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THE EFFECTS OF URBAN GREEN INFRASTRUCTURE ON MICROCLIMATE AND INDOOR COMFORT

Thesis for the Degree of Doctor of Philosophy (PhD)

by Flora Szkordilisz
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Doctoral Council of Natural Sciences and Information Technology
Doctoral School of Earth Sciences
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1949

A VÁROSI ZÖLD INFRASTRUKTÚRA MIKROKLIMÁRA ÉS BELSŐ TÉRI KOMFORTRA GYAKOROLT HATÁSAI

Egyetemi doktori (PhD) értekezés

Szkordilisz Flóra

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Debrecen, 2021.

Hereby I declare that I prepared this thesis within the Doctoral Council of Natural Sciences and Information Technology, Doctoral School of Earth Sciences, University of Debrecen in order to obtain a PhD Degree in Natural Sciences at Debrecen University.

The results published in the thesis are not reported in any other PhD theses.

Debrecen, 07.04.2021.

signature of the candidate

Hereby I confirm that Flora Szkordilisz *candidate conducted her studies with my supervision within the* Landscape Protection and Climate *Doctoral Program of the* Doctoral School of Earth Sciences *between 2017. and 2021. The independent studies and research work of the candidate significantly contributed to the results published in the thesis.*

I also declare that the results published in the thesis are not reported in any other theses.

I support the acceptance of the thesis.

Debrecen, 07.04.2021.

signature of the supervisor

THE EFFECTS OF URBAN GREEN INFRASTRUCTURE ON MICROCLIMATE AND INDOOR COMFORT

Dissertation submitted in partial fulfilment of the requirements for the doctoral (PhD) degree
in Earth Sciences

Written by Flora Szkordilisz, Master of Architecture

Prepared in the framework of the Doctoral School of Earth Sciences
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(Landscape Protection and Climate programme)

Dissertation advisor: Dr. András Zöld

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The date of the dissertation defence: ……………… 20…

’*Houses, then, will be correctly planned if, first, we take careful notice of the regions and latitudes of the world in which they are to be built. For it clearly makes sense that one type of building should be built in Egypt, another in Spain, some other type in Pontus and a different one again in Rome, and so on, depending on the different characteristics of the countries and regions.’*

Vitruvius: De architectura

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List of abbreviations

BD	Biodiversity Directive
EC	European Commission
EU	European Union
EPBD	Energy Performance Directive
GI	green infrastructure
GID	Green Infrastructure Directive
GIE	green infrastructure element
NBS	nature-based solutions
NDVI	Normalized Difference Vegetation Index
NGO	Non-governmental organization
nZEB	nearly zero energy building
OECD	Organisation for Economic Co-operation and Development
OP	Operational Programmes (of the European Commission)
SME	Small and medium-sized enterprise
UHI	Urban heat island
BLUHI	Boundary layer urban heat island
CLUHI	Canopy layer urban heat island
SUHI	Surface layer urban heat island
UUHI	Underground layer urban heat island
UN	United Nations

1. Introduction

1.1. The tendencies of urbanization

The first decades of the 21st century seem to be most crucial in urban planning and related professions for the questions that have arisen regarding the development of (urban) built environment, which has been driven by numerous factors, such as: resource-efficiency, environmental considerations, the immense technological development, economic recession and uptake, and social changes to (McPhearson, Kremer and Hamstead, 2013; Seto *et al.*, 2014). The changes of urban development are mainly due to social and economic transitions that have occurred during the last 150 years: the dimension of urbanized areas have grown (Seto et al. 2011; UN 2018), as well as the population of cities has been growing immensely, the structure of suburban areas has changed (new industrial, logistic and residential areas have been erected within a very short time), and thus new functions have appeared mainly due to digitalization. Change in technology and the development of means of mobility has led to a major suburbanization in western countries. (Duany, Plater-Zyberk and Speck, 2010). Suburbanization is not only an issue of transportation – as it leads to a lifestyle of car-dependence, hours spent in traffic jams, and thus avoidable CO_2 emissions – it is also a major environmental issue. Suburbanization usually has occupied territories with traditional green belts around the cities, resulting enormous and contiguous urban areas; thus, the territorial dimensions of urbanized areas grow, and so the diameter of urban heat island grows too. Besides, suburbanization has a negative effect on biodiversity (McKinney, 2006). Regarding social issues, traffic is believed to be a major, if not biggest source of stress in our lives. (APS 2008).

According to INRIX (INRIX, 2016) the yearly average hours spent in traffic jams per average commuter around the world give a range from 10 hours (Singapore) to 61 hours (Thailand); and with an average of 18 hours for Hungary – showing a growing tendency (See *Figure 1).*

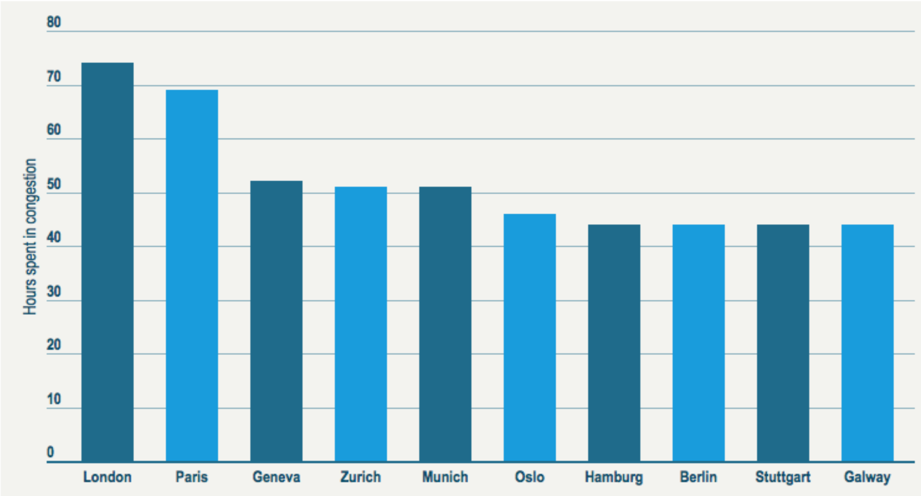


Figure 1: Hours spent in congestion in European Cities (Includes cities in the EU plus Switzerland / Chart measures average number of hours a driver would spend in congestion during peak hours based on 240 commuting days. Source: INRIX 2016

In order to minimize the trend of suburbanization, the only solution seems to be the enhancement of downtown living quality and making traditional city centres attractive for families – so that they do not tend to move to the fringes of the city. An important tool for creating walkable, liveable cities is the usage of green infrastructure, creating safe green spaces for recreation. (Speck, 2012).

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.

Besides the environmental and mobility-related aspect, green areas have a crucial role in handling social issues. Community gardens, school gardens have an important educational value (Cole *et al.*, 2017), improve public security (Berényi, Kondor and Szabó, 2007; Egedy, 2007) and ensure economic uptake on neighbourhood scale. Green projects, besides having the advantage of being attractive topics in participatory planning, also serve educational purposes. (Cole *et al.*, 2017; Raymond *et al.*, 2017)

The above listed examples and processes seem to be pointing to a basic issue, which is urban climate. As demonstrated, climate on meso or urban scale is strongly interlinked with numerous other aspects of life, such as urban planning, biodiversity, mobility, citizen engagement, public security, quality of life and economic uptake.

Breaking down to building scale the functional demands and expectations of main contractors have changed, building technologies are changing rapidly due to economic, social, technical, environmental and energetic issues as well. However, thinking about dozens of new regulations around the world trying to push architecture towards a more energy-conscious, eco-friendly, and resource-efficient approach, we have to realise, that only one issue has been neglected for a long time in urban planning and building industry: climate change. 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 great importance.

There are two main perspectives towards handling the effects of climate change in both urban and rural areas: climate adaptation and climate mitigation. Climate mitigation focuses on reducing the emissions of green-house-gases, thus, addresses the drivers of climate change. On the other hand, climate adaptation tries to make the extremes of weather phenomena tolerable for humans. Concentrating on the building sector: climate mitigation includes actions like energy-conscious retrofitting of buildings (thermal insulation, changing of windows, etc.), the usage of energy-effective building engineering services, and also maximalization of solar gain in winter and shading in summer. Climate adaptation on the other hand can be a doubled-edged sword if not used properly: the usage of building cooling systems, traditionally using electricity might lead to an energy-consumption surplus. The proper solution however for climate adaptation should be the usage of classic solar architecture toolkit, such as: shading, night ventilation, thermal mass. On city or neighbourhood scale for example climate adaptation measures managing stormwater runoff and retaining water in green infrastructure elements instead of using impermeable paving and enhancing quick runoff. However, the boundaries of the two types of measures: adaptation and mitigation are sometimes hard to define. For example, implementing intelligent building engineering systems and shading with vegetation can act both as mitigation (by reducing energy-demand) and adaptation measures (enhancing thermal comfort in a proper way).

Climate is a crucial issue in numerous areas of life: agriculture, forestry, water management (Vörösmarty *et al.*, 2000), migration and mobility, and on smaller scale climate is also an important factor in the energy-balance of buildings (Matsuura, 1995; Santamouris, 2007) regarding human thermal comfort and performance (Jokl, 1982). Climate change causes extreme weather events, coastal flooding, inland water in low-lying areas, and reduced rainfall in drylands or water shortage and flood at the same place but in different seasons. Water scarcity has a negative effect on agriculture (Reilly *et al.*, 1996), and the linkage with food deprivation and thus migration, finally social problems is obvious. Migration is important not only as a social and economic challenge, but the trend over the last decades has shown, that migration has become centralized (Foresight, 2011) towards cities and metropolises, while shrinking rural areas lose their population harshly.

The growth of city dwellers' number, and the expansion of urban areas as its result, has been an accelerating process since the industrial revolution. The development of urban habitation was most significant in the twentieth century. In 1900 there were only 16 cities having inhabitants above 1 million (Montgomery *et al.*, 2003), and in 2010 there are 449 such cities around the world. What makes this statistics more striking is the fact, that while in 1900 most of the big cities were situated in developed and industrialised countries, nowadays urbanization is most characteristic for developing countries. (UN 2018; National Research Council 2003) Concluding, we can state that urbanization hasn't reached its point of inflection, it is a process still growing. Every third human being is a city dweller; thus, a big share of the total population is affected by problems especially characteristic for metropolises.

1.2. Urban climate

Speaking of climate issues, the most important challenge to face is the phenomenon of Urban Heat Island (UHI) (Unger, 1999). The key characteristic of the phenomenon - that was first described by Luke Howard about 200 years ago (Mills, 2008) – is that temperatures in the city (both air temperature and surface temperature) are higher than that in the rural areas in the fringes. Beside social and architectural issues my research focuses on climatic and energetic extremities of the cities caused by UHI. The effects of urban heat island became particularly unbearable in summer, when heat stress occurs. Regarding the vulnerability of people living in less developed neighbourhoods, it is more likely that they are more exposed to climate extremities and have limited access to good quality green areas while the housing estates tend to be of poorer technical conditions. It stands clear, that prevention behaviour during heat waves include the usage of electrical air conditioning devices (Khare *et al.*, 2015), which has become fashionable during the last decade even in such parts of Europe, where traditionally mechanical cooling was not used. The usage of mechanical cooling during the 3-4 months of the summer period increases greatly the demand for electric energy, and in addition, due to the fact that the external units of the air-conditioning devices also heat up the air – causing a self-generating process, -the natural cooling after sunset is hindered too. This way the intensity of urban heat island increases. This consistent train of thoughts demonstrates clearly that the phenomenon of urban heat island is far more than solely an environmental issue, it is an important energetic challenge to face too.

Besides it, the correlation of summer heat waves, extreme heat stress and excess mortality must be mentioned. Numerous studies have shown that above a certain temperature threshold mortality – especially among elderly people or those suffering of chronic illness increases. (D'Ippoliti *et al.*, 2010; Brooke Anderson and Bell, 2011; Matzarakis, Muthers and Koch, 2011) According to studies carried out in Hungary, the typical excess mortality during heat waves varies between 10% and 15%. (Páldy *et al.*, 2005; Bobvos *et al.*, 2017) Thus, when discussing urban climate, it is highly relevant to research alternative ways to mitigate the effects of, and adapt to a climate in change, especially during summer heat waves. One of those measures is the development of green infrastructure elements within the city structure. Furthermore, this method incorporates an important potential of energy saving.

1.3. Objectives and motivation of research

Summing up, 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 revealing, analysing and assessing 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, neither 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 aim of my research was:

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, where 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.

2. Literature review

The objective of this chapter is to give an overview on the major research results of relating studies and to identify those gaps that this work aims to give answers to. This chapter provides an overview of last and most relevant results published by November 2020 with the following interconnected topics: climatic environment in urban areas; green infrastructure: the development of the methodology, and different definitions; finally, the role of green spaces in buildings and in city scale.

To be able to understand the differences and the importance of urban heat island, first a brief overview on the territorial dimensions of climatological phenomena should be given. Regarding meteorological phenomena: areal and temporal dimensions are usually strongly linked with each other. The areal scales of climate are distinguished as following:

– Microclimate – from 1 cm to 1 km
– Local climate – from 100 m to 50 km
– Mesoclimate – from 10 km to 200 km
– Macroclimate – from 100 km to 100 000 km (Yoshino, 1975; Unger *et al.*, 2012).

Microclimatic phenomena are usually short-lived, while phenomena of regional significance might define the weather conditions of an area for a longer period of time.

A very similar approach is true for urban planning too. Urban planning tools have their typical spatial scales and timescales. The relevance of physical geography cannot be denied either: hills and valleys, water bodies or the features of the surface play an important role in defining small-scale climate. The listed topographic characteristics also can modify: strengthen or weaken the effect of anthropogenic heat. (Unger, 2010) The following figure *(Figure* 2: Schematic illustration of the micro (M), local (L) meso (S) and macro (A) climate scales. After: (Yoshino, 1975) demonstrates the overlapping layers of all those factors shaping the climate of an area.

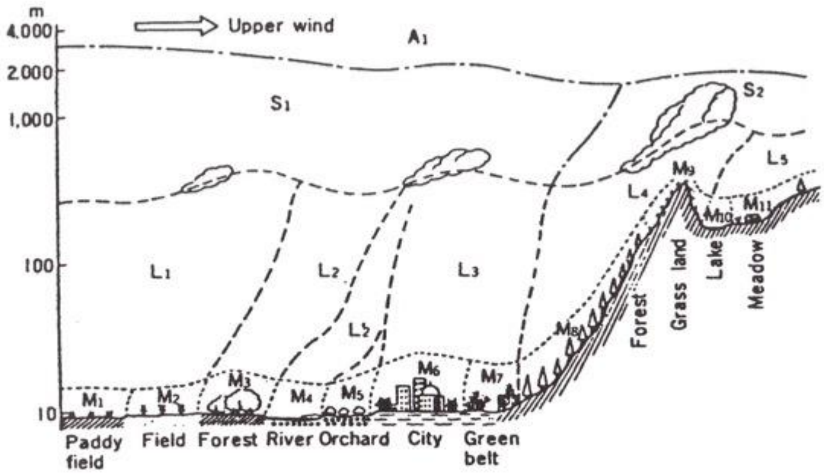


Figure 2: Schematic illustration of the micro (M), local (L) meso (S) and macro (A) climate scales. After: (Yoshino, 1975)

2.1. Urban heat island

Cities differ from their surrounding natural environment regarding the material characteristics, the geometry and thus, also the atmospheric conditions as well. Also, the artificial heat production being present in cities lead to modified climatic conditions, that is: urban climate. (Balázs *et al.*, 2009; László and Szegedi, 2015)

Urban heat island is traditionally defined as closed isotherms that delineate an area warmer that its surroundings. (Voogt and Oke, 1997) The first researcher to demonstrate isle-like isotherms characteristic for UHI was Peppler when describing usual temperature patterns on summer days in Karlsruhe in the late 1920s. (Peppler, 1929) The following Figure 4. a) Plan view of spatial patterns of air temperature causing nocturnal CLUHI; b) Cross sections of diurnal and nocturnal air temperatures measured within urban canopy layer and surface temperatures under optimum heat island conditions(calm and clear. Source: (Voogt, 2015)shows a similar schematic representation of the UHI.

Consequently, UHI is defined as a local climatic phenomenon due to the fact, that cities and urban settlements are characterized by a higher temperature that the rural areas outside the city. (Oke, 1973; Unger *et al.*, 2001; Fernández *et al.*, 2003) This temperature difference (*ΔT*) – which is the intensity of the UHI – is due to human (building) activities and causes a bunch of anomalies regarding atmospheric conditions, radiation (thermal) and water balance – all three features are discussed later in this chapter.

Urban heat island, which might be a characteristic of every settlement, regardless of its size, naturally causes modifications in the atmospheric conditions. The higher surface temperature in cities will have an effect of the lower layers of the atmosphere, that is the troposphere. (Unger, 2010). In case of urban settlements, different scale atmospheric layers can be distinguished. Above natural surfaces Rural Boundary Layer (RBL) comes to existence, where turbulence comes to existence due the roughness of the surface and the updraft of hot air too. (Flay, Stevenson and Lindley, 1982) Above urban areas a so-called Urban Canopy Layer (UCL) emerges. UCL covers the height of roofs within the city; and can be further broken down to microscale phenomena caused by buildings, streets, open spaces, parks. Urban Boundary Layer (UBL) encompasses UCL as a so-called "dome". A layer usually higher than RBL, UBL usually forms a so-called "plume" above the RBL, which stretches parallel with the prevailing wind direction. (Unger, 2010)

In accordance with the previous, UHI can be observed on four layers, which also mean different scales too (Oke, 1976). These are the following:

- Boundary layer UHI (BLUHI) – mesoscale boundary layer above the city (Oke, 1982).
- Canopy layer UHI (CLUHI) – extends from the ground up to the roof level.
- Surface layer (SUHI) – regardless of the height, surface layer is measured through satellite imagery. The scale of phenomena examined also depends on the resolution of the satellite image: from object scale to city / neighbourhood scale hot spots can be identified (Pongrácz, Bartholy and Dezso, 2010).
- Underground layer (UUHI) – due to all above mentioned layers of temperature surplus, underground UHI can be identified too (Lokoshchenko and Korneva, 2015).

The following figure *(Figure 3.)* demonstrates the listed four layers of UHI.

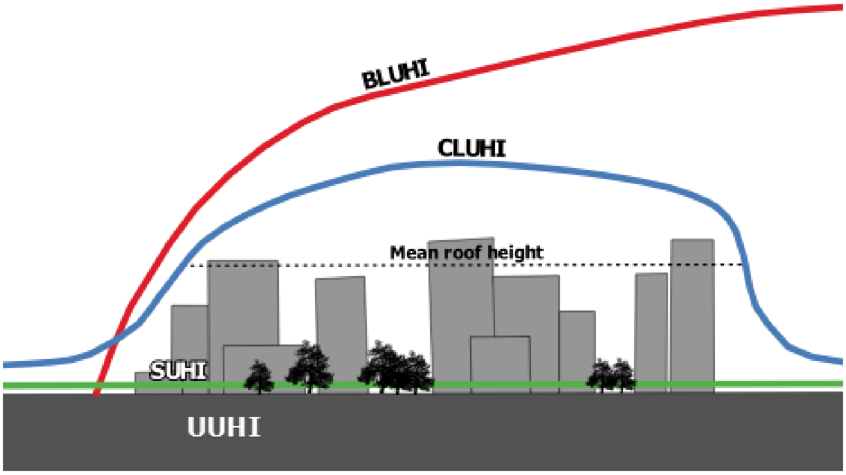


Figure 3.. Three layers of urban heat island. Based on:(Kim, Gu and Kim, 2018)

My work focuses on two of the previous mentioned layers: the surface layer (SUHI) as this is the one which fundamentally effects human thermal comfort or discomfort, and the canopy layer which is important from the building energetics point of view. The following *Figure 4. a)* Plan view of spatial patterns of air temperature causing nocturnal CLUHI; b) Cross sections of diurnal and nocturnal air temperatures measured within urban canopy layer and surface temperatures under optimum heat island conditions(calm and clear. Source: (Voogt, 2015) show a similar schematic representation of the UHI.

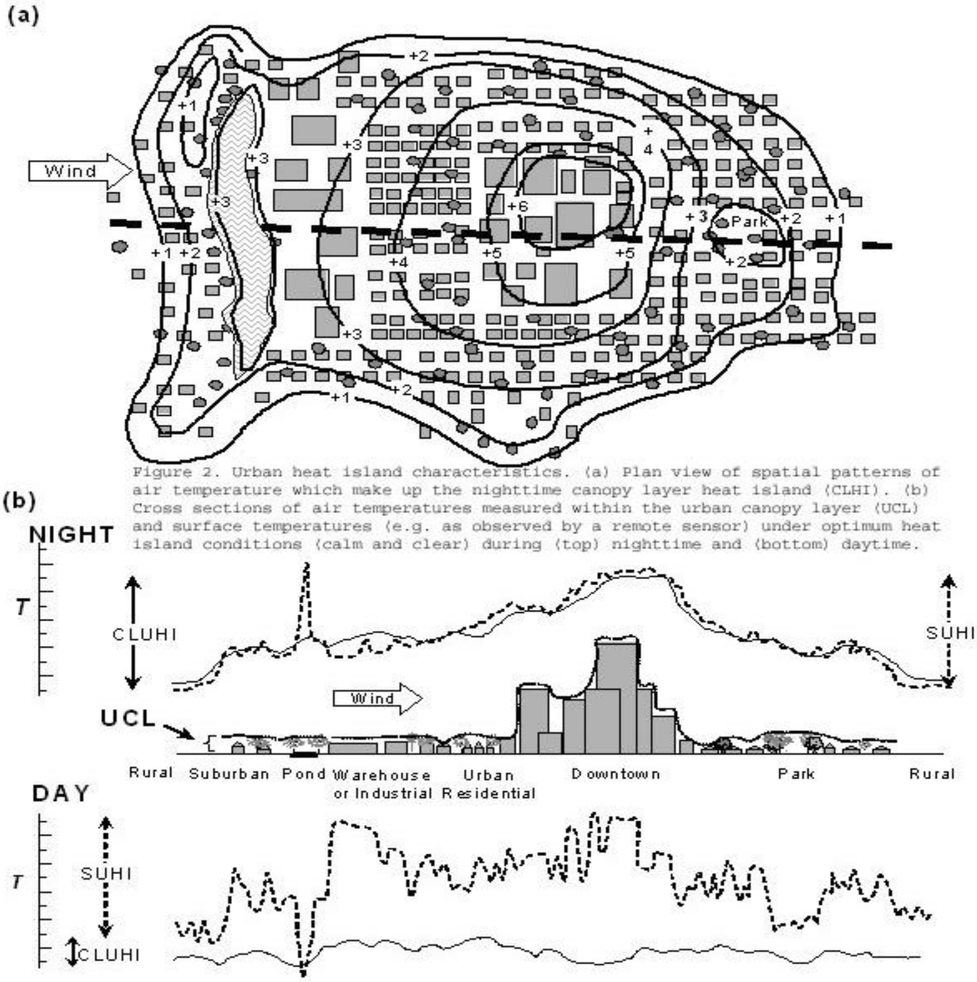


Figure 4. a) Plan view of spatial patterns of air temperature causing nocturnal CLUHI; b) Cross sections of diurnal and nocturnal air temperatures measured within urban canopy layer and surface temperatures under optimum heat island conditions(calm and clear. Source: (Voogt, 2015)

As mentioned, UHI is a complex result of various phenomena related with each other (Unger *et al.*, 2000). One of the causes of the urban heat island is the global warming, but while the latter value shows an annual average growth of 0.0075 °C, the temperatures in Budapest during the past hundred years have risen annually by 0.06 °C in average (M. Szilágyi and Jámbor, 2004). That means that the intensity of urban heat island increases nearly ten times faster than the average temperatures of the Earth.

The question occurs: what other effects create this enormous temperature-surplus if climate change alone is not liable for the local climatic phenomenon of UHI? As countless researches have proved, the cause must be found in the man-made surfaces and anthropogenic heat production, such as: transportation, industrial activities, usage of buildings (indoor heat sources, heating, cooling, and lighting). First of all, the importance of land cover must be mentioned (Owen, Carlson and Gillies, 1998; Chen *et al.*, 2006). Water and radiation absorption properties of sealed areas differ completely from those of a biologically active area (Arnfield, 1982; Sailor and Dietsch, 2007), thus the energy budget of different areas will differ too. As cities on average tend to have a great deal of sealed surfaces which enable quick stormwater runoff, causing severe problems, such as infrastructure overload (often resulting sewage backflow), quick evaporation, and a low albedo *(α)*. According to Oke (T R Oke, 1987), cities tend to have an albedo 5-10% lower than the surrounding rural areas. Besides albedo another relating index is significant when measuring UHI with satellite imagery, and that is NDVI (Normalized Difference Vegetation Index) (Dezso *et al.*, 2005; Szabó *et al.*, 2019). The significance of land use and the intensity of urban heat island, and surface temperatures was shown also in the case of Józsefváros, Budapest. (Oláh, 2012)

Besides the fact that the rate of sealed and biologically active areas is out of balance, other sources of anthropogenic heat production are also relevant and significant, such as mobility, industrial activities, and the heating and cooling of buildings. On building scale, the usage and occupation of the building itself: heating, heat generation of appliances, and human metabolism also create a surplus heat production.

Regarding mobility, it is clear, that only about one-third of the vehicle’s engine performance is utilized for movement (this means a negligible heat loss from rolling and air resistance), one-third of the performance leaves the engine block via its cooling system into the air with heat release, and finally one-third through the exhaust, which creates not only air pollution but also heat production. Braking also implies heat generation.

Cooling systems of buildings are also of major interest and related to one of the main objectives of the current work. Heat loss in winter through the building shell – even with outdated technical and thermodynamical characteristics of buildings – leads to a dynamic balance in thermal conditions on neighbourhood or city scale. If outdoor temperatures rise due to the UHI effect, the indoor heating demand will decrease. On the other hand, in summer traditional air conditioning devices heat the streets though their outdoor condenser units mounted on the façades of the buildings or on the roof. The above mentioned process leads to a vicious circle: as outdoor temperatures rise, indoor cooling demand will grow at the same time. Especially dangerous is that during summer heat waves, when city dweller's mental performance and physical health is at stake. The above listed features cause a hazardous climatic situation due to their temporal extent. A momentary off-balanced situation might be still handled, however, during heat waves anthropogenic heat production and anticyclonic conditions superponate.

Going a step further in the examination of UHI, the discussion of the raiation budget of the heat island will follow. In order to understand radiation budget, a few terms need to be introduced, such as: sensible heat *(QH)*, latent heat (QE), shortwave *(K)* and longwave *(L)* radiation. Sensible heat is defined as the energy flux utilized for the temperature change of the system. Latent heat on the other hand is the energy flux used for the phase change(s) of a particular system – in urban climatology most frequently the phase changes of water in any form. Therefore the latter causes a change in the relative humidity of the atmosphere. An additional heat source is that of human activities *(QF)*, although, usually this is a rather small component of the urban energy balance. (Mills, 2004). However, literature has shown, that in case of Budapest for example human activities might be of the same magnitude as radiation. (Seprődi-Egeresi and Zöld, 2011)

The directions of the mentioned radiation fluxes are not indifferent either: *"Net radiation (Q*) is composed of radiation arriving at (↓) or exiting from (↑) a surface each component of which can be sub-divided into radiative sources and sinks. For example, incoming radiation at a surface can be divided into that derived from the sky and that from the surrounding terrain,*

$L_{\downarrow} = L_{\downarrow \text{sky}} + L_{\downarrow \text{terrain}}$ " (Mills, 2004)

The urban energy balance is composed as follows:

$$Q^* + QF = QH + QE + \Delta QS \times Q^* = K_{\downarrow} - K_{\uparrow} + L_{\downarrow} - L_{\uparrow} = K^* + L^*$$

(Mills 2004)

"The contributions from these sources will depend on both their emittance and the proportion of the 'view' of the surface occupied by those sources." (Mills, 2004) The relevance of the described processes lays in the fact that radiation fluxes differ in an urban setting: due to air pollutants and man-made surfaces, the proportion of longwave and shortwave radiation changes.

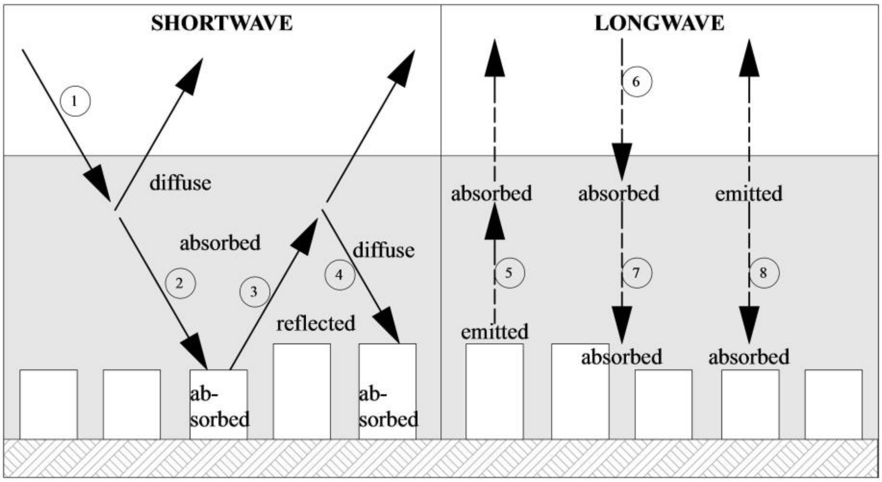


Figure 5. Short- and longwave radiations in the polluted urban boundary layer. Source:(Oke, 1982)

A commonly used indicator to describe the proportion of absorbed, reflected and emitted radiation is the albedo of surfaces. Albedo (α) is defined as the fraction of sunlight reflected by an opaque surface. The rest of the energy is absorbed, which equals to 1-α. The albedo and the emissivity in long infrared radiation together determine the surface temperature. However the emissivity is in general about 0.9 (excepting selective surfaces), therefore many times only the albedo is mentioned. (Akbari, Pomerantz and Taha, 2001) The below *Table 1.* indicates typical albedo and emissivity values of different surfaces.

Table 1.: Radiative properties of natural materials. Source: (T. R. Oke, 1987)

Surface	Remarks	Albedo α	Emissivity ε
Soils	Dark, wet Light, dry	0.05 - 0.40	0.98 - 0.90
Desert		0.2 -0.45	0.84 - 0.91
Grass	Long (1.0 m) Short (0.02 m)	0.16 - 0.26	0.95
Agricultural crops, tundra		0.18 - 0.25	0.90 - 0.99
Orchards		0.15 - 0.20	
Forest Decidous	Bare Leaved	0.15 - 0.20	0.97 - 0.98
Coniferous		0.05 - 0.15	0.97 - 0.99
Water	Small zenith angle	0.03 - 0.10	0.92 - 0.97
	Large zenith angle	0.10 - 1.00	0.92 - 0.97
Snow	Old Fresh	0.40 - 0.95	0.82 - 0.99
Ice	Sea	0.30 - 0.45	0.92 - 0.97
	Glacier	0.20 - 0.40	

Here comes the importance of vegetation when fighting negative effects of UHI. Akbari (Akbari, Pomerantz and Taha, 2001) suggests, that summer energy demand for cooling can be reduced by 13-18% by using cool coating on the roof. However, he also states, that while cool roofs bring an “indirect” contribution to the urban energy balance, the “direct” solution of planting trees helps reducing atmospheric CO_2 by sequestering CO_2 through photosynthesis. The further benefits of using vegetation in urban environment will be discussed in chapter 2.3.

Furthermore, the conflict arises between cool roofs and energy-production aspects. The energy collecting elements of active solar thermal systems as well as those of photovoltaic systems are typically: (1) of minimal reflectance and (2) are allocated on the roofs. The mentioned two factors contradict to the cool roof concept which would demand the usage of high-albedo surfaces. However, in the case of solar panels solar gain will hit the panels and not the building structure directly. Therefore, if the motivation of using cool-roof coating is to minimize the solar gain of the building is not anymore relevant. From the point of view of building energy balance the temperature on the external surface of roofs would be of importance only if the thermal insulation is poor. This is not the case, roof slabs were and are typically the best insulated parts of the buildings, moreover there is an open air gap between the energy collecting arrays and a flat roof. On the other hand, solar panels might have a heating effect in the canopy layer, which however has no or negligible effect on street comfort; what is more, warm roofs create a thermal column which animates urban breeze.

As the urban radiation balance is in a strong corelation with the alterations in the water cycle caused by urban climate (Järvi *et al.*, 2014), it is important to shortly mention that too. This means, that land cover consisting mainly of artificial and watertight materials not only induce different rainfall-patterns (Zhong and Yang, 2015), but also effects evapotranspiration (Zipper *et al.*, 2017)too.

Summing up the multiple effects of UHI we can see that those can be categorized into three groups of impact-mechanisms: the effects modifying atmospheric conditions, thermal and water balance.

The structure of the urban heat island is determined by parks and lakes (cool island, (Szegedi and László, 2012)) on one hand, and the densely built-up areas (warm islands) on the other. The intensity of the urban heat island is the difference between temperature values measured in the centre of the city and those measured in the rural area outside the city. The intensity is maximal (at stable atmospheric conditions) a few hours after sunset, and is minimal at midday.

Generally, the gradient of the temperature can rich 4 °C/km (Zöld, 1999). In the case of Budapest, the intensity of the heat island reaches 6-8 °C in the central districts (M. Szilágyi and Jámbor, 2004). Similar conditions characterize smaller cities also: in Debrecen, for example, the mean maximal intensity of UHI was 2.4˚C (Szegedi *et al.*, 2014). Oke suggested a linear equation between the population of the city and the maximal value of UHI intensity in case of mid-latitude cities, under calm and clear weather conditions:

$UHI_{max} = 2.01 \log population - 4.06$(Oke, 1973).

However, recent literature did not verify the calculation method. (Hove *et al.*, 2011)

As mentioned, before, the intensity of urban heat island is interconnected with the housing density, and cool islands can be created by the development of urban green spaces. That is why green spaces have a special role in urban climatology and are a brilliant tool in order to mitigate the negative effects of urban heat island.

2.2. Defining green infrastructure

Before specializing the benefits of green infrastructure, we need to have a clear understanding of the term itself. The concept of using green areas within urban structure dates back to the late 19th century (Pötz and Bleuzé, 2012), and even earlier.

Without getting deep in the history of planning, a short overview must be given at this point. Cities were always considered as the centre of culture and civilization, therefore no thoughts about missing greenery or parks were raised. The first city parks became important in the 19th century. The very first parks include the Városliget, in Budapest, where afforestation started in the late 18th century to the orders of the city of Pest.

Closer to our time, the thought of considering urban greenery as infrastructure: that is: a system of goods and services sustaining, enabling or enhancing living conditions; emerged in the 1980s. At that time, green infrastructure, or more correctly, the lack of greenery in the cities became an issue of civil actions, scientific work and urban planning too. (Silva and Wheeler, 2017). Beginning with the '80's there have been several expressions and approaches towards handling the same range of urban challenges: bad air conditions, water management issues (shortage of water or stormwater floods), summer heatwaves, decrease of biodiversity and healthy food supply. However, the aim remains the same: creating better living conditions within the city, ensuring high quality green spaces for recreation and also urban farming, flood protection, providing habitat and clean water and air. Nevertheless, there are differences in understanding according to the various urban planning traditions.

Different approaches in green infrastructure planning also appear regarding the planning strategies of different regions and countries. For example, the United States and European Union may have a different view on scale or components of green infrastructure. To enlighten those minor differences some definitions are quoted below:

United States Environmental Protection Agency (EPA) has defined GI in the following way: *"Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a city or county, green infrastructure refers to the patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. At the scale of a neighbourhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water. These neighbourhood or site-scale green infrastructure approaches are often referred to as low impact development."* (U.S. EPA, 2019)

The definition of the European Commission based on the Green Infrastructure Directive seems to be wider. Naumann *et al.*, 2011 describes the concept clearly: *"Green Infrastructure is the network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services. Green Infrastructure can be strengthened through strategic and co-ordinated initiatives that focus on maintaining, restoring, improving and connecting existing areas and features, as well as creating new areas and features."*

As seen from the citations, the major difference lies in the fact that EU defines green infrastructure as including natural and semi-natural areas outside urban areas while the U.S. definition focuses more on the toolkit that green infrastructure provides. On the other hand, under the EU guidelines, green infrastructure is considered as a strategic approach.

Furthermore, a relatively new term must also be introduced here. The term nature-based solutions (NBS) was first mentioned a few years ago and is defined as solutions that are "*inspired by, supported by, or copied from nature.*" (EC 2015) However, mimicry and biomaterials or renewable energy-sources are not considered as NBS. The difference between NBS and GI is rather elusive, after years of research in both fields I have concluded that NBS tend to colligate the social and economic perspectives of green-based urban planning. NBS keeps the focus on well-being and the enhancement of quality of life (QoL) through the use of natural solutions in cities providing a strong basis for marketing and branding for small and medium sized enterprises and in turn for economic uptake too (Nesshöver *et al.*, 2017). (Policy documents regarding green infrastructure in Hungary will be discussed in Chapter 7.)

In accordance with existing definitions and approaches this work focuses on both the importance of introducing nature in urban setting, but also on the implementation of green solutions within the process of urban planning. The definition used in this work lies nearer to the American definition, as I do not deal with agriculture, rural and coastal areas. **I define Green Infrastructure as an inevitable approach to implement nature, and also creating the conditions of greenery in the city on multiple scales; with regard to ensuring connectivity and complex solutions for providing a higher quality of life and numerous social, economic, environmental and climatic benefits.**

2.3. The role of green spaces in urban setting

After defining green infrastructure, it's role on multiple scales, and environmental, climatic, energetic, social and economic impacts must be discussed. In this work I focus on the first three aspects, however, social and economic effects must be mentioned too due to its importance and relevance in urban planning.

Green infrastructure as a planning strategy, and as a major topic of research began to acquire growing importance after World War 2. Interestingly, the urge for building new housing around rapidly developing cities made green infrastructure valuable and a resource to be reckoned with. Regarding the consciousness of planners and city decision-makers, the most important step was the beginning of the Garden City Movement initiated by Sir Ebenizer Howard (Howard, 1898, 1902). The movement included healthy housing for factory workers, establishing complex cities ensuring space for industries, agriculture, and residential areas, and creating green belts around the city centres. The listed ideas all proved to be some of the most important aspects of urban planning of modernism and the 20th century. (Ward, 2005)

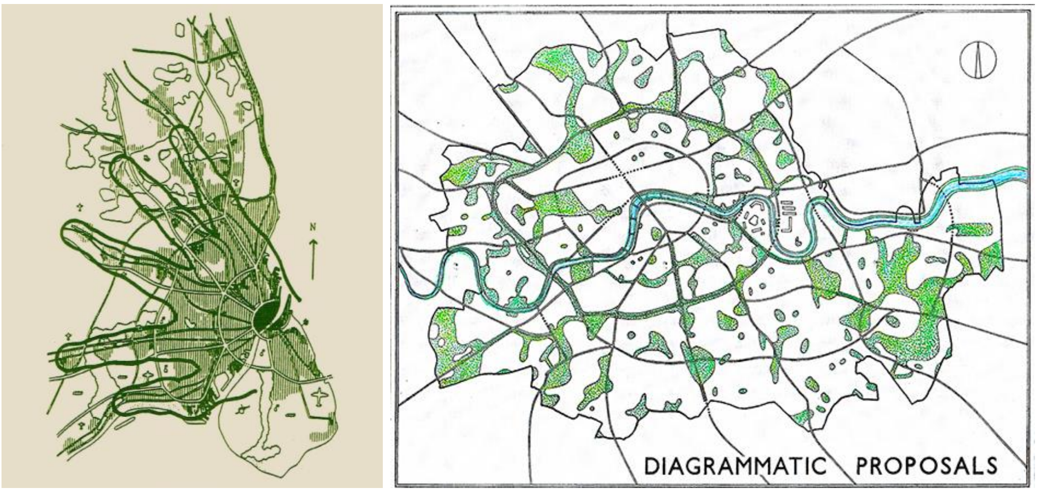


Figure 6. Left: Copenhagen and the conceptual layout of the Fingerplan; Right: the green belt proposed for Greater London in the Abecrombie plan

2.3.1. Environmental and climatic effects of green infrastructure

A great number of researches have dealt with the climatic and environmental effects of green spaces within the city. (T R Oke, 1987; Santamouris *et al.*, 2001)

The special climate created by plants is due mainly

- to the evapotranspiration;
- to the absorption and reflection of solar radiation;
- to the modified wind movement; and
- to the CO2 assimilation.

All mentioned changes create a special climate within the city, which is called Oasis-effect of the urban green spaces, which is the most important from energetic and microclimatic point of view. In the following the main characteristics of bioclimatology will be studied through.

Evapotranspiration: The Oasis-effect is mostly due to the phenomenon of evapotranspiration, which refers to the whole water steaming caused by biologically active surfaces: from water and soil (evaporation) and the movement of water within the plants (transpiration). As the process of evapotranspiration detracts heat from the air, air temperatures will decrease near of green spaces. Nevertheless it has to be mentioned that due to evaporation the relative humidity will increase too (Huddleston, 2017).

The process of transpiration needs energy, which is covered by the absorbed solar radiation.

Solar radiation: Depending on the wavelength of the radiation the leaves will absorb, reflect or transmit the solar radiation. The wavelength of the reflected, absorbed or transmitted radiation varies by the amount of chlorophyll in the leaf. During the summer when the leaves' chlorophyll content is maximal, the leaves reflect the blue and red radiation, that is why leaves are seen green. In fall, when leaves' chlorophyll content decreases, the reflection in the red range also decreases, that is why the leaves turn yellow during autumn.

Due to the reflection and absorption of radiation, leafy plants will shade the ground beneath. The effectiveness of shading depends on the Leaf Area Index (LAI), which denotes the ratio of the total leaf area and the area under the tree drip-line. Due to the shading effect solar gain can be reduced up to 80 % (if transparency of a tree can be approximated with a value of 0.8 (McPherson, 1984)). That means, that surface temperatures and so Mean Radiant Temperature (*MRT*) can be reduced through shading with leafy plants. The degree of the reduction depends on the form and the canopy of the tree. (Konarska *et al.*, 2014)

Air movement: The influence of urban trees on wind speed and profile has been shown by previous studies (DeWalle and Heisler, 1983). In a previous case study it was proved, that according to wind direction the effect of urban trees could vary. The heating energy saving due to wind shading with trees can reach 20% at certain building and tree heights (Santamouris, 2001). Less dramatical, however the effect of green façades or walls on air movement mustn't be forgotten, which will be discussed in chapter 4.1.

CO_2 assimilation: As mentioned, the activity of plants needs energy gained from the solar radiation and from the CO_2 content of the air. Due to the

respiration of leaves O_2 is produced during the day. During the night the stomata close, and the progress now operates vice versa: the plant consumes O_2 and emits CO_2. As nights are shorter than daytime in summer the balance of the process is positive from the point of view of producing O_2. The correlation with the speed of growth of plants and their capacity to sequestrate CO2 must be mentioned here as underlined in several studies. (Nowak, Crane and Stevens, 2006; Currie and Bass, 2008; Kiss *et al.*, 2015) This is a factor to be considered when choosing tree species for urban green spaces. Summing up the main features of microclimate created by plants becomes apparent that urban green spaces have a cooling and misting effect, which equilibrates the negative effects of urban heat island.

Another important effect of vegetation must be mentioned, that is the positive effects of human comfort, physical and psychological wellbeing. Without trees the development of a liveable city is unthinkable. (Zelenák and Dúll, 2016)Trees not only have a positive effect on human physiological well-being by creating better microclimatic conditions (Kántor *et al.*, 2018), but also have a great impact on mental health. (Kaplan and Kaplan, 1989; Roe *et al.*, 2013)Canopy coverage in urban streets not only fight heat, but mental stress too. (Astell-Burt and Feng, 2019) Furthermore, mental stress is lessened by trees due to the fact that they reduce noise pollution, and ensure habitat for birds and other animals, which also have a positive effect on human mental health. (Bucur, 2006)

2.3.2. Vegetation on building scale: effect on energy budget

The role of greenery and evaporative colling was an issue from early antique times in Mediterranean architecture. Greek, roman and also Arabic dwellings were built most commonly with a U or square shaped buildings with a small pond (*impluvium*) surrounded by a covered patio (*atrium*) with plants in the middle of the building. All rooms had direct access to the *atrium* thus ensuring fresh and cool air access. Arabic houses also used solar chimneys and evaporative cooling for fighting the dry climate. The atrium is perfect place to create space for indoor vegetation within the building and there are multiple examples of using the mentioned method.

However, Central-European blocks of flats built in the second half of the 19^{th} century, that still predominate the building stock in many cities nowadays also have an inner courtyard, surrounded with covered, open-air corridors on every side and each level of the building. This connects traditional architecture with current urban planning challenges.

The role of green roofs is not examined in this work, as studies have showed that they have small effect on street comfort (Gromke *et al.*, 2015) and their benefits opposite the additional grey energy required for the construction (additional thermal and waterproof insulation).

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/m2, 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 7.)

The same instruments were used for similar researches regarding the horizontal tree shading of trees (Takács, Kiss, *et al.*, 2016) and human comfort measurements too.(Kiss *et al.*, 2015; Takács, Kovács, *et al.*, 2016) This methodology of measuring the effectiveness of tree-shading, as also described in Szkordilisz and Kiss, 2016a was also used by Krause, Leistner and Mehra, 2020 for similar research purposes.

Figure 7.: The two pyranometers on measuring site.

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

Several numerical simulations were carried out through the research, most of them representing real or realistic urban settings. In most cases the results of the simulations were used in relating municipal assignments to justify planning dilemmas and to support decision-making regarding green-infrastructure development.

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. (At the time of the modelling and simulation demonstrated in this work were carried out *ENVI-met* was a free-of-charge and on-line available software – and more or less the only suitable for neighbourhood scale research purposes. When discussing other simulation tools available *“Solweig”*(Lindberg, Holmer and Thorsson, 2008) must be mentioned. *Solweig* was released in 2010, and was capable calculating *MRT, PET* and *UTCI*, however it wasn’t able to calculate wind speed or other important atmospheric conditions. From 2016 on *Solweig* is being developed as a part of *UMEP* (Urban Multi-scale Environmental Predictor) a plug-in for *QGIS* software.(Lindberg *et al.*, 2018). Another well-known simulation tool is RayMan (Matzarakis, Rutz and Mayer, 2007; Fröhlich, Gangwisch and Matzarakis, 2019), however, the evaluation of results can by only carried out cell by cell, which makes the implementation of the model tardy. Thus, *ENVI-met* was chosen for the purpose of microclimate modelling.

Most of the researches 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 to 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.

Typical settings used:

- Start Simulation at Day (DD.MM.YYYY): = 22.06.2011
- Start Simulation at Time (HH:MM:SS): = 21:00:00
- Total Simulation Time in Hours: = 23.00- 48.00
- Save Model State each ? Min = 60
- Wind Speed in 10 m ab. Ground [m/s] = 3
- Wind Direction (0:N..90:E..180:S..270:W..) = 315
- Roughness Length z0 at Reference Point [m] = 0.1
- Initial Temperature Atmosphere [K] = 296
- Specific Humidity in 2500 m [g Water/kg air] = 7
- Relative Humidity in 2m [%] = 70

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 a more general approach to the shading effect of alley trees. Modelling was carried out with Autodesk *ECOTECT* software.

4. Research results

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 courtyards of historical blocks of flats in Budapest.

While introducing the researches I will proceed from the small scale to the larger scale measures.

4.1. Green facades

Within the history of fighting the negative effects of urban heat island, we can find numerous traditionally used tools for the improvement of microclimate. Investigating traditional architecture, we can see several examples for the usage of vegetation near or inside the buildings, proving that the use of green façades was quite common. (See *Figure 8*.)

Green façades were not only used by traditional architecture, contemporary architecture has rediscovered the benefits of using plants as an added layer on the outer shell of the building. In the last years there are more and more possibilities and techniques to cover walls with plants. During the past decade it became fashionable to create vertical gardens, which usually need a specific structural and irrigating system. Vertical gardens have several advantages, besides of their positive energetic effects they have aesthetic value too, so they can also act as attractive media façade. It has to be also mentioned, that plants used for vertical gardens are less effective from the evapotranspiration point of view, and the system is still quite expensive to be spread all over the world. There is also an example of removing greenwalls because of high maintenance costs or because of not fulfilling energy-efficiency purposes after all. For example, the green mediawall of PNC Bank in Pittsburgh on the corner of Fifth Avenue and Wood Street was implemented in 2009, but the living wall was removed in 2016.(Belko, 2016) This also gives a reason for the case study to refine and clarify the effects of a green façade or wall and thus, to avoid unreasonable expectations.

The widespread use of green facades is opposed by some doubts that plants can ruin the plaster on the wall. This belief is not correct because, on one hand, climbing plants do not take their nutriment out of the wall. On the other hand it can be easily avoided by using supporting structure for the plants. There are several types of climbing plants: there are some which climb with the help sucker, aerial roots or tendrils. The first two types do not need any supporting structure, they easily grow on the plastered wall. But the climbing plants with tendrils need a supporting structure which can be made of steel or timber. Supporting structure means an additive cost in creating green facades, but on long term it also ensures easy maintenance. (Hall *et al.*, 2014; Csibi *et al.*, 2016)

Figure 8.: Green facades on traditional and contemporary housing (Left: Stein am Rhein (CH), Middle: Lausanne (CH), Right: Stockholm (SE), author's own photos)

Leaves of the green façade act as the outer skin of the building. In wintertime leaves are close to the wall, forming a crust which also acts as thermal insulation on the building envelope. On the other hand, in summer the position of the leaves is closer to horizontal, so they don't only protect the wall from direct radiation and warming up, but also enable the cooling of the wall by creating a ventilated air gap on the surface of the wall. Green vegetation also increases the resistance of the wall against weather conditions.

Summing up the main features of microclimate created by green façades we can find out that they have a cooling and misting effect, which contributes to the partial equilibration of the negative effects of urban heat island. And finally, the trees and green facades have a considerable effect on air movement, reducing wind speed in winter season, resulting in lower heating loads (Heisler, Harrje and Buckley, 1979).

4.1.1. A case study

In order to be able to prove the exact effects of green facades, a model simulation was done with the software *ENVI-met*. The main aim of the simulation was to prove differences in the microclimatic effects (focusing on air movement) of green facades if main wind direction is parallel or perpendicular to the plane of the green façade. The model consists of 6 blocks of flats, two bigger ones in the middle, and two-two blocks in the boundary area. The simulation model has two variants: one with, and another one without green façade in front of the middle blocks. Observations are mainly done around the middle block in order to be able to evaluate representative data.

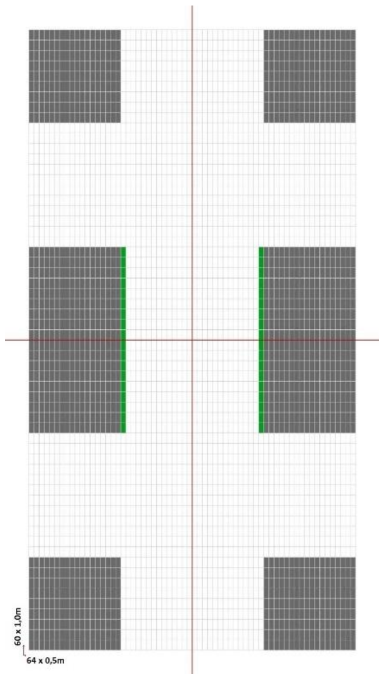


Figure 9. The plan of the studied blocks and surroundings with green façade (boundary cells are not displayed)

In order to be able to investigate the wind changes occurring with the green facades in correlation with the wind direction four simulations have been run in the following order:

- Simulation No.1.: With green façade – wind direction is parallel with the green façade (in following it will be indicated as "north" wind)
- Simulation No.2.: Without green façade – with "north" wind
- Simulation No.3.: With green façade – wind direction is perpendicular to the plane of the green façade (in following it will be indicated as "west" wind)
- Simulation No.4.: Without green façade – with "west" wind

Regarding the weather conditions of the simulations, they were defined as those on a usual, representative summer day during an anticyclonic heatwave, since the aim of the study is to prove the effectiveness of vegetative cooling during extreme hot conditions.

- Simulation time: from: 06:00 until 20:00
- Wind speed in 10 m above ground: 3 m/s
- Wind direction: "north" or "west"
- Indoor temperature: 23.85°C
- Weighted average thermal transmittance (U-Value) of façades: 1.94 W/m^2K – without plants (windows are not affected by the green façade)

The calculated variables were examined near the middle building and the centre of the model:

- Wind speed and direction

Data were examined in the following cases:

- 3 times of the day:
  - 8:00 in the morning
  - 12:00 at noon
  - 18:00 in the evening
- In 3 different heights:
  - 1.6 m – the height of an average human's head
  - 6.0 m – the height of a middle level of a building
  - 16.0 m – the height of the top level (~5th floor) of a building

4.1.2. Evaluation of the results

Wind speed and direction:

The changes due to plantation of green façade in the model are most remarkable in the development of wind speed. Due to the green façade the roughness of the building envelope will be altered, so near the green façade wind speed will be decreased. In the case of “north” wind, the pressure conditions will change too due to the wind speed deviation, so there are some alterations to be observed in the middle of the street and in the cross-streets. (See *Figure 10*.)

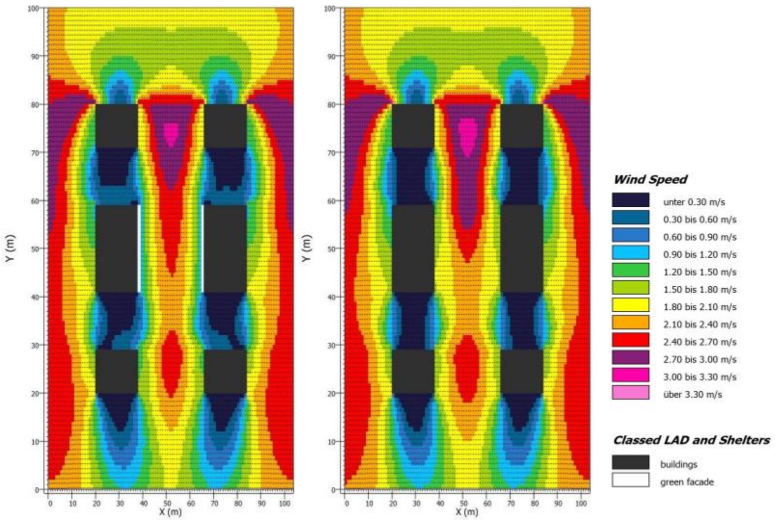


Figure 10.: Development of wind speed with (left) or without (right) green façade in summer, 12.00h, 1.6 m height

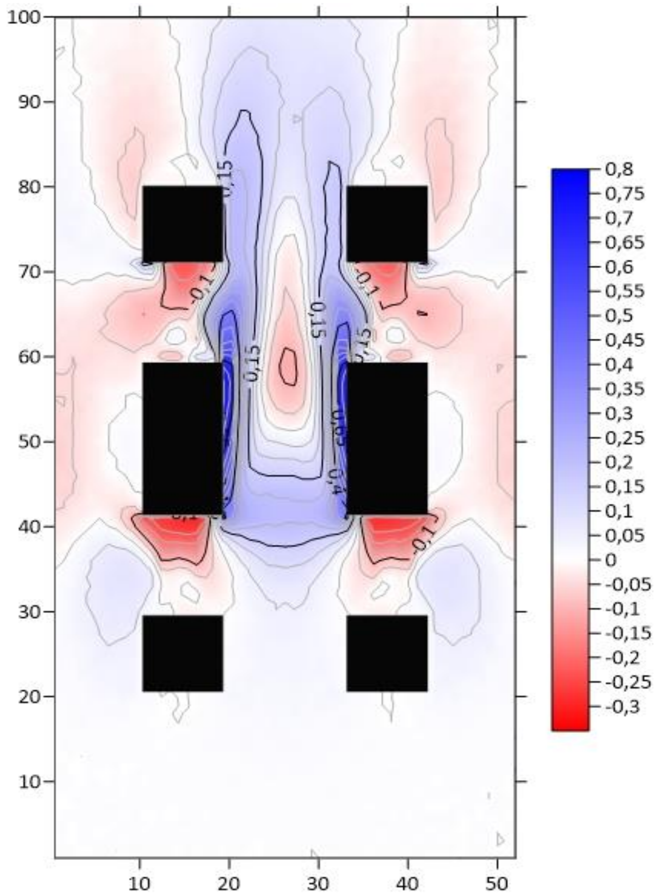


Figure 11.: Cartogram showing the difference in wind velocity (A-B, where A is without green façade, and B: with green façade).Blue colour represents a decrease due to vegetation, red colour represents an increase due to vegetation. Summer conditions, 12.00h, 1.6 m height

In case of wind direction parallel to the green façade the changes in air movement will enable stronger urban cross ventilation. In case of "west" wind, the green façade will mitigate wind speed in the cells in front of the façade and in the crossroads (parallel to "west" wind) too. The difference between the two cases makes us doubt the effectiveness of planting vegetation on facades perpendicular to prevailing wind direction as *green façade may also hinder urban cross ventilation*.

Potential Temperature: The change of potential temperature is perhaps not conspicuous, however it is not negligible. On windward part of the street there is a decrease in temperature, however, on leeward sides (in the "cross" streets) there seems to be a slight increase in Pot. Temperature (0,08°C). However, these differences are hardly sensible for a human.

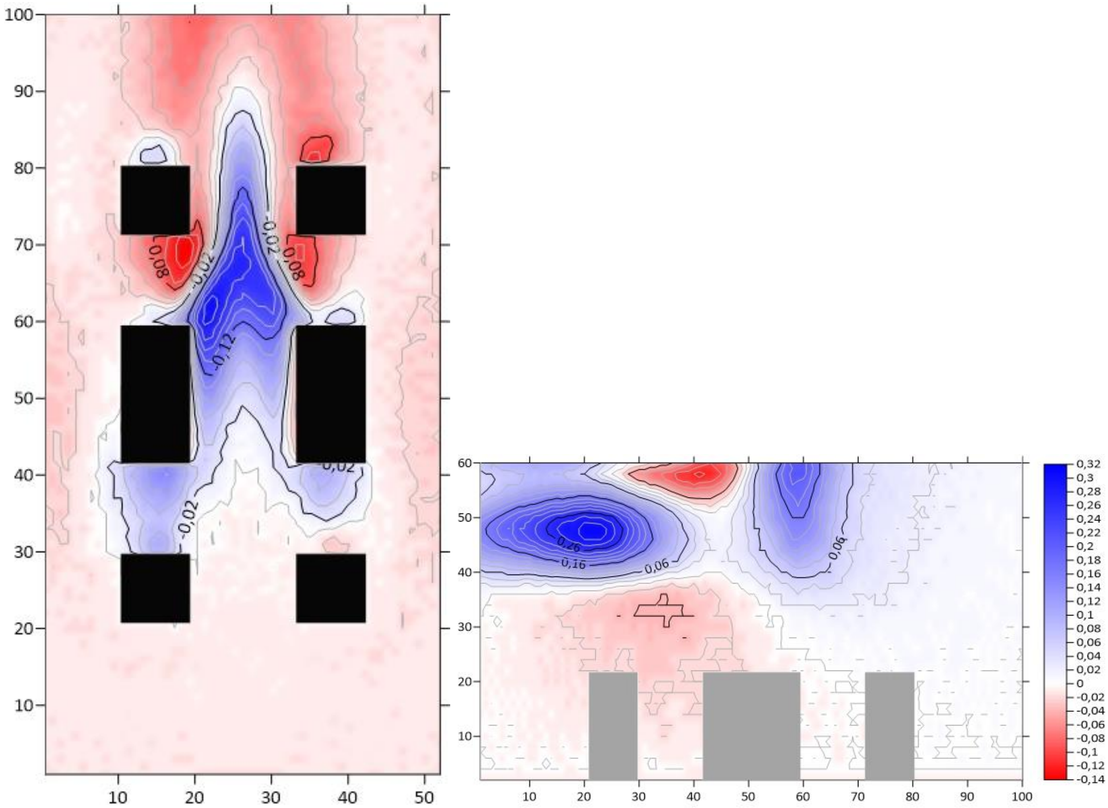


Figure 12.: Development of potential temperature: horizontal plane, 1.6 m height (left) and section along the axis of the street (right), summer, 12.00h, (The extensions of the model area are seen on the vertical and horizontal axis in meters.)

4.1.3. Findings

As a conclusion of the presented case study it can be stated that the usage of green facades has a positive effect in creating a better urban microclimate in the nearest surroundings of the building.

In fighting the growing intensity of urban heat island one of the tools is to enable urban cross ventilation. (M. Szilágyi and Jámbor, 2004) **As proved, green façades enable urban cross ventilation if parallel with prevailing wind direction. On the other hand, in case of perpendicular wind direction, only small change of the wind-profile can be observed. Thus, the planting of vegetation on facades perpendicular to prevailing wind direction is insignificant from the point of urban cross ventilation.**

4.2. Effect of vegetation on wind comfort

Air flow pattern in urban environment are radically influenced by the sophisticated topography of buildings. Although the wind velocity in general is less than that in rural areas, there are many critical points where the air movement accelerates. Such phenomenon can be observed in narrow streets, around the corners and below arcades.

As also shown in the previous chapter, vegetation can not only decrease the wind velocity but accelerate it. Trees can redirect air flow downward, whilst shrubs do upward. Around the corners of buildings high wind velocity and turbulence can develop which itself may lead to discomfort, in case of gust even the chance of accidents cannot be excluded. These phenomena may occur in any season of the year. Together with low air temperature the wind may result in thermal discomfort.

From the point of view of pedestrians, the air flow up to the 2 meters height is to be investigated. One of the questions is how the whirling air flow around the building corners can be tempered by vegetation in this band. The height of shrubs may be estimated as 1 meter while the canopy of trees hinders the air flow from about 3 meters height. Different combinations of shrubs and trees may contribute to wind discomfort as well as prevent it. In this chapter the suitable arrangement of vegetation is analysed in function of street layout and wind direction.

4.2.1. Vegetation and outdoor comfort

Vegetation in urban environment has multiple effects on environment and outdoor comfort. As far as the last is concerned mostly the summer period is analysed with regard to the shading and cooling potential due to the evapotranspiration. (Block, et al, 2012; Berry, et al, 2013; Takács, et al, 2014; Szkordilisz and Kiss, 2016b) Although the importance of these effects is unquestioned, the effect on air flow patterns should not be neglected. It can be observed throughout the year.

As an associated effect the wind influences the thermal comfort, too. Even if the air velocity is moderate, the convective heat exchange between the human body and the environment increases. In summer it has positive effect however in the winter season it results thermal discomfort.

The picture would not be complex without the thermal effect associated to the wind. For summer conditions with moderate wind velocity (and excluding the air temperatures higher than the skin temperature) the thermal effect may be expressed either as *PMV* or as *PET* values whilst in winter the wind-chill index is to be applied. (Égerházi, et al, 2013)

The wind chill index, or more popularly wind chill factor is a physiologically equivalent temperature expressing the cooling effect of wind velocity. The factor was first published in 1945 by Siple & Passel as “K” index (Siple and Passel, 1945), and a new calculating formula was suggested in 2001 (Osczevski and Bluestein, 2005). The new formula, using SI units is as follows:

$$T_{WC} = 13{,}12 + 0{,}6215 \times T_{air} - 11{,}37 \times V^{0{,}16} + 0{,}3965 \times T_{air} \times V^{0{,}16}$$

where

T_{WC} is Wind Chill Index

T_{air} is air Temperature in degrees Celsius

V is wind velocity at 10 m height.

T_{WC} is based on the phenomenon, that the convective heat loss of a certain surface depends on the temperature difference of itself and that of the fluid surrounding it; and the velocity of the fluid. The air movement near the surface will disrupt the insulating boundary layer next to the surface, thus replacing the warmer air of the boundary layer with cooler air. Thinking of a human face exposed to wind the physiological effect of wind is apparent. Thus, the Wind Chill Index is adapted to the daily weather forecasts especially in northern countries. (Canada among the first ones). Nowadays the usage of T_{WC} became common as many of the weather-forecasting applications of a smart phone also use T_{WC}.

4.2.2. Characterisation of wind comfort

In contrast with the thermal comfort the criteria of wind comfort are not widely accepted. (Janssen, Blocken and van Hooff, 2013) It may be due to the complexity of the effects and the associated phenomena, however, a brief overview of related publications (Penwarden, 1973; Gandemer, 1975; Poulton *et al.*, 1975) shows that in general 5 m/s is considered as the threshold of comfort whilst 15 m/s is that of the safety. The velocity is interpreted as “steady state” without gusts and without the effect of turbulence intensity. It is to be mentioned that these thresholds relate only to the mechanical effect of air movement, without the associated thermal effect.

The wind velocity itself characterizes a current situation. The most ambitious approach aims at a statistical evaluation based on the frequency of velocities beyond the threshold all over the year (Willemsen and Wisse, 2007) **Assessment of an urban area from the point of view of wind comfort is not easy since wind and sun are easily variable factors of the environment. Pro forma likelihood of regional wind with different directions and velocities should be transformed to the selected urban area, for which the frequency of threshold values should be calculated.** Depending on the frequency different categories have been proposed and entitled with subjective names. No doubt this method may be informative however the requested input database and the calculation method is enormous.

4.2.3. The effects of wind

A steady state wind creates a pressure on the human body which can be calculated relatively simply taking into consideration the exposed surface and the aerodynamic coefficient of the body. The balance can be kept by leaning at a given angle towards the wind. Maybe this posture is less comfortable however stability is not menaced providing the air velocity is constant. The same pressure is aggravating whilst walking against the wind: more effort is required to move forward.

Wind is accompanied by turbulence, which is perceived by pedestrians as irregular, sudden change of wind direction, velocity, gusts or eddies. “Direction” is to be understood in 3D, thus vertical air flow components shall be considered as well. The turbulence is more intensive in built environment than in most of the rural areas.

The turbulence intensity is the root mean square of the instantaneous deviations from the mean velocity divided by the mean velocity. Due to the unexpected changes the effect of turbulence exceeds that of the steady state wind. To compare turbulence effects to other wind effects, an equivalent steady wind is defined: (Arens, 1981)

$u_s = u(1 + 3 \times I)$

where,

u_s ~ Equivalent steady-wind velocity

u ~ mean velocity

I ~ turbulence intensity (from Reynolds averaged)

Pure mechanical effects of wind are disturbance of clothing and hair, resistance to walking, and buffeting of the body and carried objects like umbrellas. Accompanied effects are the **blowing grit and dust, lifting loose papers – these unpleasant phenomena start at about 5 m/s wind velocity.**

Mean velocity 15 m/s is considered as threshold of danger where people may lose their balance. It is to be emphasized that mean velocity is spoken of, which is accompanied by gusts.

Driving rain as a particle transport process is one of the most unpleasant effects. The suspension of a solid or liquid particle requires an upward air velocity equal to the terminal velocity of the particle. A horizontal wind equalling to or exceeding the terminal velocity will cause a particle to descend at an angle of 45° or less to the horizontal. For fine drizzle already 1 m/s can lead to this situation, even for large drops 7 m/s is enough. Driving rain and particles may cause irritation in the eyes and on the skin. It should not be forgotten that besides the clothed surfaces of the body some nude parts are exposed to these effects (face).

Overall thermal comfort is also influenced by the wind. As below *Figure 13.* shows it, wind velocity (on the vertical axis) modifies air temperature (on horizontal axis).

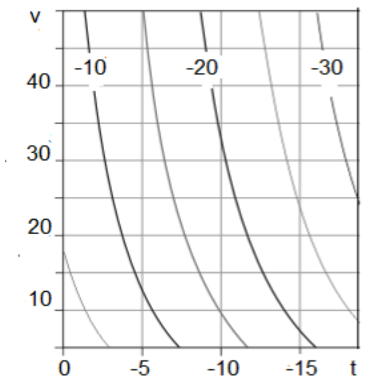


Figure 13.: Wind chill index. On the horizontal axis the outdoor air temperature ^{O}C, on the vertical the wind velocity in km/h. The parameters are the equivalent wind-chill temperatures.

4.2.4. Case study

The topography of the built environment changes the air flow in several ways: both acceleration and deceleration in comparison of regional wind in rural area are possible. Several studies present the effect of a single building, the canyon, a tall building in a low-rise environment, narrow streets, archways. The vegetation influences the roughness of the terrain, represents obstructions and deflects the air flow. Obviously, vegetation itself cannot be the subject of analysis. Except larger urban parks and public gardens, vegetation and buildings are to be considered together in typical urban environment.

Such a typical environment is a street with side streets with alleys, shrubs, green facades. In the following three analysed models will be introduced. The first model (*Base*) is a model with considerably high buildings and wide streets but no vegetation. The second two models (*Case 2* and *3*) (with the building geometry unchanged) include vegetation – trees and shrubs – in symmetric and asymmetric composition. When designing the geometry and allocation of trees and shrubs, the possible shading potential of trees, and possible impact on indoor thermal comfort was also taken into consideration, while not forgetting the necessary width of pedestrian routes and that of the street.

The *"Base"* model – where no vegetation is used – consists of four 30 m high 24x24 m big blocks and the 22 m wide streets represent a typical urban pattern where overflow problems in urban microclimate may occur. The second scenario is *"Case 2"* – contains shrubs and trees in an asymmetric disposition. Shrubs are 1 m wide and 1 m high (light green spots in the layout) and trees (dark green spots in the layout) have a canopy diameter of approximately 4 metres. The third scenario – "*Case 3"* – is a symmetric disposition of different kinds of vegetation. Trees are placed every 7 metres of distance, and shrubs both in front of the façade and at the edge of the pedestrian way. This enables to create a multifunctional and wide pedestrian way. For better understanding of the three modelling scenarios are shown in Figure 14.

From the point of view of pedestrians, the air flow up to the 2-meter height is to be investigated. The question is how the whirling air flow can be tempered by vegetation in this band. The height of shrubs may be estimated as 1 meter while the canopy of trees hinders the air flow from about 3-meter height. Different combinations of shrubs and trees may contribute to wind discomfort as well as prevent it. The suitable arrangement of vegetation is analysed in function of street layout and wind direction.

On the other hand, the layout of the models were also planned taking to avoid negative effects, that is, researches have shown, that trees planted in front of the façade could also increase the concentration of pollutants on the pedestrian way.

The models seen on *Figure 14.* have been investigated using the *ENVI-met* software. Although its capacity is restricted in comparison with *FLUENT* and other CFD programs it facilitates a relatively fast calculation of velocity and some comfort parameters. During *ENVI-met* simulation grid sizes are 1 m. However, telescoping vertical grid size (z) was used, which enables a 0.8 m grid height above the surface in order to have more detailed vertical resolution of the models. Wind speed in 10 m above ground is 6 [m/s], wind direction is 270° (~"west" wind).

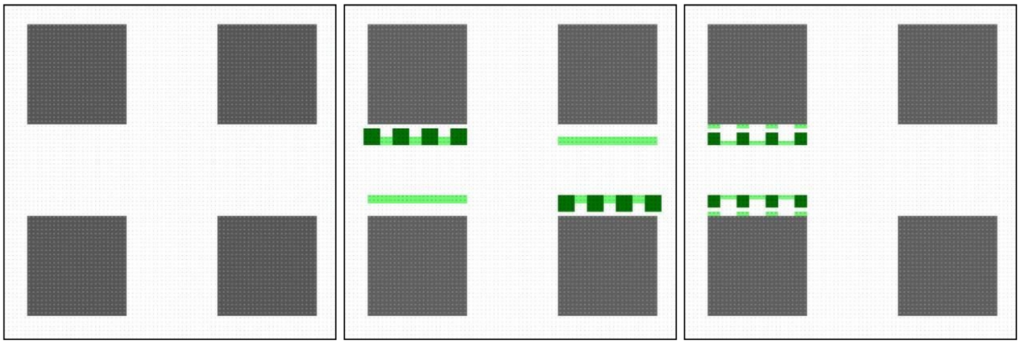


Figure 14.: Models, horizontal layout:

Base, Case 2, Case 3.

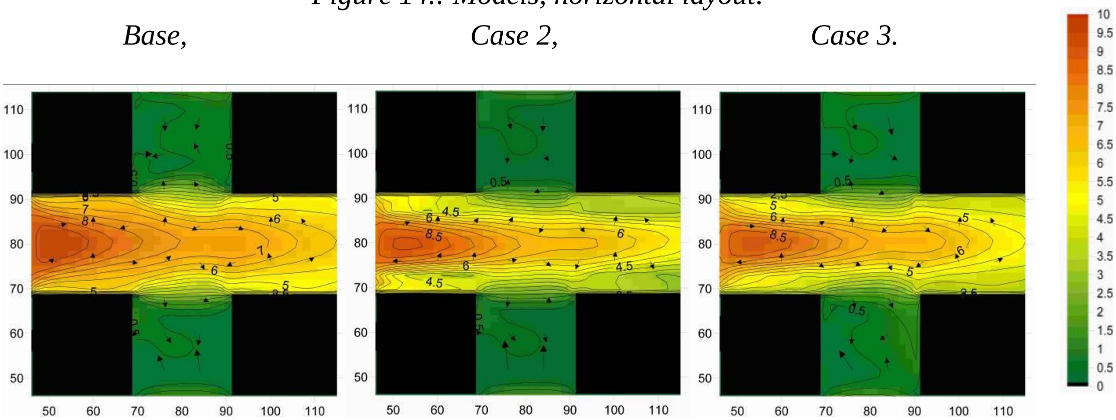


Figure 15.: Results of simulation, horizontal layout. Wind speed at 12.00, 0.8m height Base, Case 2, Case 3 respectively (The extensions of the model area are seen on the vertical and horizontal axis in meters.)

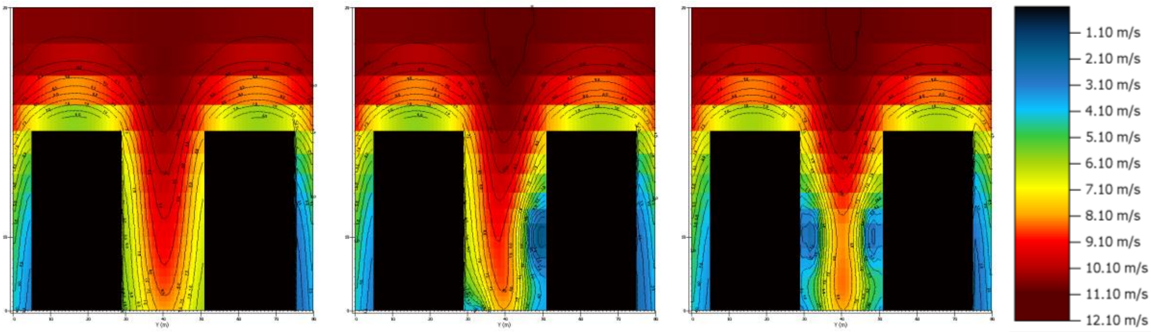


Figure 16.: Velocity distribution in YZ Vertical section, cut at X=60. Wind direction 315°, at 12.00, 0.8m height

Base, Case 2, Case 3.

4.2.5. Results

The hydraulic resistance of the boundary surfaces results in decreasing velocity along the street as well as in cross section near to the boundary surfaces. If no other comment is given, the data relate to the height of the pedestrian zone (0.8 m above the pavement). (Normally, human comfort studies use 1.2 m height for simulations and measurements, however 0.8 is more relevant in this case as the centre of gravity is lower.)

The reduction of the velocity along the street axis is the consequence of the hydraulic resistance of the boundary surfaces. Obviously in the empty street this resistance is lower, in the street axis the velocity reduction by 30% occurs at 55 m along the stream whilst in *Case 2 and 3* it takes only 25 m. Along the facades of the first (in stream direction) building in the pedestrian zone velocity as high as 4.5 m/s can be observed which remains even along the façade of the second building. In vegetated street the windward edges of the vegetation line radically decrease the velocity forcing the stream toward the centre line of the street. Along the facades in the pedestrian zone the velocity does not exceed 4 m, along the second buildings (in stream direction) is as low as 2 m/s. Certainly the asymmetry of the vegetation can be recognized in the velocity profile.

Due to the radical change of the undisturbed (by vegetation) cross section of the street the air movement is calmer in *Case 2 and 3* then at the corner of empty streets. Besides of the velocity itself the accompanying turbulence will be less, too. The arrows illustrate the whirling turbulent air movement at the building corners. It is worth of attention that in *Case 2* the windward edge of the continuous lines of trees and shrubs blocks the stream at the windward corner of the second building.

The reduction of the velocity in *Base* scenario along the street axis is 2.5 m/s or 28% on 50 m length. Near to the facades (2 m from the facade) the velocity is 6-7 m/s, 65-75 % of the maximum in the middle of the street. At the corner of the first building a bubble can be observed where the velocity decreases to 0.5-1 m/s, 5-10 % of the maximal 9 m/s observed in the middle of the street. The vector presentation shows whirling air flow here as well as at the opposite corner.

On *Figure 16.*, in the cross section of the street, it can clearly be seen that the trees push upward the air stream. High velocity can be observed in the empty street even at the mid height of the buildings, due to the vegetation the field of high velocities is in the height of upper floor. Indentations of the contour lines shows the effect of trees in both symmetric and asymmetric arrangements.

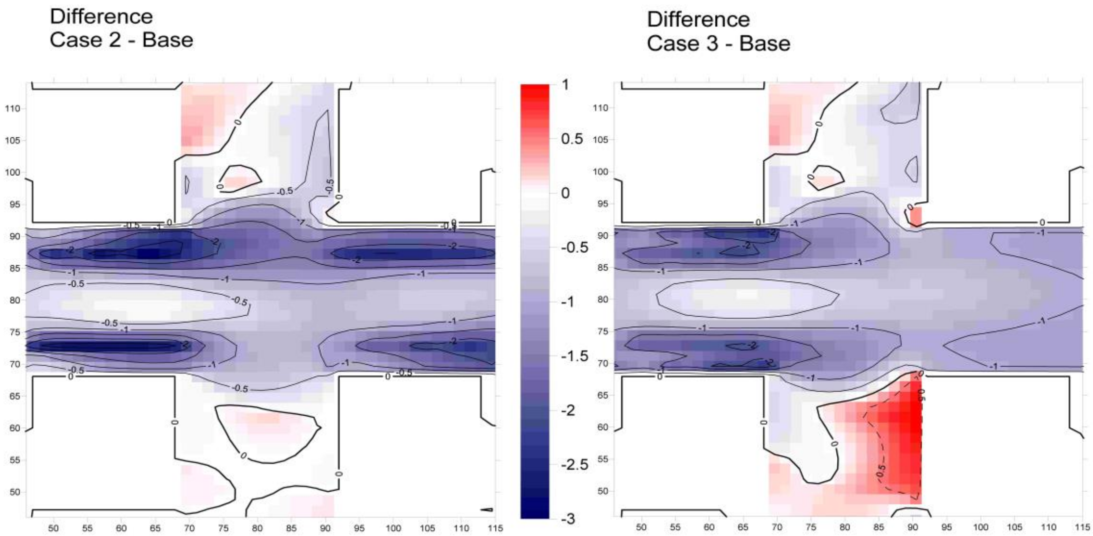


Figure 17. Results of simulation, horizontal layout. Differences in wind speed between base model and models with vegetation at 12.00, 0.8m height
W1= B [Case 2]-A[Base], *W2= C [Case 3]-A[Base].*

Figure 17. shows the differences between *Case 2* and the *Base* scenario and *Case 3* and the *Base* scenario. Reduction due to vegetation is shown in blue colour and with continuous isolines, the increase is shown in red colour and with dashed isolines. The difference maps represent well the impact of the trees and shrubs, and also the importance of symmetric or asymmetric disposition comes clear. The more trees are planted in the street the more diverse the impact on wind speed modification can be. In *Case 3* 4-4 medium sized trees were designed on each side of the street and not only the reduction of velocity, but also the growth of wind speed in the crossroads is more distinct.

The increased hydraulic resistance and the narrowing of the cross section result in higher average in velocity in the axis of the street. This means not the growth of the maximal wind speed but a bigger area where the 70-80% of the maximal velocity is typical. Along the street the reduction of the velocity is more radical in comparison with the empty variant. Nevertheless, in the pedestrian zone the velocity is lower. This is shown clearly on the cross section of *Figure 18.* The velocity in the vertical section shows that the trees push the stream upward.

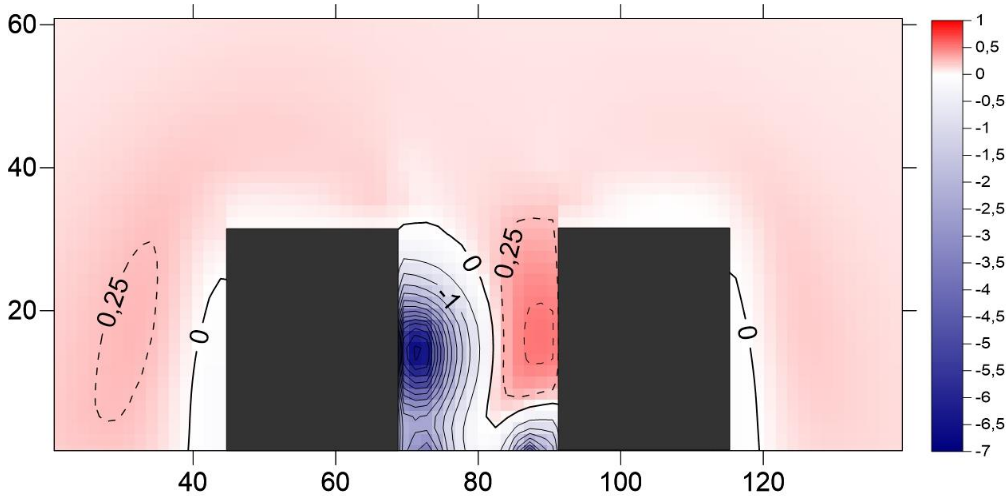


Figure 18. Results of simulation, YZ Vertical section, cut at X=60. Differences in wind speed between base model and model with vegetation at 12.00. V= B [Case 2]-A[Base].

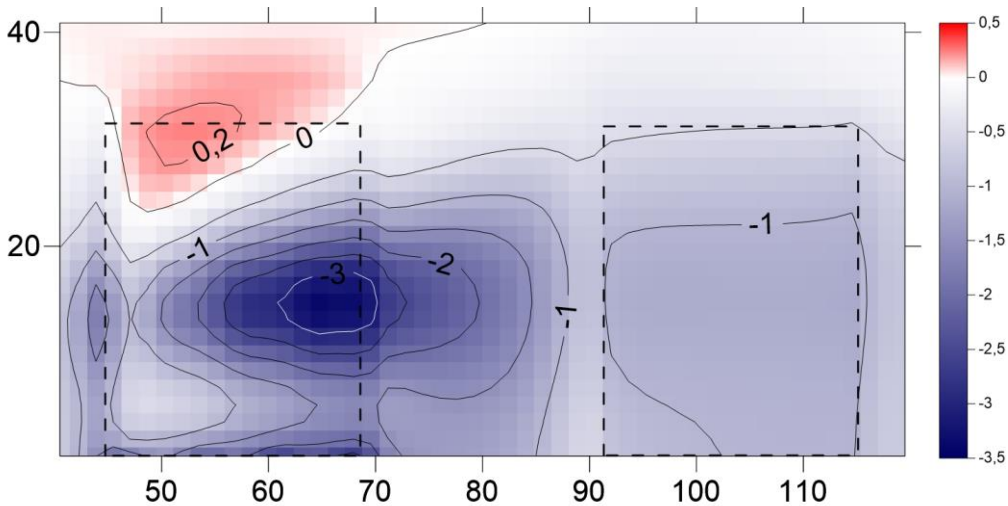


Figure 19. Results of simulation, XZ Vertical section, cut at Y=90. Differences in wind speed between base model and model with vegetation at 12.00. U= B [Case 3]-A[Base].

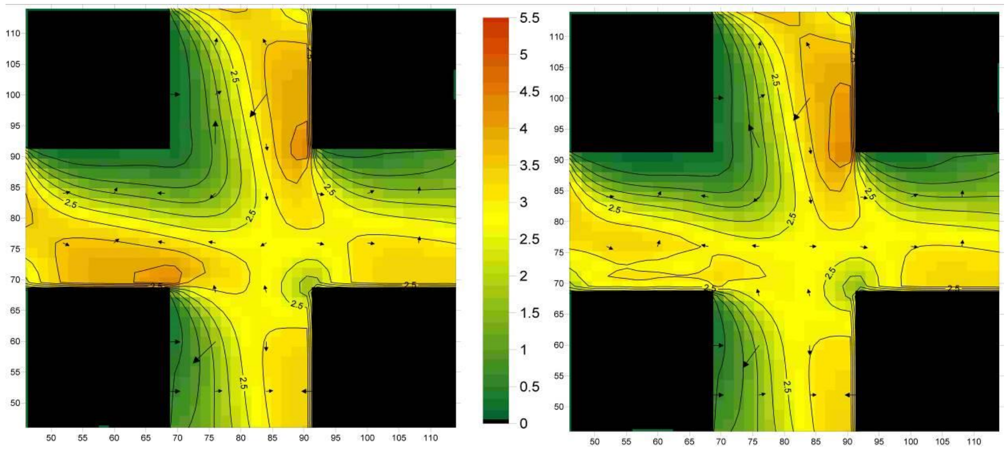


Figure 20. Velocity distribution in horizontal plane.
Wind direction 315°, initial wind speed: 3.5 m/s, at 8.00, 0.8m height
Base, Case 3.

The effect on corners is seen clearly if the wind direction is not parallel with the street axis *(Figure 20.)*. Comparing the "empty" street with that fringed with trees, the differences are considerable first of all at the marked parts of the windward side facades. (The velocity distribution is shown in horizontal plane, 0.8 m above the pavement). Without trees the velocity increases up to the double of the initial one whilst under the trees the acceleration is only about 10%. Obviously similar ratio can be observed in the axis of the street.

The differences on the leeward side are not radical.

The wind and the thermal discomfort. Together with the mechanical effects the thermal discomfort in winter is another negative consequence of air movement. Coincidence of -5 ^{O}C and 3 m/s which are far from being extreme values results in a wind-chill temperature -10. The same temperature and 14 m/s wind velocity have the same effect as -15 ^{O}C in calm air. (See *Figure 20.*

The following Table 2. *Summarizing the results of the three investigated models* of all simulations introduced.

Table 2. Summarizing the results of the three investigated models

	Base **model**	***Case 2*** **model**	***Case 3*** **model**
street axis	2.5 m/s reduction on 50 m length Relatively high wind speed along the street.	The reduction of maximum values by 0.5-1 m/s	The reduction of maximum values by 0.5-1 m/s
crossroad	There is still air (no ventilation) in the crossroad.	Velocity increases on the windward sides of the cross street by 0.25 m/s	Velocity increases on the windswept sides of the cross street by 0.25-1 m/s
pedestrian way	The 65-75% of the maximal wind speed is typical	Velocity decreases by 2-2.5 m/s. However, an increase (comparing with Base model) of 0.4 m/s occurs on the side of the street were no trees are planted.	Velocity decreases by 2 m/s. Seems to be the most comfortable solution from the pedestrian's points of view.
corners	sudden change of wind speed due to the change of cross section drag can be observed accompanying with turbulence	Velocity is decreased by 1-2 m/s.	Velocity is decreased by 1-2 m/s. But on the opposite corner where there is no vegetation velocity is increased by 0.25-0.75 m/s

4.2.6. Findings

The effects of vegetation on both outdoor comfort and energy balance of buildings are analysed in several publications. In general cooling effects in summer conditions are investigated encompassing the shadow and evapotranspiration.

Mechanical effects of air movement occur in any season of the year. The associated effect on thermal comfort is less hazardous or unpleasant in summer providing the extreme air temperature exceeding the skin temperature is excluded. In winter the associated effect on thermal comfort is negative.

Case studies have been analysed facilitating to compare "empty" streets and those of the same size with combinations of trees and shrubs.

As it could be expected, the vegetation in general decreases the wind velocity. This is more considerable in the pedestrian zone than along the centre line of the street. Appropriate position of trees and shrubs at the windward end of an alley radically blocks the stream along the sidewalk.

Preliminary simulations have shown that **the plantation of a simple alley (only on one side of the street) causes on the side of the alley a diminution of ~6-6.5 m/s in wind speed but on the other side of the street velocity will be increased by 0.5-1 m/s, when maximum wind velocity equals to 8.5-9 m/s at 0.8 m height. This asymmetry can be managed with the planting of shrubs in order to create an optimal wind comfort on the sidewalks.**

Longitudinal cross section illustrates that the plants push upwards the air, the diminution of the velocity is effective in the height of pedestrians.

Vegetation can improve the outdoor comfort not only in summer but all over the year.

4.3. Effect of vegetation on solar gain

Shading effect of plants is an important factor in creating a good or tolerable microclimate outdoors and indoors too. This chapter deals with the efficiency of shading by trees standing near the building shell and the impact is regarded from the point of view of the building shell and building itself.

The shading effect depends on multiple factors: the orientation of the wall, the position of the tree compared to the shaded wall, the height of the tree and last but not least the foliage and thus, species of the trees.

4.3.1. Shading possibilities in front of the building envelope

Shading using structural elements or vegetation was a usual solution used in historical countries especially in Mediterranean countries.

Modernist architecture seems to have forgotten the benefits of shading in the name of pursuing pure and distilled forms of architecture. However, nowadays architects seem to rediscover the use of shading in climate adaptive and energy-conscious urban planning. This chapter focuses on the importance and relevance of shading with vegetation planted near or in front of the façade.

As the benefits of green façade were described earlier (Chapter 4.1.) this chapter will focus on the difference in the shading effect of trees. As the transparent structures (e.g. window) are most relevant from the internal comfort point of view, the study concentrates on the possibilities of shading transparent structures. Climbing plants do not cast shade on the window, and it is only ensuring an insulating envelope both in summer (diminishing solar gain) and in winter (tempering the cooling effect of the wind). On the other hand, trees planted ~1-6 metres in front of a façade cast a considerable shade on windows as well, and thus, the shade changes with the altitude of the sun. Of course, the shading effect of the tree depends on several factors, such as: the albedo of the wall, transmittance of glazing, the incidence angle of the sun, and the characteristics of tree canopy: form of the foliage, and transmissivity.

4.3.2. Effect of vegetation on building energy budget

According to the EPBD (EPBD, 2010) whilst improving the thermal performance of buildings, good or at least tolerable thermal comfort conditions must be provided. But better thermal insulation and more airtight buildings increase the risk of summer overheating which apparently makes mechanical cooling inevitable. This idea has been verified by the tendency of the last decade, when people were willing to install and use more frequently air conditioning devices during the summer heatwaves – increasing their energy consumption and electricity bills at the same time, not to mention the heat island intensifying effect creating a vicious circle. We cannot neglect the importance of studies triggering an efficient way to minimise the cooling load of residential buildings by obstructing solar radiation.

The usage of plants in front of facades, and especially in front of transparent surfaces of the façade can make indoor overheating avoidable. Deciduous plants obstruct buildings' solar access, so that the microclimate around the building is improved too. The use of Green Infrastructure in different levels of planning processes, which would provide sustainable solutions for urban management, is also prescribed in the EU Biodiversity Strategy 2020. (European Commission, 2011)

Of course, in order to investigate the actual effect of trees on indoor thermal comfort, a list of other factors – such as orientation, the type and thermal properties of the windows/transparent structures used, the thermal transmittance values and heat storage capacity of the building – should be taken into consideration. With those factors in mind, the effectiveness of vegetation for each case can be proved with simulations.

Creating good indoor comfort depends on the effectiveness of shading, mitigating the solar access of walls and transparent surfaces at a great extent. Thus, it is an essential issue - regarding the scale of building and plants nearby - to quantify the amount and ratio of the obstructed solar access by the vegetation. As a first step, transmissivity measurements were carried out during the summer of 2014 in Szeged.

4.3.3. Measuring vertical transmissivity

In order to quantify the shading effect of trees – independently from building characteristics – the properties of the tree canopy must be examined. A simple parameter of the shading effect – depending on the attributes of tree foliage – is transmissivity. Transmissivity is defined as the ratio of the amount of incoming solar irradiance measured in an unshaded point to that of measured at a point shaded by the canopy. The unshaded point should be totally exposed to the sun (ideally on a cloudless summer day under anticyclonal atmospheric conditions); the shaded point should be in the middle point of the shade cast by the tree measured. Bioclimatic investigations usually focus on the horizontal transmissivity – that is shade is considered on a horizontal plane (irradiance is measured on a horizontal plane) (Berry, Livesley and Aye, 2013; Konarska *et al.*, 2014). However, from the current studies' point of view the shade cast on the façade is relevant, therefore the novelty of the investigation is that transmissivity is interpreted in vertical plane. This is relevant, as when examining transmissivity, which is strongly connected with the structure of foliage and thus, leaf area index (LAI) (McPherson *et al.*, 2018) different values occur for vertical and horizontal planes.

Our analyses aimed at the quantification of vertical transmissivity – thus filling a gap in the existing literature of tree shading efficiency – of typical individuals of three frequently used urban species. The three species analysed were:

- Celtis occidentalis *(common hackberry* [1]*),*
- Sophora japonica *(Japanese pagoda* [2]*),*
- Tilia cordata *(small-leaved lime or linden* [3]*).*

All selected trees were in good condition and were typical for their species. In

Table 3. Measures of the *trees* some data are to be seen about the trees investigated.

Table 3. Measures of the trees

	Total height of tree [m]	Height of tree trunk [m]	Radius of canopy [m]	Coordinates	Orientation of wall behind
Celtis occidentalis	15.5	2.4	6.55	46.2601; 20.1405	130°
Tilia cordata	9.6	2.3	3.65	46.2577; 20.1448	130°
Sophora japonica	8.1	2.4	2.85	46.2607; 20.1604°	100°

[1] nyugati ostorfa

[2] japánakác

[3] kislevelű hárs

In *Figure 21* the situation of the three measured trees can be seen. The trees were selected so that the orientation of the façades behind is similar (nearly southwest, with the aim of the longest irradiation that is achievable) and there are no objects to shade the tree during the day (the trees are situated in wide avenues). The distance of the trees and the buildings behind them is identical in the case of *Celtis occidentalis* and *Tilia cordata* - measuring 4.5 metres; in the case of *Sophora japonica* the distance between the wall and the tree is 5.2 m.

Figure 21. Pictures of the trees investigated respectively:
a) Celtis occidentalis, *b) Tilia cordata,* *c) Sophora japonica*

The trees analysed were all situated near the centre of Szeged, usually beside busy roads. *Figure 22.* Map of Szeged with the position of the trees shows the positions of the trees in the city centre of Szeged. The methodology of measurements were described earlier in the chapter *3.1. On-site measurements.*

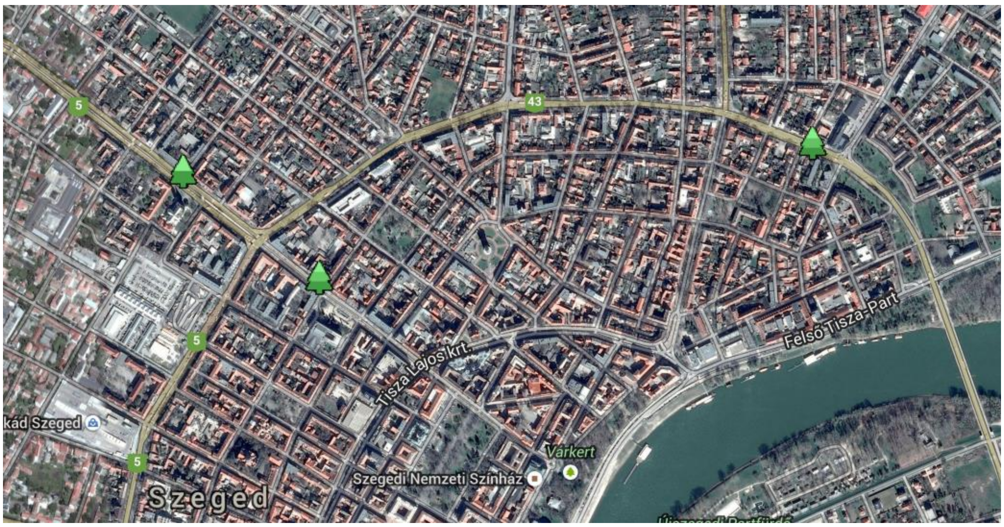


Figure 22. Map of Szeged with the position of the trees

4.3.4. Findings

For calculating the vertical transmissivity, the vertical irradiance values of the pyranometers were used. The diurnal course of radiation of the two pyranometers (for the specification of the pyranometers see chapter 3.1.) are represented in *Figure 23.*

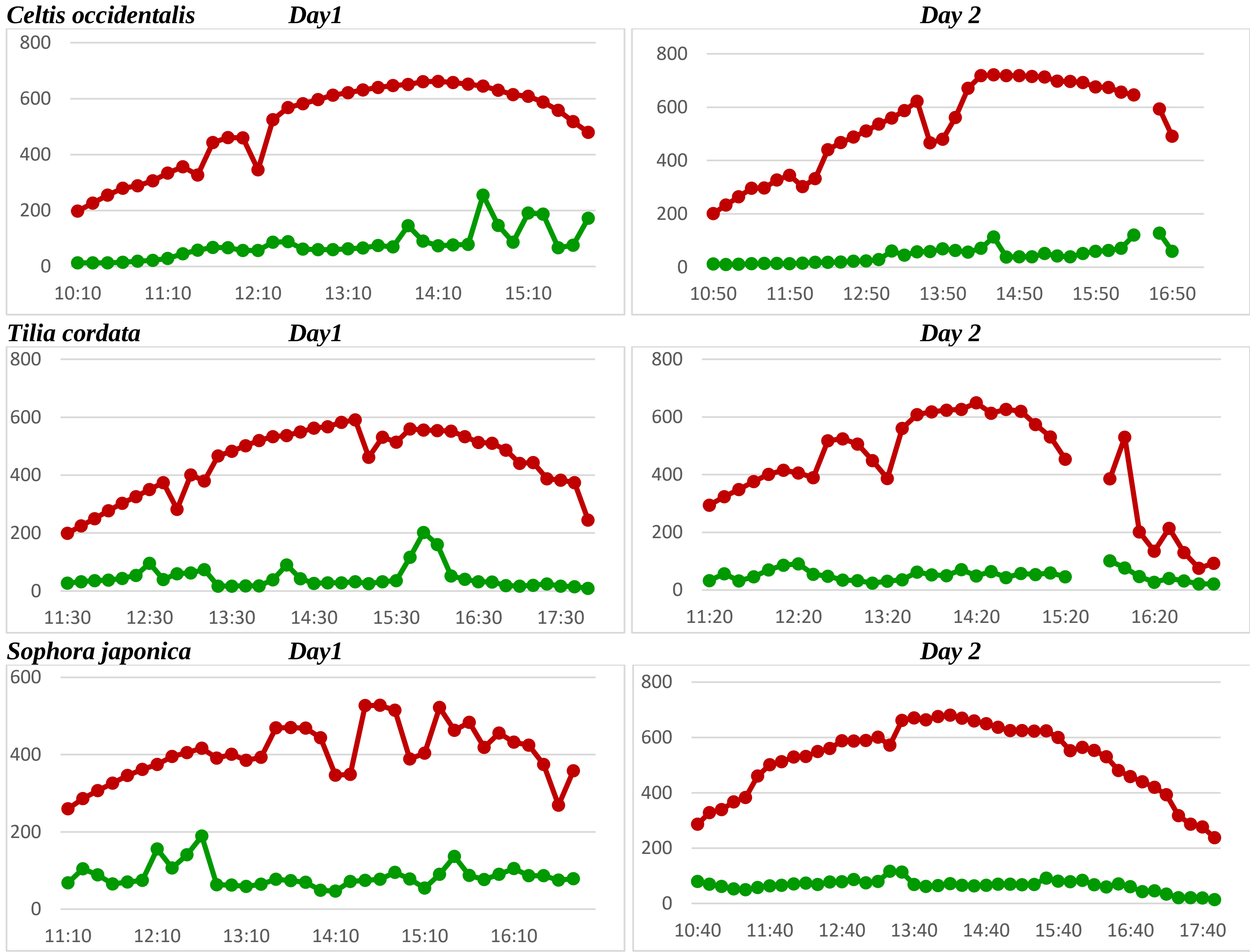


Figure 23. Course of global solar radiation (points representing the 10-minute averages) at non-shaded (reference: red line) and at shaded (below canopy: green line) point of the investigated trees. Day 1 (on the left) and Day 2 (on the right) for each tree

As presented in *Figure 23*. the data of the pyranometer gives a bell-shaped line as total irradiance values change during the day. The sudden drops in values represent short clouded periods. (Naturally, more measurements were carried out, finally, only the values of 6 days could be used for analysis, due to unexpected cloud coverage.)

The grey, horizontal-like line represents the values of the pyranometer that was always kept in the shade of the tree measured. (Of course, with keeping the pyranometer preferably always in the full shade of the tree and at the same time aiming for the less possible movement of the instrument.) The anomalies in the data of the transmitted radiation are the results of mainly two factors: (1) some variations of the species-specific structure, or (2) the movement of the foliage due to some windy periods during the day.

However, the differences between the different trees regarding the ratio of transmitted and non-obstructed total irradiance proves the hypothesis, namely that the vertical transmissivity is dependent on species – noting, of course, that some anomalies might be due to different tree conditions (between species) and dimensions (apart from the obvious differences according to species).

Transmissivity is calculated with the following formula:

$\tau = \frac{G_{sh}\left[\frac{W}{m^2}\right]}{G_u\left[\frac{W}{m^2}\right]}$, $\tau = \frac{\mathrm{G_{sh}}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]}{\mathrm{G_u}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]}$

$\tau = \frac{\mathrm{G_{sh}}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]}{\mathrm{G_u}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]}$where,

G_{sh} stands for global irradiance on vertical plane, transmitted by the tree

G_u stands for global irradiance on vertical plane, unobstructed.

Obviously, the higher the value of transmissivity, the higher is the amount of transmitted irradiance, thus the shading performance is the worst.

Transmissivity data, and the standard deviation of irradiance data of those are presented in the following Table 4.
Mean (τ) and standard deviation (σ) of the transmissivity of the studied trees– apart of the obvious reasons that determine the transmissivity of a tree (species), the results are also affected by the density of the canopy, leaf area index, and tree heath conditions.

Table 4.

Mean (τ) and standard deviation (σ) of the transmissivity of the studied trees

Species	τ (%)	σ (%)
Celtis occidentalis	**11.3**	7.5
Sophora japonica	**16.6**	7.6
Tilia cordata	**12.0**	7.6

The biggest tree of all was the common hackberry (*Celtis occidentalis*), with thick branches and a rich canopy. On the other hand, the smallest of all was the Japanese pagoda tree (*Sophora japonica*) with a loose foliage. Naturally, the latter proved to be less the least effective in shading performance, with the highest (worst) transmissivity values and highest transmitted irradiance. The third tree, the small-leaved lime (Tilia cordata), although smaller than the common hackberry showed similar values to that.

4.4. Effect of vegetation on indoor thermal comfort

After examining the shading efficiency of trees, this chapter focuses on the effect it has on indoor comfort. The focal point is a case study carried out in *ECOTECT*.

The energy-efficient building became a major issue in the past decades which is also manifested in policies. European architecture is under the pressure to meet the requirements of EPBD recast (Energy Performance of Buildings Directive, 2010, which aims at decreasing new buildings' energy-demand toward zero (nZEB: Nearly Zero Energy Building). However, the risk of summer overheating indoors rises with the effort of insulating buildings. At the same time, we also have to face the fact that directives mainly focus on new buildings, and in case of the reconstruction and rehabilitation on existing building stock moderate success can be achieved with the requisition of not lesser financial resources. Therefore, this work also focuses on the possibilities that can be achieved by using vegetation near the buildings in terms of energy efficiency. In this chapter we focus on the structure of buildings built before 1950 typical for Hungarian building stock and characteristic for the city centres of Hungarian cities. This chapter studies the possibilities besides structural reconstructions, this means achieving better indoor thermal comfort by using the methods of climate-conscious urban design in order to create a better microclimate near the building. We assume that using vegetation for shading purposes outside the building can make mechanical cooling dispensable without the risk of overheating – decreasing thus the energy demand in the summer period. Several studies have shown the importance of using vegetation for shading and obstructing solar irradiance, under specific circumstances vegetation planted near the building can decrease the use of air-conditioning devices and thus electricity-demand. (Akbari and Taha, 1992; Simpson and McPherson, 1996). The evapotranspiration of the vegetation detracts heat from the air, which decreases the nearby air temperature.

To examine the previous possibilities, simulations were carried out on the base of transmissivity measurements demonstrated in the previous chapter. Getting the transmissivity results of the previous chapter and also other studies {Szkordilisz and Kiss, 2016a} it can be concluded, that a well planted tree can decrease the solar gain on external vertical surface (that is, the façade) by 83-89%, depending on species.

The difference of obstructed irradiance to the amount of total irradiance is calculated as follows:

$G_o = G_u - G_{sh}$

where,

G_o stands for obstructed (reflected and absorbed) global irradiance on vertical plane

G_{sh} stands for global irradiance on vertical plane, transmitted by the tree

G_u stands for global irradiance on vertical plane, unshaded.

As the tree obstructs the solar access to the wall, transparent surfaces (windows in open or closed positions) and "empty" openings, that will have a positive effect on the air temperature of the room and thus the thermal comfort of the persons inhabiting the room. On the basis of the above logic further simulations were carried out to examine the incoming radiation indoors – taking into consideration glazing, and wall types as well.

Further modelling was carried out in *ECOTECT*. On the base of the created model several analyses were carried out in order to investigate the trees' effect on indoor and outdoor climate. The chapter focuses on the results of solar analysis, which was carried out for both horizontal and vertical surface (façade). The analysis of solar access to the façade aims primarily to examine how trees - depending on species - mitigate the heating up of building structures.

4.4.1. Case study

The main aim of the modelling was to provide more detailed results about the shading effect of the trees and their impact on different type of buildings' solar gain. Therefore, the effect of tree shading was studied in different building scenarios: using heavy-weight, light-weight structures, and historic box-type windows in closed an opened position.

	heavy-weight	leight-weight
insulated	Concrete wall with 18 cm thermal insulation. U-value: [0.17 W/m^{2}K]	Wooden wall with 16 cm thermal insulation. U-value: [0.18 W/m^{2}K]
not insulated	Brick wall, plastereed, U-value: [1.01 W/m^{2}K]	

Table 5. Wall structures and their physical characteristics used for modelling in ECOTECT.

In order to have more general results, it was decided to carry out simulations on an ideal model. The model consists of a cubic room 12 metres long, 6 metres deep and 4 metres high. A perspective view is seen in *Figure 24*. In the model three types of wall structures were used. Two heavy-weight and one light-weight structure as shown in *Table 5*. Insulated wall-structures are capable to fulfil in the requirements of nZEB, at the same time the uninsulated brick wall represents best the current state of a historic buildings in Hungary. (Szkordilisz, Heeren and Habert, 2014)

The window: a historic box-type window, which was used in the model, is a very typical structure for the Hungarian building stock and was commonly used mainly between 1855–1960.

Trees are approximated as nearly spherical polygons, and the transparency of the canopy material is taken from pyranometer measurements.

Modelling was carried out in summer period under free-running circumstances. Metrological data were taken from the meteorological station of Szeged (run by the Hungarian Meteorological Service) and imported to *ECOTECT*. For this reason, it must be considered that input air temperature and solar irradiance data are measured in rural environment.

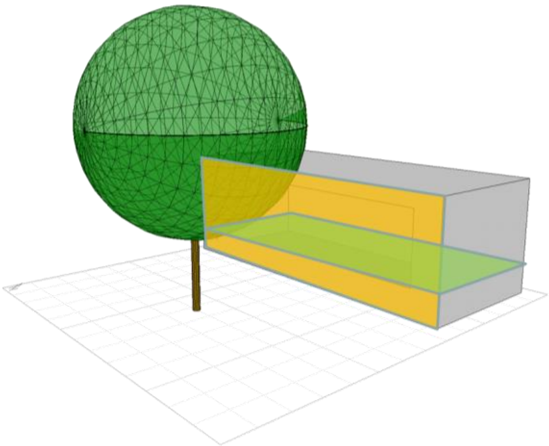


Figure 24. Perspective view of model made in ECOTECT

4.4.2. Results

As also seen in Figure 24, the modelling focused on the measurement of solar gain and the tree's shading effect on two planes:

(1) the vertical, outer surface of the façade (see *Figure 26.*)

(2) the horizontal, indoor plane 1.1 m above floor level (see *Figure 27.*).

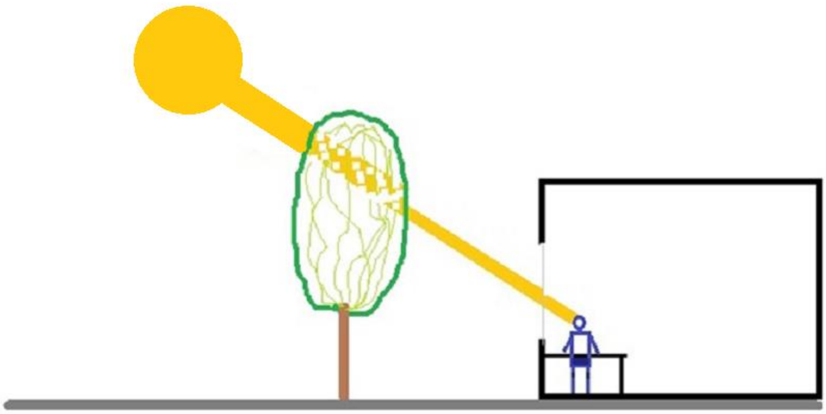


Figure 25. Conceptual illustration of the simulation

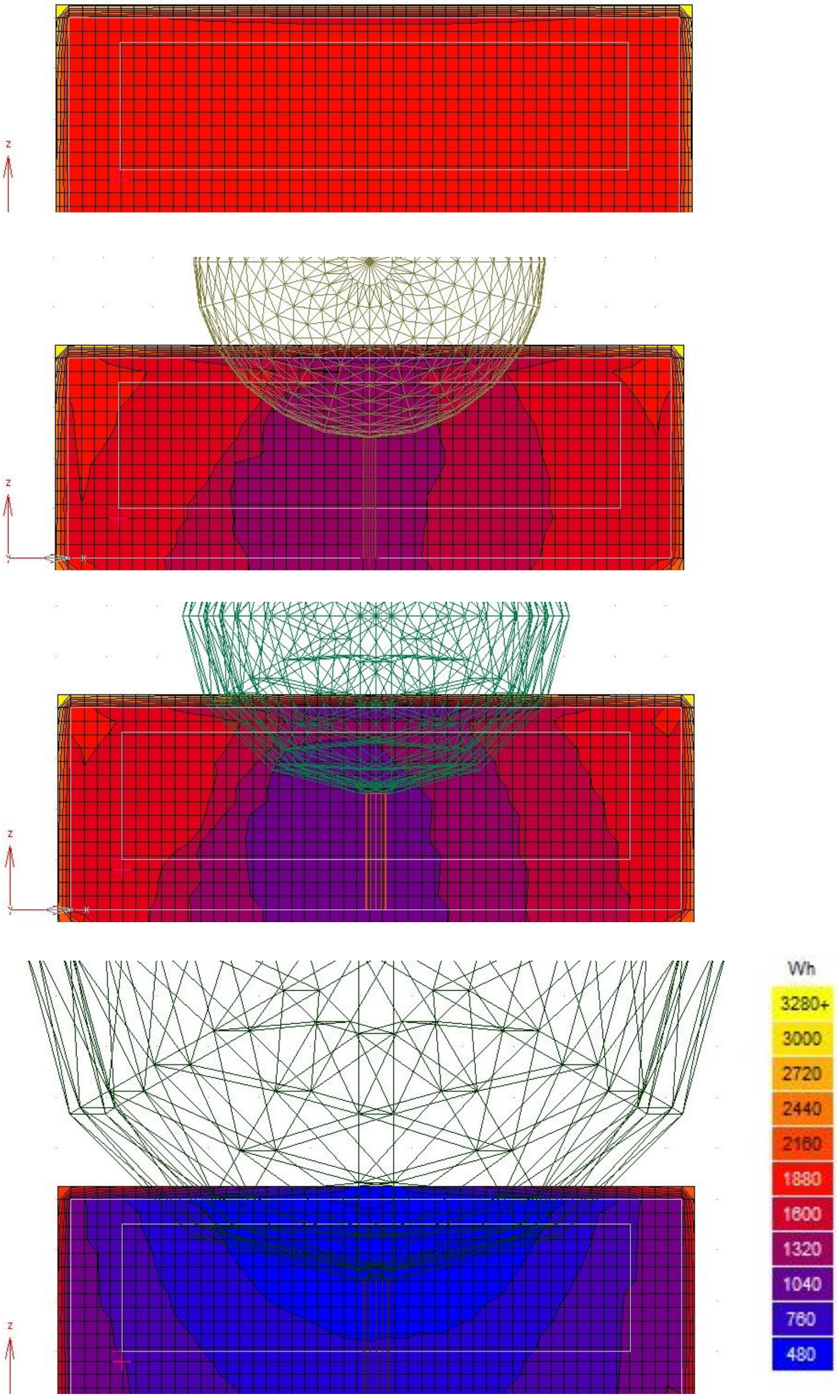


Figure 26. Diurnal solar gain values on vertical plane
(1) unshaded façade, (2) façade shaded by Sophora jap.; (3) façade shaded by Tilia cord.; (4) façade shaded by Celtis occ., value range: 480-3880 Wh/m^2)

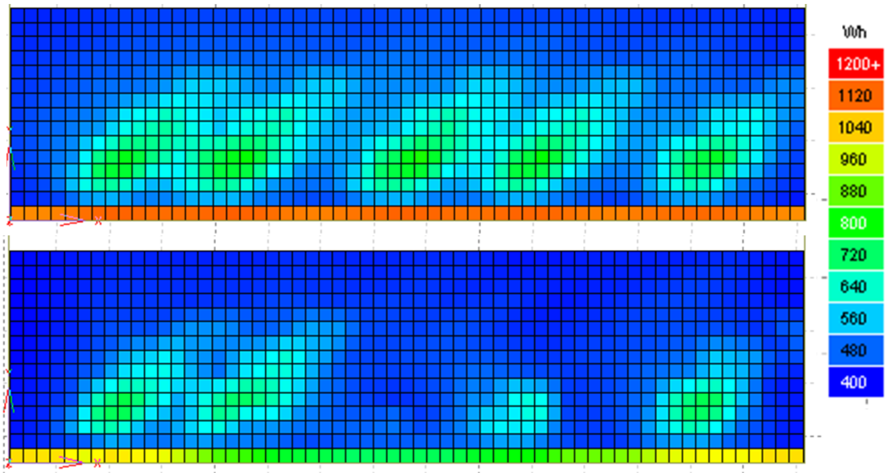


Figure 27. Diurnal solar gain values on horizontal plane, ECOTECT; Above: unshaded, below: shaded by Celtis occ. Total radiation value range 400-1200 Wh/m^2

In the below table (*Table 6.*) the result of the analysis of trees' shading effect on vertical surface is shown. The data are taken from each cell of the analysis grid. Cells are 0.25 × 0.25 m big; the grid covers the whole façade of the model (12 × 4 m). Approximately the 52 % of the façade is transparent to be able to show more precisely the shading effect. The horizontal analysis grid is in 1.1 m high above the floor level, which is approximately the height of the head of a sitting person. The next two tables show the results of described model runs.

Cumulative value of diurnal solar gain on vertical surface [kWh/m^2]				
	Unsheaded	*Shadowed by Celtis occ.*	*Shadowed by Soph. jap.*	*Shadowed by Tilia cord.*
Average	1,98	0,81	1,60	1,49
Minimum	1,72	0,46	1,18	1,05
Maximum	2,00	1,28	1,92	1,90
Rate of average reduction (%)	0%	60%	19,30%	24,80%

Cumulative value of diurnal solar gain on horizontal surface [kWh/m2]				
	Unsheaded	*Shadowed by Celtis occ.*	*Shadowed by Soph. jap.*	*Shadowed by Tilia cord.*
Average	0,74	0,52	0,67	0,60
Minimum	0,46	0,46	0,46	0,46
Maximum	1,99	0,97	1,79	1,74
Rate of average reduction (%)	0%	29%	9%	18%

Table 6.: Shading performance of different species on horizontal and vertical plane

The solar gain of a shaded façade can be ~20-60 per cent less, and 10-40 per cent less in case of indoors horizontal surface - depending on species and canopy size.

After investigating the mitigation of solar gain in case of each species a further step was to find out changes in indoor temperatures.

The results of the simulations first of all showed the importance of tree shading, the impact of transmissivity and that the shading potential can differ greatly according to building material. In the following, the daily course of inner and outside temperatures are shown for each building construction used in modelling. In addition, two cases (shaded and non-shaded scenarios) are shown when windows are open.

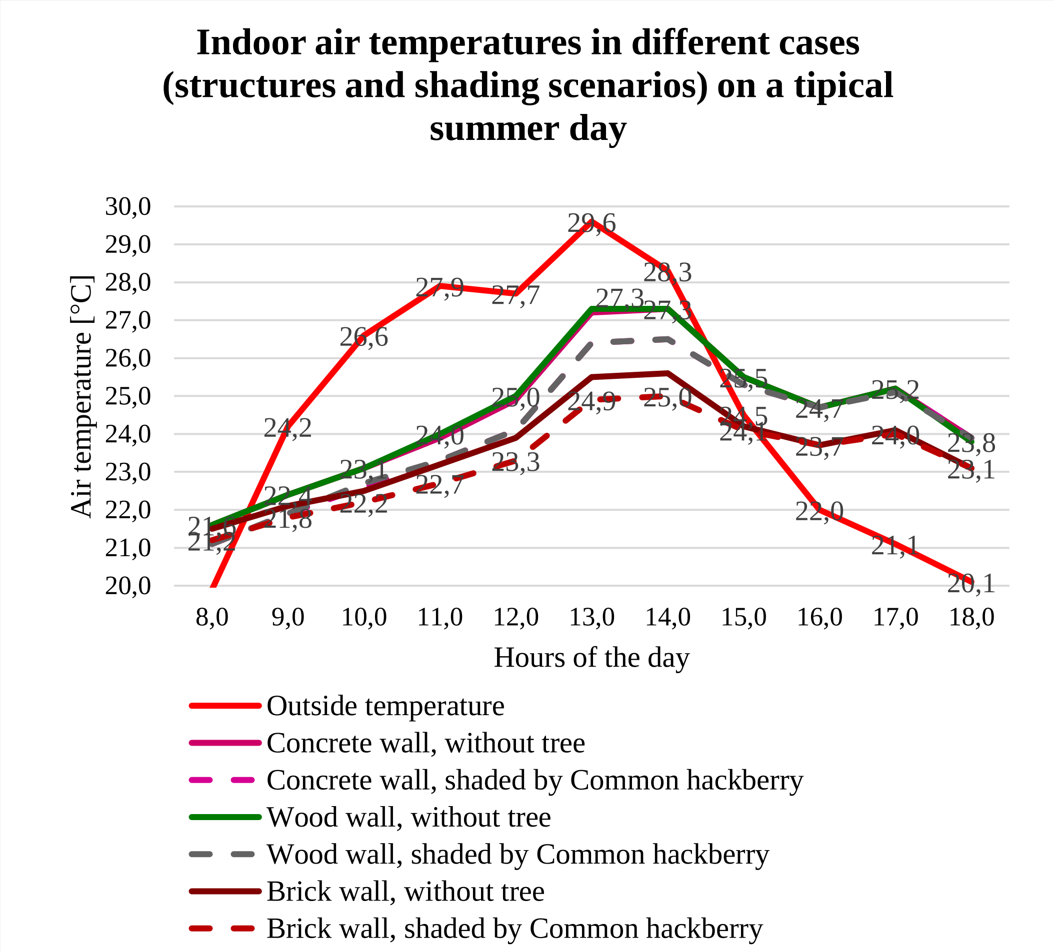


Figure 28.Graph showing the daily run (from 8.00 a.m to 6.00 p.m.) of air temperatures (outdoor) and indoor temperature in case of different constructions

Taking a look on *Figure 28.* the following conclusions can be drawn:

a) Three different structures were examined, however, because of the thick thermal insulation, concrete and wood constructions performed similarly – as the heat storage is shielded by 16 cm of thermal insulation. Consequently, the difference between heavy-weight (brick), and medium-weight (insulated concrete) structures is taken into consideration.
b) regarding the shading efficiency, Celtis occidentalis proved to be the most effective, therefore the other species are not shown here.
c) The shading effect of trees is strongest in this case between 11.00. and 15.00, when the difference in air temperature due to shading reaches its maximum.
d) However, it can be stated, that the best scenario is to exploit the benefits of both tree shading and heavy-weight structures. Opposite to the case when no shading is used in case of medium-weight or light-weight structures, the indoor temperature reaches $T_{air(in)}=27.3°C$; when tree shading and heavy-weight structures are applied, the maximum of $T_{air(in)}$ is $25°C$. Naturally, $\Delta T_{air(out\text{-}in)}$ is dependent on many factors, such as the glazing ratio, orientation, and transmissivity of the used species.
e) The difference in $T_{air(in)}=2.3$ due to different structures and shading scenarios, might seem small, however, this is a difference that determines human thermal comfort greatly, as the threshold of perspiring is above 27°C. (Mekjavic and Bligh, 1989; Höppe, 1999; Kalmár, 2016)

Figure 29. is showing the shading effect of Celtis occidentalis in case of opened window. The difference, that must be observed, that in case of opened window indoor air temperature is diminished by 1°C due to tree shading. However, the simulation can't take into consideration that due to the tree shading and evapotranspiration the heating up of external surfaces are also diminished – hence the shading effect during the afternoon hours cannot be observed.

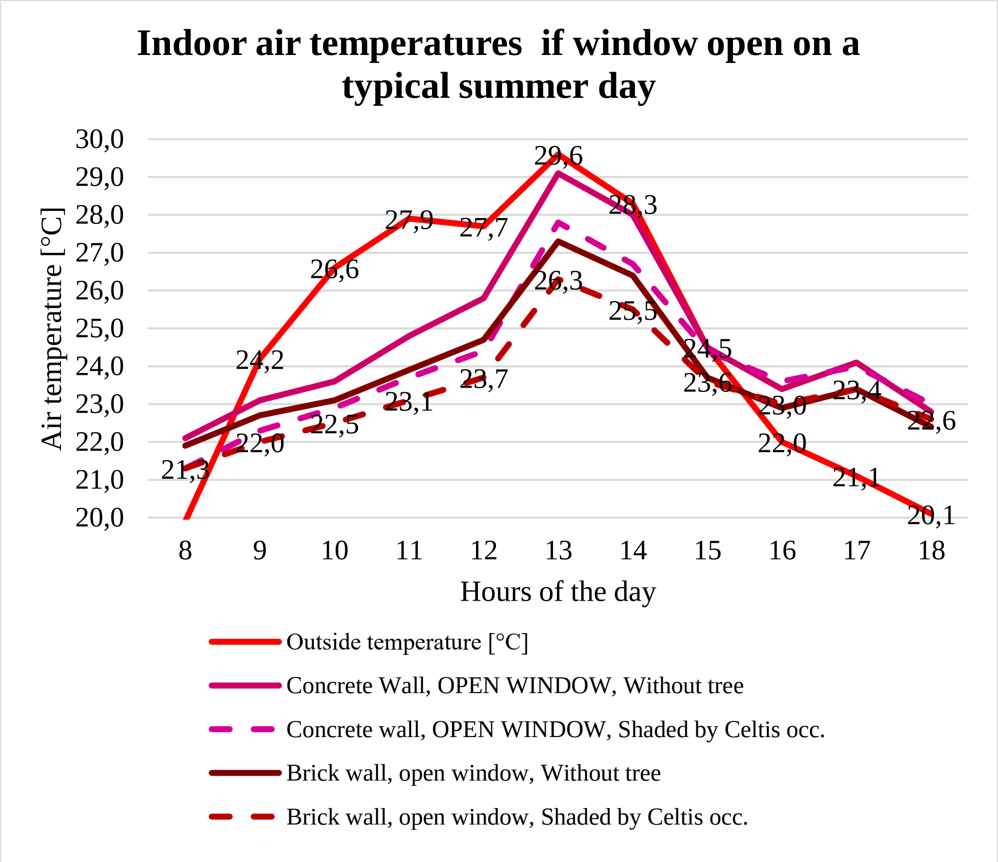


Figure 29. Graph showing the daily run (from 8.00 a.m to 6.00 p.m.) of air temperatures (outdoor) and indoor temperature in case of different constructions, window openings, and shading

Figure 30. shows the difference in indoor air temperatures in the case of opened and closed window. The vertical dotted line highlights the moment when the solid line representing air temperatures in case of closed window cuts the green dashed line representing air temperatures in case of opened window. This means, that around 14.00. p.m it seems to be adequate to open window ensuring natural ventilation. This timeslot depends on shading, orientation thermal attenuation, however, it can be stated that in current case 2 hours after the outer shell of the room was exposed to direct radiation, natural ventilation is possible.

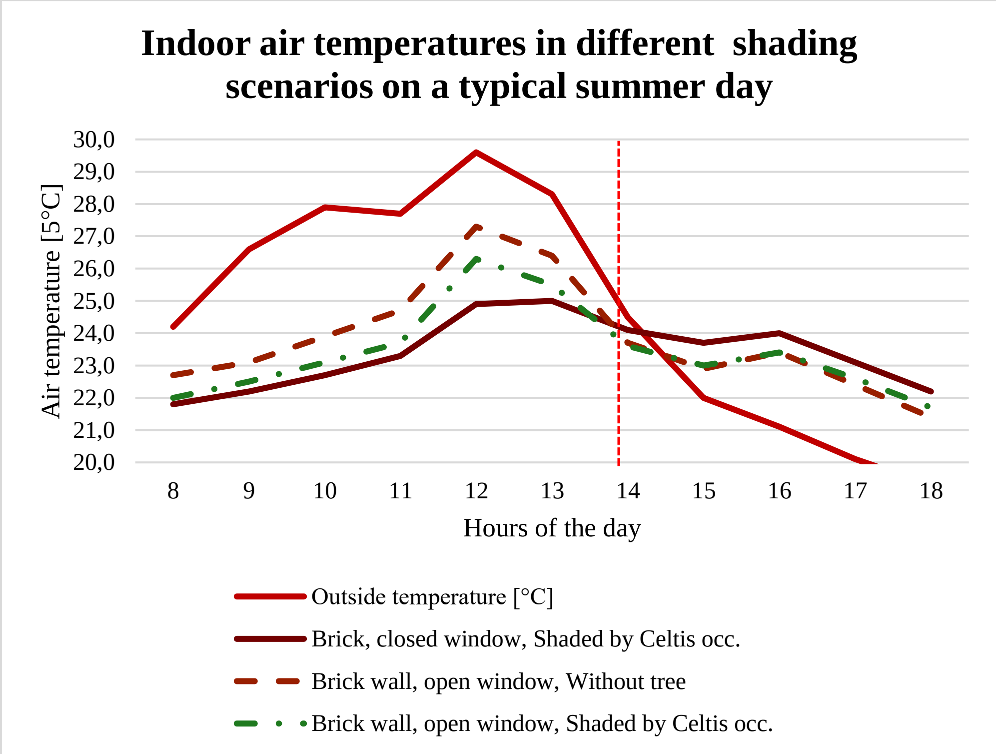


Figure 30. Graph showing the daily run (from 8.00 a.m to 6.00 p.m.) of air temperatures (outdoor) and indoor temperature in case of heavy-weight wall construction, opened and closed window, and tree shading

The cooling effect of trees prevails mainly during the daytime. But the cooling effect of vegetation is really valuable during the night when the intensity of urban heat island is maximal and the cooling down of biologically inactive surfaces is hindered. Naturally, this is due to the overall positive impact of trees on the intensity of UHI and the shading effect, which mitigates the heating up of man-made surfaces – however this is not represented in the simulation because of the limits of *ECOTECT*. As seen in *Figure 29.* and *Figure 30.*, due to tree shading natural ventilation is facilitated, as tree shading provides a lower temperature. If the window is not shaded indoor temperatures rise not only during daytime but also during the night (as the outer temperatures are also higher), thus using vegetable shading improves natural ventilation.

4.4.3. Findings

Summing up the positive effects of trees on microclimate– without wasting to many words on general remarks – there are multiple benefits to be mentioned: the study has proved that tree shading can contribute effectively to creating a good indoor comfort without using mechanical, energy-consuming devices.

First, the shading diminishes the warming up of both vertical (façade) and horizontal (room floor) surfaces, as incoming radiation is mitigated – depending on the transmissivity of the tree – by 9-60%. Accordingly, the incoming thermal flow to the building structures is also smaller, thus the outgoing longwave radiation is also less, which diminishes the intensity of the UHI too.

Secondly, regarding the potential of ventilation it can be stated, that in accordance with the previously described logic, the heat load burdening the indoor thermal environment through an opened window will be also mitigated by the shade of the tree.

1) **incoming total radiation on horizontal plane (floor) is diminished by 9-29%** as seen in *Figure 27.* and *Table 6.*

2) **incoming total radiation on vertical plane (façade) is diminished by 19-60%** as seen in *Figure 26.*

Thus, the risk of discomfort is mitigated for the inhabitant sitting in the room in a position where exposed to the direct solar radiation either through the glazing or directly.

Taking into account that **incoming radiation on horizontal plane is diminished by 70-220 *kWh/m²* it can be stated, that in case the occupant of the room exposed to direct radiation (e.g. working near the window), his/her thermal comfort will be enhanced in operative temperature by *1 / 50 kWh/m²*.**(The before ratio can be calculated based on Arens and Ballanti, 1977; Arens *et al.*, 2009)

4.5. The role of vegetation in rehabilitation of traditional blocks

Stepping a scale further, the next chapter deals with a highly relevant issue of many historic European cities, where the city centre is dominated by multi-storey blocks of flats usually concentrated around an inner courtyard. A strong share of Hungarian building stock was built before World War 2, when social demands were totally different. Not only the social transformation, but also the practice of separating bigger flats into tiny studios in the 1950s, and 1960s have contributed to the moral and structural obsolescence of these flats. For example, while in the time of their construction, the flats facing the street were regarded as precious, nowadays people prefer those facing the inner courtyard as they seem to be more quiet. However, these inner courtyards are deep and usually dark, or simply they are not well-kept – despite of the efforts of some municipalities.

According to the National Building Energy Strategy (NÉES, 2015) there are 10,226 such apartment buildings built before 1945 in the country, which means a number of nearly a quarter million flats. 88.3% of those are situated in Budapest, meaning that circa 23% of the flats in the capital are affected by the problems described above. (The percentage is calculated based on the data of the Central Statistical Office (KSH) as seen in the following *Table 7.*

Table 7. Number and share of multi-story apartment buildings

Number of apartment buildings built before 1945.
(type 10. according NÉES)

	Hungary	Budapest
Number of buildings	10 226	9 030
Number of apartments	242 287	**213 939**

	Number of apartments in Budapest (total building stock)					
year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
number of flats	909 962	911 502	913 858	916 155	919 425	924 664
Share of flats built before 1945 (type 10)	**23.51%**	**23.47%**	**23.41%**	**23.35%**	**23.27%**	**23.14%**

As proved before, nearly a quarter of the Budapest housing stock is affected by the described problem, thus it is highly relevant to analyse possibilities creating a liveable and appreciated environment for citizens.

The problem was acknowledged by some municipalities, giving funding and prizes for green inner courtyards. A guide was also published about the greening possibilities of inner courtyards by the Municipality of Capital Budapest. (Báthoryné Nagy, G. Korompay and Teremy, 2019)

An important example that should be mentioned, is the rehabilitation of Middle-Ferencváros, part of the IX. District of Capital Budapest. The rehabilitation process starting from 1995, tended to demolish some of the old inner wings of the houses, creating a huge green garden within the block. Now, after more than 20 years' time, the action seems to be a winning solution, the intervention was not only awarded the FIABCI Prix d'Excellence in 2016 (Hg.hu, 2016), but it also became one of the most liveable neighbourhoods in Central Budapest. (The author is aware of some doubts regarding the social transformation of the area, however, the discussion of this topic would be out of the thematic frames of this work. The process of planning is well documented in the book (Locsmándi *et al.*, 2007) and other works.)

Figure 31. The map of Central part of the IX. district (Középső-Ferencváros). The opened up inner yards can be clearly spotted.

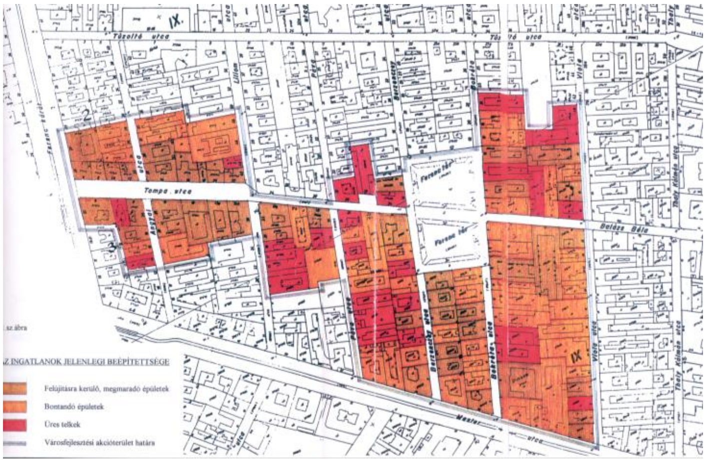
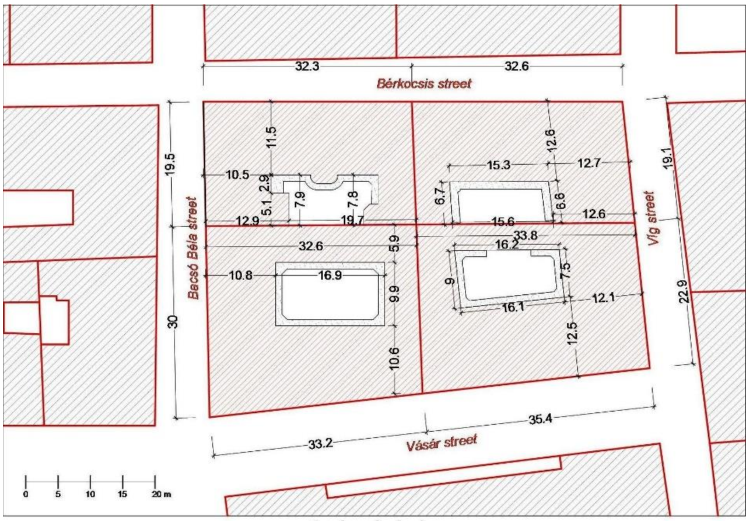


Figure 32.: Analysis sheet of the original 1992 action plan, Ferencváros (Source: VárosfejlesztésZrt., 1992)

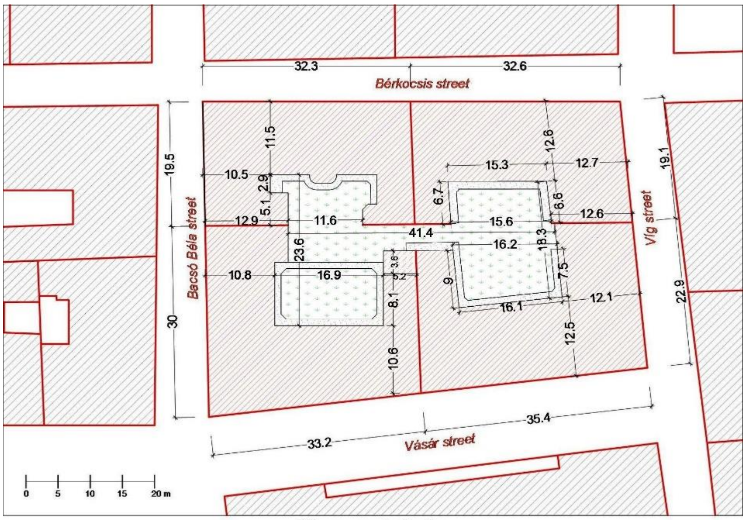
4.5.1. The location

The location of the case study is in the 7th district of Budapest, a block of four buildings - blocks of flats- near Rákóczi square. The block - north of the market hall at Rákóczi square - is bordered by the Bérkocsis, Bacsó Béla, Vásár, and Víg streets (see Figure 33 and Figure 34). The block consists of four buildings, each built in the first decade of the 20th century. The two south buildings have a bigger share of the area of the block and they are also one or two stories higher than the other two buildings.



Actual state

Figure 33. The plan of the studied block and surroundings in actual state



Planned state

Figure 34. The plan of the studied block and surroundings in planned state

As a consequence of the relatively high buildings the inner courtyards are deep and well-like (see *Figure 35*). That means that the microclimate of the yards is quite unpleasant: shady, humid, the air is not ventilating.

As studies (Gandemer, 1975; M. Szilágyi and Jámbor, 2004) haveproved urban spaces can be properly ventilated if the height of the space wall is not more than one-and-a-half time the width (indicated with **a** in *Figure 35*).

It can be stated that the inner courtyards do not complete this important precondition. In a courtyard with the described proportions the planting of vegetation wouldn't be effective at all. That is why - due to the bad givens of the courtyard - the study first recommends the demolishing of the two inner building wings in order to get a bigger courtyard with better proportions so as to facilitate air ventilation in the yard. *Figure 36.* shows the proportions of the opened up inner courtyard of the block.

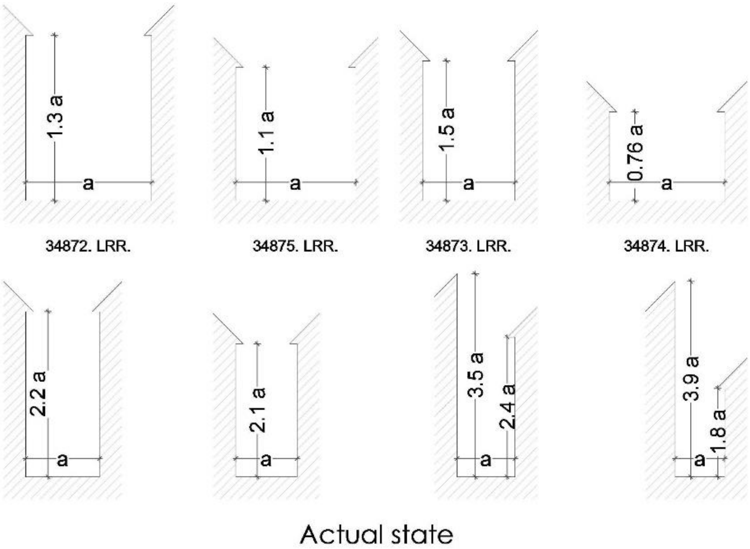


Figure 35. The ratio of inner courtyards in actual state; above: longitudinal section, down: cross section (LRR. = land register reference)

After creating the primary conditions for vegetation three different models were analysed in order to be able to investigate the effect of the opening up of the yards and separately the effect of the vegetation in the case study.

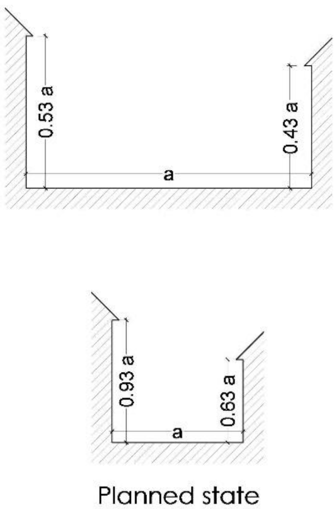


Figure 36. The ratio of inner courtyards in planned state up: longitudinal section, down: cross section

4.5.2. Modelling

The first model represents the actual state of the block. The second model represents a state where the courtyards are opened up, but the yard is floored with asphalt. Finally, the third model shows the state where the opened up inner courtyard is planted with vegetation.

Different values in various cases were analysed in order to be able to investigate the changes occurring in the microclimate of the inner courtyard..

- 3 seasons:
  - Winter: 3rd January;
  - spring: 15th April;
  - summer: 23rd June;
- 3 times of the day:
  - 8:00 in the morning;
  - 12:00 at noon;
  - 18:00 in the evening;
- In 3 different vertical sections:
  - 1.6 m – the height of an average man's head ;
  - 6.0 m – the height of a middle gangway;
  - 12.0 m – the height of an upper gangway.

- The conditions of the simulations are:
- Simulation time: from: 06:00 until 20:00;
- Wind speed in 10 m above ground: 3 m/s;
- Wind direction: *northwest*;
- Indoor temperature: 20°C;
- Thermal transmittance (U-Value) of façades: 1.94 W/m^{2}K.
- The measured values are the following:
- Wind speed and direction;
- Mean Radiant Temperature;
- Predicted Mean Vote;
- Relative Humidity;
- Sky View Factor.

The mentioned variables give us approx. 248 different results. After evaluating the different charts the conclusions are described below.

4.5.3. Results

Wind speed and direction: With the opening-up of the inner courtyard changes can be observed regarding not only the speed but also the direction of some air movements inside as well as outside the block. In the inner courtyard effective natural ventilation becomes possible, so the air quality of the inner courtyard will be better, mould contamination and musty smell of the yards can be prevented.

Mean Radiant Temperature: It is obvious that due to the opening up of the yards solar exposure conditions will increase the values of *MRT* greatly. As it can be seen in *Table 8.* the growth of the values of *MRT* can be maximal with a value of ~44 K in summer. If shaded with trees and other plants, the value of *MRT* can be kept at a mean of 307 K, which is only 6 K more than in original, actual state. That means that the risk of over-heating in summer can be avoided by using plants for shading and adiabatic cooling.

Table 8.: MRT values in the inner courtyard

	MRT value [K] summer, 12 h 1.6 m		
	1st model	2nd model	3rd model
Nr of cells	111	175	175
Mean	300.715	317.953	307.554
Median	300.715	303.234	301.996
Minimum	300.388	300.925	300.035
Maximum	301.346	345.516	330.195
Std. Deviation	0.195	19.645	10.542
Variance	0.038	385.908	111.127

Predicted Mean Vote: As *PMV* values are interconnected with the values of *MRT* it isn't a surprise that very similar changes can be observed. In the case of *PMV* values minimal changes can be observed in the morning and evening hours, the changes are maximal in summer at noon. That shows that the opening up of the inner courtyards will cause over-heating in summer, which means that the method of only opening up the inner yards is not a god solution. *PMV* values can grow maximally by 1 (see *Table 9.*), which means that more than 30% of the people will feel uncomfortable in the yard. But with the usage of vegetation *PMV* values will normalize and even in summer nearly 90 % of the people will feel comfortable in the inner courtyard.

Table 9. PMV values in the inner courtyard

	PMV value [ ] summer, 12 h 1.6 m		
	1st model	2nd model	3rd model
Nr of cells	111	175	175
Mean	0.142	1.183	0.600
Median	0.139	0.505	0.328
Minimum	0.111	0.363	0.249
Maximum	0.189	2.538	1.673
Std. Deviation	0.020	0.950	0.499
Variance	0.000	0.903	0.249

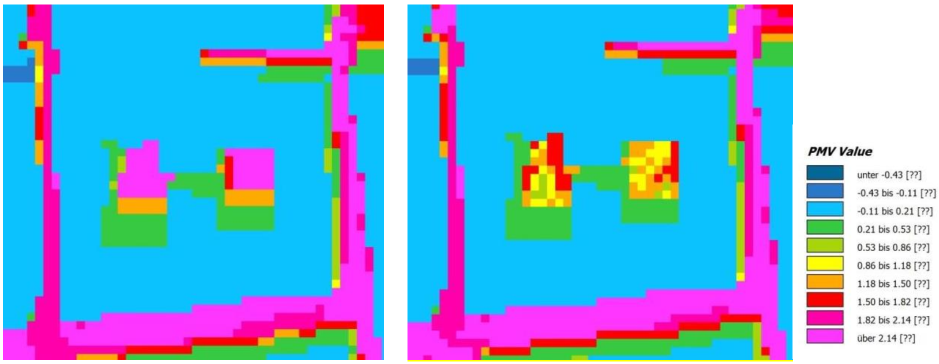


Figure 37. Change in PMV values in the inner courtyard due to the plantation of vegetation

Relative Humidity: From the point of physiological wellbeing it is important to observe changes in the humidity of the courtyards. In actual state the humidity of the inner yards varies between 64 and 66%. 66 per cent is typical in the northeast courtyard - according to on-the-spot inspection this yard was the mustiest one of the four. In the 2nd model the values of *RH* are homogenous in the opened-up inner courtyard. Due to the planting of vegetation *RH* will increase by 2-3 per cent, which is an obvious consequence of the evapotranspiration of vegetation. However these changes do not influence the thermal comfort in the strictly arithmetical sense, but there is still a positive effect that results from the difference between a damp and dark inner courtyard and a sunny vegetating yard.

Sky View Factor: In the measurement of *SVF* we observe only the first two models, as the effect of plants in this case is not taken take into consideration. In the 1st model *SVF* values are between 13-22% but noticed just in a small part of the four yards. In the 2nd model values vary typically from 23 to 32% but the maximal value reaches 50% in the middle of the opened-up inner courtyard.

4.5.4. Findings

As a final conclusion of the presented case study, it can be stated that opening up and planting is an excellent solution for the revitalization of the old and dilapidated blocks of flats in the city of Budapest. Of course, a few flats should be demolished, but as usual - as it is the situation in this case also - there is a possibility of building one storey or two on top of the low building of the block. (The northeast building of the block is two stories lower than all others, so this would be a good solution also from architectural point of view.) With this method the typical façades can be preserved, and high standard flats can be created in the city of Budapest.

The method of planting vegetation in opened-up courtyards is very fruitful from energetic and of social point of view, as a liveable and sustainable environment can be obtained for city-dwellers, better energetic circumstances, and a greater range of possibilities for using renewable energy sources can be created in the block, and what is more, a place of encounter, rest and recreation for the residents is provided.

Accordingly, to the above listed aspects, it is proved that the reconstruction of blocks of flats is a complex problem to solve. **The results in *MRT* and *PMV* values have shown that with only opening-up of inner yards – however desirable it seems from architectural point of view –, no better living standards will be achieved due to the risk of over-heating in summer. But the usage of vegetation is a tool with which the microclimate within the block can be changed positively. A better indoor comfort in the flats can be assured as the due to the reconstruction wind speed increases as well – giving the possibility of natural ventilation, and also a better solar**

exposure and natural lighting is ensured especially for the flats on ground floor.

Without the usage of vegetation desirable thermal comfort can only be achieved with the mere help of building engineering. However, it stands clear that it would not solve the problems of the well-like inner courtyards, the bad solar exposure conditions and social barriers, and above all it would consume a great deal of energy. **At the same time, the presented case study proves that with the help of architectural and sustainable bioclimatic tools energy-efficient living environment can be created, and the negative effects of urban heat island can be mitigated.**

4.6. Microclimatic effect of greening neighbourhoods

The following chapter deals with the microclimatic effects of implementation of GI elements on neighbourhood scale. The study is relevant to analyse which solutions are more effective under certain circumstances.

4.6.1. The location and it's microclimate

The spot of the case study to be presented is situated in the II. District of Budapest, northwest of the Margaret Boulevard, near Millenáris Park and its wider surroundings. The building stock of the area is quite diverse in terms of its function: the two huge blocks of the Mammut Shopping Centre on either side of Lövőház Street, the Millenáris building complex, market, public and educational buildings, a church and, of course, numerous residential condominiums are situated here. (See *Figure 38.*) Due to the diversity of the area, it even can be considered as a city within a city, which is why it is justified to reconsider the rehabilitation of the area in a complex way. The so called Millenáris II, SzéllKapu Park development project has just been finished and opened in August 2020[4]. However, the re-planning and simulations presented in this chapter were carried out in 2014, in the frames of the UHI (3CE292P3) Central Europe project, on the order of the Hungarian Meteorological Service. (Microclimate modelling was carried out by the author, Baranka *et al.,* 2016)

The microclimate of the area is influenced by numerous factors. On the one hand, the prevailing north-northwest wind arriving from Hűvösvölgy, and on the other hand, the topography also plays a role in shaping the microclimate of the area, as the area is located on the southwestern slopes of the Rózsadomb, all the way to Margaret Boulevard. In addition, we must not forget the heat load of larger buildings, which is especially significant for narrow streets - such as Lövőház Street, which is also parallel to the prevailing wind direction, making it the most significant urban canyon in the area. The width-to-height ratio of the street is not only an important factor in shaping the local microclimate, but also determines the possibility of planting plants. (Goh and Chang, 1999) It is important to mention that the II. District, and thus, the planning area is also quite well-populated with urban trees. Nevertheless, the

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[4] http://szellkapu.hu/

condition of the trees and in some cases the neglected conditions justify the rehabilitation of the area.

Figure 38. The pilot area on Google Earth in 2012 (above) and in 2020 (below).

4.6.2. Principles of planning, means of intervention

The conditions created by traffic and street width, as well as the parking habits of the population, had to be taken into account in the rehabilitation planning. Considering the circumstances, the possibilities, and the changes to be achieved, the application of the following GI elements were implemented:

- **tree-lines** are placed in streets where there is enough space for doing so, and at a density that does not yet significantly reduce the number of parking spaces in parking lanes. Where possible, not only single but also double rows of trees are placed.

- use of **planting boxes**: Firstly, planting boxes were places wherever there is not sufficient space for tree rows, however, an increase in the proportion of green space is possible. Secondly, planting boxes were created in combination with rows of trees, thus, multi-level vegetation can be created in an urban environment. The planting boxes used are 50-60 cm high and contain low woody plants and perennial ornamental grasses.

- **green facades** are used where, the width of the street does not allow the installation of other green surfaces, or on building façades where the raster of windows and doors allow the implementation of green walls or facades. In addition to the significant aesthetic and physiological benefits, the use of green facades has positive microclimatic effects already described earlier.

- **green roofs**: the role of green roofs is again very diverse, as they have a very important recreational value for both public and residential buildings, in addition to stormwater infiltration and other microclimatic and energy benefits associated with the appearance of plants. Within the design site it was proposed to implement green roofs for several blocks of flats, municipal and other public buildings. (Green roof on the buildings of another legal entity: Tulipán u. 24, Marczibányi tér 3, Kis Rókus utca 18, 16, 14, 12, 2, 4, 6, Lövőház u. 1-6, 12, 14, Fényes Elek u. 7- 13, 14-18, etc .; green roof on municipal buildings: Marczibányi tér 5a, 13, etc .; green roof on residential buildings: Kis Rókus utca 33-31, 1-1a-3-5-7, etc. See *Figure 39.*)

- green spaces: since the planning area also has two major public green spaces in good condition, (Millenáris Park and the recently renovated Mechwart liget) their redesign was not proposed. However, the so-called “SzéllKapu Park” which has been developed on the site of the demolished, joining the Millenáris area.

Figure 39. The rehabilitation plan of the area. (Landscape architecture: O. Kocsis.)

4.6.3. Modelling

In order to investigate the impact on microclimate of the main interventions planned for the area, microclimate modelling was executed in ENVI-Met (software described in chapter 3.2.1.). The whole area would not have been suitable for modelling, so the model area was cut into 3 sample areas.

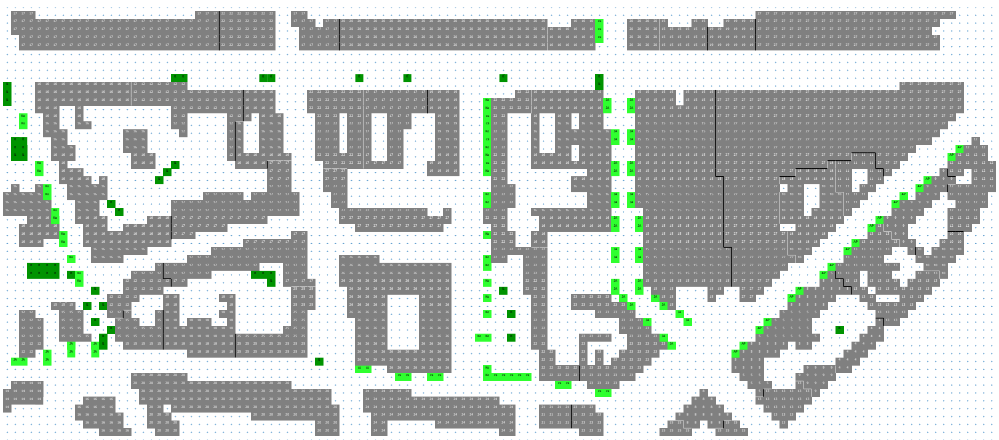

Figure 40. 1st model area: bounded by Lövőház, Retek, Fillér, Ezredes streets

Microclimate modelling was carried out with a uniform cell size of 4x4 meters. The wind direction is uniformly northwest, the wind speed at an altitude of 10 m is 3 m/s. The simulation starts at 9 a.m. on a typical summer day and the simulation time is 24 hours. Initial air temperature is set at 23 ° C, and relative humidity at 2 meters: 70% - according to data from the meteorological service. For each sample area, two variants are modelled: the first reflecting the original conditions and the second reflecting the planned conditions. The impact of the implemented GI elements – already described – are briefly summarized below.

- alley trees: the effect of single and double alleys causes a spot-like decrease both in the *MRT* and *PMV* index. By the growth of the tree canopies, or by planting the trees closer together, this reducing effect might be made linear along the street, yet, the mitigating effect does not exceed the area of intervention.

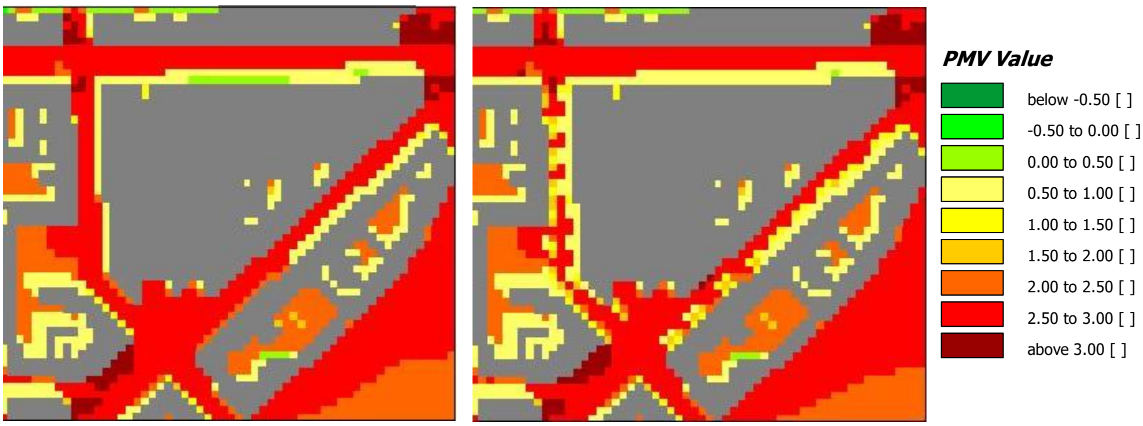

Figure 41. Effect of single and double alley in Fény and Retek streets (summer, 12: 00h, 1.6 m)

As shown in *Figure 41. Effect of single and double alley in Fény and* Retek streets
(summer, 12: 00h, 1.6 m) **the alley of trees typically reduces the value of *PMV* by 2, sometimes by 3 units**. In our case, this means that while **in the original state, 80% of pedestrians walking on the sidewalk feel uncomfortable, this proportion can be reduced to 10-30% by planting trees.** (Baranka *et al.*, 2015)

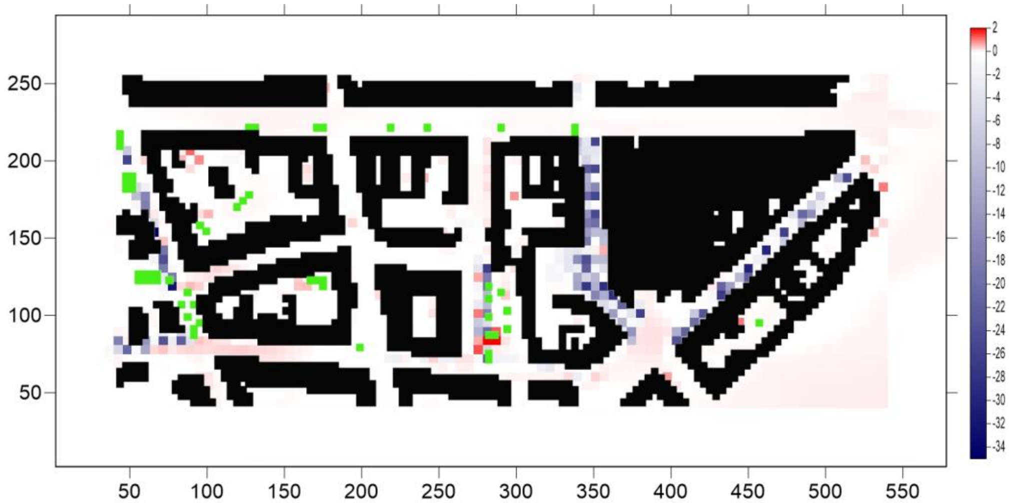

Figure 42.Cartogram showing the difference in MRT values around Lövőház utca due to the planting of vegetation in Retek and Fény utca, (greened – original state), summer, 12.00 a.m., 1.6 m height (The extensions of the model area are seen on the vertical and horizontal axis in meters.)

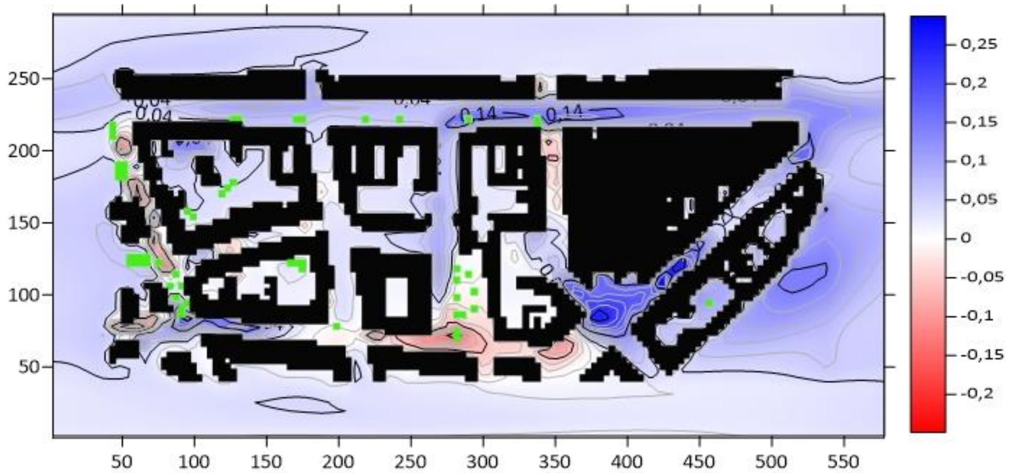

Figure 43. Cartogram showing the difference in Potential Temperature[5] *values around Lövőház utca due to the planting of vegetation in Retek and Fény utca. (greened – original state), summer, 12.00 a.m., 1.6 m height (The extensions of the model area are seen on the vertical and horizontal axis in meters.)*

[5] Potential Temperature is a nomenclature used by ENVI-met, it equals to Air Temperature. Potential Temperature *„is calculated as an average temperature over all grid cells of height z, excluding those occupied by buildings"*. (Bruse, 2004)

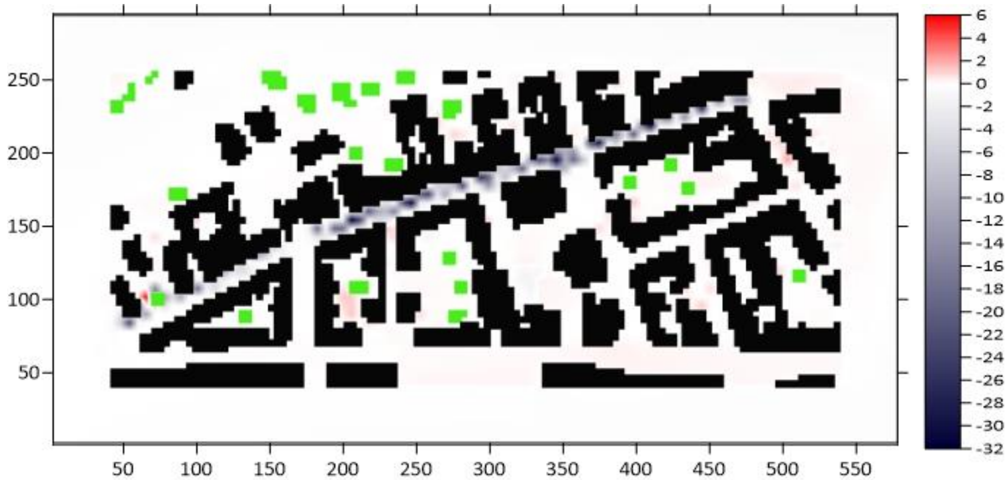

Figure 44.: Cartogram showing the difference in MRT values around Keleti Károly utca due to the planting of alley trees. Greened – original state, summer, 12.00 a.m., 1.6 m height (The extensions of the model area are seen on the vertical and horizontal axis in meters.)

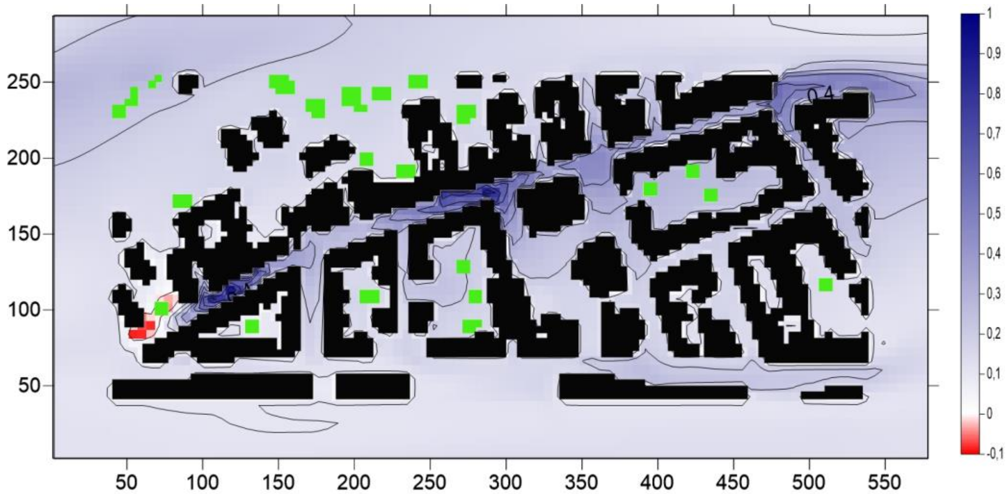

Figure 45. Cartogram showing the difference in Potential Temperature Keleti Károly utca due to the planting of alley trees. Greened – original state, summer, 12.00 a.m., 1.6 m height (The extensions of the model area are seen on the vertical and horizontal axis in meters.)

- planting boxes:

if implemented alone and not complemented with other measures, the effect of planting cassettes on the microclimate is negligible, but it is undeniable that they have a positive impact on the streetscape and the psychological well-being of the population.

. A planting box appears in the Bimbó road in combination with alley trees, thus, its microclimatic effect cannot be clearly separated from that of the alley trees, so, a far-reaching conclusion about the effect of planting boxes cannot be drawn.

- green façades: The planned green facades could not be modelled on the scale of the model area, but it is known from previous research that in the case of prevailing wind direction they significantly reduce the average radiation temperature and the *PMV* in their immediate vicinity. (Szkordilisz, 2014)

- green roofs: the effect of the planned green roofs is very complex and therefore difficult to model. A green roof, in addition to reducing the intensity of the urban heat island, slows down the water runoff, thereby reducing the amount of gray water to be treated; it plays a significant role in the living standard of those working or living in a building providing a natural space for rest and recreation.

- green spaces: the designers did not propose any changes to the planning area in two significant public green areas - Millenáris Park and Mechwart liget. However, the "SzéllKapu"park appeares as a new element on the site of the recently demolished ministry, significantly increasing the green area of the Millenáris. According to the results of microclimate modelling, the disappearance of the ministry block and **the appearance of a new green area will also reduce Mean Radiant Temperature by ~30-40 K, and the air temperature by 1.5-3.0 ° C**, as seen in *Figure 46.* and *Figure 47* respectively.

Overall, due to the increased proportion of green spaces in the study area, the microclimate – accordingly to the spot-like nature of measures - improves: enhances ventilation, increases relative humidity, significantly reduces *MRT* and *PMV* values, and in case of drastic intervention (demolishing a 33 m high building) air temperature will also show a significant decrease.

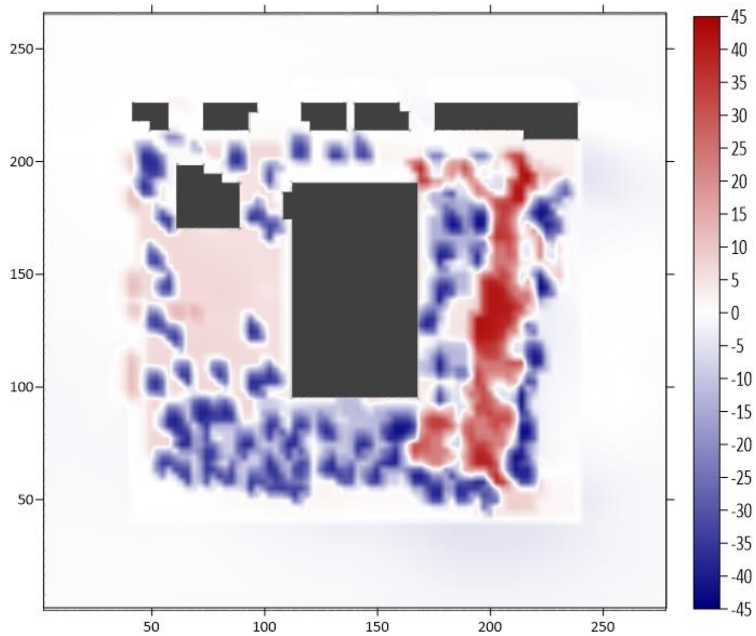

Figure 46.: Cartogram showing the difference in MRT values due to creation of SzéllKapu park (summer, 12:00h, 1.6 m)

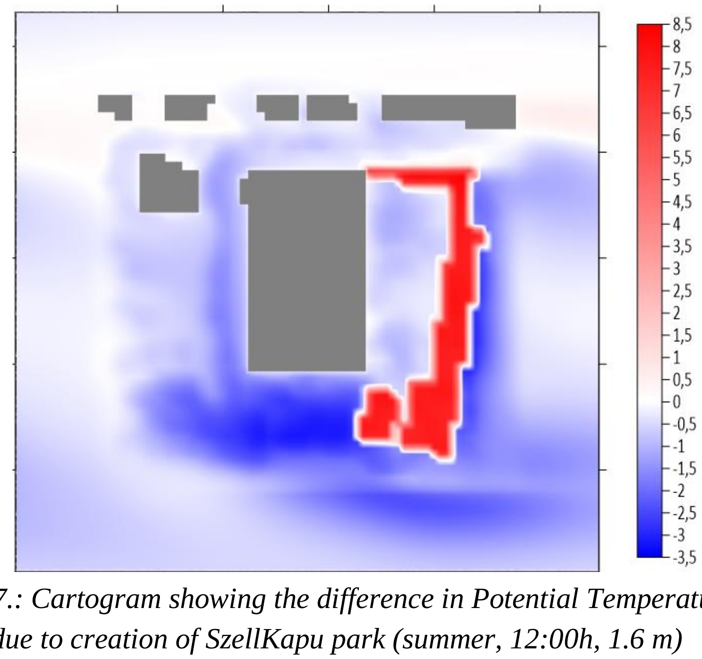

Figure 47.: Cartogram showing the difference in Potential Temperature values due to creation of SzellKapu park (summer, 12:00h, 1.6 m)

4.6.4 Findings

The case study had two objectives. In particular, to demonstrate that urban regeneration considering **the development of green infrastructure on neighbourhood scale**, as its basic concept, **leads not only to the improvement of the aesthetics of urban environment and the well-being of citizens, but also of the urban microclimate: *MRT* and *PMV* values can be decreased to a significant extent contributing to a satisfactory thermal comfort during the summer heat waves**. Secondly, there was an aim to analyse the efficiency of different kinds of measures: which GI elements are best to use. When selecting the measures to be applied the physical and infrastructural feasibility, as well as the financing possibilities of the planned investments were kept in mind. **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. Recently, 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. (For example, in the case of SzéllKapu park the costs of maintenance are partly financed by the income from the underground car park under the park.)

The application of GI elements has a positive impact on social, ecological issues and human physiology, which should take priority over short term financial benefits. To understand this, however, a paradigm-shift is required for professionals, decision-makers and as well as laymen.

5. Results, conclusions and recommendations

The context of results in urban planning

Summing up the results it is essential to put those into the context of existing literature and the history of microclimate research in terms of the effects of green infrastructure.

In recent years, the interest towards the methodology and toolkit of climate adaptive planning has risen remarkably among urban planners and architects. This is partly due to the media coverage of the topic as well as to the shift in the requirements in numerous EU funded operative programmes. Nevertheless, the knowledge available and useful for urban planners is still limited and there is a need for the capacity building of planners, experts and decision-makers. Experience shows that climate conscious planning and the implementation of green infrastructure requires the engagement and cooperation of various sectors. This necessity also emerged for linking the scientific results of multiple fields.

The pioneering period of research in this field started with fundamental literature from the sides of meteorology, architecture and landscape architecture such as Olgyay and Olgyay, 1963; Lee and Givoni, 1971; T. R. Oke, 1987; Szokolay, 1998.

Following these works, an attempt has been made to combine both meteorological and architectural perspectives and provide research results that help planners to create a more liveable and environmentally sustainable urban environment from building to neighbourhood scale.

Methodology

Therefore the aim of my research was to examine the microclimatic (and eventually energetic) effects of small and medium-scale GI interventions: green walls and facades, alley-trees, shrubs and planting boxes, and in neighbourhood scale: inner gardens and new green spaces. I focused on the analysis of Transmissivity related to tree species, Air Temperature, Mean Radiant Temperature, Predicted Mean Vote, and Wind Velocity. I deliberately choose metrics, that are easy to understand also for urban planners and architects also.

For the purpose of analysing the effect of selected GI elements I used numerical simulations and on-site measurements.

Conclusions

Examining the effect of green façade on the scale of buildings, the plantation of vegetation is undoubtedly positive. In summer the leaves decrease the heating-up of the wall, so due to green façades the inner cooling demand will significantly be reduced (Ottelé *et al.*, 2011). In winter, the green façade – if evergreen – will decrease the air movement near the wall, so heating demand might be decreased. The case study described in Chapter 4.1. 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.**

Further simulations were carried out to investigate the effect of different plantings in the street on wind comfort. 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, where sudden gusts might reach the pedestrian, thus these spots are crucial in creating an agreeable wind comfort. **Apart from the obvious result, that vegetation decreases wind velocity in the immediate proximity of the plants, the conclusion from the study is, that an asymmetrical disposition of various plants (shrubs and trees together) is most desirable, as this kind of solution ensures an acceptable wind comfort but does not hinder urban cross ventilation.** Previous studies 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.

The second research area was the investigation of the effect of trees on solar irradiance, vertical transmissivity, and indoor thermal comfort. **Since the horizontal transmissivity of trees has been investigated in recent years, 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%.**

Based on the values retrieved from on-site measurements, further energetic simulations were executed. The aim of the modelling was to have results on the effect of trees on the warming-up of the façades and indoor air temperatures. It was found that **tree shading diminishes significantly the warming up of both vertical (façade) and horizontal (room floor) surfaces.**

The effect of opening the window was also studied, with the result that it makes sense to open the window in the afternoon hours, as the indoor temperatures can be lowered when the façade is shaded.

Regarding neighbourhood scale investigations, first, the effect of opening traditional blocks and implementing vegetation in the inner courtyards was studied. It was 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.

The last case study examined the effects and possibilities of climate-adaptive planning with implementing multiple green infrastructure elements at the same time on neighbourhood scale. **It has been demonstrated that alley trees, planting boxes and new green spaces momentously reduce 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.

6. Theses

6.1. 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*.

6.2. Creating better wind comfort with plants

I analysed the effect of combined greening (trees and shrubs) on wind comfort with multiple numeric simulations carried out with ENVI-met. **I have proved 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 on 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.**

6.3. The vertical transmissivity of typical urban tree species

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 *τ=11.3%,* and *Sophora japonica* is the least effective in terms of vertical shading with a transmissivity value of *τ=16.6%*. *Tilia cordata* has similar values to *Celtis occidentalis* with a transmissivity value of *τ=12%.*

6.4. 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 of alley trees on outdoor thermal comfort.

A) I have proved 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** (oriented to south, southwest) **can diminish the daily solar irradiance on vertical surface** (if *τ=12-16%*)**by *20-60%* (maximal *1 kW/m2/day*) under summer conditions** This phenomenon, of course, also affects the Mean Radiant Temperatures measured on the pedestrian way both during the day, and in the evening hours, as it reduces the surface temperature of the wall, and thus, the intensity of UHI too.

6.5. The effect of alley trees on indoor thermal comfort

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 (oriented to the south, southwest) of the investigated room 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) The simulations have shown that shading by trees also promotes natural ventilation, since in the case of shading by trees and opening the windows during the afternoon hours, the average indoor air temperatures decrease compared to the case without shading by trees and closed windows.

6.6. Role of vegetation in urban rehabilitation

I examined the effect of opening up and greening of city centre blocks. I have proved - with using ENVI-met numeric simulations - that joining inner courtyards along with demolishing the inner building wings, bring a favourable outcome in terms of microclimate if the courtyards are greened. I have proved 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 *ΔMRT=17 K* 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 *ΔMRT=~10 K* in average and by *ΔMRT=~15 K* in terms of maximal values – compared to the non-planted conditions.**

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

6.7. 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 *ΔMRT=~30-40 K,* and reduce Potential Temperature by** ΔT_{pot}**=1.5-3.0°C**

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.

7. Summary: green infrastructure in the planning practice

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

At the same time, however, to implement those principles, theory must be turned into practice which includes:

- create a favourable and flexible governance system adapting green infrastructure on multiple levels, sectors and scales,
- ensuring policy alignment at the local level, and engaging local authorities and decision makers;
- capacity building among the executors of the planning and implementation process;
- and finally involving local actors (NGOs, civil movements, educational institutions, 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 green infrastructure implementation is related to the planning traditions of a country or macro-region.(Szkordilisz *et al.*, 2018)

Regarding the Hungarian situation of green infrastructure planning, the national framework is guaranteed by the *28/2015. (VI. 17.)* Parliamentary Decree (*A biológiai sokféleség megőrzésének 2015-2020 közötti időszakra szóló nemzeti stratégiájáról*, 2015) which sets the foundations of biological diversity. However, the question of green infrastructure development is rather fragmented, the implementation of GI is it is more related to the execution of Operational Programmes, and thus to municipal action plans. Guidelines for the development of those plans are ensured in the document Methodological Guide for the Creation of Green Infrastructure Development and Maintenance Action Plan (EHÁT, 2016). Besides this, numerous strategies and development concepts have been created on the commission of local municipalities and county municipalities including the Municipality of the Capital Budapest.

However, the implementation of these plans does not always go smoothly: the larger the scale, the more complex the execution.

Many other works have been published to support the better understanding of green infrastructure planning among professionals, planners and decision-makers. As a pioneer among those works the so-called Urban Climate Guide (Szilágyi *et al.*, 2011) must be mentioned, which aimed to give a brief overview of the effects and relations of urban planning and development to decision-makers. A series of reports summed up the international best practices and state-of-art regarding green infrastructure development, and also the inconsistencies and potentials in creating a more favourable institutional background and legislation to support the planning, realization and maintenance of green infrastructure. (Kollányi, Máté, Mezősné dr. Szilágyi, Ádám, *et al.*, 2017; Kollányi, Máté, Mezősné dr. Szilágyi, Báthoryné Nagy, *et al.*, 2017)

The point is reached when the question also arises as to how urban planners can be supported by researchers in using the results of theoretical research in their everyday planning routine. This question has been addressed in some publications (Szkordilisz, F ; Kiss, M ; Égerházi, LA ; Kassai-Szoó, D ; Gulyás, 2016). The following *Figure 48.* summarizes the differences of interests and needs of the target groups.

Urban climate researches ⟷	**Urban planning & design**
Considerably high amount of **researches** conducted in the field of urban climate.	Active urban designers and architects were ***not educated to cope with climate issues***.
Modelling and field measurements are available on the effect of different green infrastructure elements on urban (micro)climate.	Climate-conscious principles are not implemented in urban planning.
	There seems to be **a lively interest among architects** towards climate-adaptive planning.

Figure 48.: Showing the gap between the results of urban climate research and the knowledge necessary for urban planners.

The effectiveness of Green Infrastructure elements in urban setting comes up more often recently in urban planning (for example: Sustainable Energy and Climate Action Plan, Municipal Climate Strategy, Integrated Urban Development Strategy, etc) when the planning expert should have ready answers to particular problems and lead the decision-makers to a solution that will be environmentally effective, socially accepted and economically reasonable. This is a complex and not an easy task confirmed by many years of practice.

In order to make the conclusions of urban climate research more understandable for urban planners the methodology of presenting the results need to be changed. For that purpose, multiple projects have been carried out with my participation, including: 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. In cooperation with my colleagues, I am currently also working as a consultant in green infrastructure development on the commission of municipalities, but presenting these results would exceed the frames of this study.

8. Összefoglaló

Az éghajlatváltozás hatásához köthető súlyos környezeti, gazdasági és társadalmi folyamatok a szemünk előtt zajlanak. Ezen folyamatok felerősödése leginkább a városokban érvényesül. Az extenzív urbanizáció negatív hatásainak leküzdése és az ennek eredményeként erősödő városi hősziget negatív hatásainak csökkentéséhez elengedhetetlen a zöld infrastruktúra-elemek hatékonyságának vizsgálata a mikroklimatikus viszonyok megváltoztatásában. A zöld infrastruktúra azon intézkedések összessége, amelyek összekapcsolják a természetet a városi környezettel. A zöld infrastruktúra-elemek megvalósításának legfontosabb hajtóereje az élhetőbb városok létrehozása és a városlakók szemléletformálása a projektekben való részvétel és bevonás által.

Jelen kutatás célja, hogy megvizsgálja a zöld infrastruktúra elemek mikroklímára, és az épület energiafogyasztására gyakorolt hatásait; kültéri és belső téri hőkomfort; és a kutatási eredmények könnyen alkalmazható alapot adjanak a ZIE elemek várostervezésben való kivitelezéséhez és tervezéséhez, és további vizsgálatokhoz – tipikus magyar városi területekre koncentrálva.

A témában elérhető szakirodalom áttekintése után elsősorban kisléptékű zöld infrastruktúra elemek: fasori fák, zöldhomlokzatok, belső kertek és kis kiterjedésű városi közparkok hatását vizsgáltam. A kutatásban mértem a fa lombozatának függőleges síkra vonatkoztatott transzparenciáját, és modelleztem a belső hőmérsékletre, valamint a szellőztetési potenciálra gyakorolt hatását. A helyszíni mérések piranométer és infrakamera használatával történtek, a modellezéshez több szoftvert is használtam: numerikus szimulációkat futtattam le az ismert és széles körben használt, validált ENVI-met szoftver használatával. A beltéri hőérzet modellezéséhez az ECOTECT nevű szoftvert alkalmaztam.

A kutatási eredményeim igazolták, hogy a zöld infrastruktúra elemek sikeresen tudják pozitívan befolyásolni épület és szomszédsági léptékben a mikroklímát, és gátolják a nyári hőstressz kialakulását. A zöld homlokzat hatásai között kiemelendő, hogy az uralkodó széliránnyal párhuzamosan telepítve, a városi átszellőzésre gyakorolt hatása erősebb. A fasorok esetében is hasonló hatást figyelhetünk meg a szélsebesség és szélprofil változásában, köszönhetően a megváltozott érdességnek, éppen ezért célszerűbb a növényzetet az utcán aszimmetrikus módon telepíteni, amely ily módon javíthatja a szélkomfortot.

A fák vertikális transzparenciájának vizsgálata során három jellemző városi faj árnyékolási potenciálját mértem: az eredmény azt mutatta, hogy a legjobb árnyékoló a nyugati ostorfa (*Celtis occidentalis*; *τ=11.3*%), hasonló értékeket mutatott a kislevelű hárs *(Tilia cordata, τ=12%.)*; és a legrosszabb teljesítményű a japánakác *(Sophora japonica, τ=16.6%)*. A transzmisszivitás értékeket alapul véve további szimulációkat végeztem a fák a belső térre gyakorolt sugárzási nyereség csökkentő hatását vizsgálatának érdekében. A szimuláció kimutatta, hogy az épület homlokzata elé ültetett fa (délre, délnyugatra tájolva) nyári körülmények között 20-60% -kal (maximum 1 kW / m2 / nap) csökkentheti a napi napsugárzást függőleges felületen (ha = 12-16%).

Szomszédsági léptékben a belső udvarok, illetve kisléptékű városi közparkok, valamint fasorok telepítésének hatását vizsgáltam. A modellezés kimutatta, hogy hagyományos körfolyosós bérházak belső szárnyainak lebontásával, és az egybenyitott udvar zöldítésével a szélsebesség és az égbolt láthatósági tényező (*SVF*) növekszik, ami kedvező, azonban az épületek belső szárnyainak lebontása növeli a nyári túlmelegedés kockázatát is. Minden negatív hatás megoldható az udvarok intenzív parkosításával, ezáltal jobb hőkomfortot és lakókörnyezetet teremtve az udvaron és az udvarra nyíló lakásokban is.

Az utolsó esettanulmány a klímaadaptív tervezés hatásait és lehetőségeit vizsgálta több zöld infrastruktúra elem egyidejű, szomszédsági léptékű alkalmazásával. Igazoltam, hogy a fasori fák, ültetőládák és az új zöldterületek jelentősen csökkentik a nyári hőstressz kockázatát, vagyis az *MRT*, a $T_{lég}$ és a *PMV* értékeit. Ugyanakkor nyilvánvalóvá vált az is, hogy a fák megvalósításának mikroklimatikus hatása nem haladja meg a beavatkozás területét, mégis az új zöldfelület hatása térben kiterjedtebb, mint például egy fasoré.

Összefoglalva, a dolgozat eredményei hozzájárulhatnak a kisléptékű zöld infrastruktúra elemek hatékonyabb alkalmazásához a város- és szabadtértervezésben.

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