Short theses for the degree of Doctor of Philosophy (PhD)

THE EFFECTS OF URBAN GREEN INFRASTRUCTURE ON MICROCLIMATE AND INDOOR COMFORT

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Table of contents

1. Introduction

Climate change has been strongly influencing our everyday life on global, regional (meso) and object (micro) scale too. We see serious environmental, economic and social processes being driven by climate change happening before our very eyes. Thus, it seems even stranger, that considering climate hasn't yet reached the point to become a driving factor in urban planning, however, the effect and the seriousness of climate change cannot be neglected. Only during the last decade, the movement of climate-conscious planning practice have arisen, and it is becoming an issue of big importance.

To fight the negative effects of extensive urbanization (meaning both in number of population and in the extension of urban areas) and as it's result the negative effects of urban heat island – it is essential to investigate the potential of green infrastructure elements in changing microclimatic conditions.

Green infrastructure is a term that has been used in the last three decades as a tool for sustainable urban development. Many definitions exist – which will be discussed in the next chapter – however approaches agree on one important point: green infrastructure is a sum of those measures that are connecting nature to urban environment. Besides, using soft technologies is usually cheaper than "traditional" grey infrastructure. The key driver for implementing green infrastructure elements is the aim of creating more liveable cities and educate city dwellers by engaging them in green infrastructure projects on different levels.

2. Objectives and motivation of research

The motivation of this work is to investigate the effects of green infrastructure elements on micro-climate, on building energy consumption; outdoor and indoor comfort; and based on the findings to create a smooth basis for further investigations regarding the implementation of GIE in urban planning. This work is devoted to reveal, analyse and assess some of the most relevant issues regarding the practice of climate-conscious urban planning on small – that is building and neighbourhood – scale, concentrating on typical Hungarian urban areas.

As literature review proved, alley trees are the most effective for creating satisfactory outdoor thermal comfort in summer. (Gromke *et al.*, 2015) Concentrating on trees, studies dealt with the horizontal transmissivity of trees, and the shadow-casting on horizontal surface. (Konarska *et al.*, 2014). There are also studies that investigated the mitigating effect on surface temperature of walls due to some types of trees (Berry, Livesley and Aye, 2013). However, there were no studies to be found connecting the two processes, and also predicting the effect of tree-shade on internal temperatures and ventilation potential nor the vertical transmissivity of tree foliage. It was also found, that outdoor thermal comfort is greatly influenced by wind velocity. (Arens and Ballanti, 1977) Summer wind breeze is desirable, creating a more agreeable thermal comfort, however, in winter the aim is to block strong wind gust. Moving towards a bigger scale, in recent years there were some urban rehabilitation programmes that implemented the green inner courtyards in traditional blocks of flats with deconstructing inner wings of the blocks. Despite of the undoubted success of the project from urban development and housing market point of view, microclimatic effects of the project were never analysed.

Concluding, the aims of my research were:

1) to investigate the vertical transmissivity of the most common urban tree species, such as: Common Hackberry (*Celtis occidentalis*), Japanese Pagoda (*Sophora Japonica*) and Small-leaved Linden (*Tilia cordata*)

2) to investigate the effect of alley trees on outdoor thermal comfort – how the values of Mean Radiant Temperature, Predicted Mean Vote change due to vegetation.

3) to investigate the potentials of tree shading on indoor thermal comfort and to describe the facilities of natural ventilation.

4) to investigate the orientation-dependence of the changes in wind-velocity-profile due to vegetation in streets: in case of trees, shrubs and green façades as well.

5) to investigate the potentials and threats of neighbourhood scale projects, were inner courtyards are opened up and green infrastructure is implemented.

6) to build up a methodology for urban planners to use easily the results of scientific research in the fields urban climatology, bioclimatology and climate-adaptive urban planning in order to facilitate climate-adaptive urban planning.

3. Methodology of research

In this chapter the methodologies used for this work will be introduced. Mainly two forms of research have been carried out: on-site measurements during the summer and autumn of 2014 in Szeged for the investigation of tree-canopy transmissivity; and modelling using mainly well-known and widely-used, validated *ENVI-met* modelling between 2010 and 2015. Another software was used for modelling indoor thermal comfort: *ECOTECT*, which has been a discontinued product of Autodesk since then.

3.1. On-site measurements

The aim of on-site measurements was to investigate the vertical transmissivity of tree foliage. As previous studies (Konarska *et al.*, 2014) have shown, a horizontal transmissivity of trees is a characteristic dependent on tree species, but no study dealt before the vertical shading efficiency of trees. Carrying out on-site measurements during the summer of 2014 using two pyranometers for measuring global radiant flux we have investigated the vertical transmissivity of three typical urban tree species: Common Hackberry, Japanese Pagoda and Small-leaved Linden. The measurements were carried out with Kipp&Zonen CNR 1 and 2 pyranometers (sensitivity: 10 to 20 μV/W/m^2, spectral range: 310 to 2800 nm and Directional error: <20 W m^{-2}). Measurement days were selected during full foliage, mid-summer, clear sunny days during anticyclonic weather conditions. Each tree was measured at least on two days. Pyranometers were placed at 1 m distance from the wall, at a height of 1.1 m (standard measurement height in human bio-climatological investigations). (See *Figure* 1.)

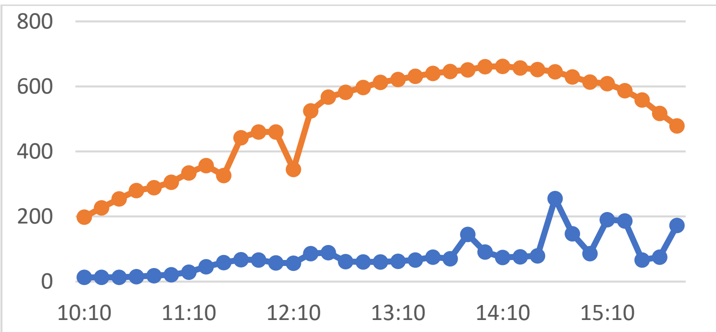

Figure 1.: Course of global solar radiation (points representing the 10-min averages) at non-shaded (reference: red) and at shaded (below canopy: blue) point of Celtis occidentalis

The one measuring instrument was always placed in the shadow of the tree cast facing the shaded wall; while the other instrument was always placed under direct radiation. Some cloudy periods of time (5-15 min) were not considered in the database. The measurement design (approximate duration of the measurements, places of instruments) was helped with preliminary modelling of the time course of the shade in *ECOTECT* software, based on size parameters of the trees and on the orientation of the buildings. Transmissivity was calculated from 10 minutes averages of irradiance data.

3.2. Numerical simulations

3.2.1. ENVI-met

ENVI-met (developed by Michael Bruse and team, (Bruse and Fleer, 1998; Bruse, 2004, 2007) is numerical simulation software widely used for investigating changes in microclimate

Most of the projects were carried out with the usage of Version 3.1. or 3.5 of *ENVI-met.* From Version 4.0 the software is only available as a paid service.) Amongst the advantages of the three-dimensional software is a high areal (5-10 m) and temporal (30-60 min) resolution *ENVI-met* is capable of calculate 50 different measures of air quality, thermal environment, and bioclimatology, such as: air temperature, relative humidity, Mean Radiant Temperature, wind speed and direction, Sky View Factor and Predicted Mean Vote. Despite of the difficulties of building up models, it is a favourable and suitable tool to investigate the differences between different scenarios, planting dispositions.

3.2.2. Energetic modelling (Autodesk *ECOTECT*)

ECOTECT is a sustainable design tool which makes possible a detailed building energy analysis from building to city scale. As *ECOTECT* is capable of detailed solar simulation too, it was suitable for my modelling aims.

As described transmissivity data obtained from field measurements were used for further modelling in order to give more general approach of the shading effect of alley trees. Modelling was carried out with Autodesk *ECOTECT* software.

4. Theses

In this chapter we give an overview of measurement and modelling projects carried out between 2010 and 2020. The research results presented here were chosen to focus on the effect of vegetation on outdoor human comfort and also the changes in indoor temperatures. The following green infrastructure measures were carried out:
- green façades,
- street trees,
- combined use of trees and shrubs,
- vegetation in typical inner opening-up and greening typical courtyards in historical blocks of flats in Budapest.

In introducing the projects, I will proceed from the small scale to the larger scale measures.

4.1. The effect of green facades on urban wind velocity and wind profile

I examined the effect of green facades on urban air movement with using ENVI-met numeric simulations. Analysing the implementation on an ideal model, I found, that:

A) In case of wind direction parallel to the green façade the maximal value of wind velocity does not change, however, the wind field changes (the area where maximal wind velocity is typical is elongated compared to the state with no greening) due to the change in roughness of façades. This phenomenon increases inflow from the cross streets, thus enable stronger urban cross ventilation.

B) In case of wind direction perpendicular to the green façade, the implementation of green facade will mitigate wind speed in the cells in front of the façade and in the cross streets (parallel to wind direction) too.

C) The difference between the two cases questions the effectiveness of planting vegetation on facades perpendicular to prevailing wind direction as *green façade may also hinder urban cross ventilation*.

The case study proved, that the effect of green façade on wind speed depends on the angle of the façade and the prevailing wind direction. In case the green façade is implemented parallelly with the prevailing wind direction, the effect is stronger: due to the change of roughness of surfaces, a sort of “bottleneck” is created in the street, therefore in the middle of the street the velocity of the air will increase, and the static pressure will decrease – the latter has, but not negligible effect on the inflow of air from the cross-streets.

4.2. Creating better wind comfort with plants

I carried out further simulations to investigate the effect on wind comfort of different plantings in the street. This time, the effect of greenery in case of diagonal wind direction was also analysed, to have more information on the air movement around the corners – as these are the spots, when sudden gust might reach the pedestrian, thus these spots are crucial in creating an agreeable wind comfort. I analysed the effect combined greening (trees and shrubs) on wind comfort with multiple numeric simulations carried out with ENVI-met. **I have proven that alleys have a complex effect on urban airflow pattern according to orientation and prevailing wind direction.**

A) The effectiveness of vegetation planted in front of the façades in modifying the microclimatic environment is greatly determined by the angle of the prevailing wind direction and the orientation of the street. If parallel with prevailing wind direction, the planting of an alley or green façade and shrubs mitigates the areal expansion of maximal wind speed and thus mitigates maximum values by 0.5-1 m/s – thus increasing wind comfort in urban canyons in winter.

B) On other hand on windswept sides of the perpendicular street velocity can be increased by 0.25-0.75 m/s – enabling urban cross ventilation, or in extreme case creating an unpleasant wind comfort in front of the façade.

Apart from the obvious result, that vegetation decreases wind velocity in the immediate proximity of the plants, the conclusions drawn from the study is, that an asymmetrical disposition of various plants (shrubs and trees together) are most desirable, as this kind of solution ensure an acceptable wind comfort, but does not hinder urban cross ventilation. Previous studies (Žák *et al.*, 2016) have shown that planting trees near the façade might increase the concentration of air pollutants on the pedestrian way – due to limited air velocity around the canopy of the trees. However, shrubs might have an opposite effect creating an upflow above the pedestrian way.

4.3. The vertical transmissivity of typical urban tree species

The second research area was the investigation of the effect of trees on solar irradiance, vertical transmissivity. **Carrying out on-site measurements during the summer of 2014 using two pyranometers for measuring global radiant flux I have investigated the vertical transmissivity of three typical urban tree species: *Celtis occidentalis* (common hackberry), *Sophora japonica* (japanese pagoda) and *Tilia cordata* (small-leaved linden.**

A) Among the three investigated species the *Celtis occidentalis* proved to have the densest canopy with a transmissivity value of $\tau=11.3\%$, and *Sophora* *japonica* as the least effective in terms of vertical shading with a transmissivity value of *τ=16.6%. Tilia cordata* had similar values than *Celtis occidentalis* itself with a transmissivity value of *τ=12%.*

Given, that in recent years the horizontal transmissivity of trees was investigated, I aimed to measure the vertical transmissivity of three different, typical urban species (*Celtis occidentalis, Tilia cordata and Sophora japonica)* with the usage of pyranometers. It was found that transmissivity ranges from 11,3% to 16%.

4.4. The effect of alley trees on outdoor thermal comfort

Regarding the effect of green infrastructure elements on neighbourhood scale, first, the effect of implementing treelines and alleys in streets on outdoor thermal comfort was investigations. **Applying different methods – on-sight measurements and numerical simulations – I investigated the positive and negative effects on outdoor thermal comfort of alley trees. I found, that:**

A) I have proven that alley trees diminish Mean Radiant Temperature and thus Predicted Mean Vote – depending on the distance of canopies – in a patchwork-like or linear way. Predicted Mean Vote can be mitigated by maximum of 2.5-3 units in a typical summer day at midday.

B) I have shown that a tree planted in front of a building façade (orientated to south, southwest) can diminish under summer conditions by 20-60% (maximal 1 kW/m2/day) the daily solar irradiance on vertical surface (if τ=12-16%). This phenomenon has of course an effect on Mean Radiant Temperatures measured on the pedestrian way too, during the day, and also in the evening hours, as it diminishes the surface temperature of the wall, and thus, the intensity of UHI too.

It was proven, that alley trees, planting boxes and new green spaces momentously decrease the risk of summer heat stress, that is the values of *MRT*, T_{air} and *PMV* values. However, it came also obvious, that the microclimatic effect of implementing trees does not exceed the area of intervention, on the other hand the effect of a new green space is more extensive spatially.

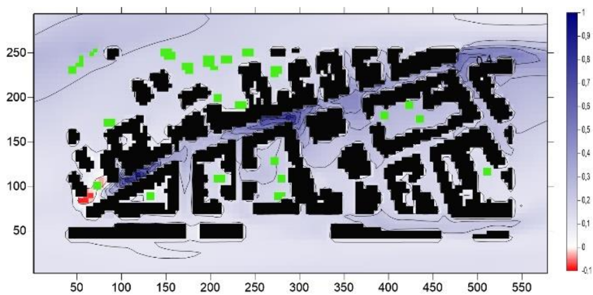

Figure 2. Cartogram showing the difference in Potential Temperature Keleti Károly utca due to the planting of alley trees. Greened – original state, summer, 12.00 a.m., 1.6 m height.

4.5. The effect of alley trees on indoor thermal comfort

The aim of the executed numerical modelling was to have results on the effect of trees on the warming-up of the façades and indoor air temperatures. **Based on transmissivity measurements and further energetic simulations I have shown, that depending on the thermal performance of the building envelope and natural ventilation scenarios, a tree in front of the transparent surfaces (orientated to south, southwest) of the room investigated diminishes the irradiance on vertical and horizontal surfaces in the following ways:**

A) The average of incoming total radiation on horizontal plane (floor) is diminished by 9-29% and on vertical plane (façade) is diminished by 19-60%.

B) Simulation showed that, tree shading facilitates natural ventilation as well, as in case of tree shading and opening windows during the afternoon hours decreases the average indoor air temperatures compared with the case of no tree shading and closed windows.

It was found that **tree shading diminishes significantly the warming up of both vertical (façade) and horizontal (room floor) surfaces.** The effect of window opening was also investigated, resulting that it is reasonable opening the window during the afternoon hours, as indoor temperatures could be diminished, if the façade is shaded.

4.6. Role of vegetation in urban rehabilitation

The case study examined the effects and possibilities of climate-adaptive planning with implementing multiple green infrastructure elements at the same time on neighbourhood scale. **I examined the effect of opening-up and greening of city centre blocks. I have proved - with using ENVI-met numeric simulations - that the joining inner courtyards with demolishing the inner building wings, brings a favourable outcome in terms of microclimate, if the courtyards are greened. I have proven that:**

A. The described method of opening-up itself is not a successful intervention from microclimatic point of view, as Mean Radiant Temperature values on the surface of the yard will increase by $\Delta MRT=17°C$ and Predicted Mean Vote values by 1 in average, under summer conditions.

B. In order to avoid the negative effect of the described urban rehabilitation method vegetation can improve the microclimate of the opened-up courtyards. Mean Radiant Temperature values are decreased by $\Delta MRT=\sim10°C$ in average and by $\Delta MRT=\sim15°C$ in terms of maximal values – compared to the non-greened states.

C. The average value of Predicted Mean Vote is decreased by 0.6 units (percentage of dissatisfied people decreases by 50%) – that is due to vegetation (trees, shrubs and lawn).

I found that wind speed and sky view factor will be increased, which are favourable, however, the demolition of the inner wings of the buildings also increase the risk of summer overheating. All negative impacts can be addressed with using intensive greenery in the yards, thus, creating a better thermal comfort and living environment in the yard, and the adjoining flats as well.

4.7. The microclimatic effect of implementing a green space

I examined the effect of creating a new green space of 20,000-25,000 m^2 on the plot of a demolished building. I have proved - with using ENVI-met numeric simulations, that the new green space will:

A) reduce the value of Mean Radiant Temperature by ~30-40 K, and reduce Potential Temperature by 1.5-3.0° C

The simulations proved the great efficiency of green spaces, however, it came also obvious, that the microclimatic effect of implementing trees does not exceed the area of intervention, on the other hand the effect of a new green space is more extensive spatially.

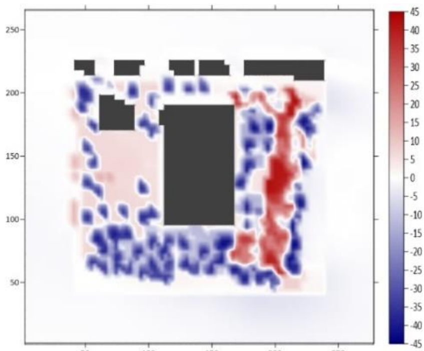

Figure 3.: Cartogram showing the difference in MRT values due to creation of SzéllKapu park (summer, 12:00h, 1.6 m)

Creating new green spaces and planting alley trees proved to be the most efficient in creating a better thermal environment, however these measures are feasible with a remarkable investment – economically as well as in terms of construction**.** In recent several calls for projects (ERDF operational programs, LIFE projects) have been available thus, the municipality might be able to finance a similar development. However, the involvement of private capital is not inconceivable.

5. Summary

Urban microclimate has been a fashionable topic in the last decade to involve quite a few researchers. Many have come to the conclusion that green surfaces are essential in achieving a climate-conscious urban environment. Urban parks, green facades and roofs provide not only shade and shelter for the urban dwellers but also play an important role in creating cool islands inside the urban heat island.

However, for implementing those principles theory must be turned into practice which includes:

- creating a favourable and flexible governance system adapting green infrastructure on multiple levels, sectors and scales,
- ensure the adaptation of policies on local level, and engaging local authorities and decision makers;
- capacity building among the executors of the planning and implementation process;
- and finally involving local stakeholders (NGOs, civil movements, institutions of educations, SMEs and local entrepreneurs).

The process of the above listed steps is very complex and as previous studies have shown (Körmöndi, Tempfli, Kocsis, Adams, and Szkordilisz, 2019) the success of implementing green infrastructure is interrelated with the planning traditions of a country or macro-region.(Szkordilisz *et al.*, 2018)

It has come so far to facing also the question how urban planners can be helped by researchers to use in everyday planning routine the results of theoretical researches. This question has been addressed in some publications (Szkordilisz, F ; Kiss, M ; Égerházi, LA ; Kassai-Szoó, D ; Gulyás, 2016).

To make the conclusions of urban climate research more understandable for urban planners the methodology presenting the results must be changed. For that purpose, multiple projects have been carried out with my participation, among others: Nature4Cities (Horizon2020; (Kántor *et al.*, 2017; Szkordilisz *et al.*, 2018; Bouzouidja *et al.*, 2019, 2020; Körmöndi *et al.*, 2019); The UHI project (CEE; Baranka *et al.*, 2015, 2016; Szkordilisz, 2018), and numerous smaller commissions from Hungarian municipalities.

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List of publications related to the dissertation

Hungarian book chapters (2)

1. **Szkordilisz, F.**: A természetalapú megoldások a város-rehabilitációban.
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