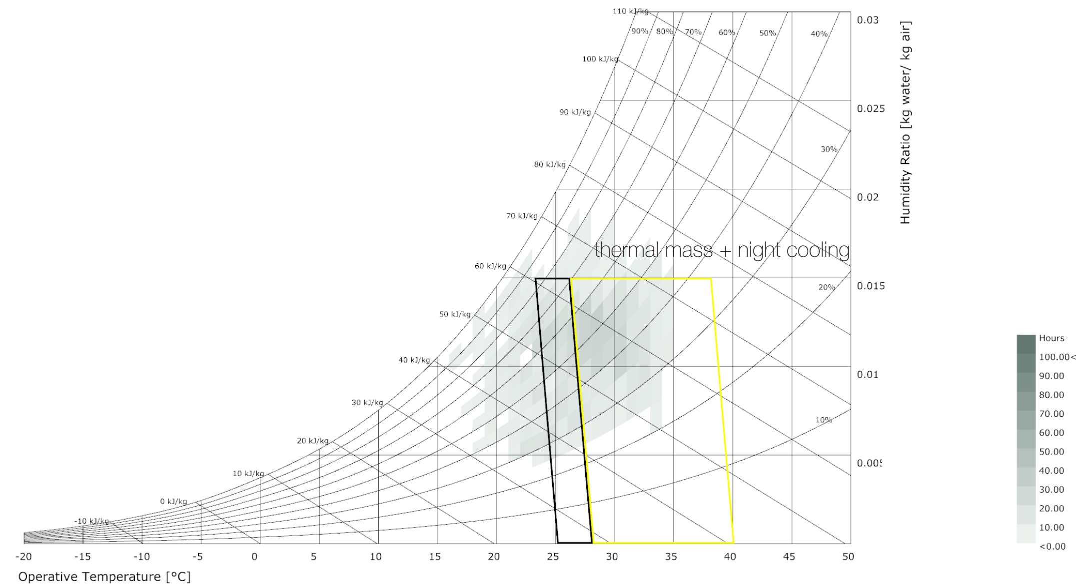
Annual hourly outdoor comfort (2019)



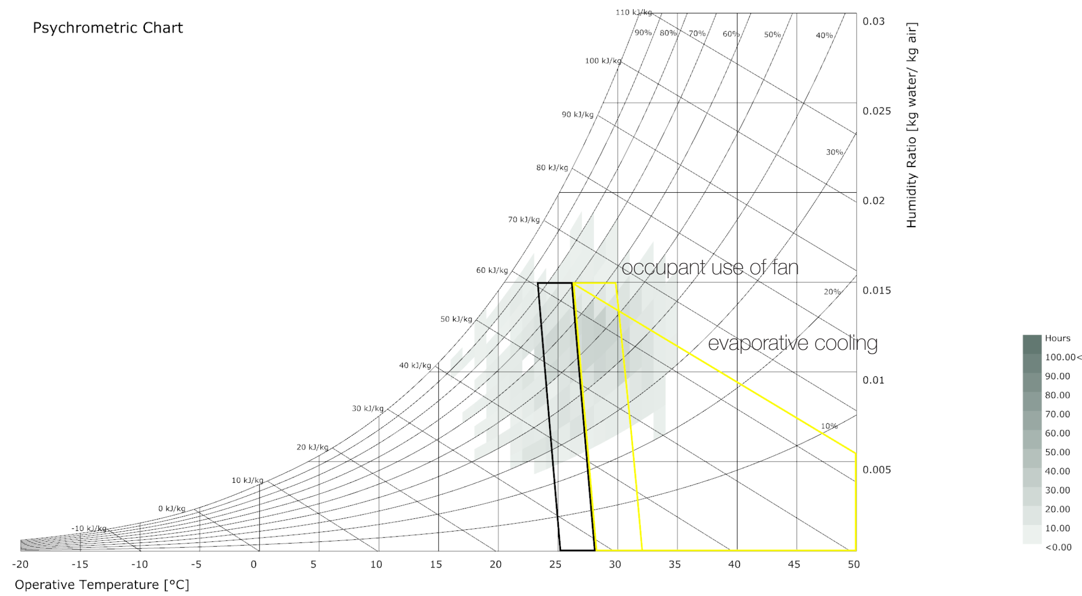
Annual hourly relative humidity (2019)



Annual hourly relative humidity under 60% (2019)



Psychometric chart (2019 Jun-Aug) with building measurment: thermal mass+night cooling (29%)



Psychometric chart (2019 Jun-Aug) with building measurment: evaporative cooling (41%)

FIG. 23: CLIMATE ANALYSIS

(own analysis with Ladybug)

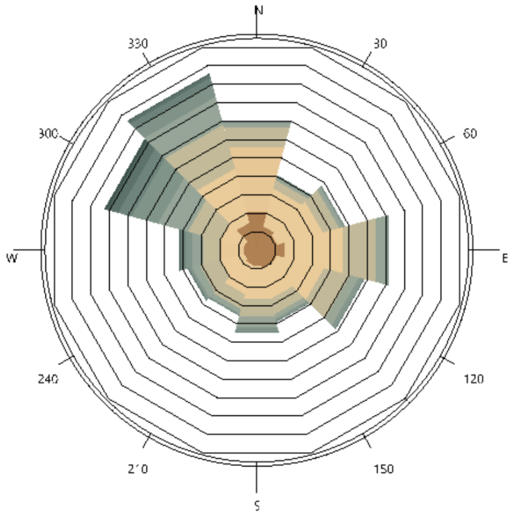
Budapest has a very continental climate. Cold in the winter and hot in the summer. In the summer period (July-Aug) 60% of the daytime is above the comfort level (26°C). Perceived temperature (UTCI) is very similar to the dry bulb temperature. Almost half of the summer days results as hot or extremely hot (outdoor comfort). At the same time, Budapest is dry during the day (according to the high dry bulb temperature) in summer.

FIG. 24: CLIMATE ANALYSIS / PSYCHROMETRIC CHART

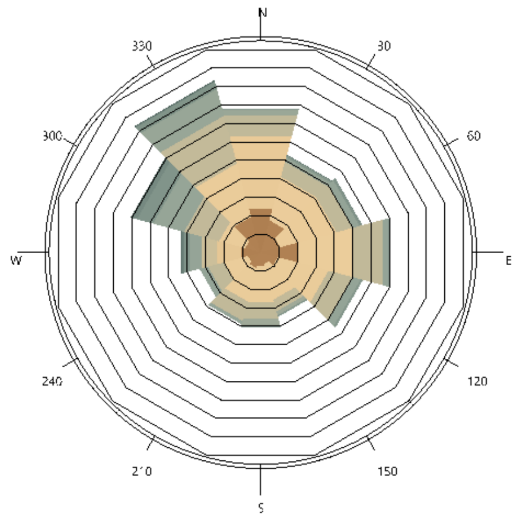
(own analysis with Ladybug)

Warm and dry climate conditions in summer are the ideal circumstances for the evaporative cooling strategy, as the air still has a large capacity for moisture. Evaporation causes heat loss as the conversion of water to gas requires energy. According to the Ladybug psychrometric chart, another possibly good strategy could be the thermal mass where the cold of the night can be stored in architectural elements with a high thermal mass, such as walls and slabs. However, in a dense city, the urban heat island effect (UHI) significantly blocks night-time cooling, therefore it is probably not the appropriate solution.

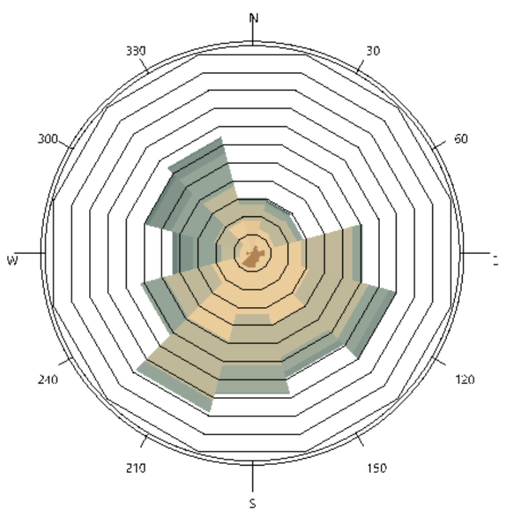
5.2. RESULTS



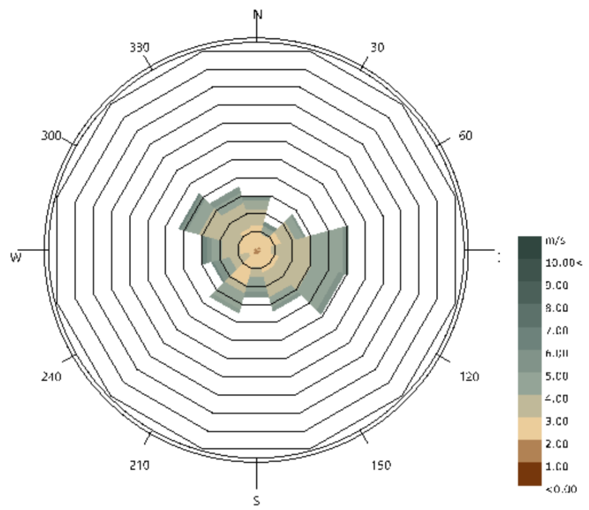
Windrose (2019 JAN-DEC)



Windrose (2019 JUN-AUG)

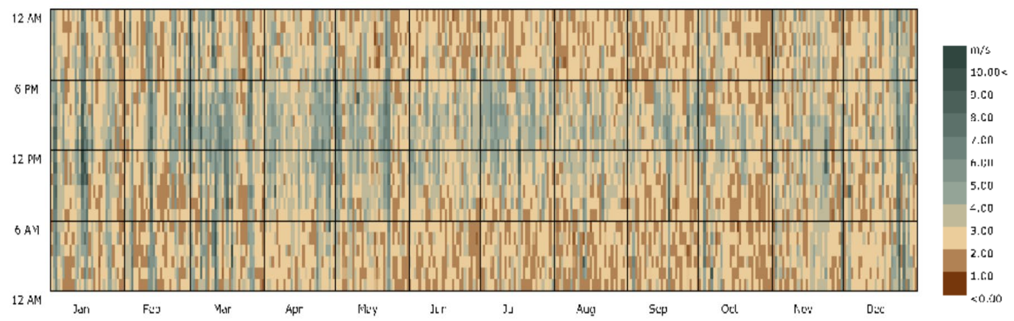


Windrose (2019 JUN-AUG), above 26°C
wind in 27.8% of the time

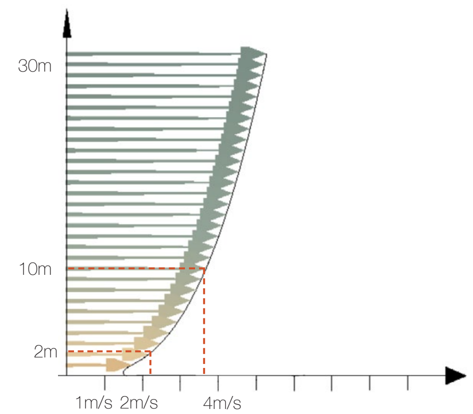


Windrose (2019 JUN-AUG), Daytime (7a.m-8 p.m.) above 26°C
wind in 27.8% of the time

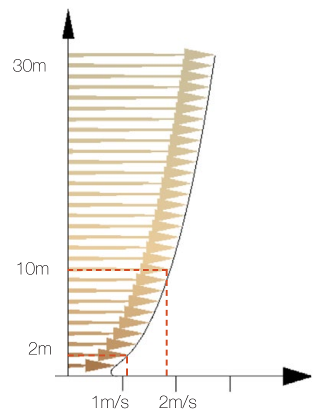
FIG. 25: CLIMATE ANALYSIS / WINDROSE
(own analysis with Ladybug)
Budapest is moderately windy during summer daytime (77% is over 3,5m/s in 10 meters height). There is a higher windspeed during higher temperatures in the summer but with a relatively small frequency. The prevailing wind blows from N/NW. However, this is precisely the point where we can see the importance of accurate climate analysis. If we look at the wind only in the hours above 26°C, the prevailing wind actually blows more from the W/SW.



Annual hourly windspeed (2019)



Annual average wind speed profile for Budapest (2019 JAN-DEC)

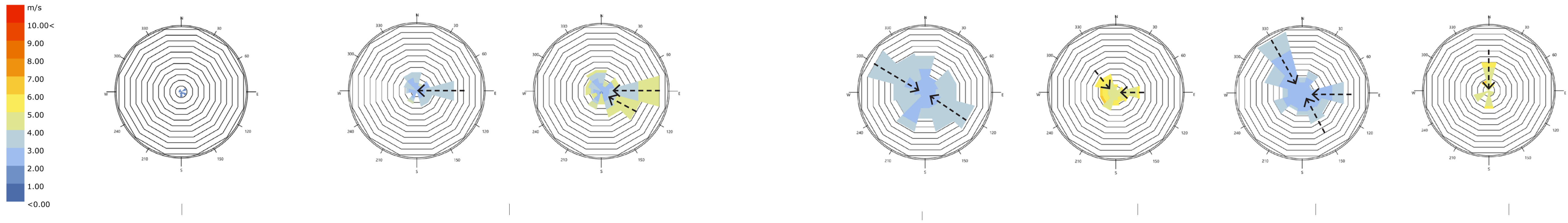


Average wind speed profile for Budapest (2019 JUN-AUG)

FIG. 26: CLIMATE ANALYSIS / WIND AND UBL
(own analysis with Ladybug)
The annual hourly wind graph shows us a clear difference in wind speed between daytime and nighttime and no significant difference during the year. We can observe a higher wind speed at a height of 10 meters (4-5 m/s) which, due to the high surface roughness, drops to about 1,5 m/s in the dense city at the pedestrian level (2 meters height). This graph is called the Urban Boundary Layer (UBL term seen before p.14) wind profile, which predicts average wind speed in dense urban areas. As the higher wind speed is not that frequent in Budapest, the average wind speed in the summer is 2-3 m/s at a height of 10 metres, which is approximately 1 m/s wind speed at the pedestrian level.

5.2. RESULTS

JUN1-AUG31 DAYTIME	NO WIND, WARM DAYS LESS CLOUD	WINDY, WARM, CLOUDY DAYS		WINDY, WARM DAYS, LESS CLOUD		WINDY, COOLER DAYS	
conditional statement in LB	DBT > 26°C and WIND <2 m/s and CC < 5	DBT > 26°C and WIND >=2 m/s or >= 4 m/s and CC >= 5		DBT > 26°C and WIND >= 2 m/s or >= 4 m/s and CC < 5		DBT < 26°C and WIND >=2 m/s or >= 4 m/s and CC >= 5	
WINDY	✗	✓ moderate or	✓✓ strong	✓ moderate or	✓✓ strong	✓ moderate or	✓✓ strong
CLOUDY	✗	✓		✗		✗	
WARM (>26°C)	✓	✓		✓		✗	
LADYBUG AN.	11 hours, 0.85% of summer (2 hours with clouds (CC>5))	65 hours, 5.5 %	48 hours, 3.7%	163 hours, 12.7%	64 hours, 5%	258 hours, 20.0% of summer	37 hours, 2.9% of summer
		113 hours, 9.2%		227 hours, 17.7%		295 hours, 23%	



THERMAL DRIVEN VENTILATION	WIND DRIVEN	WIND + THERMAL DRIVEN	WIND DRIVEN	WIND DRIVEN
		DEPENDS ON DIRECTION WHETHER THERMAL PROC. MAKES VENTILATION STROGER OR WEAKER		
1%	9.2%	12.7%	5%	23%

FIG. 27: WIND-DRIVEN AND THERMAL DRIVEN VENTILATION IN BUDAPEST
(own analysis with Ladybug)

I used the wind analysis with different conditional statements to figure out when the flow is driven by thermal effects when by the ambient wind and probably when it is a combination of both. This I considered it interesting, because I found out, that when the weather is warm then it is almost always windy. Only in 1% of the cases it has low windspeed. Therefore, pure thermal driven flow (causing urban dome) never happens during the daytime.

In windy warm and cloudy days, or on windy cool days there is more synoptic flow. On windy days when it is warm and there is no cloud – the solar irradiation significantly rises the mean radiant temperature of the surfaces (causing urban plum), as such, only by very strong wind will the synoptic mechanism dominate over the thermal effects. Also, we can notice how the prevalent wind changes in the different cases.

5. CLIMATE ANALYSIS
5.3. CONCLUSIONS

The climate analysis helps to to figure out the general characteristics of the city. One of the most important conslusion is that evaporative cooling could be the most relevant strategy to cool down the city. This means that to water and wind network of the city should be analyzed in detail. In the framework of this study, I have concentrated on the analysis of the wind network of the city.

We have seen, there is a moderate average wind speed above the city. A higher windspeed during higher temperatures in the summer but with a relatively small frequency can be observed and because of the surface roughness of the urban tissue it drops to 1m/s on the pedestrian level. To the CFD simulations, I have used 3 m/s wind speed (at 10 meters height) which lies between the annual and summer average.

The information of the wind direction has are especially important in my method. The The annual prevailing wind is coming from NW, but during a summer daytime the wind is coming generally from all directions.

According to my method, it was important for me to understand when synoptic effects and when thermal effects influence the urban flow. As we have seen, without ambient wind, the flow creates an urban dome and with ambient wind an urban plume. The idea is that with the help of ladybug analysis,it is predictable when or how often does the wind come and also from which direction it happens. As such, I can split methodologically the different cases, when there is an urban dome, plume or absolutely wind driven flow. During the summer day, the wind-driven flow is 3 times more frequent than the combination of wind and thermal-driven flow, while the frequency of fully thermal-driven flow is negligible and occurs more locally in the dense downtown area where the wind-driven flow is blocked. The wind driven flow is blowing from NW/ W/SW whereas in the cases when also thermal driven flow is present, the wind is blowing in the NW - SW axes.

6. LANDSAT IMAGE ANALYSIS - UHI ANALYSIS

6.1. METHOD

In the following chapter, the creation of the Landsat thermal images is in the focus. In the chapter 6.1. method, I am going to discuss the domain knowledge, the input data and parameters. In chapter 6.2. I am going to present the results of my analysis. For the detailed conclusions of the results see chapter 6.3.

These thermal maps serve to define the hot and cool areas of the city. In chapter 7.3.1./ 7.3.2., the identified urban cool and hot spots help to qualitatively predict the thermal-driven flow and the combination of thermal-driven and wind-driven flow of the city.

Domain knowledge

“The Landsat Program is a series of Earth-observing satellite missions jointly managed by NASA and the U.S. Geological Survey. (1972-present) It provides essential land change data and trending information not available otherwise. Both Landsat 7 and Landsat 8 are currently in orbit and collecting data. Landsat satellites acquire data in different ranges of frequencies along the electromagnetic spectrum.“ (USGS, 2020)

Landsat data products held in the USGS archives can be searched and downloaded at https://landlook.usgs.gov/viewer.html. I worked with the Landsat 4-5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM). (USGS, 2020)

The Band 6 of the Landsat images are called the thermal infrared data. This data is the thermal radiation emitted by a body (Mean Radiant Temperature). The spatial resolutions of the images are 120*120m for Landsat 4-5 and 60*60m for Landsat 7. (USGS, 2020)

6.1. METHOD

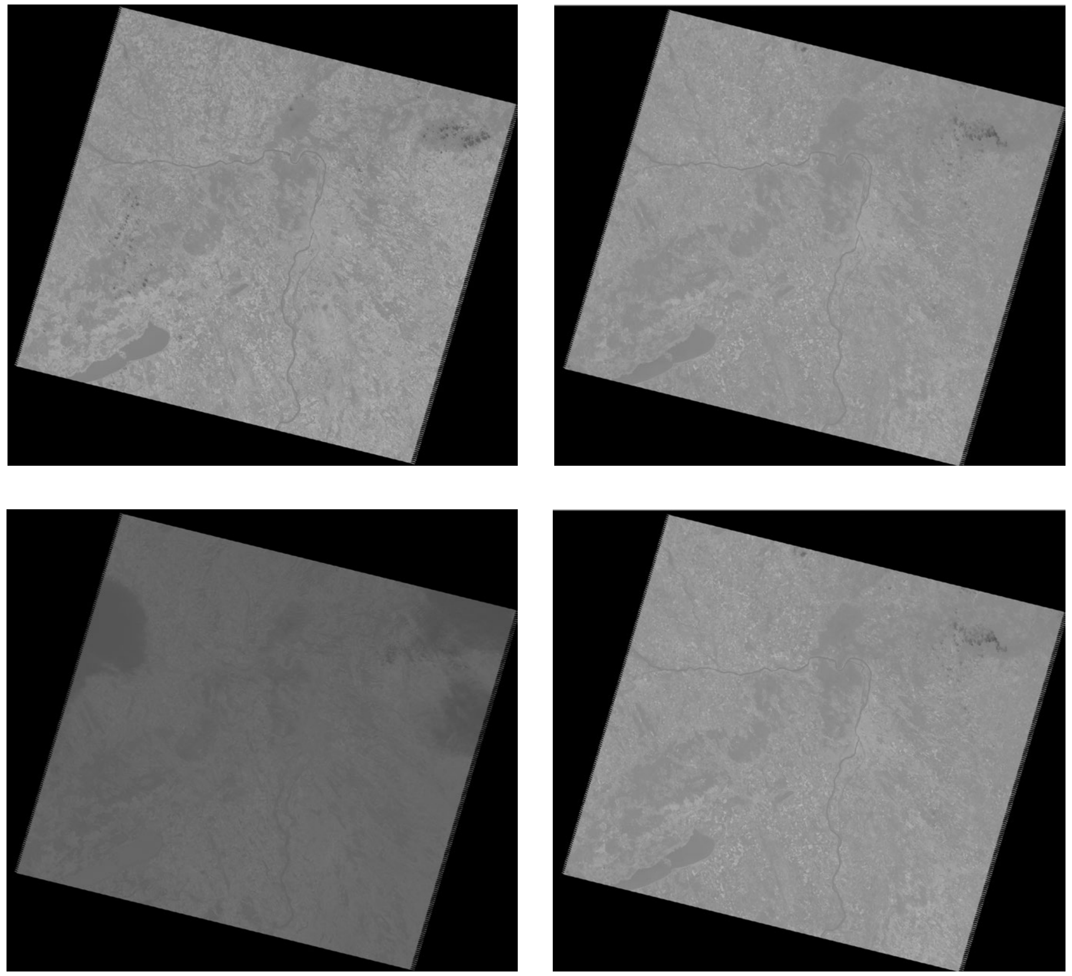


FIG. 28: EXAMPLES OF LANDSAT 4-5 IMAGES, CENTRAL HUNGARY
(NASA USGS archive, 2020)
Band 6 .Tiff data captures the wavelength 10.40-12.50 which gives us information about the thermal infrared radiation of an area.

Bands of Landsat 4-5

"Band 1 – blue (wavelength 0.45-0.52) Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation

Band 2 – green (wavelength 0.52-0.60) Emphasizes peak vegetation, which is useful for assessing plant vigor

Band 3 – red wavelength (wavelength 0.63-0.69) Discriminates vegetation slopes

Band 4 - Near Infrared (wavelength 0.77-0.90) Emphasizes biomass content and shorelines

Band 5 - Short-wave Infrared wavelength (1.55-1.75) Discriminates moisture content of soil and vegetation; penetrates thin clouds

Band 6 - Thermal Infrared (wavelength 10.40-12.50) Thermal mapping and estimated soil moisture

Band 7 - Short-wave Infrared (wavelength 2.09-2.35) Hydrothermally altered rocks associated with mineral deposits

Band 8 - Panchromatic (Landsat 7 only) (wavelength 0.52-0.90) 15 meter resolution, sharper image definition" (USGS, 2020)

Data acquisition:

- Landsat 4-5 / Landsat 7 images at https://landlook.usgs.gov/viewer.html.
- Download Standard Product / Level 1Geotiff Data Product

Input data:

- Landsat 4-5 _B6.tiff image - only band 6 (thermal infrared)
- Landsat 7 _B6.2.tiff image - band 6.2 (thermal infrared, high gain)
- MTL.txt - detailed meta data (exact time of the record etc.)

Input parameters:

- Latitude and Longitude of the city- small shifts between different images are possible
- Image width and height defines the area (in km)
- Sample size is the refinement of the area (maximum refinement - 1)
- Legend Parameter was set to a minimal bound of 20°C and maximal bound of

40°C

- No .epw data is necessary aslong as we know the latitude / longitude

Limitations:

The dragonfly tool converts of the raw Landsat image thermal data from Kelvin into °C. This means that does not consider any atmospheric correction, which could change the values with up to 5 degrees. However, no correction is needed if one is interested only in qualitative aspects, because the atmospheric correction is homogenous for all values. (Röösli, 2020)

Furthermore, this data is a record of one specific minute. Therefore it is not directly applicable for comparisons of years etc. However, by overlaying and observing a larger series of images for multiple timesteps, one can identify the spots which are constantly cooler or constantly warmer relative to the surrounding city. This is the concept which will be followed in my method.

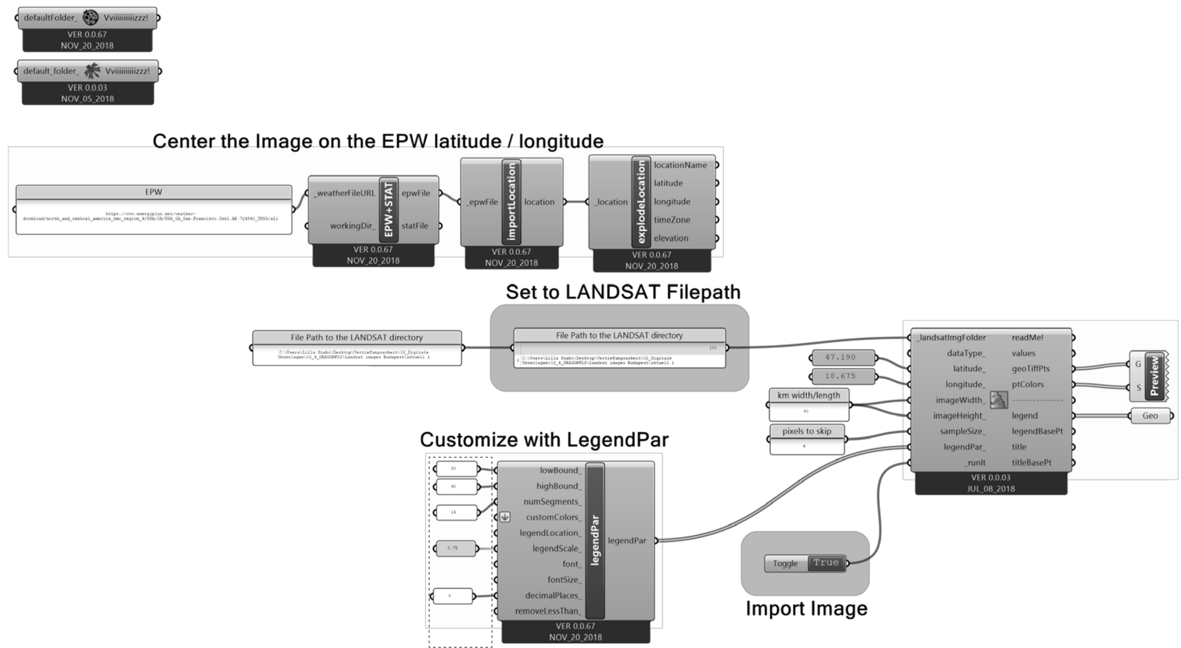


FIG. 29: GRASHOPPER SCRIPT AND INPUT PARAMETERS
(Dragonfly, 2020)
Dragonfly scripts are relatively easy to use. The script can be downloaded from the same website as the installation file. There are relatively few input parameters that can be changed (e.g. legend parameters). For input data and parameters, see Chapter 6.1. Method.

6. LANDSAT IMAGE ANALYSIS - UHI ANALYSIS

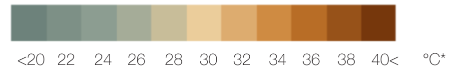
6.2. RESULTS

Fig 30a: Thermal map Budapest - 07.08.2016, 09:35

Fig 30b: Thermal map Budapest - 23.08.2016

FIG. 30: SATELITE IMAGES / THERMAL MAPS
(own analysis with Dragonfly)
The plugin creates thermal maps of the raw.tiff data. Only one image, however, is hardly usable. As shown in chapter 6.1., this data is a record of one specific moment and, furthermore, it is not atmosphericly corrected. Therefore, the only correct method is to evaluate as much satellite images as possible.

6.2. RESULTS



* Values without atmospheric correction. This could change the values upto 5°C.

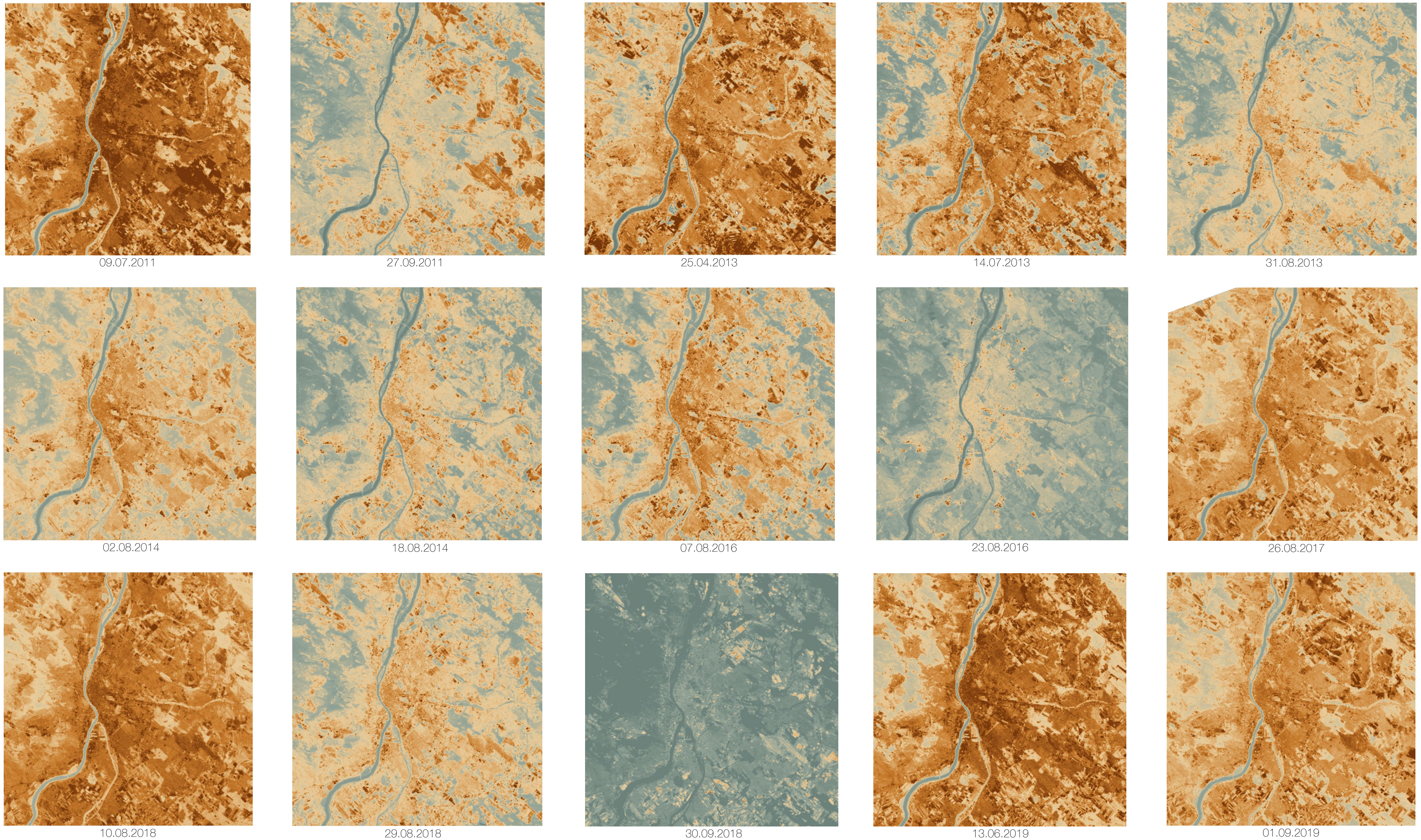


FIG. 31: HEAT MAPS / SATELITE IMAGES

(own analysis with Dragonfly)

As described before, we should be aware that these are records of only one moment, therefore it is really not available for the purpose of comparing years or to identify the size and location of the urban heat island from one image.

But what is also interesting that all records are from the morning around 9 o'clock so that they are comparable and that there is a vast amount of data, because the satellites have already collected data for 50 years. With a large amount of Landsat images, I would like to identify the areas which are constantly warmer or constantly cooler. This is probably the only - however very powerful - scientificly correct conclusion which van be drawn from these images.

6.2. RESULTS

<= 26 °C

* Values without atmospheric correction. This could change the values upto 5°C.

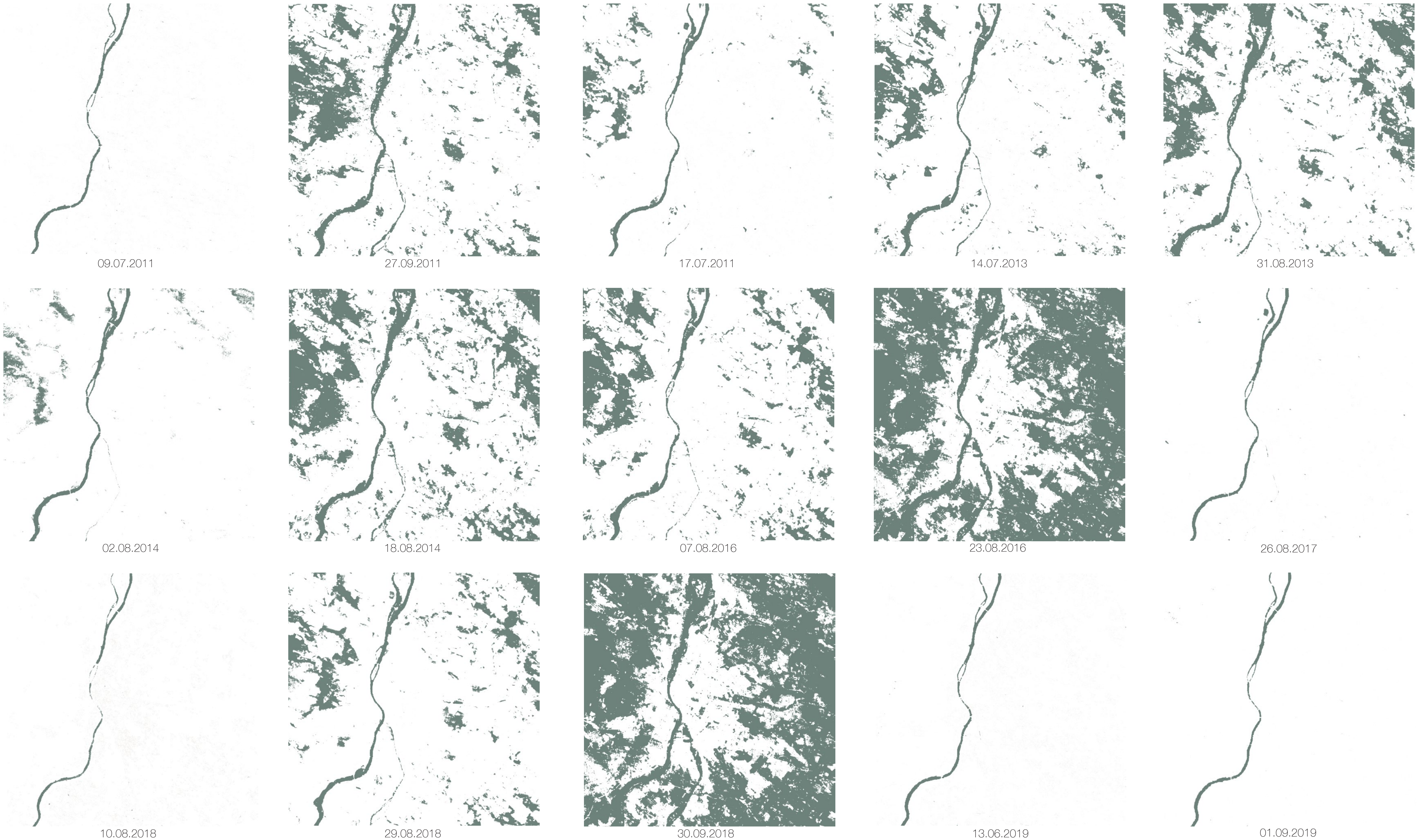


FIG. 32: "COOL SPOTS" / SATELITE IMAGES
(own analysis with Dragonfly)
With the help of the setting of the legend, we can subtract the areas which are under 26°C.

If we compare these images, it will be clear that there are areas that are constantly cooler than its surrondings.

6.2. RESULTS

38 =< °C

* Values without atmospheric correction. This could change the values upto 5°C.

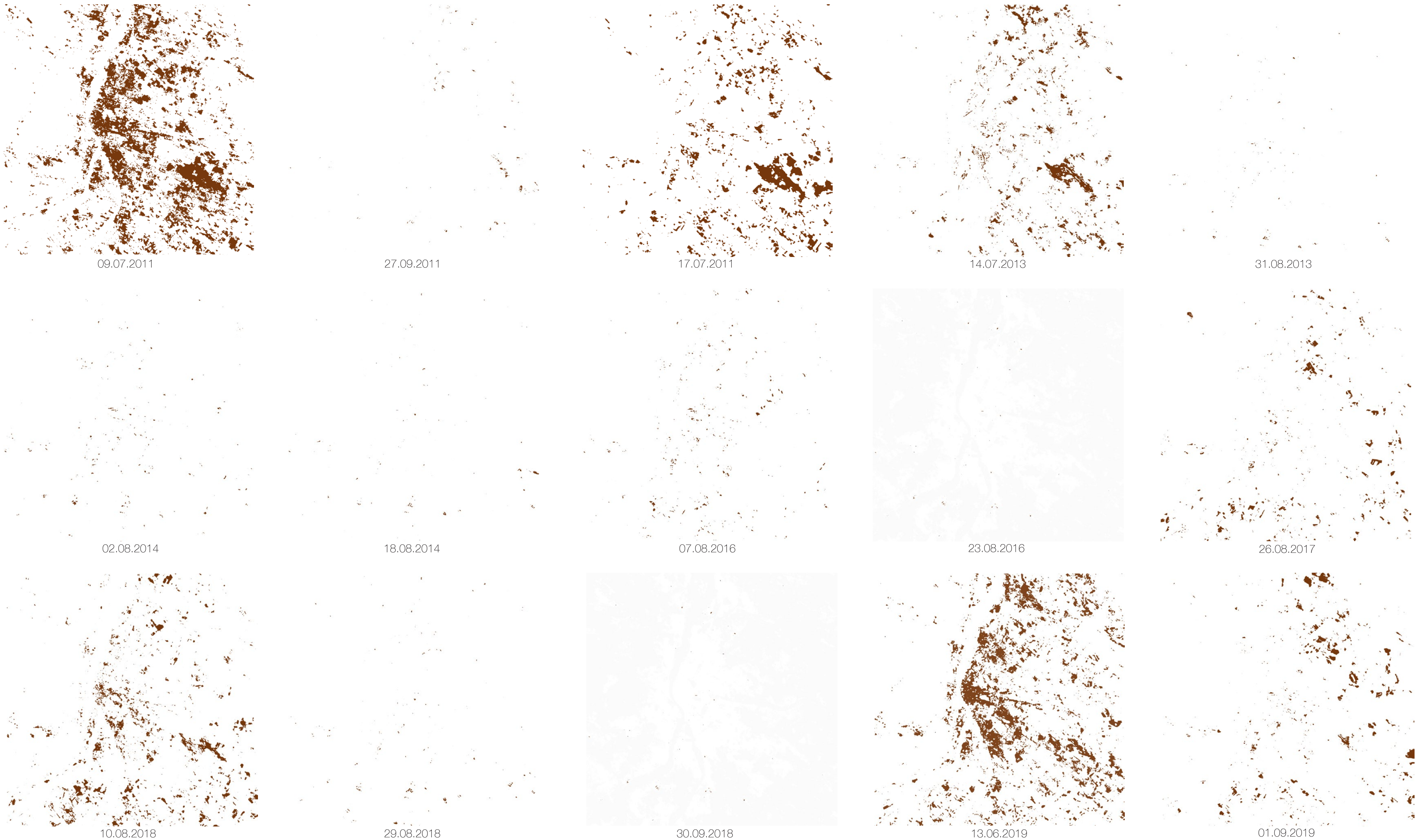


FIG. 33: "HOT SPOTS" / SATELITE IMAGES
(own analysis with Dragonfly)
Similarly to the "cool spots", we can subtract the areas which are over 38°C.

By the comparison of these images we come to the same conclusion. There are areas that are constantly hotter than their surroundings.

6.2. RESULTS

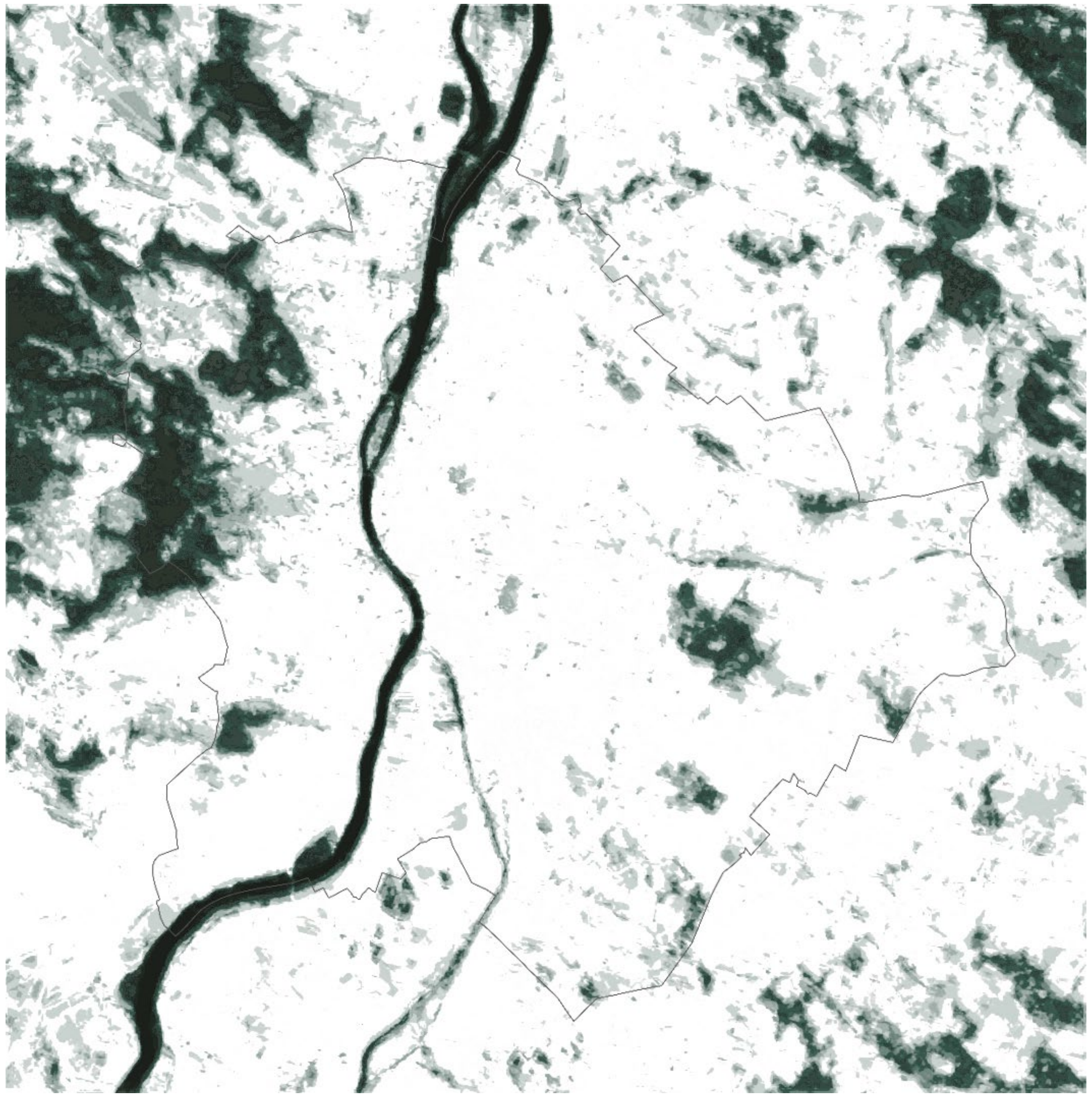


FIG. 34: "COOL SPOTS" / SATELITE IMAGES
(own analysis with Dragonfly)
I overlayed these 15 records in Photoshop. The result clearly shows the urban spots which are constantly cooler.

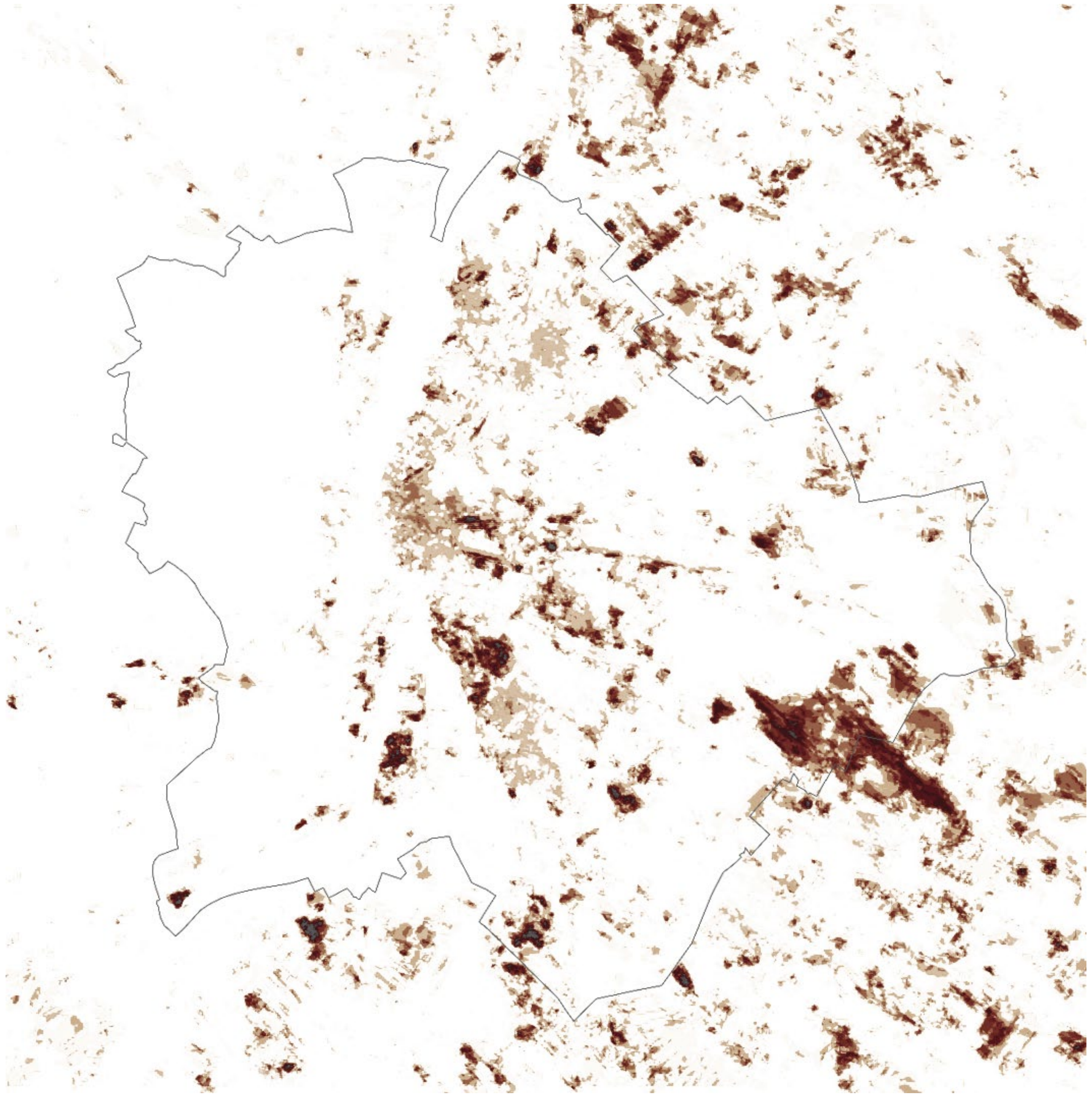


FIG. 35: "HOT SPOTS" / SATELITE IMAGES
(own analysis with Dragonfly)
The same method was used to identify the urban spots of Budapest which are constantly hotter.

6.2. RESULTS

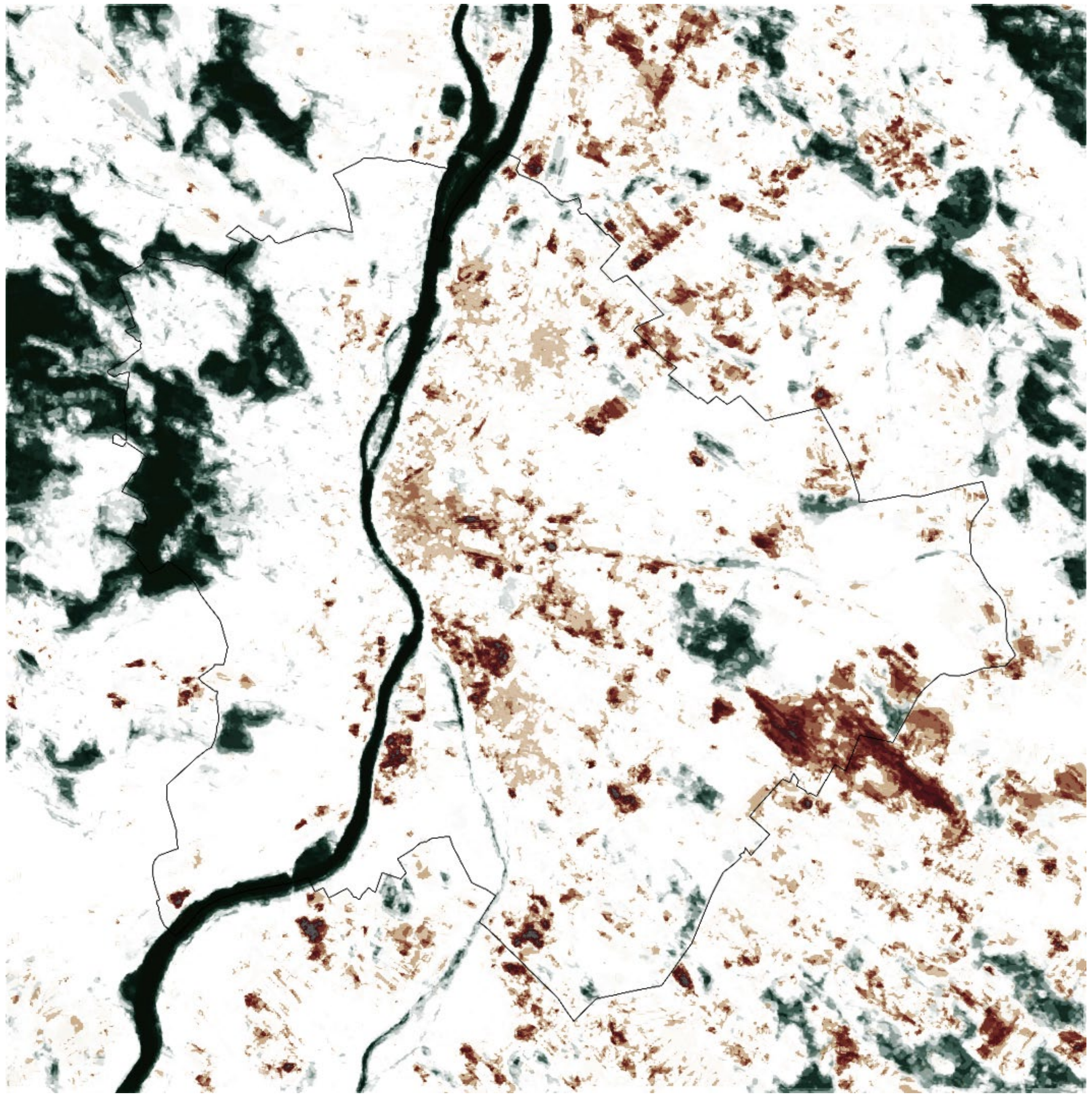


FIG. 36: URBAN HEAT ISLAND MAP // URBAN "COOL AND HOT SPOTS" OF BUDAPEST
(own analysis with Dragonfly)

6. LANDSAT IMAGE ANALYSIS - UHI ANALYSIS

6.3. COMPARISON WITH URBAN ANALYSIS MAPS

The objective of this chapter is to find the reasons behind the map of the urban heat island. The comparison of urban structure analysis with urban cool and hotspots will give us insights why some areas are hotter or cooler than others and how specific urban elements influence the city's urban heat island.

The cool spots will be compared with the map of the water bodies and the green area ratio, while the hot spots will be compared with the building density, the different uses-with special attention to the industrial use and the street classification (main traffic axes).

6.3. COMPARISON WITH URBAN ANALYSIS MAPS

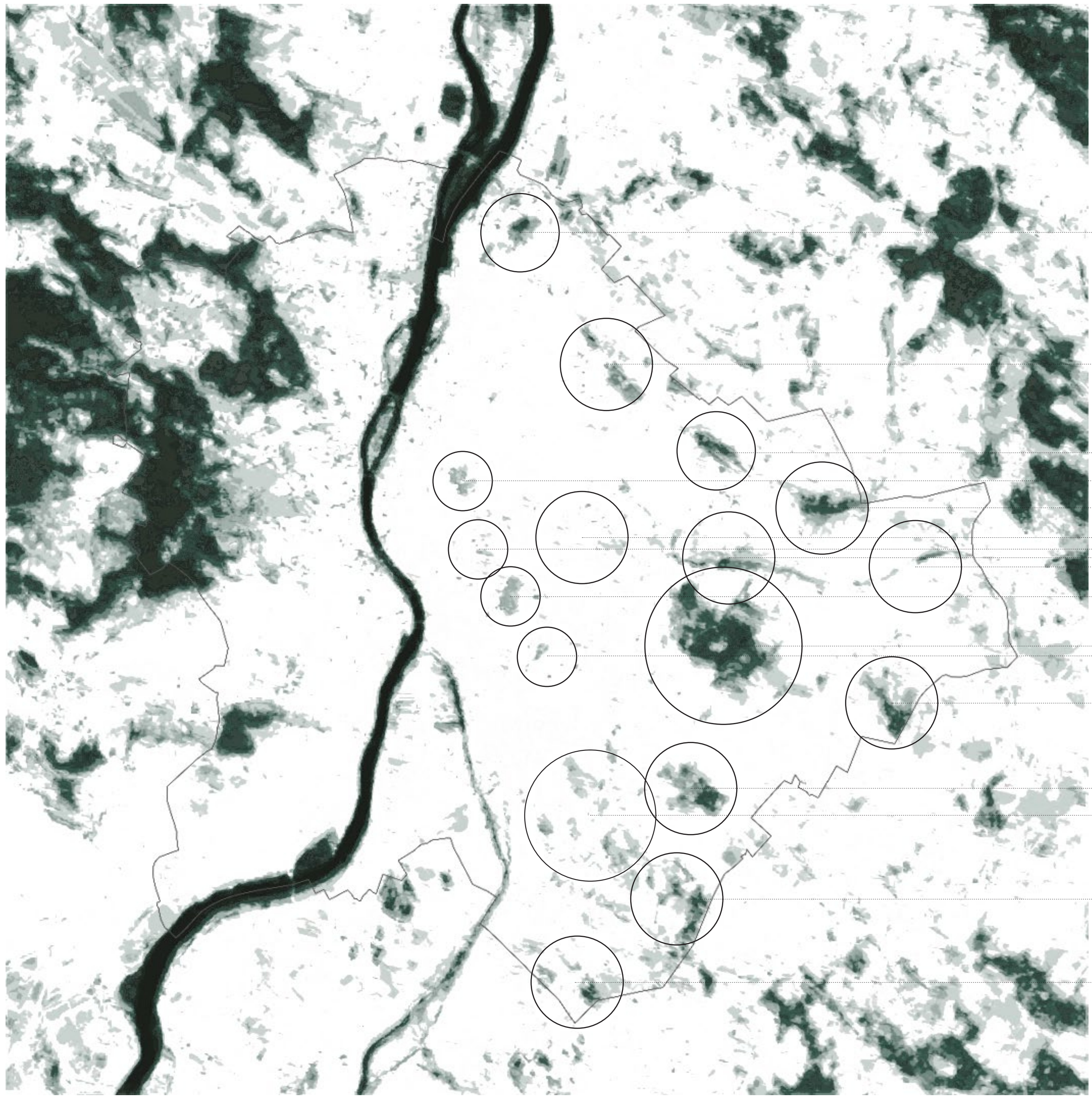


FIG. 37A: "COOL SPOTS" / SATELITE IMAGES
(own analysis with dragonfly)
The comparison of the urban cool spots with the map of the green area ratio clearly shows the correlation between the two maps. The large forests of the outskirts are clearly outlined. The three larger parks of the downtown are recognizable but less dominant. The larger the green area, the cooler is the spot compared to its surroundings.

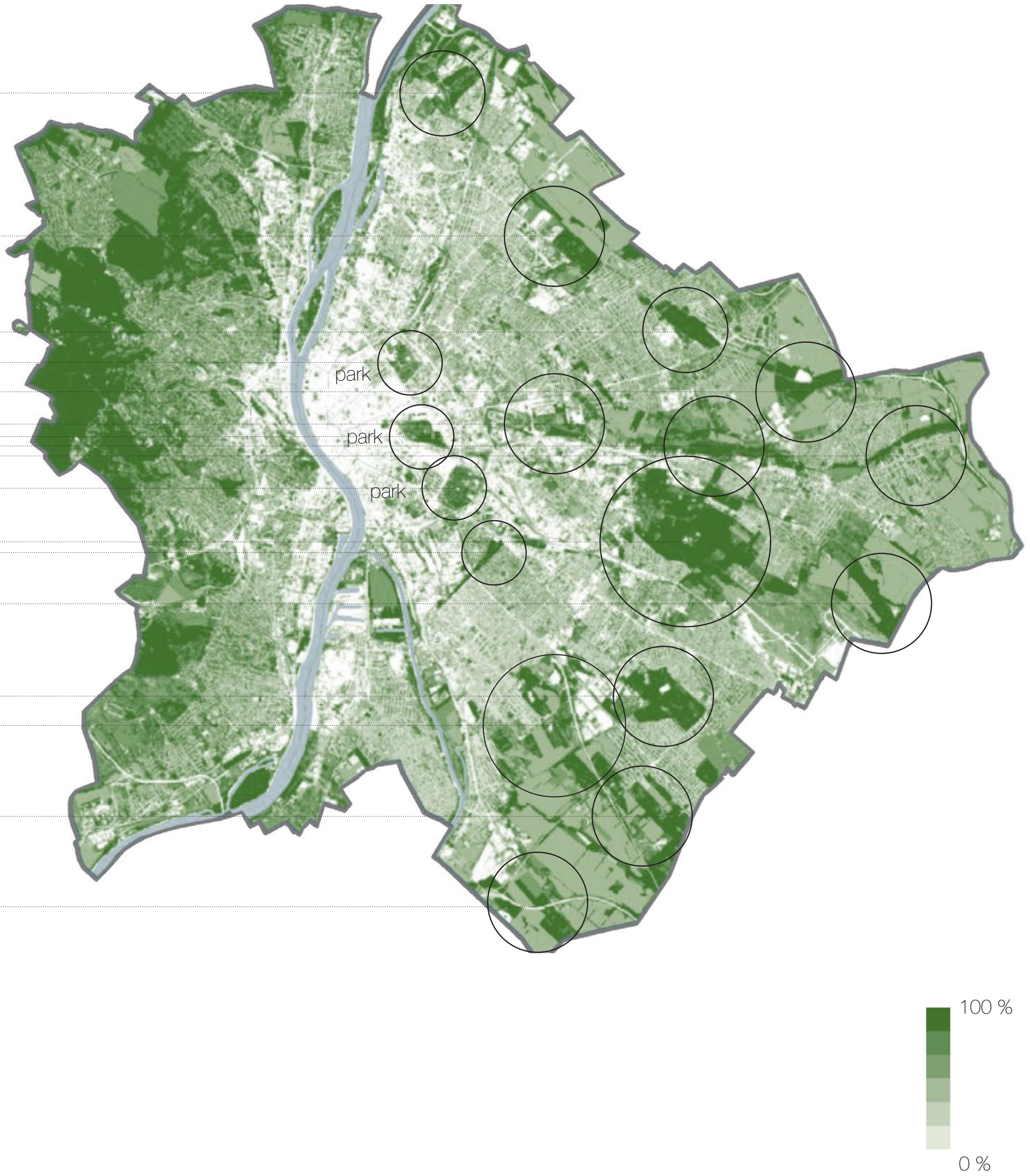


FIG. 37B: GREEN AREA RATIO
(Sandor JOMBACH In: TATAI, 2018)

6.3. COMPARISON WITH URBAN ANALYSIS MAPS

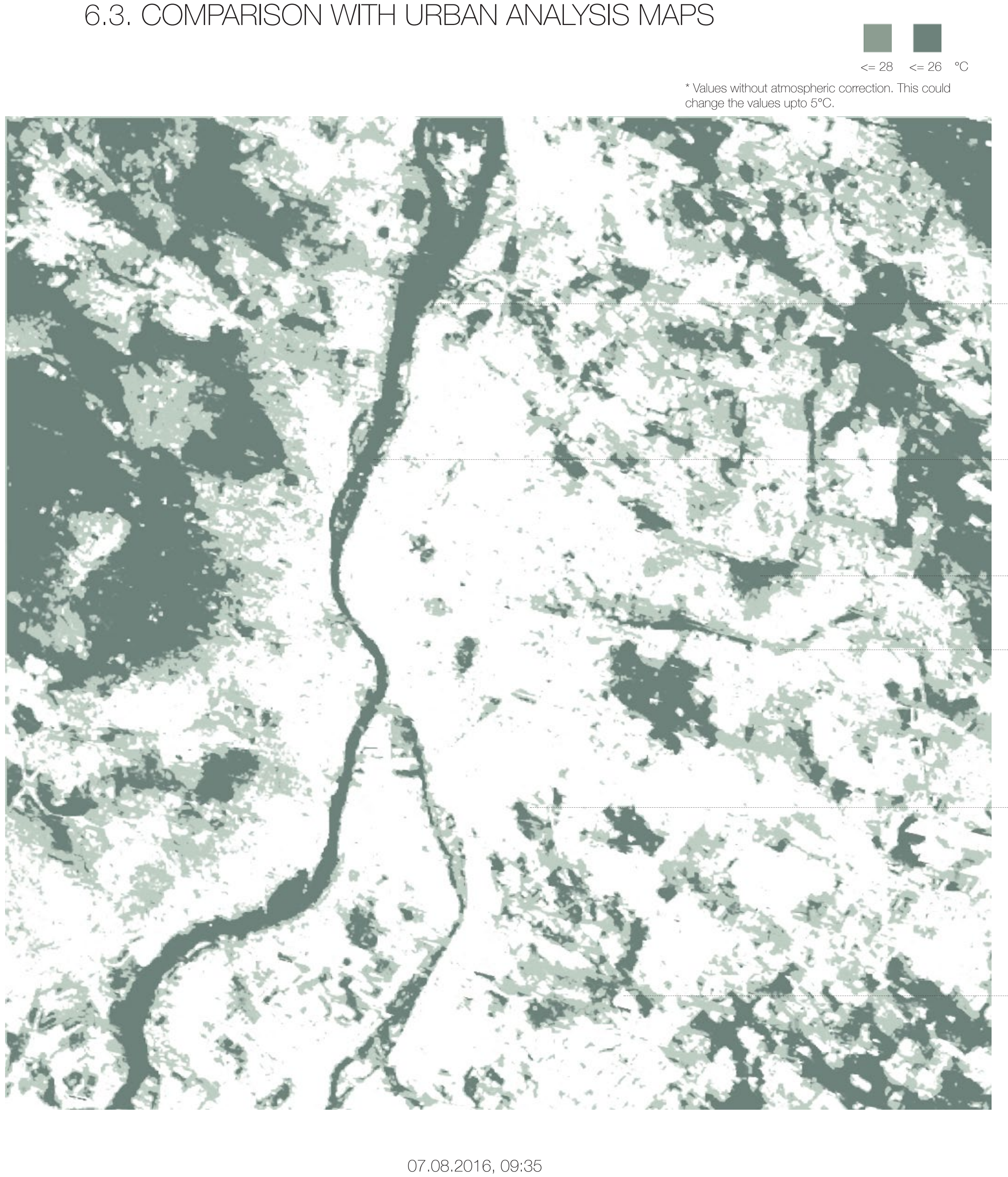


FIG. 38A: "COOL SPOTS" OF ONE RECORD / SATELLITE IMAGES
(own analysis with Dragonfly)
A single record of cool spots can provide more information about the boundaries of cool spots as they are less blurred. Therefore, for the comparison with the map of the water bodies, it is more accurate if one single record is compared. Large water bodies as the Danube are clearly visible. Smaller creeks are hard to identify, only the connecting green areas are noticeable.

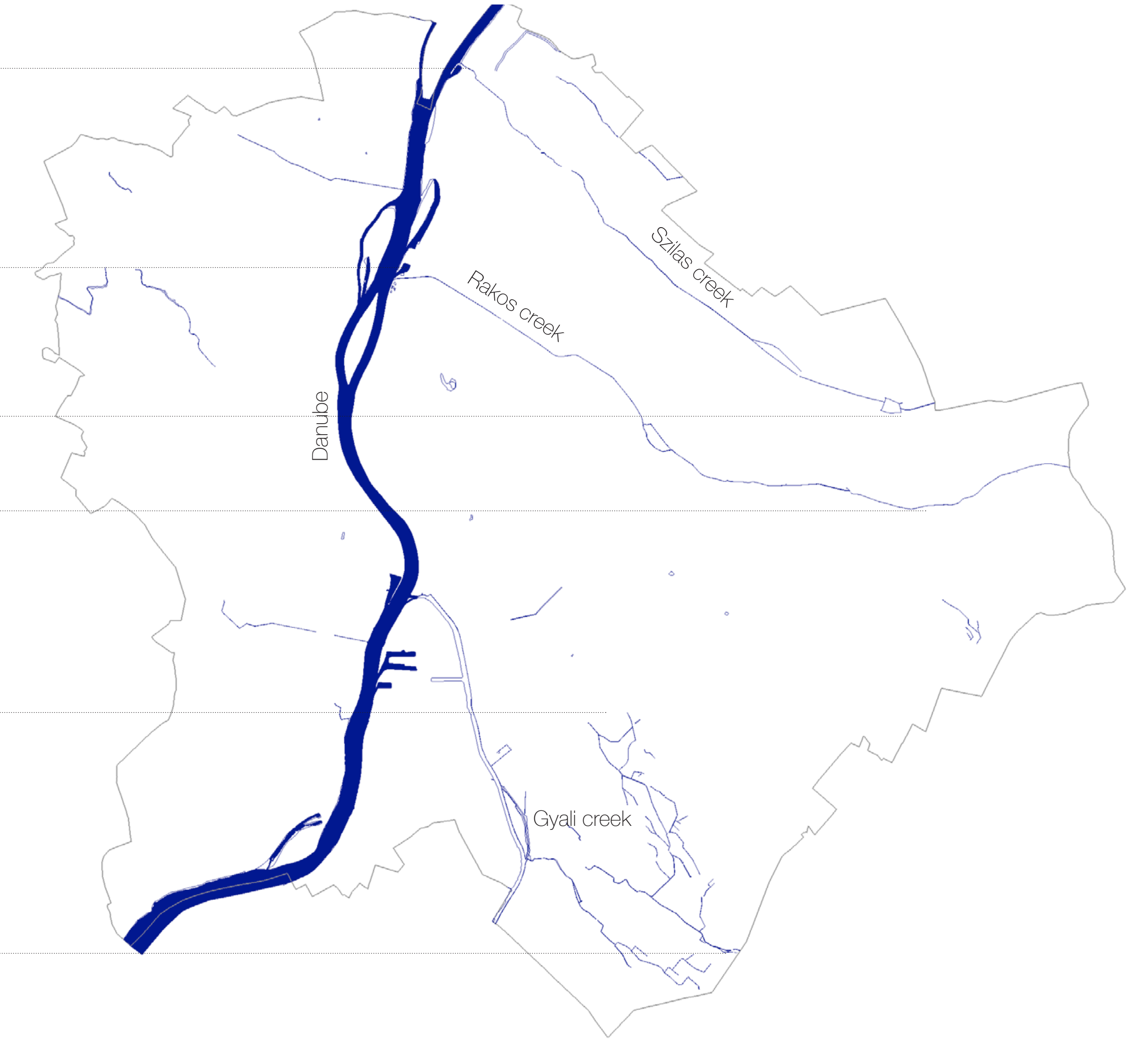


FIG. 38B: WATER BODIES
(own graphic, data from CADMAPPER, 2020)

6.3. COMPARISON WITH URBAN ANALYSIS MAPS

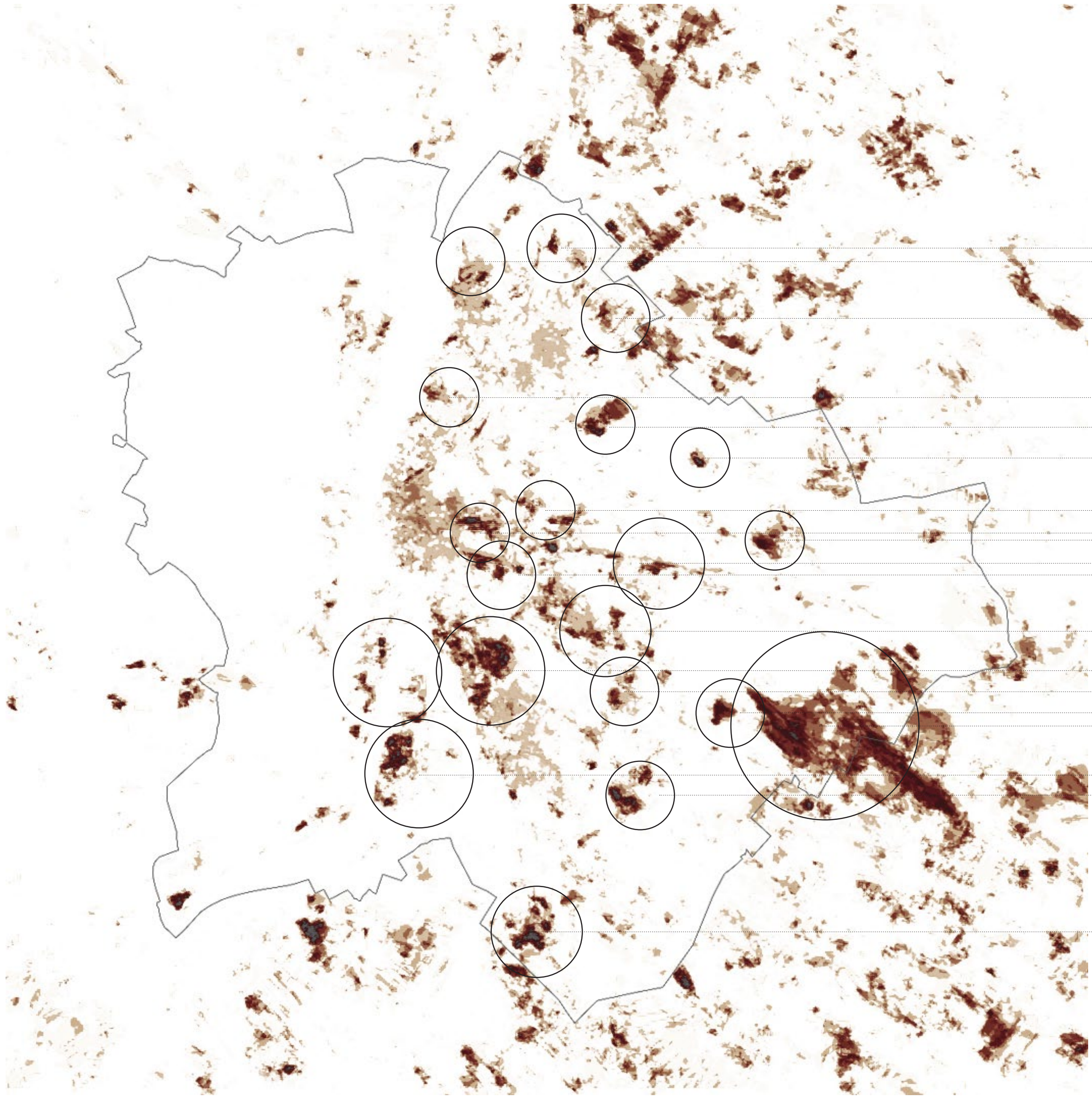


FIG. 39A: "HOT SPOTS" / SATELLITE IMAGES
(own analysis with Dragonfly)
Interestingly, almost all hot spots are either large, paved traffic areas or brownfields and industrial areas. These industrial areas also have large, paved asphalt areas and for the most part, very low green area ratio. This means also a high potential, because the change in the quality of the pavement and its green area ratio could significantly mitigate the thermal hot spots of the city.

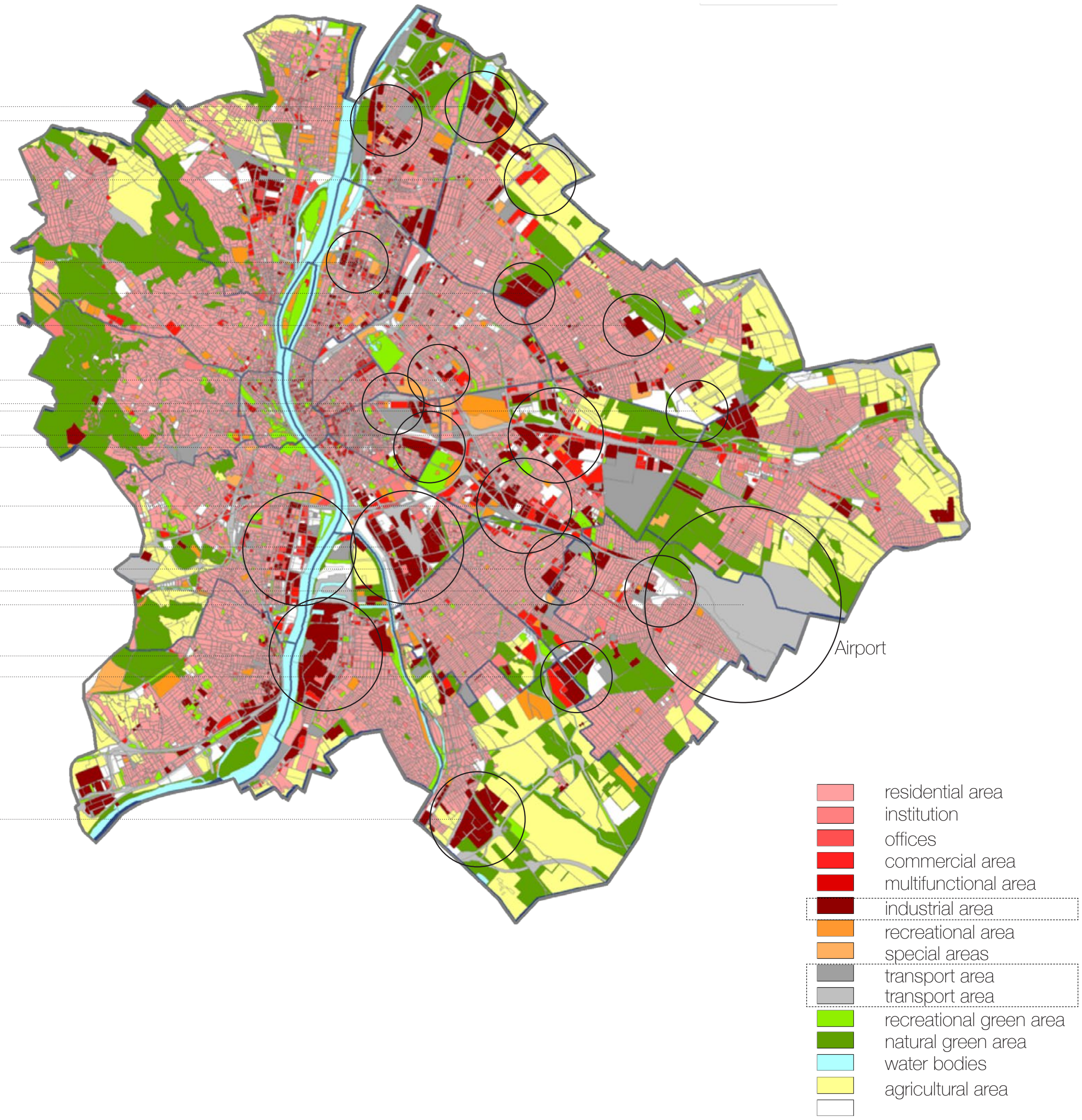


FIG. 39B: FUNCTIONS / ZONES
(BFÖ, 2014)

6.3. COMPARISON WITH URBAN ANALYSIS MAPS

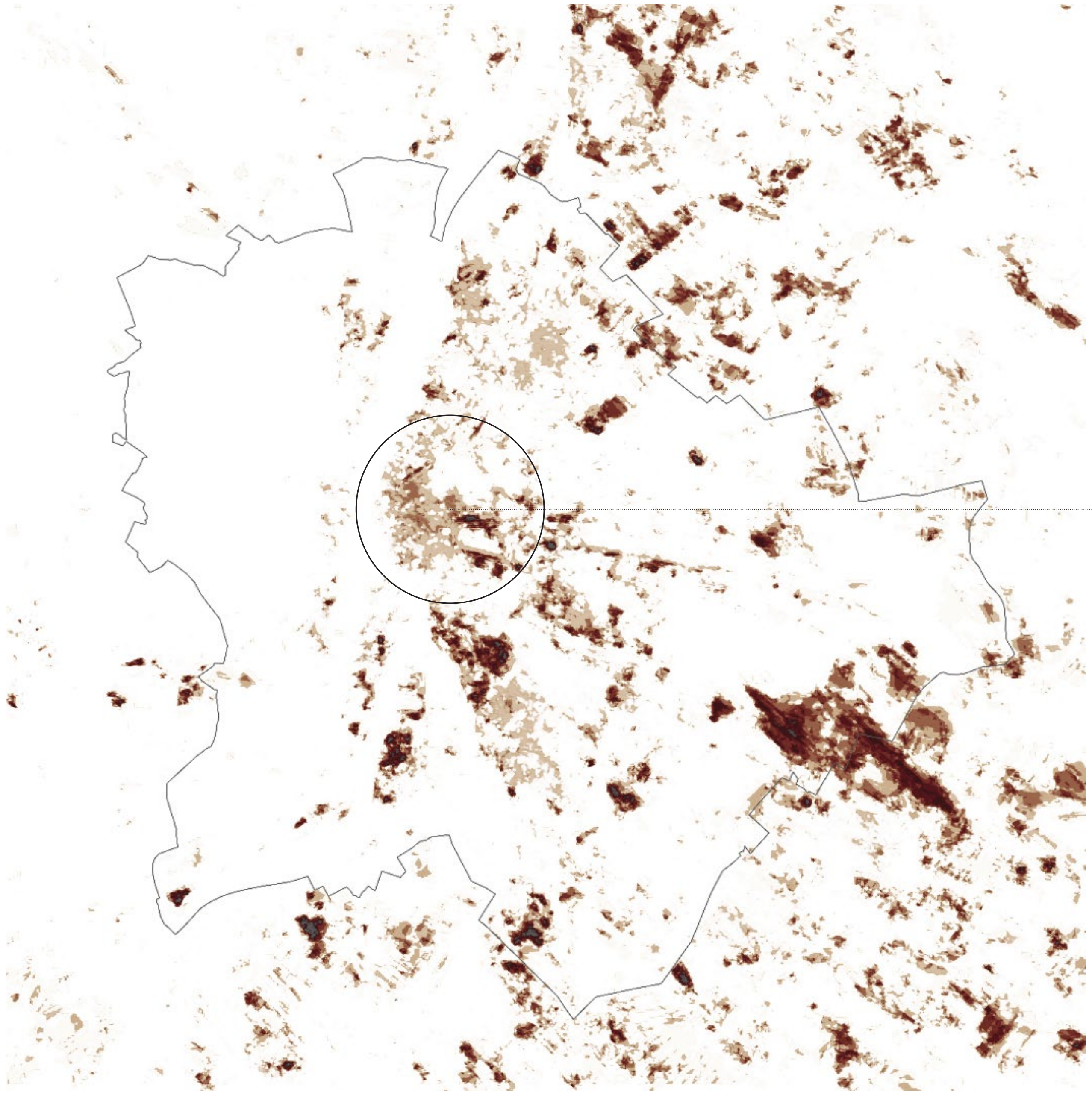


FIG. 40A: "HOT SPOTS" / SATELLITE IMAGES
(own analysis with Dragonfly)
The hot spot of the downtown is probably the consequence of the dense urban tissue. This area of the city is less ventilated, and has more anthropogenic heat release like traffic, energy consumption of buildings etc.

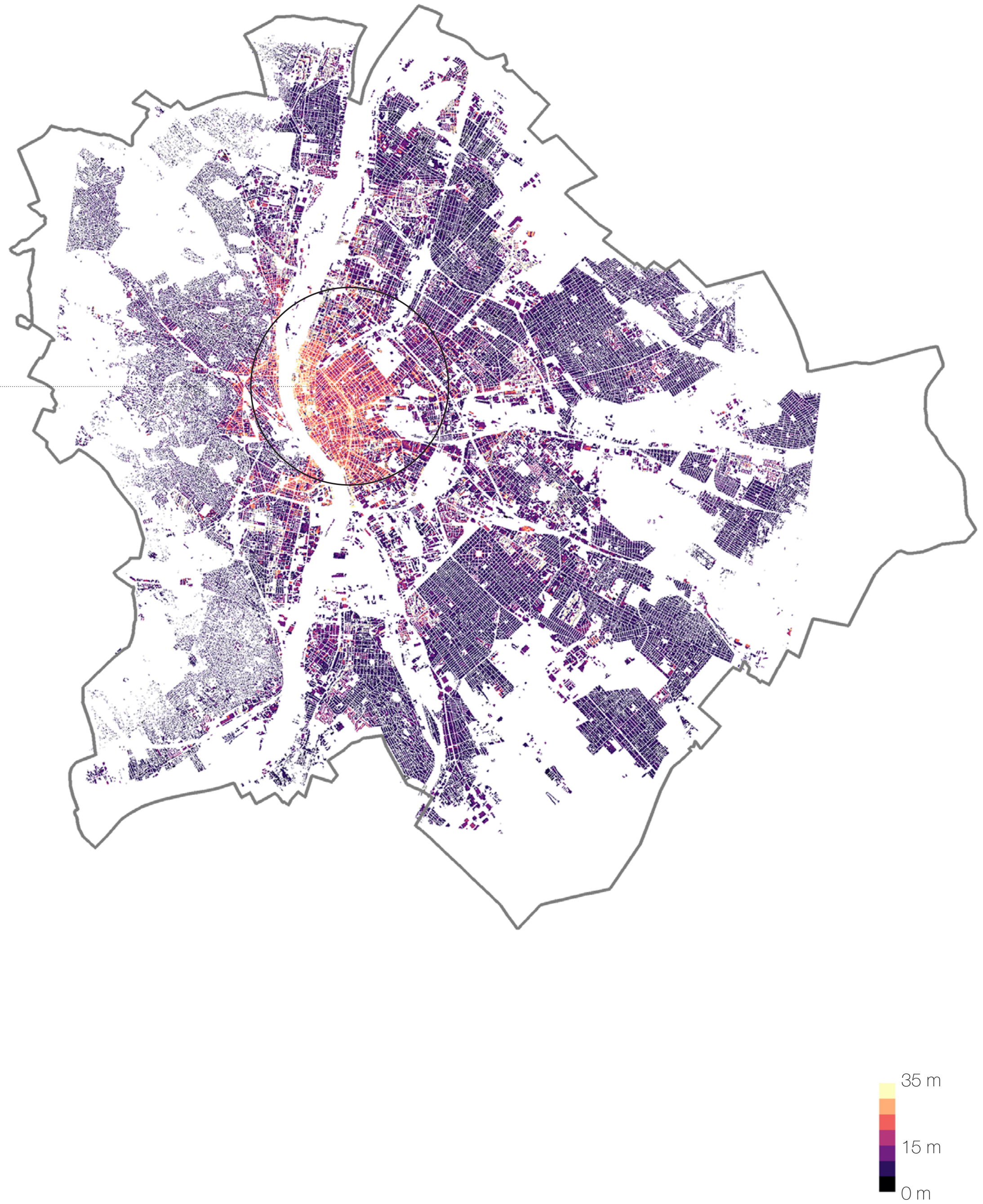


FIG. 40B: BUILDING HEIGHT
(DEMUZERE et. al.,2019)

6.3. COMPARISON WITH URBAN ANALYSIS MAPS

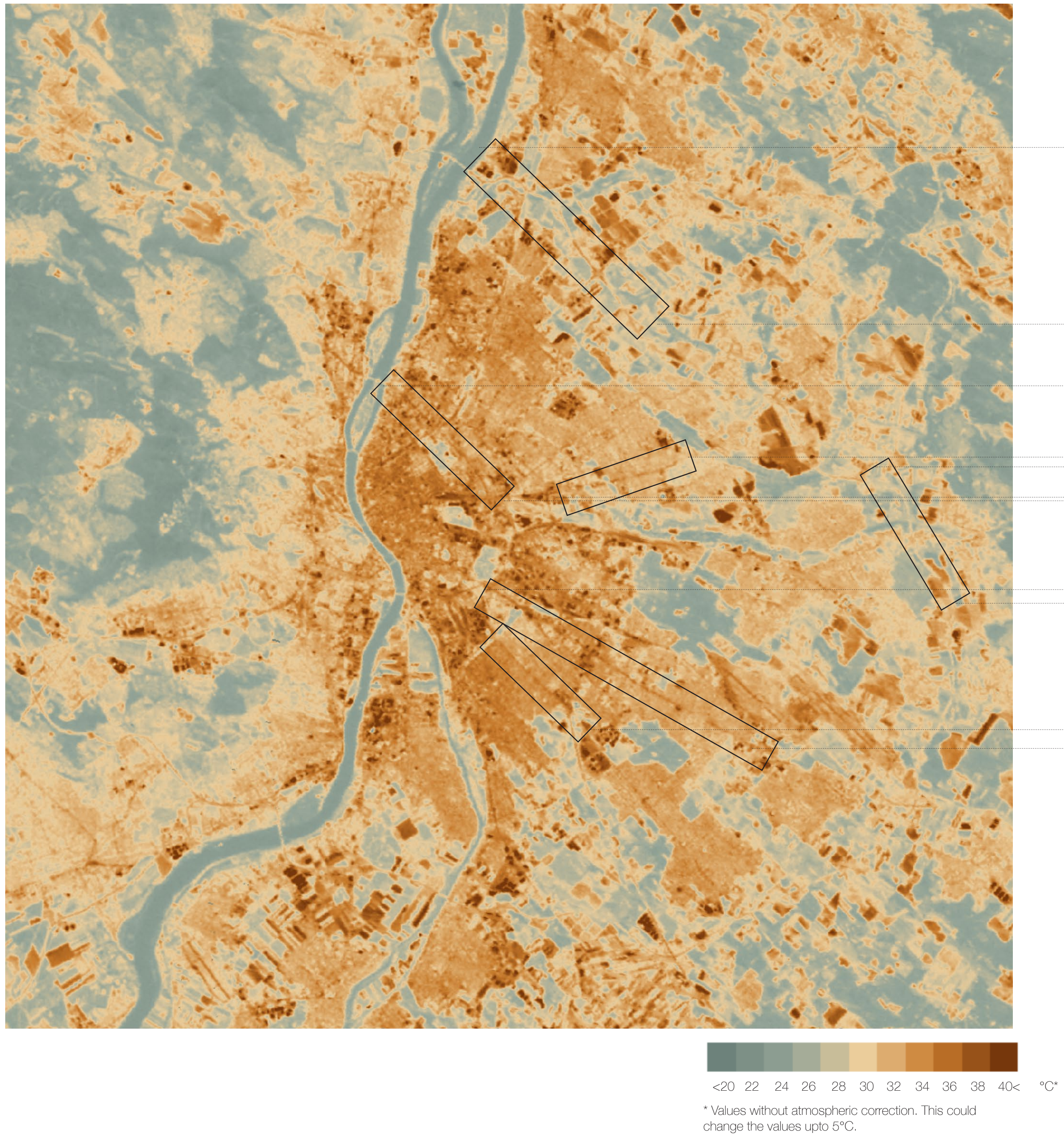


FIG. 41A: "HOT SPOTS" / SATELITE IMAGES
(own analysis with Dragonfly)
One of the most interesting observations is that some of the main high-traffic roads are clearly noticeable on the thermal maps. The reason behind their high mean radiant temperature is on the one hand that these large paved areas are likely to have high sky-view factor (not shaded). On the other hand, traffic as an antropogenic factor also produces significant release of heat.

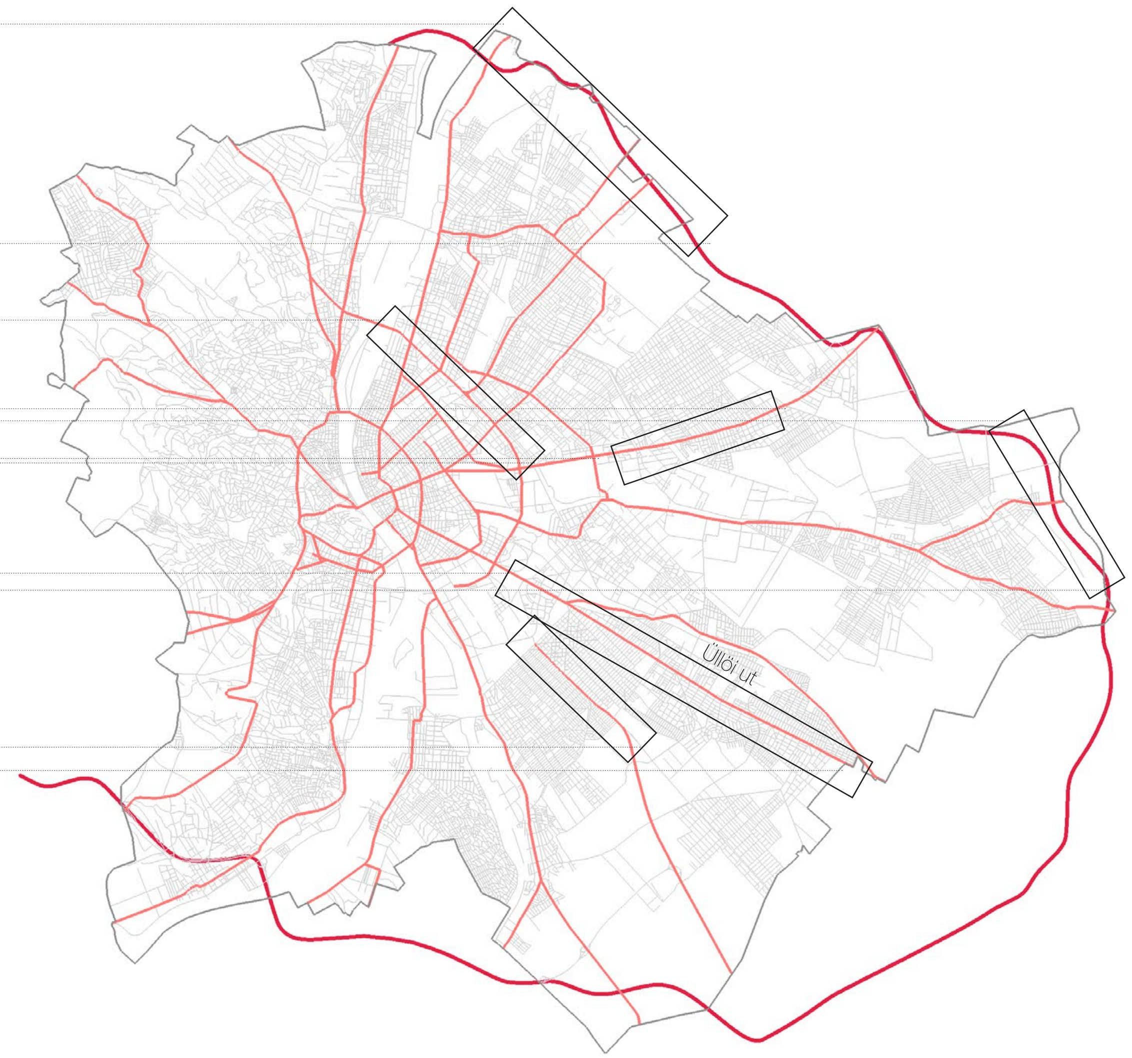


FIG. 41B: STREET NETWORK HIERACHY
(own graphic, data from CADMAPPER, 2020)

6. LANDSAT IMAGE ANALYSIS - UHI ANALYSIS
6.4. CONCLUSION

Green areas of the outskirts turn out to be urban cool spots: each larger green surface and the large water body of the Danube can be seen as cooler areas in figures 37-38. Smaller creeks tend to be irrelevant, although the connecting green areas are visible. (Fig. 38) The larger and more compact the green area, the greater the difference in temperature and the colder the core area is. Smaller urban parks are almost unrecognizable. It is noteworthy that the scale and compactness of the three large urban parks are similar to the green areas next to the “Szilas Creek,” but the latter is much cooler than the former. This may be because of two reasons. Almost all urban parks (s. Fig. 37) have hot spots in their immediate vicinity, which moderates the cooling effect. In addition, this can also mean that the creek has a major impact on cooling. This subject may be of interest to further research.

It should be remembered that the analysed data is the mean radiant temperature of the objects. This clearly affects the temperature of the air; however, it mixes more rapidly with higher air temperatures because the temperature differences cause air flow. This means that the real variation in air temperature is much lower than the differences in the mean radiant temperature shown in the figures. The cooler air of the parks is likely to mix easily with the warmer air, and so it is unclear if these parks provide cooler temperatures at all. And if they do, there is possibly a very small difference (ca. below 1-2 °C).

Hot spots are mainly caused by three factors: wide, paved surfaces with a high sky-view factor and a high albedo(1); and two major anthropogenic factors of the heat release: traffic (2) and buildings (3). Hot spots with a high contrast to the surroundings are primarily industrial areas (Fig. 39). Since these are not heavy industrial areas, but rather logistic centres, I would suggest that the large, paved surfaces of these areas cause these hot spots. Beneath, some of the high-traffic roads are also visible (Fig. 41). Interestingly, not all large roads with a high aspect ratio are noticeable, which may mean that this difference is mostly due to traffic. This notion could be valid because one of the roads with the heaviest traffic leading to the airport (“Üllöi ut” s. Fig. 41) is most clearly visible on the thermal map. Further investigations and comparisons with traffic maps could yield interesting results.

The area of the downtown is especially interesting. (Fig. 40) Despite having a green ratio of almost 0 %, it does not display large hot spots, but rather the entire region is consistently warmer than its surroundings. The explanation may be that this is the location of the dense mid-rise zone, which means relatively high and closed building blocks shading even larger streets. This typology also has a negative impact next to the positive one: as we have shown, it clearly blocks ventilation. The higher anthropogenic heat release of the downtown (traffic and buildings) cannot escape easily and cause the whole city to be warmer than its surroundings (Fig. 40).

To sum up, larger water bodies and green areas of the city are causing urban cooling spots primarily in the suburbs, while the entire downtown is acting as a warmer region caused by anthropogenic heat release. In addition, industrial areas in the outskirts are also acting as hot spots. I see a high potential for further investigations in the relation of thermal maps to urban structure research. The identification of the causes of hot and cold urban areas could affect and inspire UHI mitigation strategies.

7. CFD ANALYSIS

7.1. METHOD

In the following chapter, the focus lies on the computational fluid dynamic analysis. I conducted the CFD analysis for the dense downtown area. The analysis of the ventilation flow of the outskirts had two steps, I conducted CFD analysis for each local climate zone identified in the spatial analysis in chapter 4.2. These CFD analysis serve the idea that with the simulation of the flow pattern of each LCZ typology and with the information how each of this type is distributed, in the end, the ventilation of the entire outskirts of the city can be identified.

In the following all individual steps for conducting the climate analysis are briefly explained. In the chapter 7.1. method, I will discuss the domain knowledge, the input data and parameters. In chapter 7.2. I will present the results of my analysis. For the conclusion and qualitative wind flow analysis in detail see chapter 7.3.

Domain knowledge of CFD

To conduct aerodynamic analysis, It is primarily possible in two ways: laboratory testing and computational fluid dynamics (CFD). Prototypes, wind tunnels and test tracks are used by the former, making it a very costly choice. CFD uses computational methods to solve the equations of Navier-Stokes within a discretized domain of computation. Therefore, CFD is basically constrained by the computing resources available and the expertise of the modeler. (Osorio, 2017) With the advancement of machines and the consequent increase in computation capacity, CFD has been seen to be an extraordinary method to minimize costs and improve efficiency in many situations. (Osorio, 2017)

Fluid flow is analyzed in accordance with its physical characteristics, such as velocity, pressure, temperature, density, and viscosity. These properties must be regarded concurrently in order to produce an accurate response to a physical process associated with fluid flow. In a CFD software tool for the study of fluid flow, a mathematical model of the physical case and a numerical approach are used. The primary structure of the study of thermo-fluids is driven by governing equations dependent on the physical properties of the fluid conservation law. Inside a closed system, mass, momentum, and energy are stable constants.

These three laws of conservation are the fundamental equations. (Simscale, 2020)

The solution domain is separated into several sub-domains which are called cells in order to do an analysis. Meshing is the method of discretizing the domain into small cells or components under the assumption of linearity pertaining to each cell in order to apply the mathematical model and the mesh is the name of the arrangement of these cells in the computational system. This means we need to ensure that inside each cell, the behavior of the variables that need to be solved can be expected to be linear. This criterion also ensures that a finer mesh is needed for locations where it is assumed that the physical properties to be expected are extremely changeable. (Simscale, 2020) A frequently found problem that results in the simulation causes errors dependent on mesh configuration. This may happen because the mesh is too coarse and does not cover all the effects one by one that occur in this single cell element, but rather covers many effects that shift as the mesh becomes finer. Therefore, the precision of the solution depends greatly on the mesh configuration. (Simscale, 2020)

For computational analysis, convergence has a great significance. With several dynamic models such as turbulence, phase change, and mass transfer, fluid flow has a non-linear mathematical model and convergence is highly affected by them. The numerical approach goes through an iterative scheme where results are obtained by eliminating errors between previous phases. The error is specified by the variations between the last two values. (These are called as residuals.) The efficiency of the outcome increases as the absolute error reduces, which means that the conclusion converges into a consistent solution. Convergence is reached as iterations get down to a threshold value. (Simscale, 2020)

“The usual steps of a recurring CFD analysis in a design process for the built environment consist of:

(1) modelling the building geometry with CAD software;

(2) meshing the building geometry and topography;

(3) simulating the problem with appropriately-assigned boundary conditions for multiple wind directions;

(4) postprocessing the variables of interest, likely followed by design alterations that lead back to (1) if goals or constraints have not been met.” (Kastner, 2020)

Eddy 3D:

The skills required to conduct such analysis and the related overhead preprocessing also hinder the broader usage of natural ventilation studies in workflows for architecture and urban scale architecture. As a result, CFD analysis are costly and are typically only performed late in the design process. As such, drastic improvements are often no longer possible to boost the natural ventilation capacity.

Therefore, the workflows for annual wind analysis need to be streamlined and the time needs to be minimized to deliver actionable data in order to consolidate natural airflow assessments into early design processes, Kastner et al. suggest a new approach by using the CFD library OpenFOAM to minimize the preprocessing and simulation process. The Eddy 3D plugin automates the preprocessing phase, including the assignment of boundary conditions. (Kastner, 2020)

One of the limitations of eddy3D is that it does not consider thermal properties. The thermal driven flow also called buoyant flow is driven by hot (urban) surfaces. These surfaces of high temperatures vary temporally and spatially. (Piroozmand, 2020) “This interaction within a highly heterogeneous urban environment leads to complex spatially and temporally varying vertical profiles of atmospheric variables.” (Piroozmand, 2020) However, over around 1 m/s the wind driven flow will dominate. Because of this reason, I have methodologically split the cases when wind driven flow and thermal driven flow dominates. (s. 5.2. Climate analysis)

Input data & data acquisition:

- 3D GEOMETRY of the city / urban area: own modelling and online ressources.

- For simple wind analysis there is no need of weather data. With weather data a more accurate annual wind analysis is possible, however it needs a much larger computational power. Therefore, in this research only simple windanalysis was conducted.

Input parameters:

1. Boundary conditions:

- Wdir: Wind direction - 0° and +/- 45°
- Uref: Wind speed - 3 m/s (according to Ladybug analysis)
- zref: Wind speed reference height - 10 m
- z0: Aerodynamic terrain roughness length - setting 2 m (chaotic)
- zGround: - default setting 0
- epw: weather data for annual wind analysis

2. Simulation Domain

- Geometry (3D geometry of the urban area)
- Terrain: - to save computational power the terrain was considered as flat
- BS: Block size / Cell size of the domain - dafault setting 20 meters
- L / W / H: length / width/ height of the domain should be automatically set according to the size of the geometry. Whereas width and height of the geometry sets properly according to the size of the input geometry, the length seems to have a bug. Therefore I have adjusted it. (s. later)

3. a Meshing

- Accbuilding: Accuracy of building mesh - default setting 2
- AccFeatures : Accuracy of building features - such as corners - setting 3
- AccRefinement: Accuracy of bounding box mesh - default setting 0
- Accground - Accuracy of the terrain - setting 3
- nLay - Number of mesh layers - default setting 3
- Mode: No snapping no layers / With snapping no layers / With snapping with layers - default setting with snapping, no layers

3. b Simulation

- Iteration - number of iterations to be simulated - setting 1'000 by all simulations it stopped before because of convergence

- WriteInt: Simulation write interval - default setting 20
- Tsteps: Number of timesteps to keep in simulation folder - default setting 2
- Turb: Turbulance model : kepsilon(quick)/RNGkepsilon(more accurate)/ kOmegaSST (most accurate) - setting RNGkepsilon
- Relaxation factors: Openfoam / Fluent / Simscale - default setting Openfoam
- Mode: Robustness of the solver - quick /robust / orthogonal (70-80) / orthogonal (60-70) / orthogonal (40-60) / accurate and stable / more accurate but oscillatory / robust but diffusive - setting quick
- CPUs - number of CPUs - setting 4
- Operation System - autodetect

4. Probing points & Probing:

- Plane Geometry as Brep - 2 m / 5 m / 10 m / 20 m heights and 2-3 vertical planes
- Number: Density of the interpolated vectors on the plane - setting: 3/ 5 (depending on the size of the urban geometry)
- Field: - velocity / pressure coefficient / pressure (p) / turbulent dissipation rate (epsilon)/ scale of turbulence (omega) / turbulent kinetic energy (k) / turbulent viscosity (nut) / mass flow (phi) - setting velocity

CFD Grasshopper tool "Eddy 3D" tool by Kastner, 2020

7.1. METHOD

FIG. 42: INPUT 3D GEOMETRY // LCZ TYPES - BUDAPEST

East from the river, in the outskirts there are mostly low-rise buildings up to 10 meters and there is a large suburban area. (s. chapter 4.1. Local climate zones of Budapest) If we run a CFD for each Local Climate Zone, we could qoualitatively understand the general flow pattern of the whole city without any computationally heavy analysis. For the categorization, I used the local climate zone classification of Oke et. al.(s. chapter 4.1.)

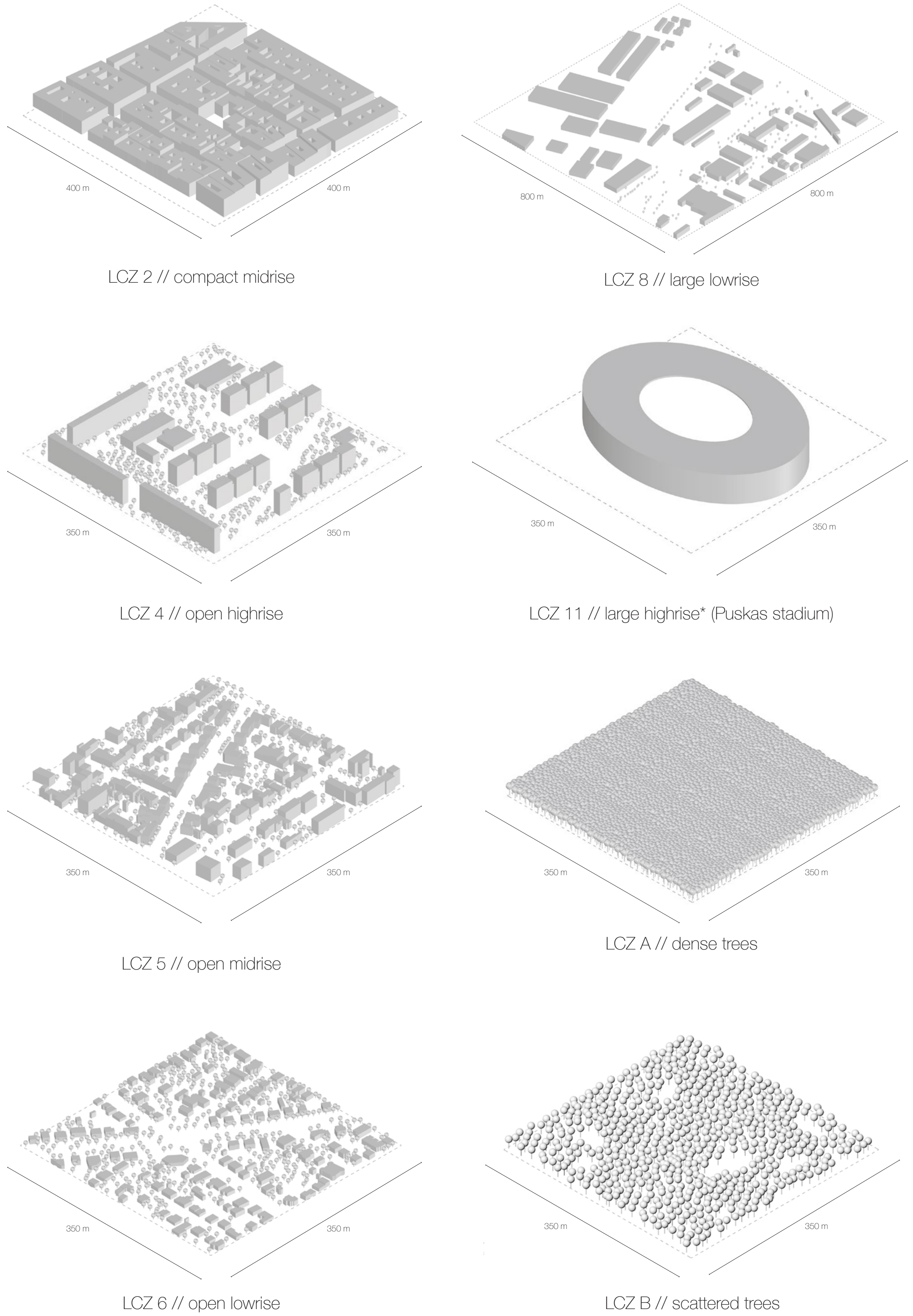


FIG. 43: LCZ TYPES

(* LCZ 11- is not part of the classification of OKE et. al. and was added by myself. In Budapest there are several stadiums in the city, and I was intrested how this can influence / block the ventilation corridors of the city.)

7.1. METHOD

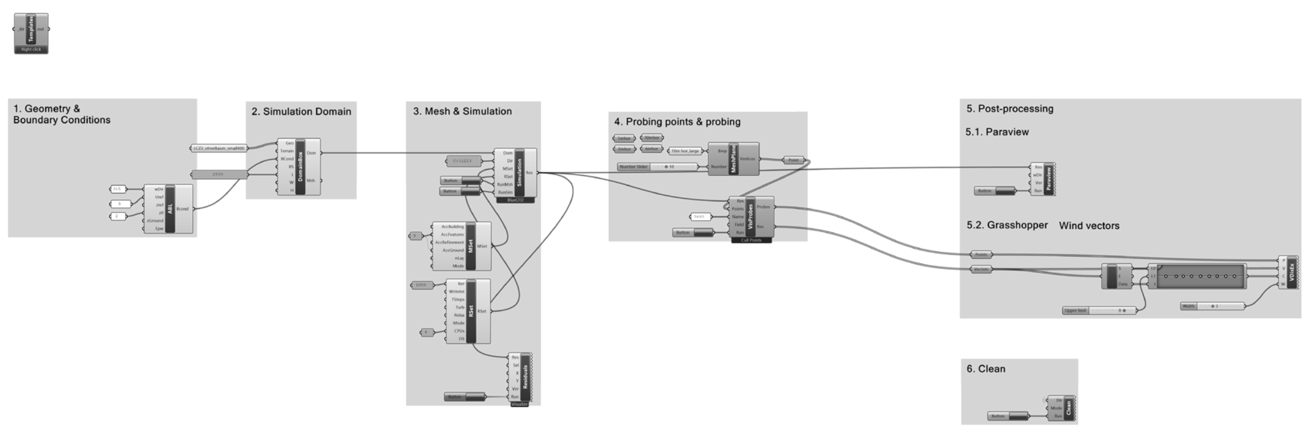


FIG. 44: EDDY 3D IN GRASHOPPER AND INPUT PARAMETERS

(KASTNER, 2020)

The script for simple wind analysis is preset through the main component of the plugin. Please find the comments regarding the input data, the options and input parameters in the description of chapter 7.1. Method.

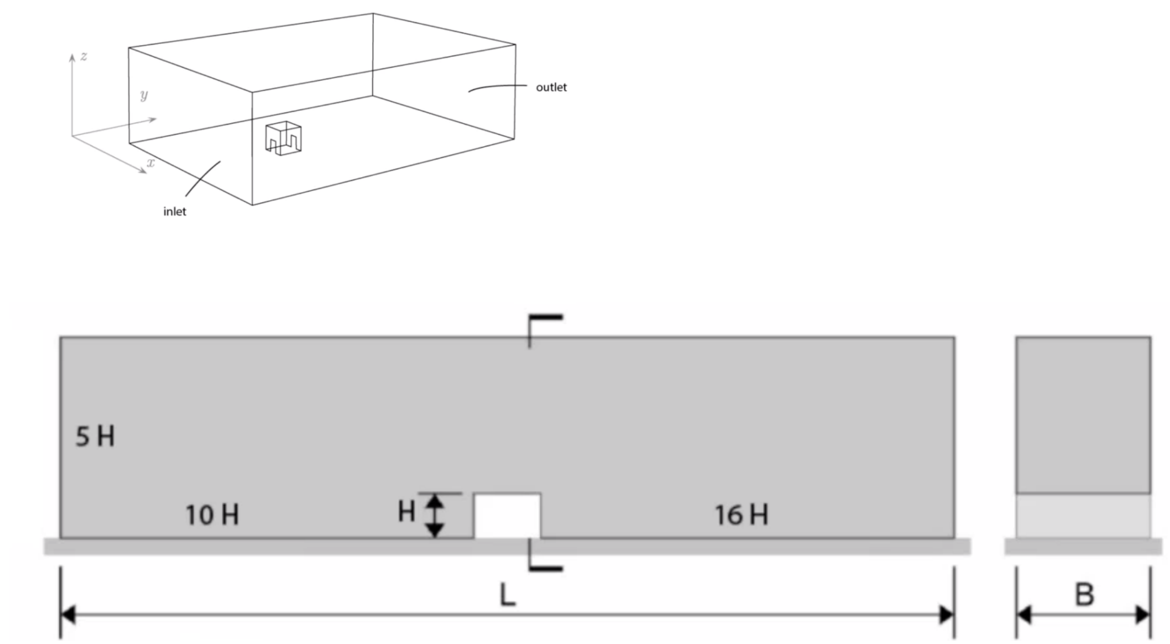


FIG. 45: DOMAIN / BOUNDING BOX (eddy3D.com, 2020)

The size of the bounding box is automatically set in eddy 3D. The lentgth and width of the domain was adjusted to have a larger domain which resulted to produce less errors.

7.1. METHOD

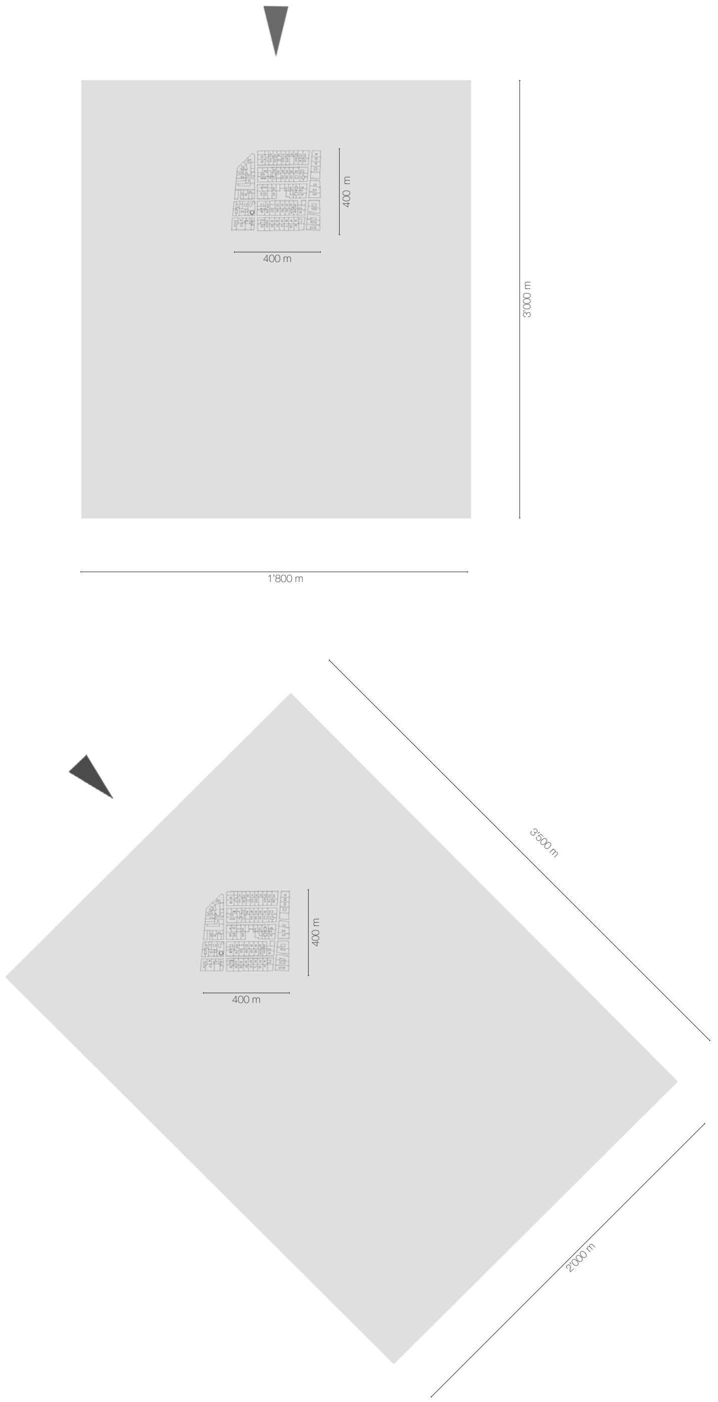


FIG. 46: DOMAIN / BOUNDING BOX - DIRECTION 0° AND 315° (EXAMPLE ON LCZ2)

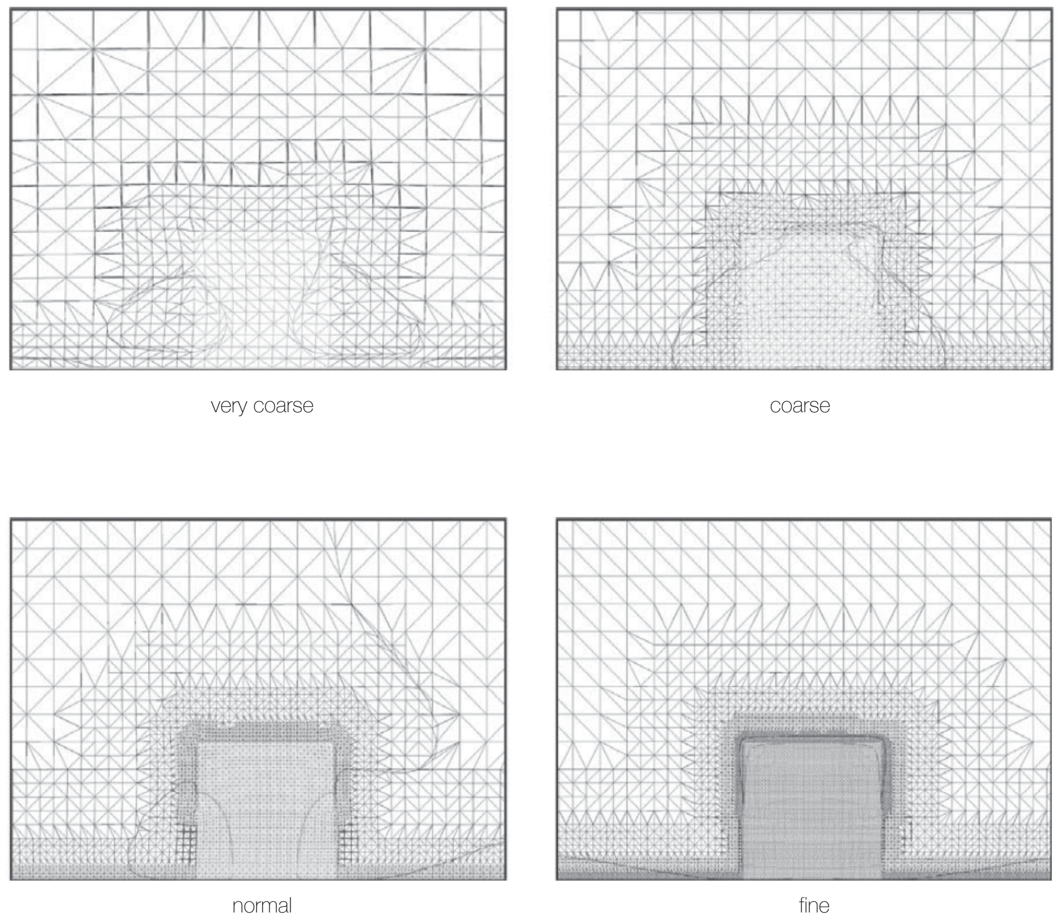


FIG. 47: MESH (KASTNER ET AL., 2020)

As mentioned before the Eddy3D plugin automates the assignment of boundary conditions including the meshing."The mesh is created by using the blockMesh utility for the background mesh and snappyHexMesh to subsequently snap the background mesh to the building geometry, producing a mixed polyhedral mesh." (Kastner, 2020) I worked with coarse mesh.

7.1. METHOD

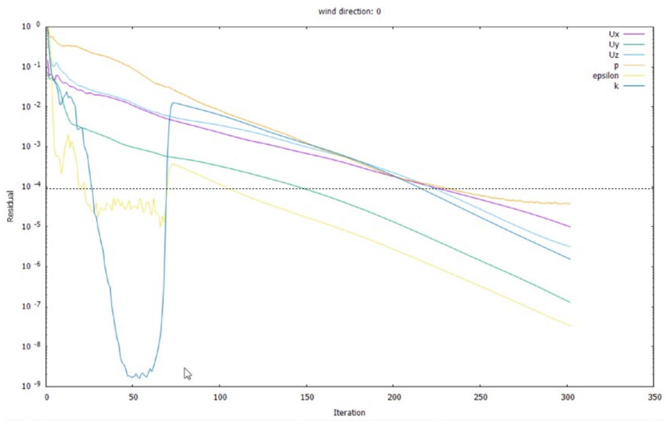


Fig. 48a: correct residual graph

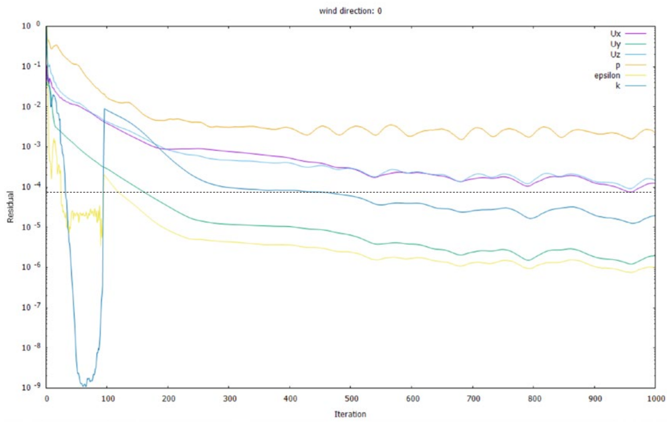


Fig. 48b: questionable residual graph (not fully converged)
(LCZ 11)

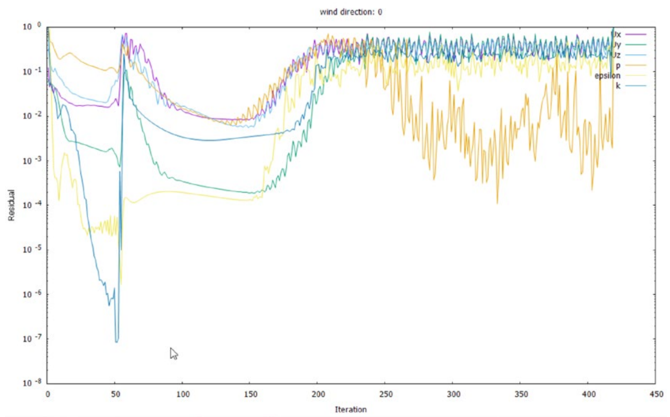
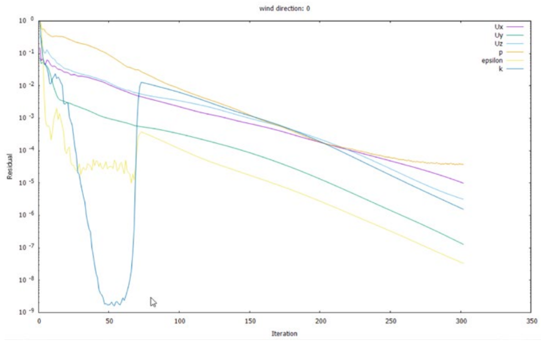


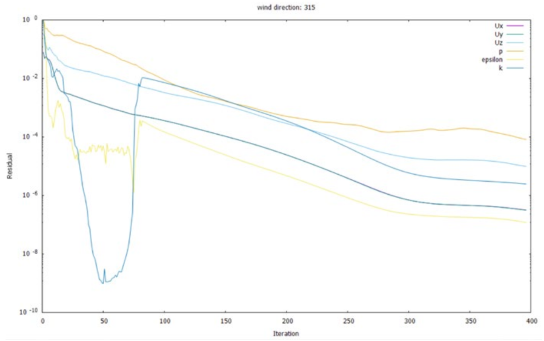
Fig. 48c: incorrect residual graph (error)

FIG. 48: RESIDUALS AND ITERATION (TIME STEP)

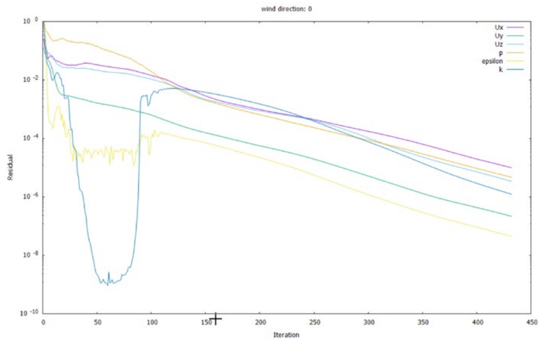
Residuals: velocity (Ux, Uy, Uz) / pressure (p) / turbulent dissipation rate (epsilon) / turbulent kinetic energy (k)
The numerical approach goes through an iterative scheme where results are obtained by eliminating errors between previous phases. The error is specified by the variations between the last two values of the residuals. The efficiency of the outcome increases as the absolute error reduces, which means that the conclusion converges into a consistent solution. Convergence is reached as iterations get down to a threshold value. (Simscale, 2020) Errors under 10^{-4} are considered as acceptable but still do not mean a very high accuracy. Eddy 3D stops if all the residuals reached this treshold.



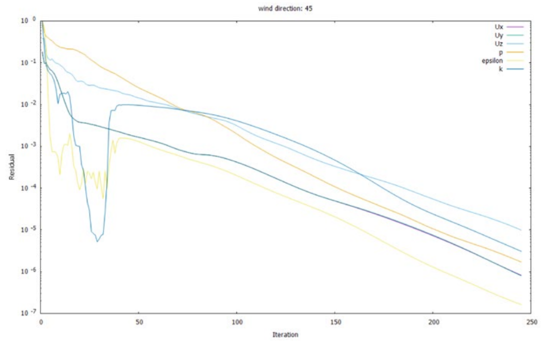
LCZ 2 // wind direction: 0



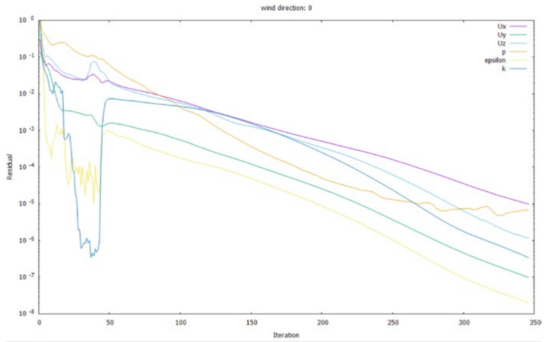
LCZ 2 // wind direction: 315



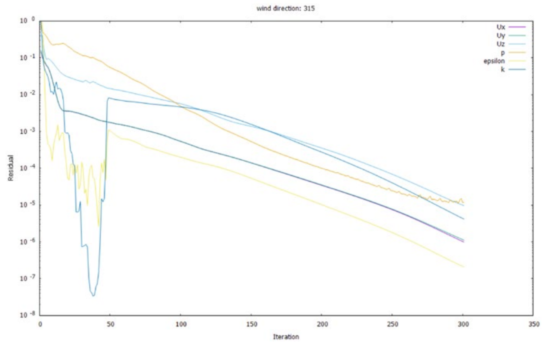
LCZ 4 // wind direction: 0



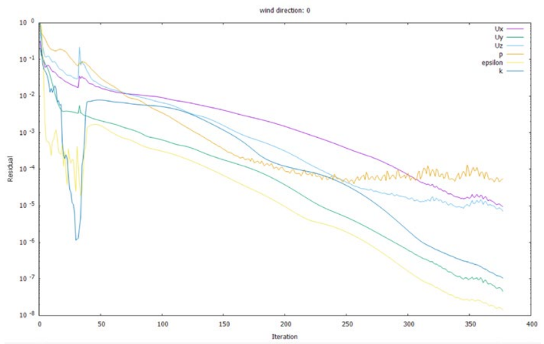
LCZ 4 // wind direction: 315



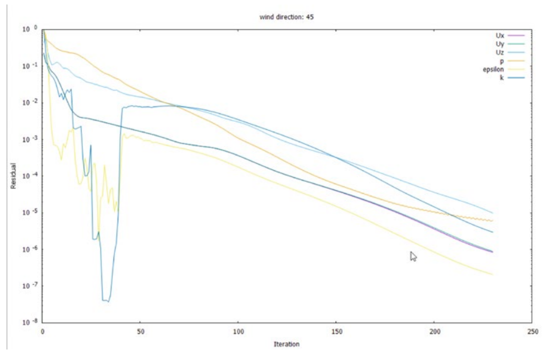
LCZ 5 // wind direction: 0



LCZ 5 // wind direction: 315



LCZ 6 // wind direction: 0



LCZ 6 // wind direction: 315

FIG. 49: RESIDUALS OF SOME RUNNED CASES

7. VENTILATION ANALYSIS

7.2. CFD SIMULATION RESULTS

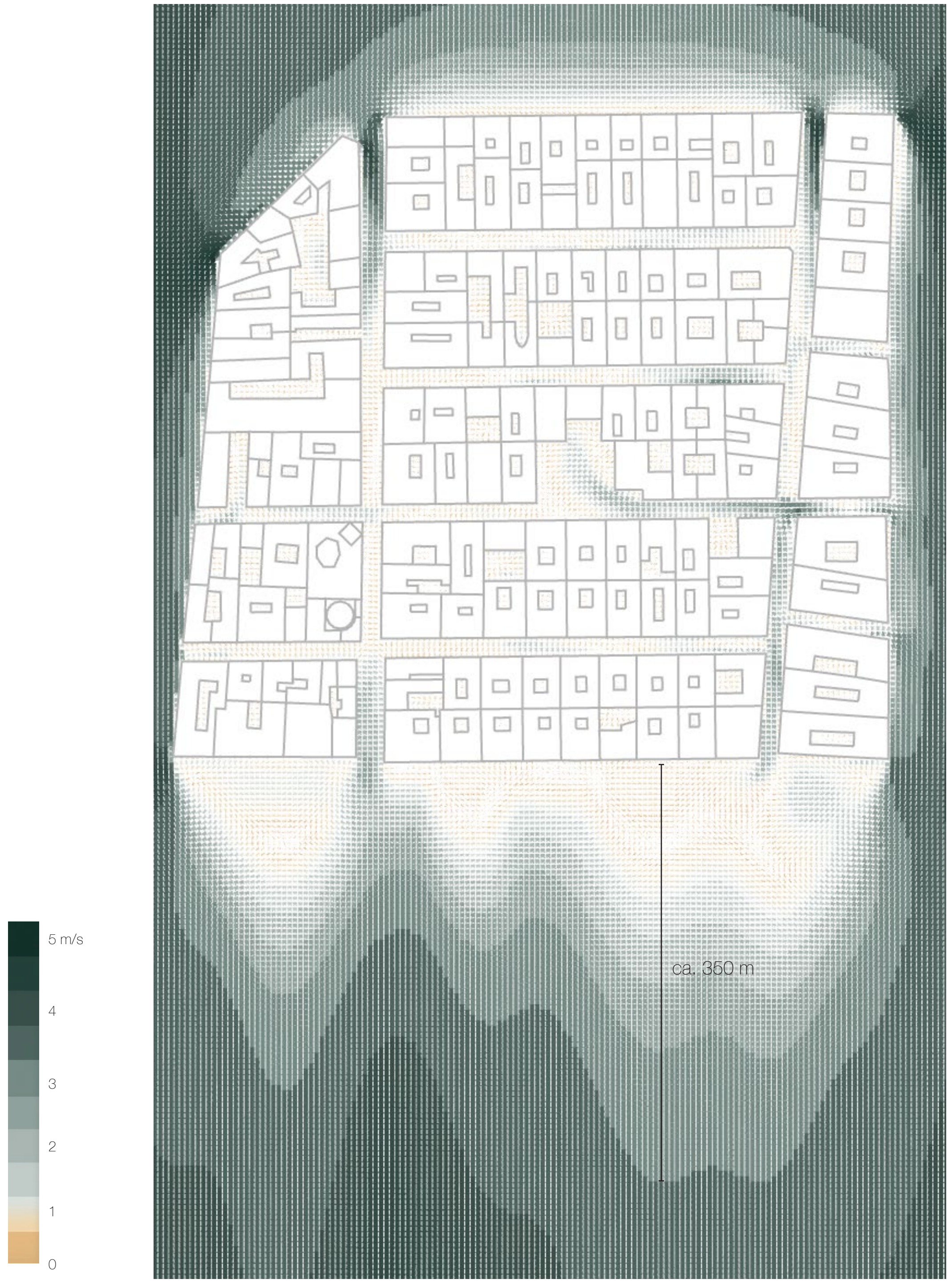


Fig. 50a: 10 m height

Direction 0°

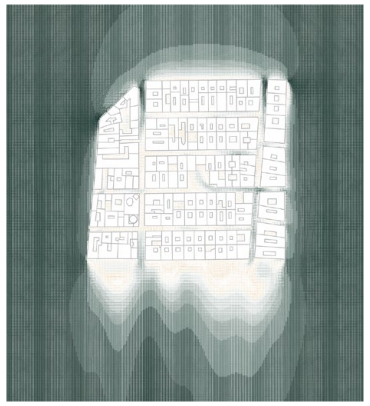


Fig. 50b: 10 m height

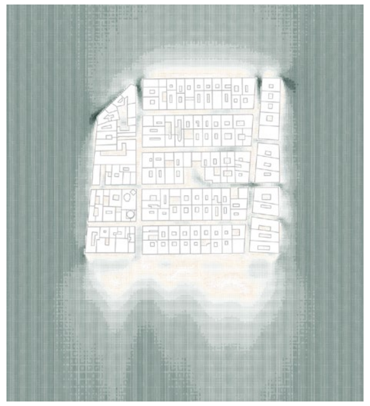


Fig. 50c: 5 m height

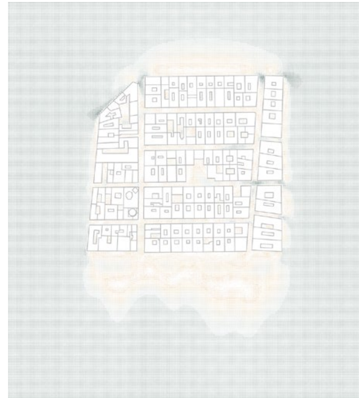


Fig. 50d: 2 m height

Direction -45°

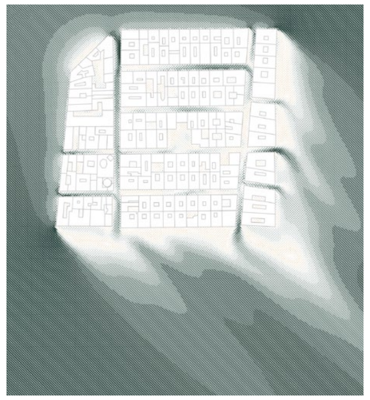


Fig. 50e: 10 m height

Fig. 50f: 5 m height

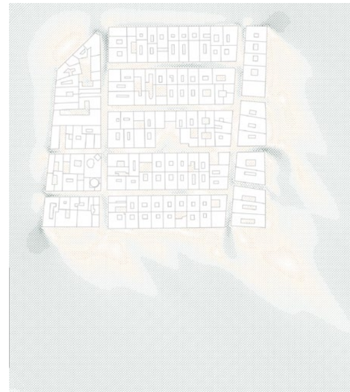
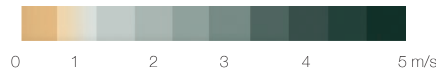


Fig. 50g: 2 m height



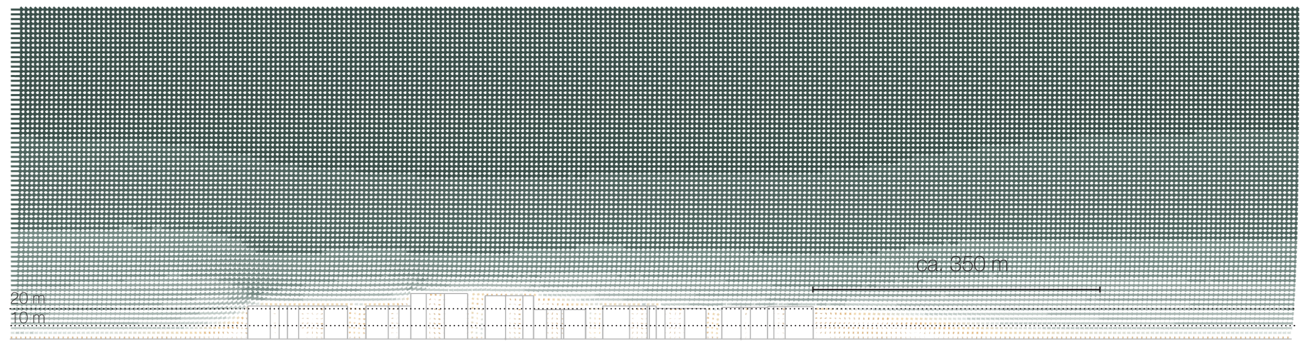


Fig. 50h: section

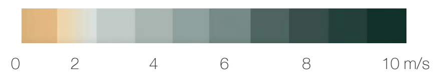


FIG. 50: LCZ2 - DENSE MIDRISE // DIRECTION 0°

As described before, these CFD results and consequences served as a base to qualitatively define the wind-driven ventilation of the outskirts. The dense midrise zone significantly blocks the windflow. At the height of 10 meters it creates a wind shadow of around 3-400 meters. By this typology the streets have almost no windflow.

7.2. CFD SIMULATION RESULTS

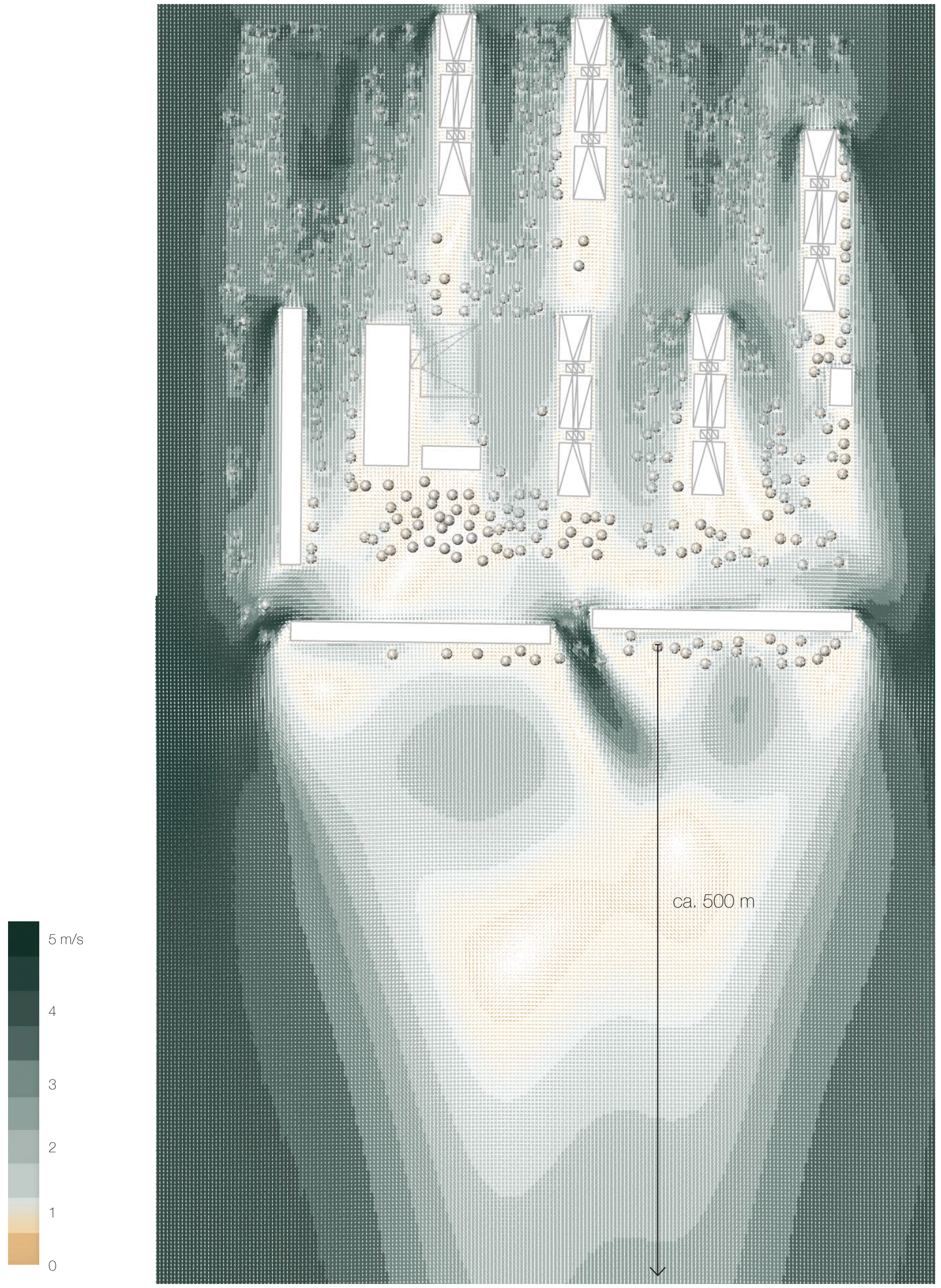


Fig. 51a: 10 m height

Direction 0°

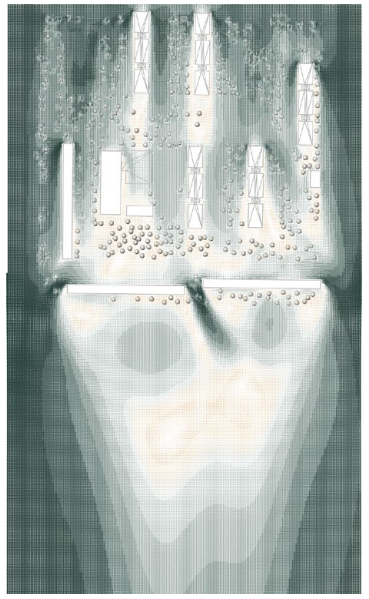


Fig. 51b: 10 m height

Fig. 51c: 5 m height

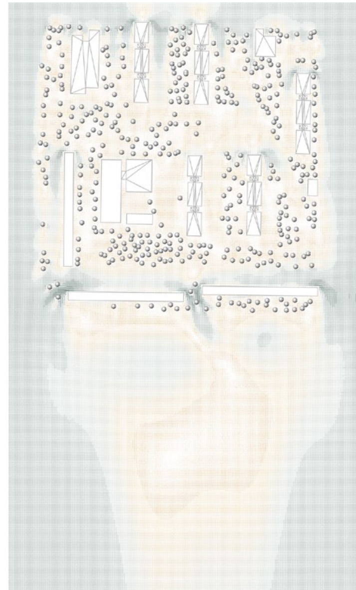


Fig. 51d: 2 m height

Direction -45°

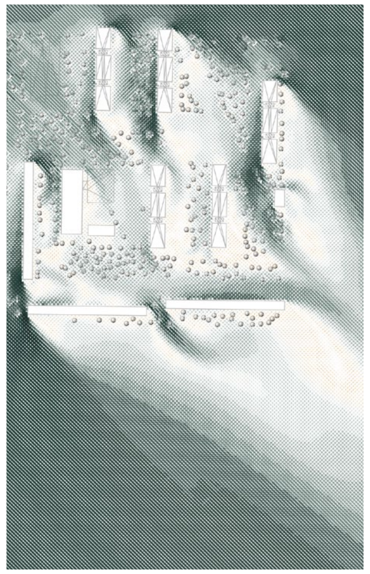


Fig. 51e: 10 m height

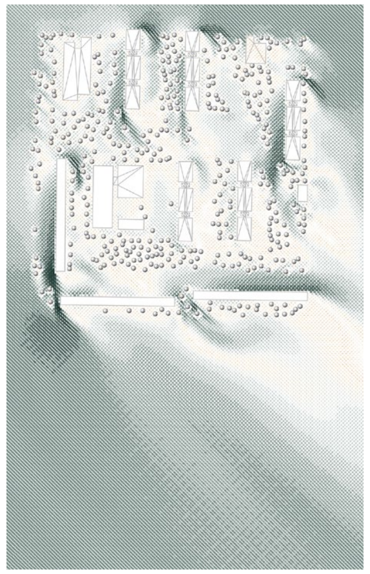


Fig. 51f: 5 m height

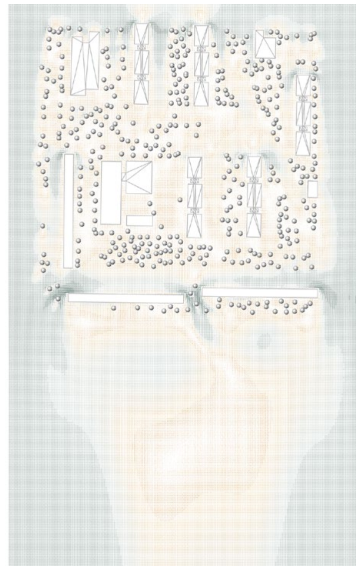


Fig. 51g: 2 m height

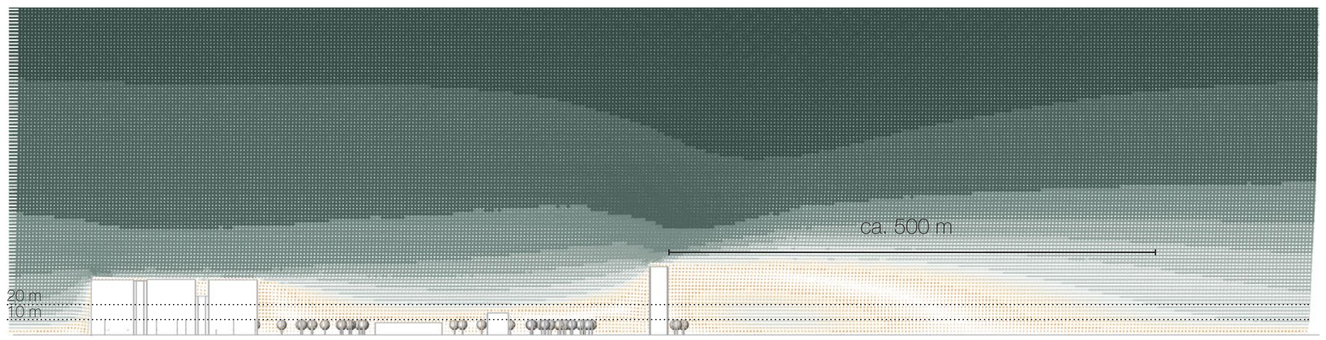


Fig. 51h: section

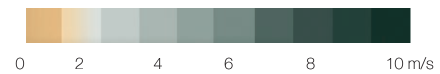


FIG. 51: LCZ4 - OPEN HIGHRISE // DIRECTION 0°

The open high rise typology can block the windflow extremely. At the height of 10 meters it creates a wind shadow over 500 meters. By this typology the wind shadow higly depends on the orientation of the buildings. The buildings not only block but with the so called downwash effect can even locally extremely accelerate the flow.

7.2. CFD SIMULATION RESULTS

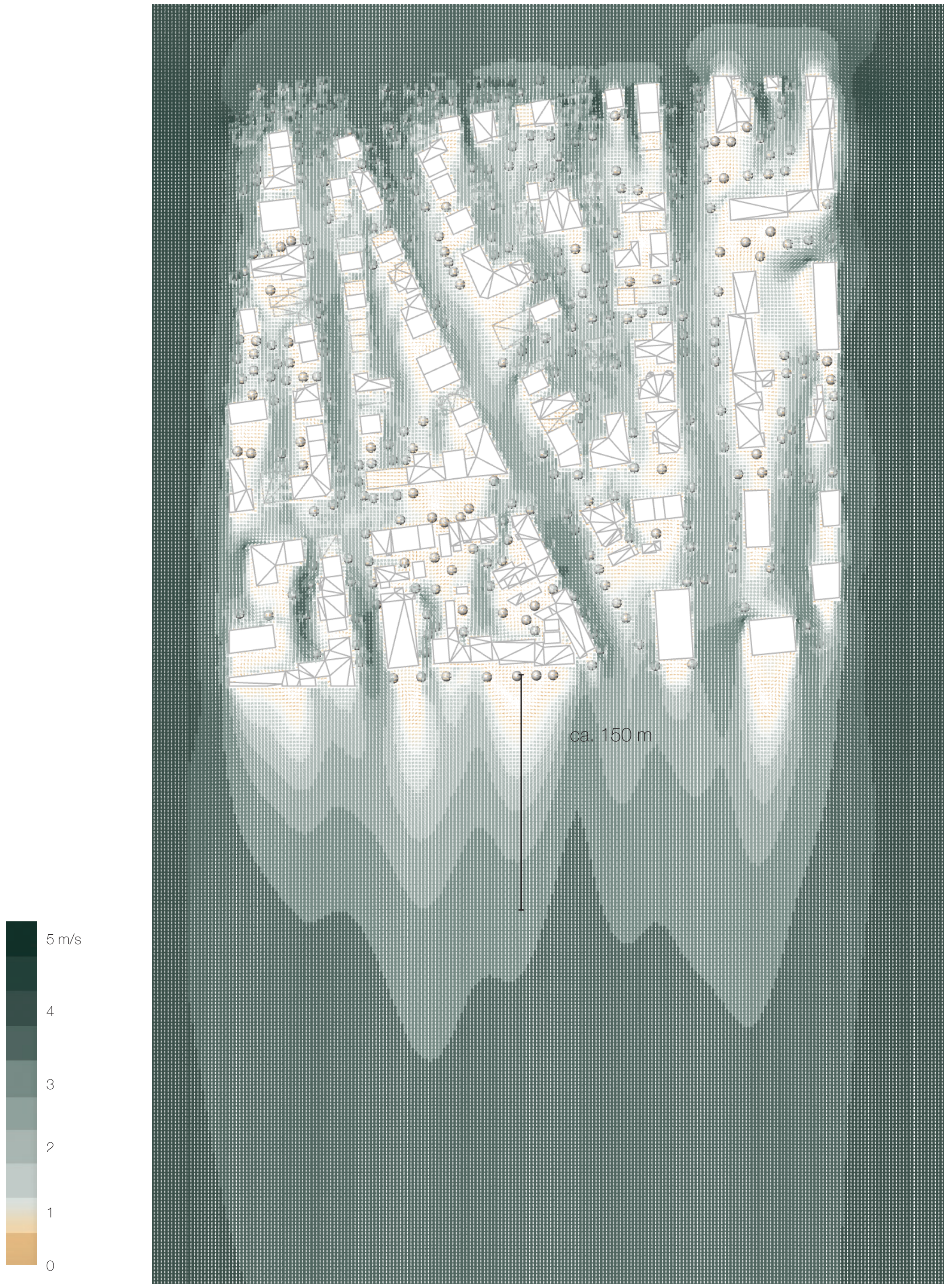


Fig. 52a: 10 m height

FIG. 52: LCZ5 - OPEN MIDRISE // DIRECTION 0°

The wind pattern of the open midrise typology is somewhere between LCZ2 (dense midrise) and LCZ 6 (open lowrise). At the height of 10 meters, it creates a wind shadow of around 1-200 meters. By this typology, the streets have somewhat weakend but still dominant windflow.

Direction 0°

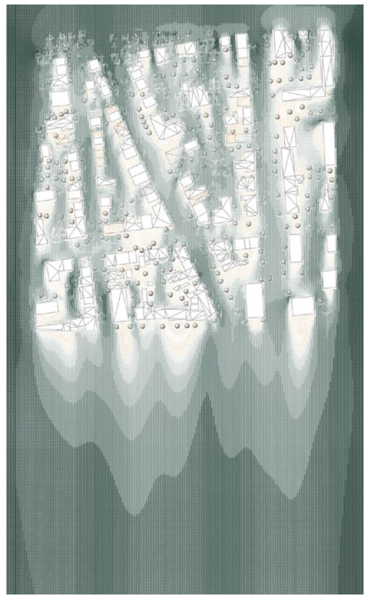


Fig. 52b: 10 m height

Fig. 52c: 5 m height

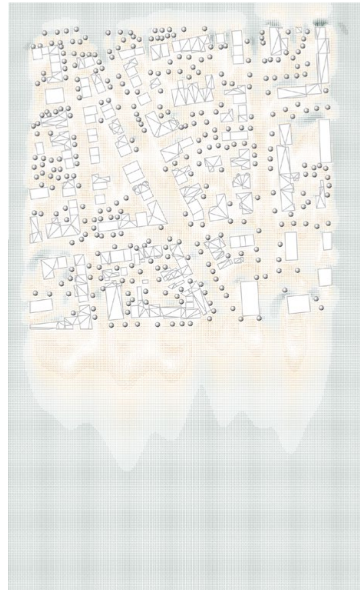


Fig. 52d: 2 m height

Direction -45°

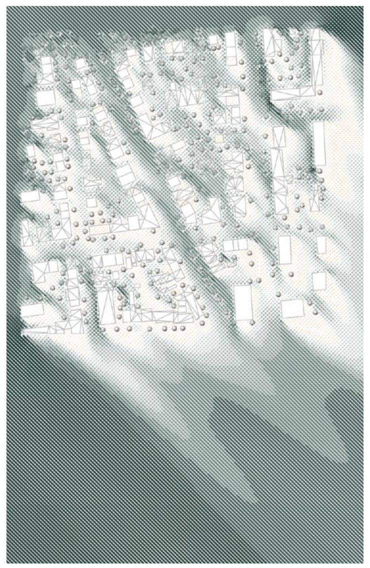


Fig. 52e: 10 m height

Fig. 52f: 5 m height

Fig. 52g: 2 m height

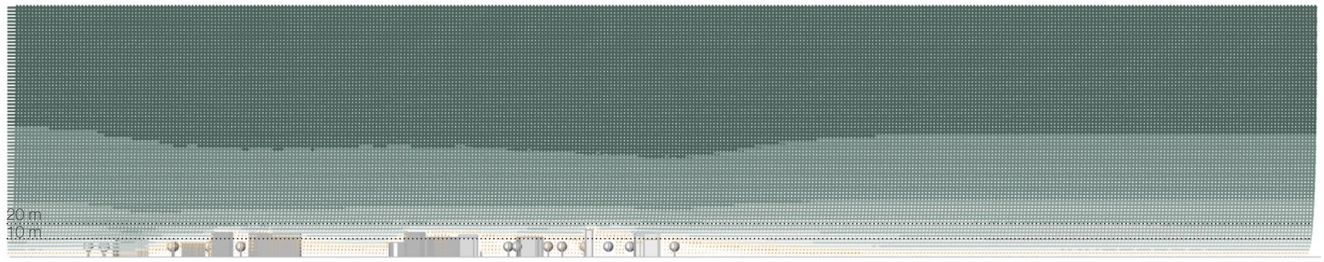
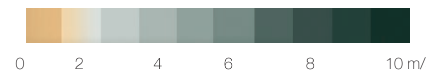


Fig. 52h: section



7.2. CFD SIMULATION RESULTS

Fig. 53a: 10 m height

Direction 0°

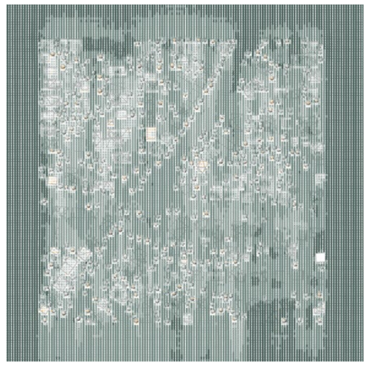


Fig. 53b: 10 m height

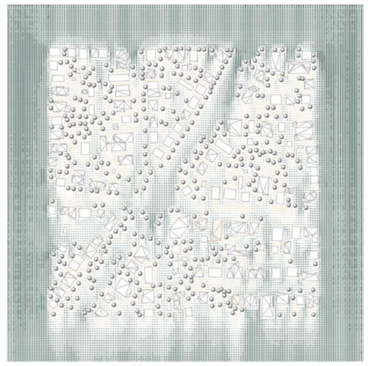


Fig. 53c: 5 m height

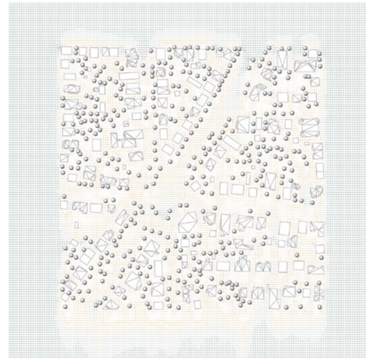


Fig. 53d: 2 m height

Direction 45°

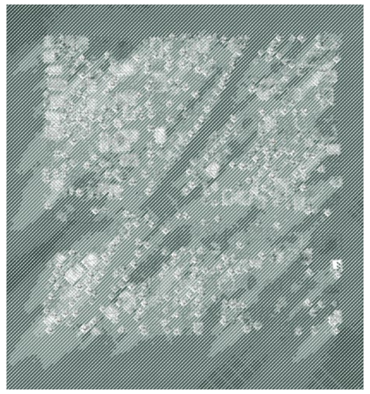


Fig. 53e: 10 m height

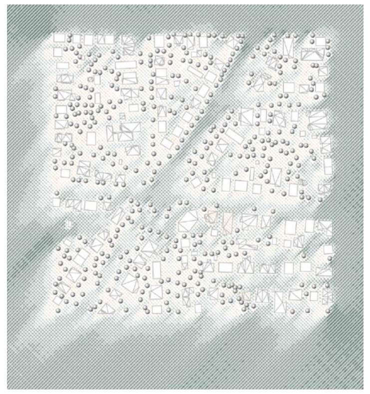
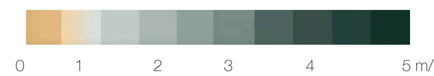


Fig. 53f: 5 m height

Fig. 53g: 2 m height



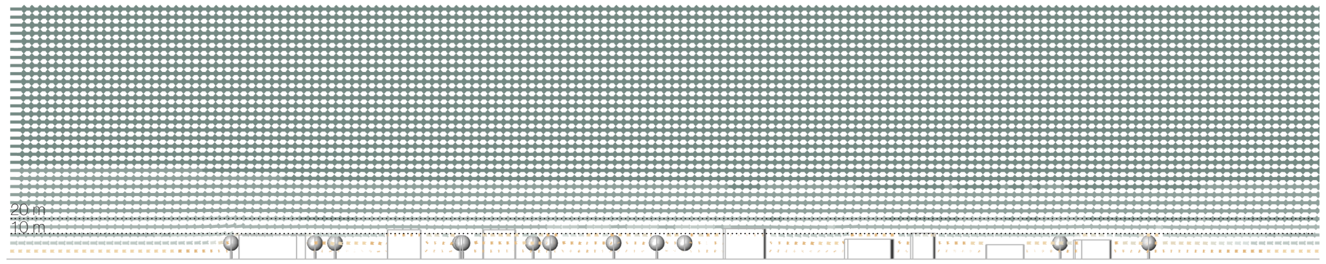


Fig. 53h: section

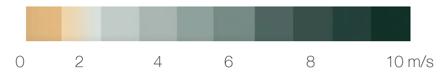


FIG. 53: LCZ6 - OPEN LOWRISE // DIRECTION 0°

At the height of 10 meters this typology creates no significant wind shadow. Therefore, for the identification of the urban ventilation corridors, this typology was considered as an open area. (s. chapter 4.2., Fig.17)

7.2. CFD SIMULATION RESULTS

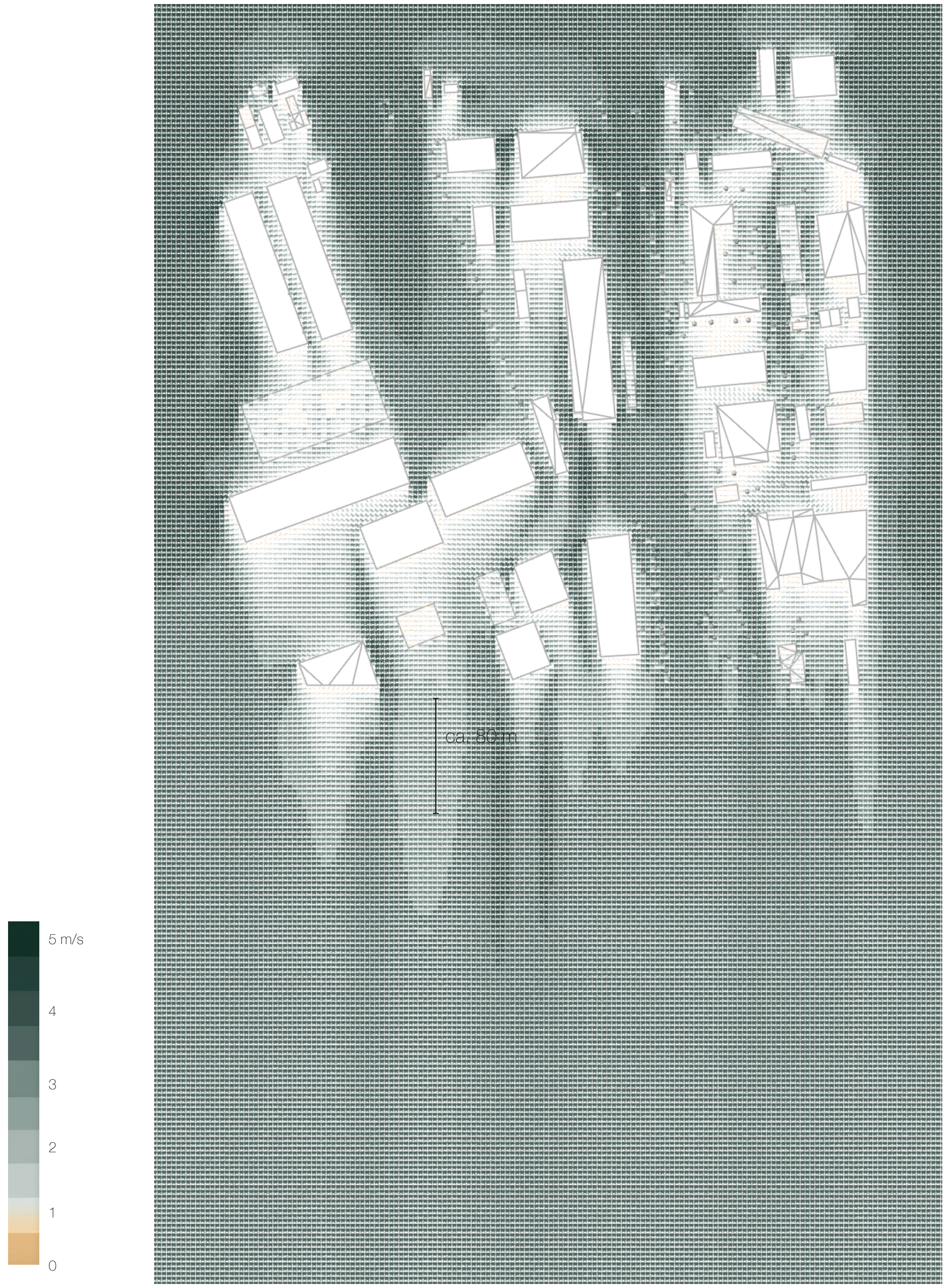


Fig. 54a: 10 m height

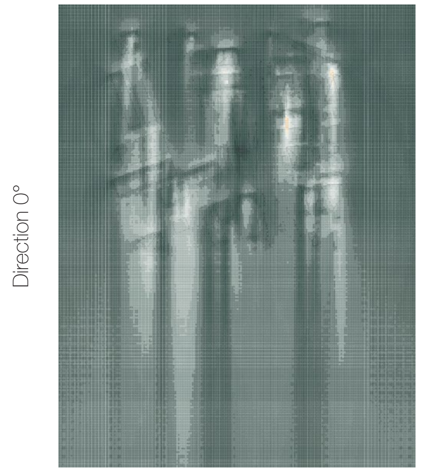


Fig. 54b: 10 m height

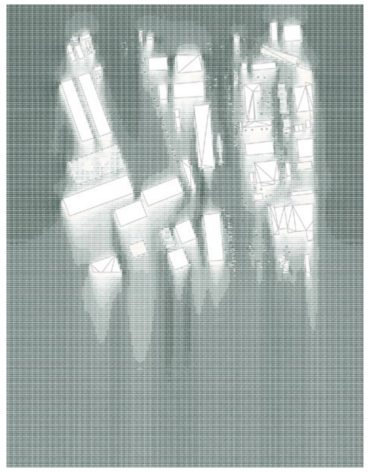


Fig. 54c: 5 m height

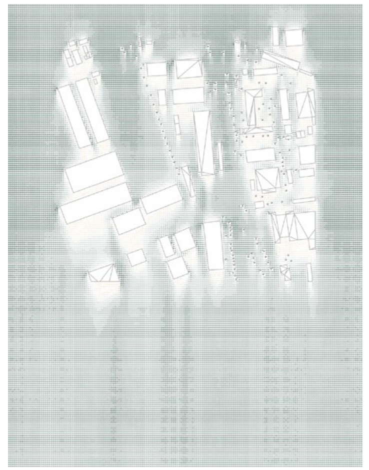
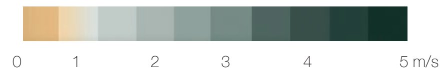


Fig. 54d: 2 m height



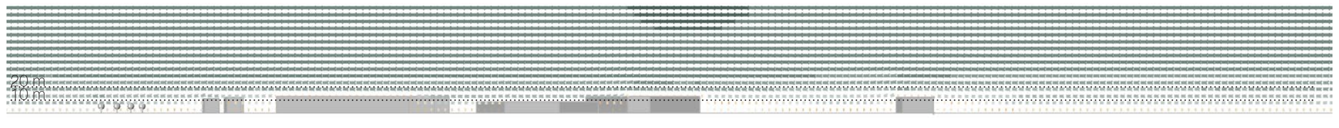


Fig. 54e: section

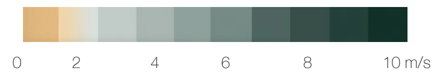


FIG. 54: LCZ8 - LARGE LOWRISE // DIRECTION 0°

From a geometric point of view, the large low rise typology can block the windflow extremely. At the height of 10 meters, it creates a wind shadow of around 50 -100 meters. By this typology, the streets have somewhat weakend but still dominant windflow. Note, that this CFD analysis does not consider thermal flow. In the case of this typology the bouyant flow could change the flow considerably. The upwards moving thermal flow can block the windflow of these areas. (s. chapter 7.3.3.)

7.2. CFD SIMULATION RESULTS

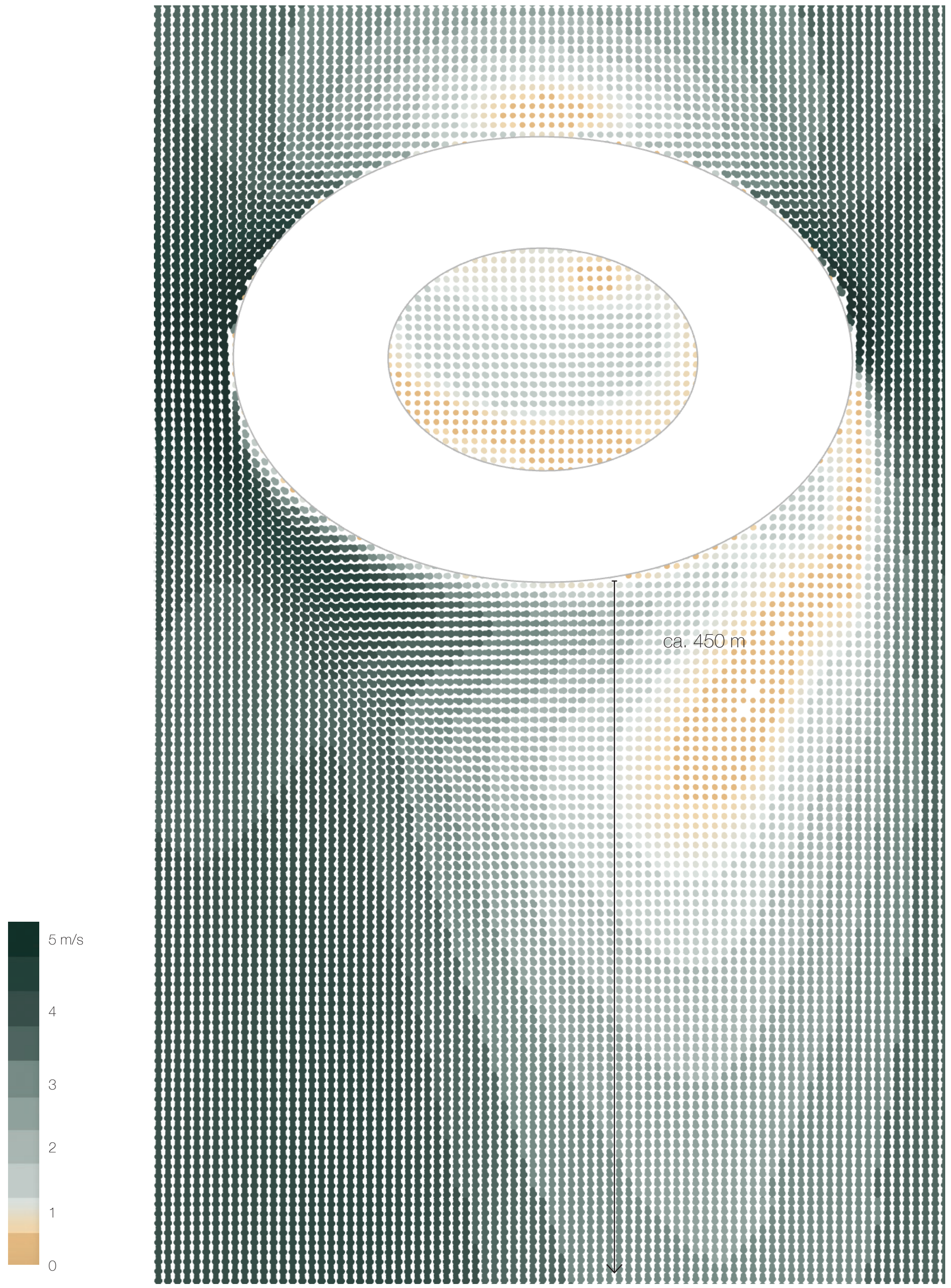


Fig. 55a: 10 m height

Direction 0°

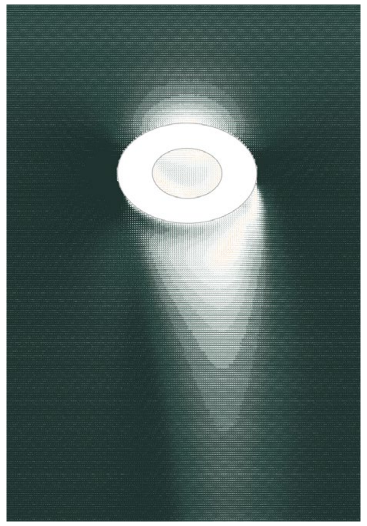


Fig. 55b: 20 m height

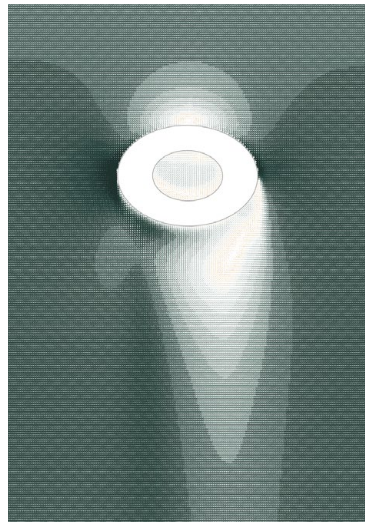


Fig. 55c: 10 m height

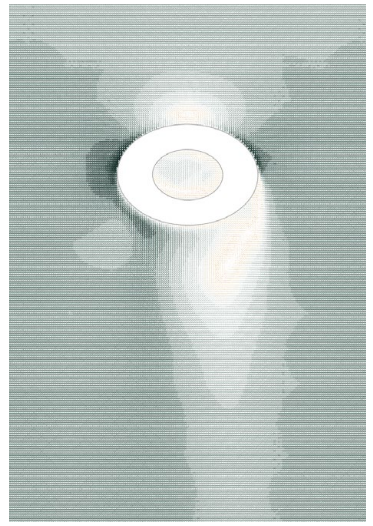
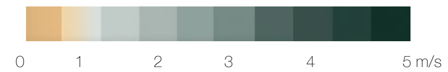


Fig. 55d: 5 m height



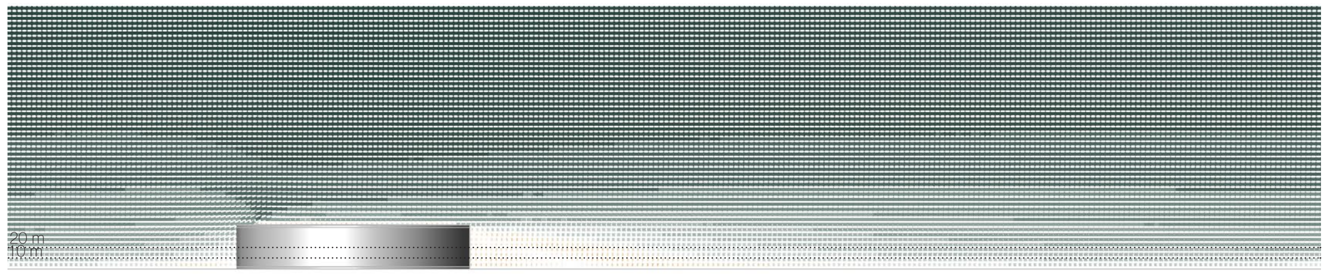


Fig. 55e: section

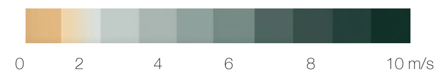


FIG. 55: LCZ11 - LARGE HIGHRISE* // DIRECTION 0°

This CFD analysis is not entirely correct as the flowfield is asymmetrical. The pattern probably shows the famous Karman vortex effect. The explanation behind can be that this simulation was stopped due to its computational demand prior to the converging of the residuals.(s. residual graph Fig. 48b) At the height of 10 meters, this typology creates a wind shadow of around 500 meters.

7.2. CFD SIMULATION RESULTS

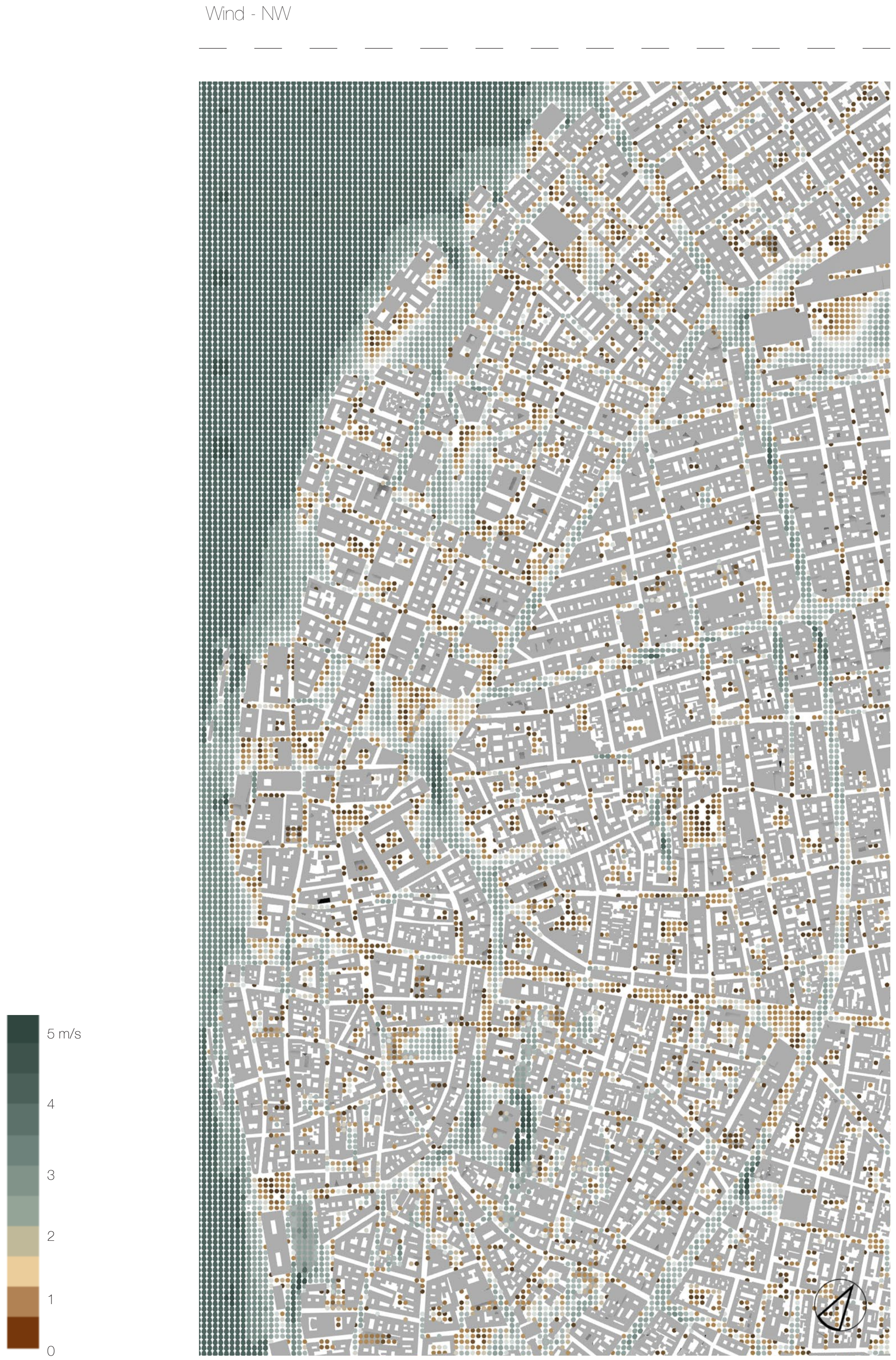


FIG. 56: CFD ANALYSIS - DOWNTOWN - DIRECTION 315°
The dense urban area (LCZ 2 - dense midrise) significantly blocks the wind. Only bigger squares and wider streets allow the windflow. The ever changing orientation of the streetnetwork makes impossible to allow the cooled (cooling effect of the Danube) Northwestern wind to enter the city.

FIG. 57: DOWNTOWN // VENTILATION CORRIDORS AND BLOCKAGES - DIRECTION 315°
Still, wider streets (high aspect ratio) can be considered more or less as ventilation corridors. Thus, especially on these streets trees can effect the flow, as such, the ventilation of the city and the urban heat island effect negatively.

7.2. CFD SIMULATION RESULTS

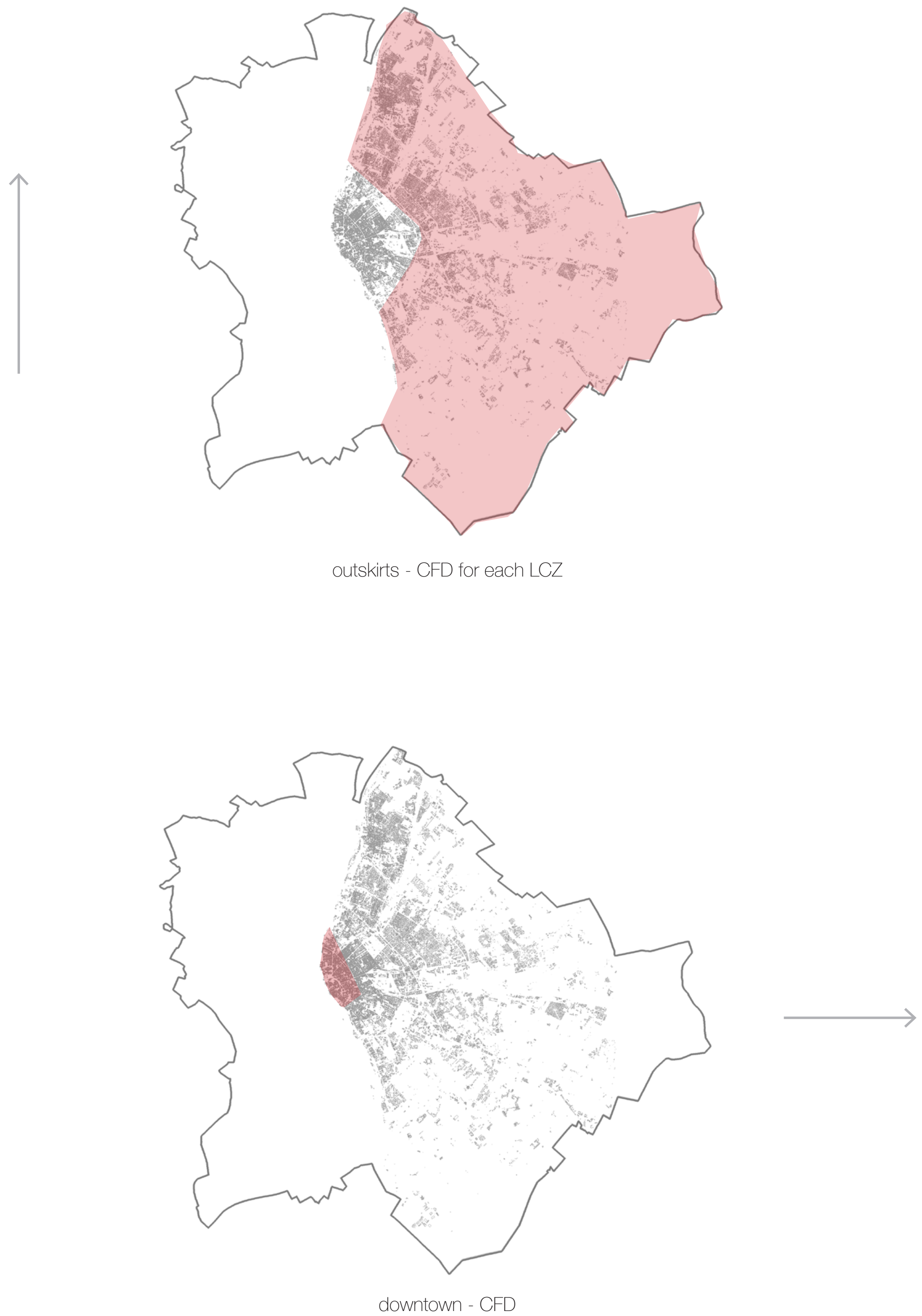


FIG. 58: METHODOLOGICAL SPLIT
As defined in detail in the method (chapter 3), a CFD analysis was performed for the local climate zones of the outskirts of Budapest, which helped to define qualitatively the city's ventilation corridors. A separate CFD simulation was conducted for the downtown area. The flow of a dense urban area is too complex and cannot be described qualitatively.

FIG. 59: VENTILATION CORRIDORS OF THE DOWNTOWN ACC. TO CFD ANALYSIS // DIRECTION 315°
As it is visible from the CFD study, streets with high aspect ratio form ventilation corridors of the downtown. In the case of North-western wind, this means the two circular roads of the city.

7. CFD ANALYSIS

7.3. QUALITATIVE RESULTS

7.3.1. THERMAL DRIVEN FLOW

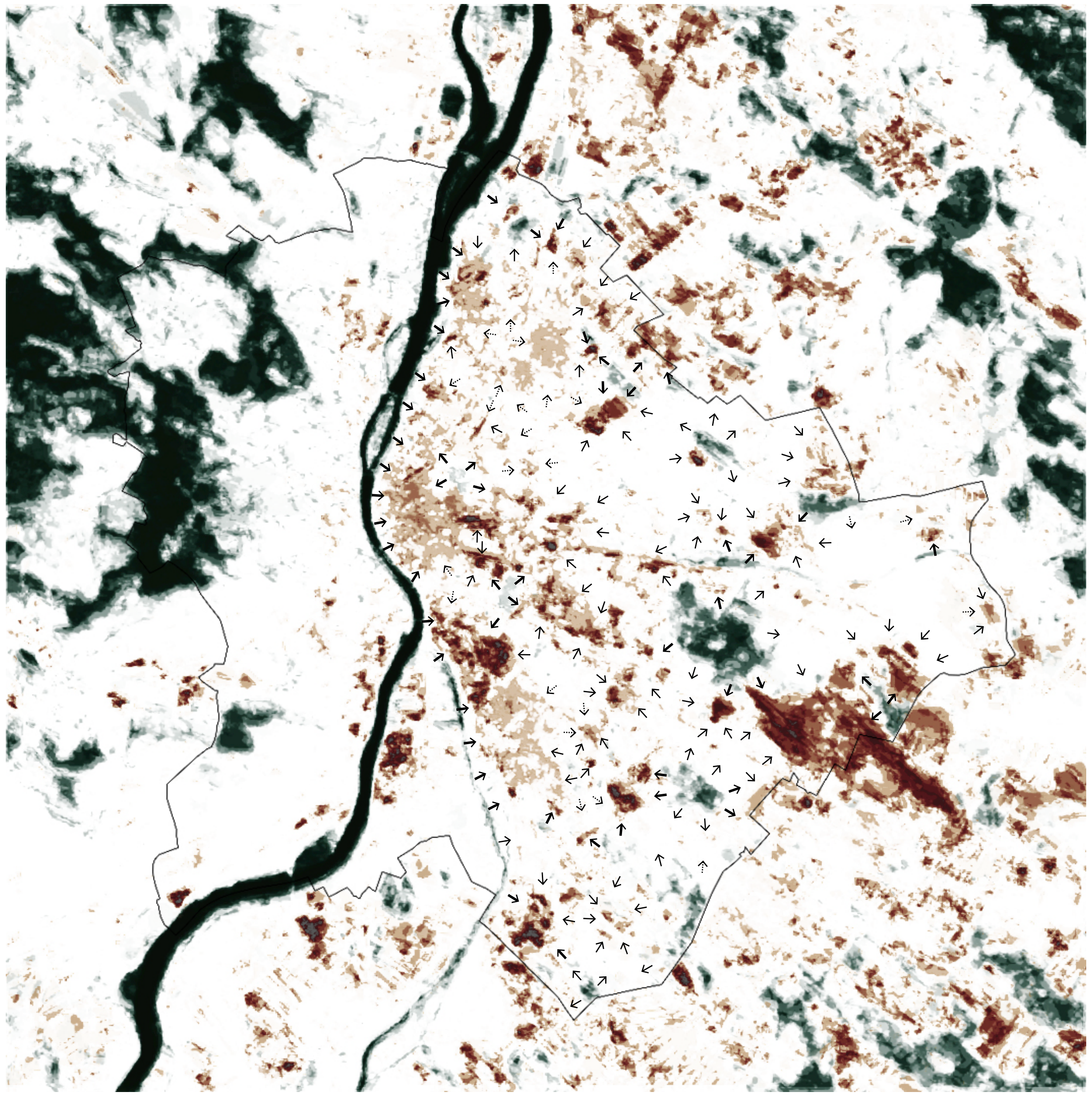


FIG. 60: URBAN "COOL AND HOT SPOTS" AND BOUYANT DRIVEN FLOW
The basis of the qualitative assessment was the principle that flow moves from cold areas to the hot areas. The typical urban dome can be observed where the flow moves from the cooler suburban areas to the hotter central areas.

FIG. 61: VENTILATION // BOUYANT DRIVEN FLOW

7.3. QUALITATIVE RESULTS
7.3.2. WIND DRIVEN FLOW // OUTSKIRTS

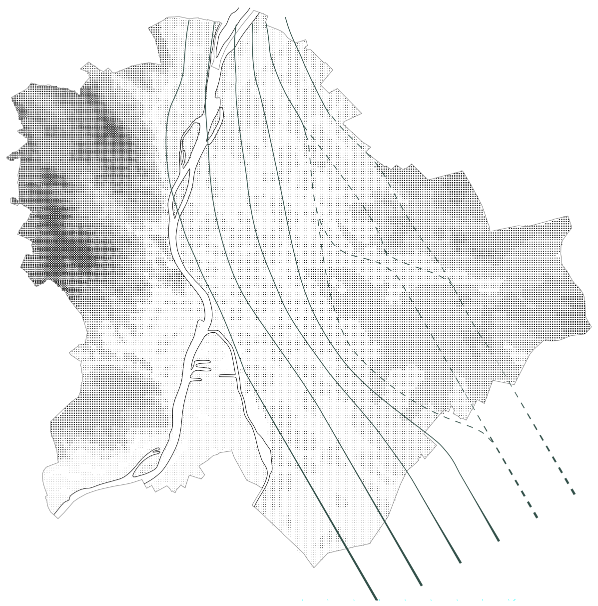


Fig. 62a: Terrain modifying the windflow ca. at 50 -100 m height

Fig. 62b: Windflow ca. at 10-20 m height (without considering the influence of the terrain)

FIG. 62: VENTILATION // WIND DRIVEN FLOW // DIRECTION SW
The pattern of wind-driven flow was qualitatively estimated. Potential open areas for ventilation corridors and potential blockades have been established with the help of local climate analysis. (s. chapter 5.2.) With the help of a CFD analysis for every category, the flow characteristics were also described. In a second phase, the estimated flow pattern was overlayed with the atmospheric processes caused e.g. by the terrain.

FIG. 63: VENTILATION // WIND DRIVEN FLOW // DIRECTION SW
The result of the combination of mesoscale flow and the flow at height of 10 -15 meters was also carried out qualitatively. Equally distributed blockades in the city hinders the formation of ventilation corridors throughout the entire city. The flow is blocked in the transition zone thus, the downtown area that would need the most ventilation the most remain in the wind shadow.

7.3. QUALITATIVE RESULTS
7.3.3. WIND + THERMAL DRIVEN FLOW // OUTSKIRTS

Fig. 64a: Wind driven flow ca. at 10-20 m height

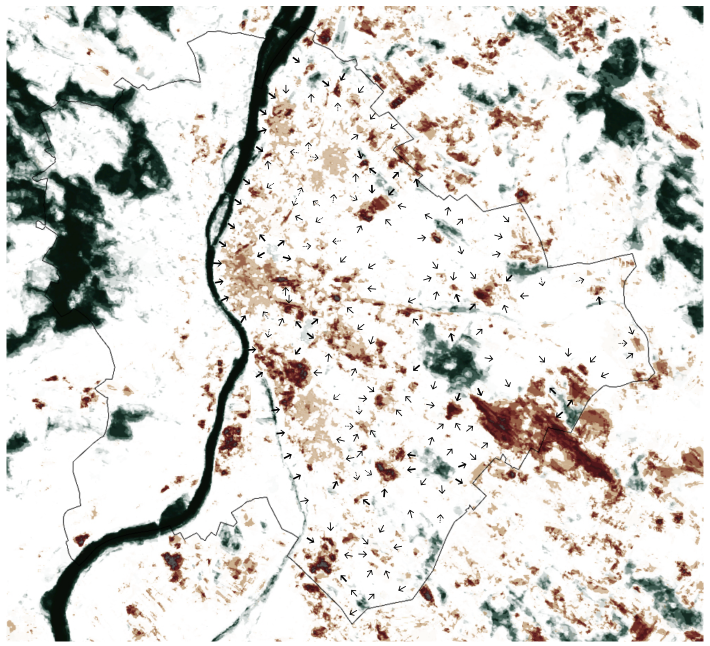


Fig. 64b: Thermal driven flow ca. at 10-20 m height

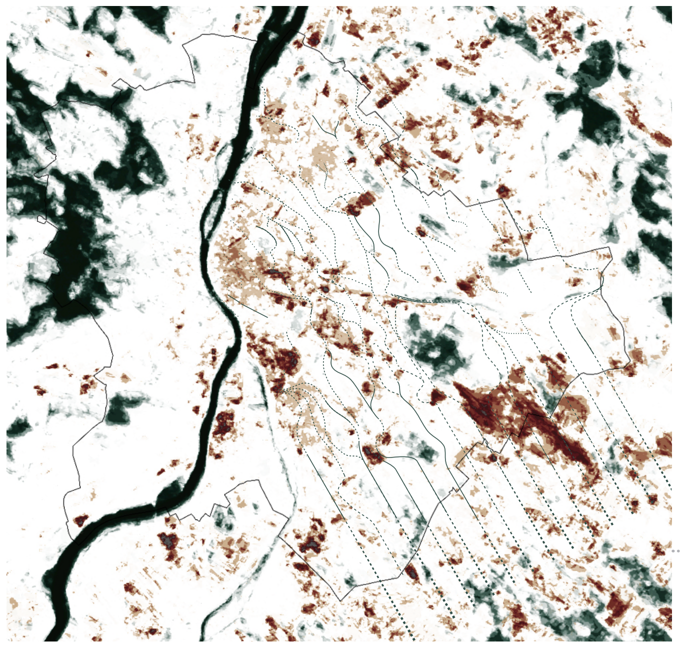


Fig. 64c: wind driven + bouyant flow ca. at 10-20 m height

FIG. 64: VENTILATION // WIND DRIVEN + BOUYANT FLOW // DIRECTION SW

Thermal-driven flow can change the movement of the wind. If their directions overlap, they may accelerate the flow, but this is rarely the case in Budapest. Most of the buoyant forces disrupt the wind flow and as such, block the city's ventilation corridors.

FIG. 65: VENTILATION // WIND DRIVEN + BOUYANT FLOW // DIRECTION SW

Traffic and some industrial zones with large, paved areas were considered to be open spaces. However, by sunny and hot climate conditions they can turn to the exact opposite. These are the hot spots that disturb the ventilation corridors. Thus, by the combination of buoyant and wind driven flow, there are almost no long, continuous ventilation corridors.

7. CFD ANALYSIS
7.4. CONCLUSIONS

The goal of this study was to define the city's ventilation corridors. The various typologies of urban flow have been distinguished methodologically: when there is only buoyant flow and no ambient wind (urban dome), when there is a mixture of ambient wind and buoyant flow (urban plume), or when there is only wind-driven flow. According to the Ladybug analysis, it will be clear how often and in which direction it occurs.

On days of high solar irradiation, no clouds and no relevant ambient wind, there is only a buoyant or thermal-driven flow. If the air heats up and expands, its density also decreases. This induces a buoyant force which causes the warmer air to rise. As a consequence, the flow is from the colder areas to the warmer areas. This mechanism generates a so-called urban dome in the city, explained earlier. The middle of the city is warmer, and the flow moves from the cooler parts of the suburbs to the hotter part of the city center. The buoyant flow rate is up to around 1 m/s.

On summer days that are less hot and cloudy, but very windy at the same time, the wind-driven flow is dominant, and the buoyant flow is too weak to disrupt the synoptic flow. The ladybug analysis has shown that this case happens most frequently. The prediction of the wind-driven flow was made with the aid of a local climate zone analysis. In addition, the CFD analysis of each local climate zone helped to identify the flow characteristics of the region. For example, from the CFD study, I concluded that suburban areas can be seen almost as open areas, as they do not significantly block the wind at a height of 10 metres. Another example may be the open high-rise typologies which, on the other hand, may significantly block the wind.

The combination of wind-driven flow and buoyant flow will occur on sunny and medium windy days, but also on windy days in the downtown, where large areas are blocked from wind-driven flow. In this scenario, the circulation of wind in the downtown is far too complex to describe or simulate. The latter depends on the albedo of each surface (façade, roof, street) and on the ever-changing movement

of the shadow of the building. The combined effect of synoptic (wind-driven) and buoyant flow can be very complex. Basically, if the wind and the buoyant flow are blowing in the same direction, they will reinforce each other and accelerate the flow, if they are in the opposite direction, they will slow down the flow. This logic has been applied to the qualitative study of the combined flow system.

On the final maps of wind-driven (p.110-111) and wind-driven + buoyant flow (p.112-113), it can be seen that the city's ventilation corridors are mostly blocked by high-rise or dense mid-rise typologies or forests. The latter is particularly interesting since densely placed trees clearly help to improve the city's climate, but in certain extreme situations they can ultimately block ventilation corridors. In a further step, it could be examined which blockades could be removed or improved so that it does not block the ventilation corridor.

8. SUMMARY

In this study, I examined the local climate, from which analysis it became clear that evaporative cooling and the effect of the wind flow is crucial to mitigate the summer heatwaves of the city. Further from the ladybug analysis, I found out the characteristics of the local wind (speed, direction and frequency). The street orientation analysis gave me a first short impression that the city is very poorly ventilated.

In the following, I differentiated the urban flow to three different cases according to the idea whether thermal flow occurs or not. The evaluation of the thermal maps created by the dragonfly plugin defined the urban hot and cool spots of the city. In a next step of qualitative study, I defined the typical buoyant flow of the city. The wind driven flow was defined in several steps. First, the open and blocking typologies and areas and the local climate zones were defined, in a second step for each local climate zone CFD analyses were conducted, in a final step the ventilation corridors of the city was qualitatively defined.

In fact, this study is not all-embracing and missing several further steps to be complete. (Such as the simulations for all the relevant wind directions, the methodological split of buoyant and wind driven flow for the case of summer night etc.) However, by this study the methodological invention and its testing was in focus demonstrating the power of the combination of quantitative and qualitative tools.

Summarizing, I would like to highlight how important is that we realise that there is a vast amount of data online, such as three-dimensional city models, hourly weather data of all relevant cities of the world. Besides, free plugins enable one - after a limited amount of time - to conduct climate, urban heat island or wind flow analysis. These tools can give us exciting possibilities and with some methodological creativity can provide thought-provoking results. Nonetheless, careful research regarding the domain knowledge of each field is necessary. Hence, I see high potential especially in those methods where the combination of quantitative research and qualitative analysis (like by the heat maps and the CFD for the local climate zones) are combined.

The results may scientifically not entirely correct, but it is also not the aim of this study. With a method like this, one can get a holistic understanding of general processes of the urban wind flow. I believe that both architect and urban planners have to gain a higher understanding about climatic processes and in general about urban physics. In the first phase of the planning, a better knowledge of urban planners would allow to involve climate specialist into the project in a second phase. This would hopefully help to transform the city regulations in a way that our cities can react on the challenges of the future in a more sustainable way.

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