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AUTHOR

AUTOR PRÁCE

Bc. Kristina Šmídová

SUPERVISOR

VEDOUCÍ PRÁCE

Ing. OLGA RUBINOVÁ, Ph.D.

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Student	Bc. Kristina Šmídová
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doc. Ing. Pavel Schmid, Ph.D.
Vedoucí ústavu

prof. Ing. Miroslav Bajer, CSc.
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Ing. Olga Rubinová, Ph.D.
Vedoucí diplomové práce

ABSTRACT

This paper is focused on introducing urban greenery as an element of sustainable building and mainly as an element which contributes to pollution-free air and a better environment in the cities. Also, this Master's thesis is focused on the relation between urban greenery and air pollution in Brno city. For six months, from June to November of 2019, carbon dioxide concentration, oxygen concentration and other secondary elements were measured in Brno city. The measurements took place at four locations which were then compared.

Also, green measures were designed. The design consists of an extensive roof implementation on existing roofs at two selected locations in Brno city.

KEYWORDS

Urban greenery, sustainable building, sustainability, emissions, oxygen, carbon dioxide, quality of life, urban heat islands, design, green measures, extensive green roof

ABSTRAKT

Tato práce se zaměřuje na představení městské zeleně jako důležitý prvek udržitelné výstavby, a především jako prvek, který zbavuje okolní vzduch znečištění a přispívá k lepšímu prostředí ve městech. Dále se tato diplomová práce zabývá vztahem mezi městskou zelení a znečištěním ovzduší oxidem uhličitým v Brně. Ve městě byla prováděná měření koncentrací oxidu uhličitého, kyslíku a sekundárních veličin po dobu půl roku od června do listopadu roku 2019. Měření byla prováděna na čtyřech místech v Brně a dále tato data byla mezi sebou porovnána.

Dále byla navrhnutá zelená opatření. Ve dvou vybraných lokalitách v Brně byly vybrány střechy, na které byla navrhnutá extenzivní zelená střecha.

KLÍČOVÁ SLOVA

Městská zeleň, trvale udržitelná výstavba, udržitelnost, emise, kyslík, oxid uhličitý, kvalita života, městské tepelné ostrovy, návrh, zelená opatření, extenzivní zelená střecha

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DECLARATION OF CONFORMITY OF THE PRINTED AND ELECTRONIC FORM OF THE FINAL THESIS

I declare that the electronic form of the submitted master's thesis titled *Green as a healing element of buildings and cities* is identical to the submitted printed form.

Brno, 6. 1. 2020

Bc. Kristina Šmídová
author

DECLARATION OF AUTHORSHIP OF THE FINAL THESIS

I, Bc. Kristina Šmídová declare that this master's thesis titled *Green as a healing element of buildings and cities* is my own work and the result of my own original research. I have clearly indicated the presence of quoted or paraphrased material and provided references for all sources.

Brno, 6. 1. 2020

Bc. Kristina Šmídová
author

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Bc. Kristina Šmídová
author

CONTENT

1	INTRODUCTION	10
2	THE AIM	11
3	URBAN GREENERY	12
3.1	Czech Legislation	12
3.2	Urbanization	13
3.3	Urban Greenery Impact	15
3.3.1	Function	16
3.4	Types of urban green space	19
3.4.1	Green roofs, facades, green applications	20
3.4.2	Urban heat islands	22
4	SUSTAINABLE DEVELOPMENT	25
4.1	Sustainable Building	25
4.1.1	Certificates	25
5	AIR QUALITY	27
5.1	Air pollution	27
5.2	Pollutants of main concern.....	28
5.2.1	Particulate matter PM10 and PM2,5.....	28
5.2.2	Nitrogen oxides NO _x	29
5.2.3	Ground-level ozone O ₃	29
5.2.4	Sulphur dioxide SO ₂	29
5.2.5	Carbon monoxide CO	30
5.2.6	Volatile organic compounds VOC and Hydrocarbons HC.....	30
5.2.7	Smog	31
5.3	Greenhouse gasses	31
5.3.1	Carbon dioxide CO ₂	31
5.3.2	Methane CH ₄	33
5.3.3	Nitrous oxide N ₂ O	33
5.4	Noise pollution.....	33
5.5	Monitored indicators in Czech Republic.....	34
5.5.1	Brno Agglomeration.....	35

6	MEASURING	36
6.1	Locations	38
6.2	Preconditions.....	42
6.3	CO ₂ Sources	42
6.4	CO ₂ concentration results.....	45
6.4.1	Daytime comparison.....	45
6.4.2	Months comparison.....	46
6.4.3	Locations.....	48
6.5	O ₂ concentration results	58
6.6	Temperature, humidity, windspeed	59
6.6.1	Months comparison.....	59
6.6.2	Locations.....	61
6.7	Summary.....	68
7	GREEN MEASURES DESIGN	69
7.1	Design.....	71
7.1.1	Brno-Zábrdovice district	72
7.1.2	Brno-Černovice district	74
	CONCLUSION	76
	REFERENCES.....	77
	LEGISLATION.....	81
	LIST OF ABBREVIATIONS	82
	LIST OF FIGURES	83
	LIST OF GRAPHS.....	84
	LIST OF TABLES	86

1 INTRODUCTION

When the Industrial revolution began, the new construction in the suburbs has not stopped since. The so-called urbanisation created the demand for a healthy environment in the cities. The healthy environment was supposed to be ensured by sufficient amount of fresh air and greenery; however, the environment in the cities only got worse. Because of that, people started to seek the greenery in the suburbs, creating the so-called urban sprawl. Thereby, the cities are getting wider and emptier, with many brownfields left inside the urban areas. As a result, the efforts to preserve urban greenery have been growing in recent years, as the urbanisation puts pressure on the open space.

Urban greenery is one of the most important aspects of current cities. It is a place for recreation, sports, for spending free time, for relaxation and other activities. It is also an important element of human health and well-being. Vegetation reduces stress levels, diminishes noise and air pollution, cools air – thus reduces the urban heat island effect. Besides, urban vegetation fulfils the aesthetic role.

Greenery, in general, is also important in reducing the CO₂ concentration from the atmosphere and, more importantly, it creates oxygen, which is an essential element for all living creatures on Earth. Therefore, the emphasis on preserving the urban environment healthy is essential for people's lives, as more people are now living in cities.

This Master's thesis is divided into three sections. The first section is focused on introducing urban greenery and aspects that are connected to it, like sustainable development, the impact of urban greenery, green measures and other.

The second part is focused on measurements which were collected for six months from June to November of 2019. The carbon dioxide concentration and the oxygen concentration was measured as well as the secondary elements such as temperature, humidity and wind speed. The measurements were monitored in four locations in Brno city. The locations were chosen according to their nature. Two locations represented areas with rich vegetation and greenery and the other two represented locations with a little to no vegetation, with high-rise buildings and high traffic loads. Then these locations were compared to each other. The measurements were collected to find out whether the vegetation contributes to the reduction of CO₂ concentration from the air.

The third part of this paper is focused on the implementation of green measures on selected locations in Brno city. Two locations were chosen for this purpose, one in the urban centre and the second one in the suburbs, in the industrial area of Brno city.

2 THE AIM

This paper aims to introduce urban greenery as a healthy and sustainable aspect of current cities. Also, to compare selected urban areas in Brno city with rich vegetation and areas with high traffic loads, based on monitored indicators such as carbon dioxide, oxygen and secondary indicators like temperature, humidity and wind speed. Then, according to the measurements, to design green measures on selected buildings in appointed locations in Brno city.

3 URBAN GREENERY

Green areas in urban centres are those with natural elements and intentionally established elements according to garden and landscape architecture. The elements could be of the natural or artificial origin or of organic or inorganic origin. For instance, natural and organic elements are trees, bushes, flowers etc. Inorganic elements are water, ground and rocks and finally, artificial elements are buildings, outdoor furniture, stairs, pavements etc.

Urban green is one of the most important aspects of a contemporary city. It is a place for recreation, free time, sports or just for rest. It affects the quality of human health and life, also the life of urban fauna. It has a positive impact on the urban microclimate, urban biodiversity, water retention, human health and well-being.

3.1 CZECH LEGISLATION

In the Czech Republic there are acts, regulations and norms connected to the environment, air quality, greenery, and emission levels. These documents address environmental impact, quality of the air, levels of pollutants in the atmosphere allowed within specified time etc.

Act no. 201/2012 Coll. on air protection

The Act determines how to prevent and reduce air pollution, to limit the risks to human health and the environment. The Act also defines how to protect the environment from the pollutants emitted into the atmosphere and creates prerequisites for the regeneration of the environmental compartments affected by air pollution. [53]

Table 1 The emission limits declared for the protection of human health and a maximum number of overrun according to the Act. no. 201/2012 Coll. on air protection [53]

Pollutants	Avg. Time	Emission limit	Max. number of overrun
Sulphur dioxide	1 hour	350 $\mu\text{g.m}^{-3}$	24
Sulphur dioxide	24 hours	125 $\mu\text{g.m}^{-3}$	3
Nitrogen dioxide	1 hour	200 $\mu\text{g.m}^{-3}$	18
Nitrogen dioxide	1 year	40 $\mu\text{g.m}^{-3}$	0
Carbon monoxide	Max. daily eight-hour avg.	10 $\mu\text{g.m}^{-3}$	0
Benzene	1 year	5 $\mu\text{g.m}^{-3}$	0
Particles PM10	24 hours	50 $\mu\text{g.m}^{-3}$	35
Particles PM10	1 year	40 $\mu\text{g.m}^{-3}$	0
Particles PM2,5	1 year	25 $\mu\text{g.m}^{-3}$	0
Lead	1 year	0,5 $\mu\text{g.m}^{-3}$	0

Act no. 17/1992 Coll. on environment

The law defines basic concepts and lays down the basic principles of environmental protection and the obligations of legal and natural persons to protect and improve the state of the environment and the exploitation of natural resources; Based on the principle of sustainable development. [54]

Act No. 100/2001 Coll. on environmental impact assessment

In accordance with European Union law, the law governs the assessment of environmental and public health effects and the procedure of natural and legal persons, administrations and territorial self-governing units (municipalities and regions). [55]

The main focus of this act is on defined impacts and concepts, the implementation of which could seriously affect the environment. [55]

The purpose of the environmental impact assessment is to obtain an objective technical basis for the issue of the decision and, where appropriate, measures under specific legislation, thereby contributing to the sustainable development of the society. [55]

3.2 URBANIZATION

Contemporary problems of urbanism and spatial development are undoubtedly the result of urban development in the last 200 years linked to the urbanization period. [2]

According to the findings, the natural conditions, like terrain configuration, watercourses, estuaries, were the most important for the ancient populations. Towns were built near rivers, because communities were mainly focused on agriculture, e.g. ancient civilization in Mesopotamia near Euphrates river and Tigris river. [2]

The main element of the medieval town was the fortification system – walls. The system was there to provide protection of towns and it should have ensured the potential enemy would not get beyond the walls. Around these walls was left a strip without green or houses for security and strategic reasons. In medieval times castles with huge towers and chapels were built. Monasteries had become the centres of cultural and economic development. Natural conditions were in medieval towns as important as in ancient towns. [2]

The population in the medieval towns was around 2000 people maximum. The most populated town in the 14th century was Paris with approx. 110 thousand people. The population was very variable due to wars and diseases. The towns were centres of trade with squares in the central position. Churches and monasteries were also in the towns' centres. On the other hand, the greenery was rather

occasional. The technical infrastructure was at a very low level and the main cause of the vast majority of diseases was caused by missing sewage system. [2]

The modern period is characterised by changes in economic activities. Agriculture is more mechanized, and the workforce is directed to the cities. With this fact, towns got bigger because people started to realize the advantages of living in the centre or near the centre of the towns. The main benefit was, that there was a smaller commuting distance people had to take in order to get better or more goods or a better job. [2], [3]

The biggest increase of population could be dated in the 18th century when the Industrial revolution begun. People from rural regions moved into towns for new factory workplaces. Due to the technological and scientific development, industries were able to build factories outside of towns, therefore many cities became larger. Simultaneously the population in towns has grown dramatically. For instance, within just one hundred years the number of towns with a population of more than 100 000 people increased from 15 to 87. In the United Kingdom, the urban population had increased by 40%, from 30% to 70%, within just sixty years. This phenomenon is called urbanization – people from rural regions moving into cities. [2], [3]

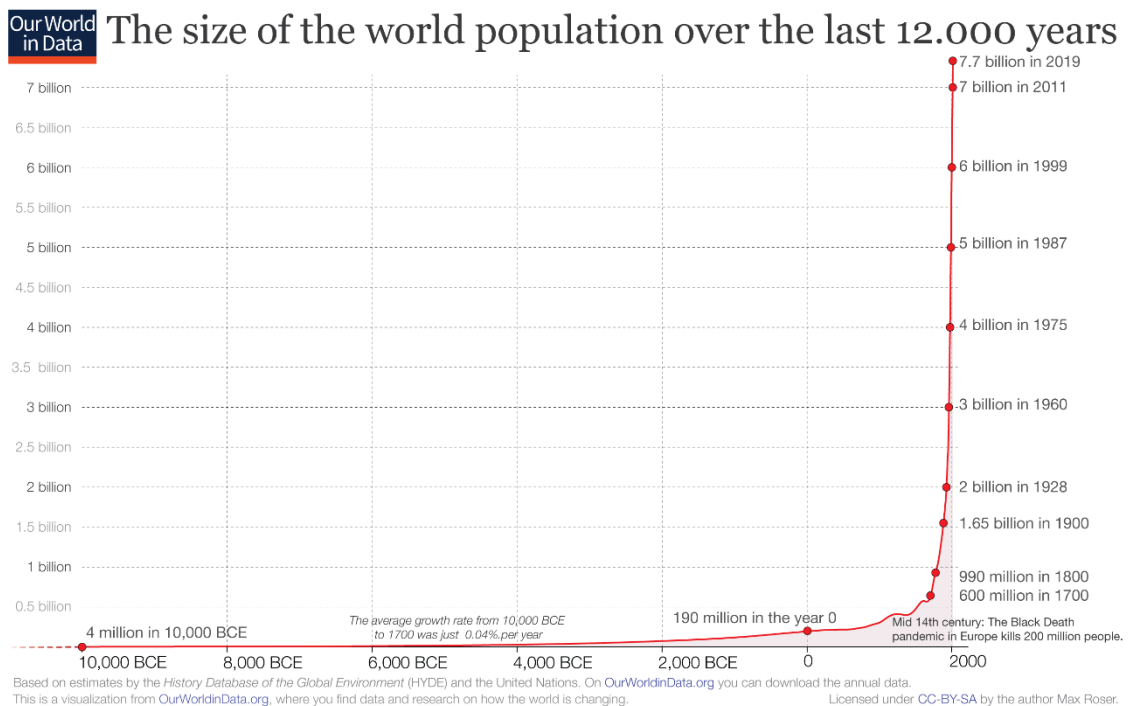


Figure 1 World Population Growth, source [6]

The Industrial Revolution had several consequences. It has created new workplaces for many inhabitants, smaller commuting distances to work, market development, education development etc. On the other hand, the necessity of

spatial growing due to the urban expansion had become larger. The medieval fortifications had been demolished and factories built instead. People were crammed into tiny living spaces, and the conditions they were living in were atrocious. Citizens started to realise that living in urban areas has also many disadvantages – little space, polluted air, noise from factories and others. So, the demands for better living conditions had increased. [3]

People started to leave the cities, seeking for better living environment, calmer areas and more greenery. By shifting population from urban areas and settling down in the suburbs the towns were becoming less populated creating formations of so-called 'urban sprawl'. This new ideology started approximately in the 19th century and has not stopped since. This phenomenon promotes spatial vastness and low population density. [1], [3]

Cities are becoming more vacant and full of uninhabited spaces creating brownfields and contaminated areas while in the suburbs more and more new houses are built. Land that was once used for agriculture is now becoming suburbs. This building in the rural areas so-called 'green fields' is unsustainable in the long run. And the paradox is that people that are leaving urban areas want to get back to the rural regions which they once left. And with a good reason. Citizens want better living conditions – more greenery, less noise and air pollution. However, looking for better living conditions in the suburbs is not a solution to this problem. Not only is this unsustainable, but also uneconomical and unecological. For instance, commuting distances to centres are longer, therefore, the emissions and air pollution are rising again. [1], [3]

So, is there even a solution to how this problem could be fixed? This negative phenomenon could be fixed by making cities more attractive to its citizens - by improving its environment, to take care of brownfields and contaminated areas.

One thing to improve cities environment could mean to lower the number of vehicles that pass through, repairing and restoring the old and contaminated sites which are no longer in use, to incorporate more green elements into the cities e.g. parks, recreational areas, more trees and vertical gardens etc.

3.3 URBAN GREENERY IMPACT

Greenery forms lungs of towns and cities. It can cool down the urban areas, clean up the air, provide places for rest for citizens, has a positive effect on humans' health and provide a haven for animals and insect. Also, vegetation can store carbon dioxide, lower the noise pollution, decrease the urban heat islands effect, provide a canopy and lower the stress levels. [4][10]

Greenery in urban areas can have a different impact on its citizens. For instance, it is proven that there is a positive relationship between human health and the

presence of urban trees. Hospital patients with views of trees heal much faster, unlike those without such views. [5]

On the other hand, greenery can have a negative impact like infrastructure and utility lines damages, allergies, polluted runoffs etc. However, such problems can be solved. For example, through thoughtful selection of plants and trees, or to ensure proper cleaning of runoffs is done.

3.3.1 Function

Greenery has several functions:

- a) Recreational – psychological and aesthetical function
 - b) Hygienic – positively contributes to better microclimate in urban areas, contributes to higher humidity, equalizes temperature differences, lowers the noise and air pollution, creates oxygen
 - c) Forming urban spaces – spatial division, highlights landmarks...
 - d) Resource protection – soil erosion protection, better water infiltration into the soil
 - e) Economical – tourism
 - f) Ecological - biodiversity protection, providing habitats for many species
- [8]

Ad a) Recreational and psychological function

Green is an essential aspect of the recreational function in cities. These effects result from the very nature of greenery, especially from psychological, aesthetic and hygienic aspects. Green helps to improve the respiratory functions. It is also known for its soothing effect. [8]

Greenery has a positive effect on humans' mental hygiene. The natural elements (greenery, water, terrain) are precepted by the nervous system as a rest. Natural scenes, colours, sound of falling water etc. creates a sense of harmony and well-being. [8]

Ad b) Hygienic function

Green affects urban microclimate such as temperature, humidity, quality of the air and influences the airflow, which could be used in the design of public spaces. Vegetation provides shade, prevents from excessive sun exposure and overheating in public areas in hot summer days. This is important, especially in exposed southern locations. Resulting effect of this so-called 'air conditioning' depends on quality, quantity, age and vegetation species composition used in such locations. [8]

The humidity in urban areas is influenced by transpiration. Urban air tends to be drier than in the surroundings, because of the built-up surfaces. [8]

Greenery affects air quality by:

- Mechanical collection of particulate matter,
- CO₂ absorption and O₂ production,
- Indirectly by reducing airflow speed or by moisture production,
- Creating oxygen. [8]

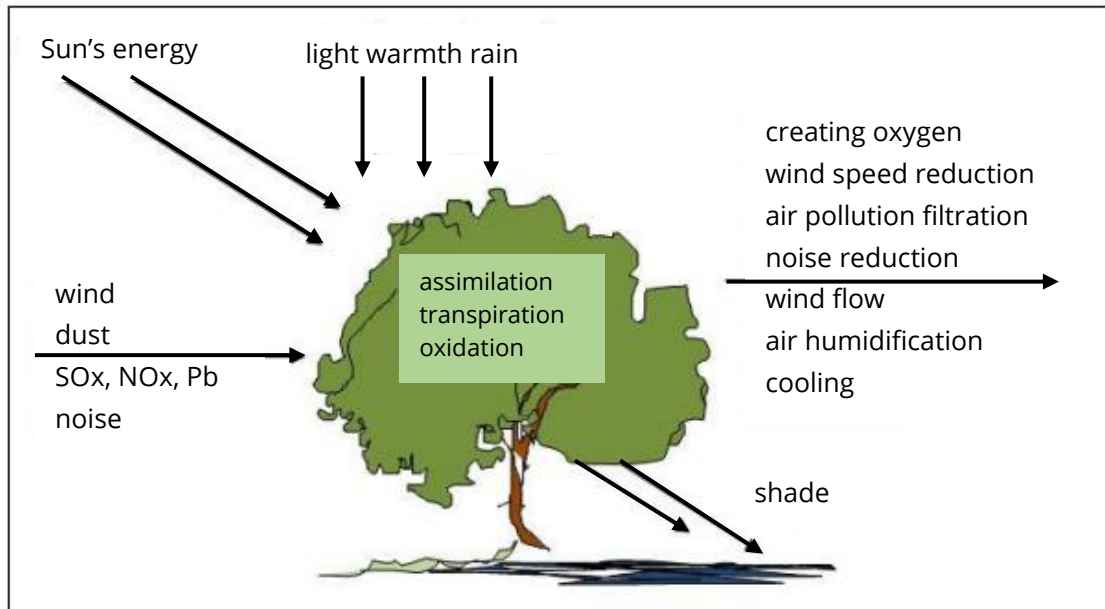


Figure 2 Greenery in the streets [8]

The amount of particulate matter collected highly depends on the nature of the vegetation – leaf size and surface, rotation etc. Smooth leaves or moving leaves, due to the wind, do not catch as much dust as the larger, wrinkled, sticky or horizontal leaves. Therefore, grass surfaces are more efficient. During rainy days, the dust is flushed into the soil or lawn, from where it cannot be swirled back into the air, unlike from the hard surfaces (pavements, streets...).[8]

Trees (deciduous) compared to air conditioning provide shade and canopy in summer. In addition, trees create oxygen, wind protection, refresh and humidify the air and can bind the dust from it. In the winter and early spring, trees let through the warmth from the Sun's radiation. Moreover, the cost and maintenance of trees are minimal. Air conditioning, on the other hand, requires high energy use, the cost and maintenance is much higher, and the AC cannot create oxygen. [8]

„ For example, in tropical climates, increasing building ventilation increases cooling demand, which increases both energy requirements and the amount of CO₂ indoors through greater use of air conditioning.”¹ [7][8]

¹ [7] JACOBSON, Tyler A., Jasdeep S. KLER, Michael T. HERNKE, Rudolf K. BRAUN, Keith C. MEYER a William E. FUNK. Direct human health risks of increased atmospheric carbon dioxide. *Nature*

The ability of trees to reduce noise levels is relatively low. It depends on spatial structure, size of green areas, etc. Nevertheless, it is known that tree's branches can absorb some of the acoustic energy by resonance. Sounds of lower frequency are taken in more than noises of high frequency. However, the most efficient method of reducing noise levels is to combine vegetation with technical measures. For instance, noise barriers paired with green. [8]

Ad c) Forming urban space

Greenery is essential in terms of spatial design and design of the urban areas. Vegetation can close, extend, open, frame and define most important urban spaces and landmarks. Moreover, it can direct attention in the desired direction. Vegetation affects the aesthetic impression from urban centres. [8]

Ad d) Resource protection

These include soil protection, against water and wind erosion, protection of surface and underground water resources, as well as the water management. [8]

Greenery contributes to the protection of soil and water resources by slowing down the surface water runoff and helps with water infiltration. Furthermore, vegetation contributes to the strengthening of banks of streams, rivers, ponds and reservoirs. Vegetation also contributes to the protection against wind erosion by implementing windbreaks. Their function is to reduce wind speeds. [8]

Ad d) Economical function

The economical function is primarily provided by farmlands. That include vineyards, hop fields, orchards, forests as well as fields and meadows. [8]

Ad d) Ecological function

Vegetation as well as the water, soil and climate are basic aspects of the ecosystem. The more it corresponds with the permanent ecological conditions of a given area, the higher its ecological value is. Furthermore, the ecosystem creates habitats for numerous of plant and animal species. Therefore, it is important to protect and maintain these habitats. It is ensured by networks of specially protected areas. Territorial System of Ecological Stability (TSES) ensures the basic conditions for the preservation and reproduction of natural assets. [8] [9]

Sustainability [online]. 2019, 2(8), 691-701 [cit. 2019-11-24]. DOI: 10.1038/s41893-019-0323-1. ISSN 2398-9629. Available from: <http://www.nature.com/articles/s41893-019-0323-1>

„ Its main purpose is to reinforce the ecological stability of the landscape by conservation or restoration of ecosystems and their mutual interconnection.”²

It consists of a network of Supraregional, Regional and Local biocentres. These parts of TSES are designed and defined to create a network of habitats in the territory, which represent typical communities in these areas. [9]

3.4 TYPES OF URBAN GREEN SPACE

There are many types of urban greenery which can be applied in urban areas. Trees, green roofs, vertical gardens and facades, parks, community woodlands, tree-lined roads, wetlands etc. Each of these types can be applied in different conditions, yet they all are important.

„ They can create an extensive and powerful recreational, cultural and community facility, improving environmental quality and health, as well as providing diverse and species-rich habitats. The term ‘urban forest’ is often used to describe greenspace that brings all the benefits of the natural environment to the heart of urban communities.”³[11]

Green roofs and vertical gardens or facades are vegetative layers with a highly positive effect on the environment. In many cases, they have potential to make convectional urban spaces more attractive for residents. [12]

Green roofs and facades conserve energy, provide shelter for wildlife, provide sustainable drainage (especially green roofs) and may improve air quality.

Green areas fulfil ecological, hygienic, recreational and spatial function in the urban structure. Green spaces in built-up spaces can be divided into four types:

- Private greenery – private, accessible to owners only - gardens
- Semi-private greenery – only for a limited group of people (e.g. university courtyard)
- Public greenery – accessible to everybody - parks, alleys etc.
- Semi-public greenery – accessible with time limitation – chateau park [13]

Public greenery can be distinguished into types like urban parks, alleys, recreational forests, accompanying greenery of rivers, isolated greenery (solitary trees). The so-called Green System is the sum of all the greenery in the city. Its form describes how large areas of green space are found in the city, how they are connected, and whether there is any at all.

² [9] Territorial system of ecological stability. *Agentura ochrany přírody a krajiny České Republiky* [online]. [cit. 2019-11-24]. Available from: <http://www.ochranaprirody.cz/en/what-we-do/territorial-system-of-ecological-stability/>

³[11] Types of greenspace. *Forest Research* [online]. [cit. 2019-11-29]. Available from: <https://www.forestresearch.gov.uk/tools-and-resources/urban-regeneration-and-greenspace-partnership/greenspace-in-practice/types-of-greenspace/>

There are three types of green systems:

- Point system
- Liner system
- Or a combination thereof. [13]

3.4.1 Green roofs, facades, green applications

The green roofs are building roofs that are fully or partially covered with vegetation. The choice of vegetation depends on local weather conditions, climate etc. There are three types of green roofs that are usually distinguished. Extensive, intensive and semi-intensive roof. The difference between those three roofs is mainly in the soil mass and the type of vegetation used. [12]

Green roofs are considered effective in the reduction of atmospheric CO₂, they also have the ability to reduce the energy consumption of buildings and sequester carbon in plants and substrates. Green roofs can also absorb rainwater, which would otherwise flow away in runoffs. Vegetation can take in water which is evaporated later. Evaporation is the most important aspect of the cooling effect in urban centres, thus reducing the urban heat island effect. [18]

On the other hand, green roof components may cause CO₂ emissions during their lifecycle. However, according to the study on payoff of extensive green roofs, Kuronuma et al. concluded that, „ *The results of the study show that CO₂ emissions are offset through CO₂ sequestration and energy savings after 5.8 to 15.9 years, which indicates that extensive modular green roofs contribute to atmospheric CO₂ reduction and global warming mitigation within their lifespan.*”⁴ [18]

Extensive green roofs

Extensive green roofs do not have large soil mass, approximately from 60 – 150 mm. Usually, the small vegetation or vegetation with thick leaves (they can absorb more water) is used. Also, this type of green roof should be able to maintain its appropriate quality without regular irrigation and only with a minimal care of humans, approx. once or twice a year of control (removal of unwanted vegetation, fertilization etc.). The selection of used plants is necessary to adapt to the local conditions.[12]

The vegetation of extensive roofs consists of plants with the high regenerative ability and are able to adapt to extreme habitat conditions. Plants must be

⁴ [18] KURONUMA, Takanori, Hitoshi WATANABE, Tatsuaki ISHIHARA, Daitoku KOU, Kazunari TOUSHIMA, Masaya ANDO a Satoshi SHINDO. CO₂ Payoff of Extensive Green Roofs with Different Vegetation Species. *Sustainability* [online]. 2018, **10**(7) [cit. 2019-11-30]. DOI: 10.3390/su10072256. ISSN 2071-1050. Available from: <http://www.mdpi.com/2071-1050/10/7/2256>

sufficiently competitive under the given conditions to suppress the development of undesirable plants. [12]

The entry to areas with vegetation is allowed only to selected people for inspection and technical maintenance.

Types of vegetation used:

- Moss,
- Sedum, other succulents, where appropriate,
- Grasses and herbs,
- Or a combination thereof.

Intensive green roofs

These green roofs have large soil mass usually thicker than 300mm, depending on used vegetation. They contain more resilient vegetation with deeper roots, unlike the extensive roofs. The adjustment of conditions for selected vegetation including intensive regular maintenance like irrigation, fertilization, removal of unwanted plants, regular mowing of the lawn etc. is essential. [12]

The choice of plants is a subject to an architectural intent and (as a rule) a residence function. The conditions and care are adapted to vegetation as much as possible. [12]

Types of vegetation used:

- Lawn,
- Perennials,
- Bushes,
- Trees,
- Vegetables, fruits.

Semi-intensive green roofs

These roofs have medium size soil mass, approximately 150 mm to 350 mm. In addition to vegetation suitable for extensive green roofs, other plant species such as grasses, perennials, trees that have higher demands on the composition of vegetation formations, water supply and nutrients can be used on semi-intensive green roofs. The higher intensity of care lies mainly in the need for irrigation in drier periods of the year. Other interventions do not significantly exceed the care of extensive roof (twice a year inspection, removal of unwanted vegetation, fertilization etc.) [12]

Types of vegetation used:

- Grasses and herbs,
- Perennials,
- Bushes
- Or a combination thereof.

Green facades and green walls

There are two types of green walls distinguished. Systems linked to the ground (climbing plants) and systems which are not linked to the ground (vertical gardens). Systems linked to the ground are those where plants are planted directly into the ground which surrounds a building. Vegetation like lianas or other climbing vegetation is usually used. Because these climbing plants grow fast, they are weak, thus they need support in form, for example, steel net. [32]

Systems which are not linked directly to the ground are distinguished into three types – shelf system, modular system and surface construction system. [32]

The shelf system consists of containers with plant suspended on the wall. [32]

The modular system consists of prefabricated parts that are installed on the supporting structure on the wall. The main advantage of this system is an easy installation and subsequent replacement of dead plants. [32]

In case of the surface construction system, the installation of the supporting construction is necessary, subsequently it is possible to plant vegetation. [32]

3.4.2 Urban heat islands

Urban heat islands occur when urban areas are warmer compared to their rural surroundings. This is caused when original open lands and green lands are replaced by urban infrastructure, roads, sidewalks, parking lots and buildings - towns. Materials such as asphalt, concrete etc. accumulate heat from the sun and cannot store water, unlike plants. As a result of this impermeable and dry ground covers is quick water runoff and surface reduction, where water can be stored and evaporated. Therefore, there is less moisture to keep urban areas cool.

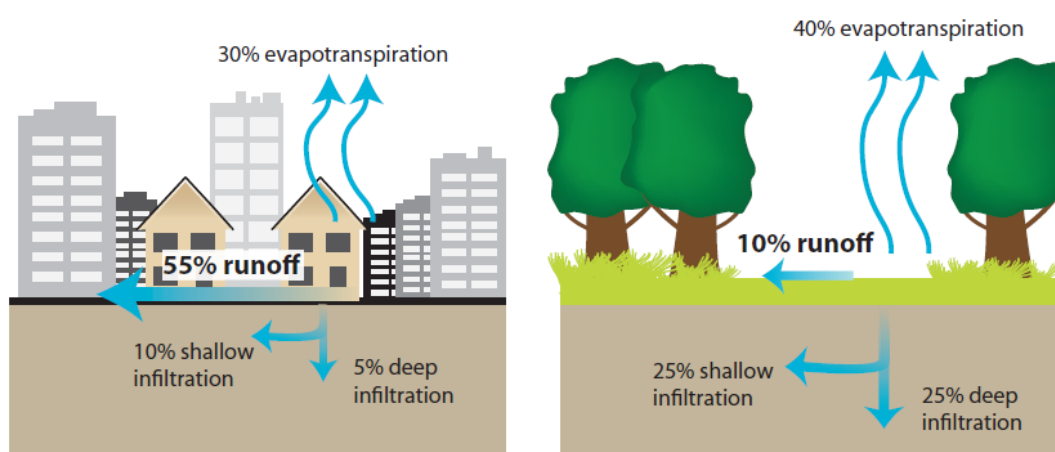


Figure 3 comparison built-up area with the rural area, evapotranspiration, [14]

„ Build up areas evaporate less water, which contributes to elevated surface and air temperatures.”⁵ [14]

That, coupled with concentrated energy use and less airflow inside urban areas, creates a heating effect. [15]

Urban heat is also influenced by materials used on roofs, pavements etc. More specifically by material's solar reflectance, thermal emissivity and heat capacity. They determine how the Sun's energy is reflected, emitted and absorbed. For instance, during summer days, the Sun can heat up dry, exposed urban surfaces (roofs, pavements) to temperatures from 27 to 50°C hotter than the air, while shaded and moist surfaces - parks, rural surroundings - remain close to the air temperatures. Surface urban heat islands tend to be strongest during the day than night and are typically largest in the summer, because surface UHI varies with seasons, due to changes in the Sun's intensity. [14]

Urban geometry is another factor that influences the urban heat island effect. It influences wind-flow, energy absorption and a given surface ability to emit long-wave radiation back to space. At night, the air above urban centres, is typically warmer than the air above rural areas, because densely built-up areas become thermal masses and cannot release their heat very readily into the atmosphere.

„ Higher night-time temperatures can already lead to nocturnal heat-stress and disrupted sleep for city residents in some parts of the world.”⁶

Night-time especially can have serious health implications for urban residents. The narrow street lined by tall buildings, so-called 'urban canyons' is an aspect of urban geometry that researches are often focused on. [14]

„ On the one hand, tall buildings can create shade, reducing surface and air temperatures. On the other, when sunlight reaches surfaces in the canyon, the sun's energy is reflected and absorbed by building walls, which further lowers the city's overall albedo—the net reflectance from surface albedo plus urban geometry—and can increase temperatures.”⁷ [14]

Urban heat island effect can affect human health and quality of life and the community's environment. Especially during the summer, when outside

⁵ [14] U.S. Environmental Protection Agency. *Reducing urban heat islands: Compendium of strategies: Urban heat island basics* [online]. In.: 2008 [cit. 2019-11-29]. Available from: <https://www.epa.gov/sites/production/files/2014-06/documents/basicscompndium.pdf>

⁶ [15] *Climate Conversations - Urban heat islands by Met Office* [online]. In.: 2012 [cit. 2019-11-29]. Available from: <http://climaterealist.com/index.php?id=10318>

⁷ [14] U.S. Environmental Protection Agency. *Reducing urban heat islands: Compendium of strategies: Urban heat island basics* [online]. In.: 2008 [cit. 2019-11-29]. Available from: <https://www.epa.gov/sites/production/files/2014-06/documents/basicscompndium.pdf>

Sailor, D.J., and H. Fan. 2002. Modeling the Diurnal Variability of Effective Albedo for Cities. *Atmospheric Environment*. 36(4): 713-725.

temperatures are elevated. While impacts like the plant-growing season seem positive, due to elevated temperatures, most impacts are negative and include:

- Increased energy consumption,
- Elevated emissions of air pollutants and greenhouse gases,
- Compromised human health and well-being,
- Water quality degradation.

The demand for cooling during the summer increases with elevated summertime temperatures. That leads to additional pressure to the electricity grid during peak periods of demand. Electric demand rises by 2-4 percent for each 1K increase in summertime temperature. „ *Thus, the additional air-conditioning use caused by this urban air temperature increase is responsible for 5-10% of urban peak electric demand.*⁸ [16]

Before 1940, the average urban-rural temperature differences were always negative – cities were cooler than their rural surroundings. However, after 1940 when built-up areas started to replace vegetation, the urban centres became as warm or warmer than the suburbs, where the majority of surface is covered with vegetation. [16]

The use of green measures (roofs, facades etc.) and vegetation in towns and cities can have a substantial effect on air temperature and the urban heat island effect. These measures can cool down the cities, as well as reducing the cooling-energy use, by selecting suitable surfaces (with high albedo or, as mentioned, the vegetation) for the buildings and pavements.

⁸ [16] AKBARI, H. *Potentials of urban heat island mitigation*. 2005.

4 SUSTAINABLE DEVELOPMENT

„ The term “sustainability” should be viewed as humanity's target goal of human ecosystem equilibrium (homeostasis), while “sustainable development” refers to the holistic approach and temporal processes that lead us to the endpoint of sustainability.”⁹

[17]

According to Act No. 17/1992 Coll. about the environment, sustainable development is a development that preserves the abilities of current and future generations to satisfy their needs, while not reducing the natural diversity and preserves natural ecosystem functions.

4.1 SUSTAINABLE BUILDING

The sustainable building plays a considerable part in sustainable development. The sustainable building also known as green building requires different approach to ‘conventional’ building industry. It requires changes to attitudes, paradigms, processes and systems to deliver the project.

Sustainable building involves land use, use of brownfields, green building, use of renewable energy sources, lowering emissions and waste, usage of more sustainable or recyclable materials etc. The sustainable building emphasises on lowering the impact on environment during the building’s lifecycle. It focuses on the effective use of renewable energy resources such as water, solar energy, land and materials. [19]

The concept of sustainable development in the building industry has been defined as a set of indicators in the multicriteria analysis to include environmental, social and economic aspects of sustainability. [19], [20]

4.1.1 Certificates

‘Sustainability’ of buildings is measured by certificates, which can buildings acquire. The most common certificates are BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design), SBTool (Sustainable Building Tool), and others. The certificates are not mandatory. However, in recent years there is starting to be more emphasis on these certificates as a building's quality and sustainability sign.

The main topics of the building assessment are:

⁹ [17] SHAKER, Richard Ross. The spatial distribution of development in Europe and its underlying sustainability correlations. *Applied Geography* [online]. 2015, **63**, 304-314 [cit. 2019-11-29]. DOI: 10.1016/j.apgeog.2015.07.009. ISSN 01436228. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0143622815001745>

- Energy use and energy sources
- The location quality where the building is
- The quality of the management
- The quality of materials used
- The quality of the indoor environment

BREEAM

„ A BREEAM assessment uses recognised measures of performance, which are set against established benchmarks, to evaluate a building's specification, design, construction and use. The measures used represent a broad range of categories and criteria from energy to ecology. They include aspects related to energy and water use, the internal environment (health and well-being), pollution, transport, materials, waste, ecology and management processes.“¹⁰[22]

LEED

The LEED (Leadership in Energy and Environmental Design) certification was developed by the U.S. Green Building Council (USGBC) in 2000. [21]

„ LEED certification provides independent, third-party verification that a building, home or community was designed and built using strategies aimed at achieving high performance in key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality.“¹¹[21]

SBToolCZ

SBToolCZ is based on international SBTool (Sustainable Building Tool). The Czech version was developed by the Faculty of Civil Engineering (Czech Technical University) in Prague. The certification fully respects the conditions of the Czech building industry, as well as the Czech legal system.[23]

„ SBToolCZ indicates the level of building quality regarding principles of sustainable construction. SBToolCZ examines and certifies the influence a building has on the environment, its social and cultural aspects, functional and technical quality, economical aspects, management and location of the building.“¹²[23]

¹⁰ [22] BREEAM Certification. *Building Engineering and Sustainable Development* [online]. [cit. 2019-11-30]. Available from: <http://www.ces.be/sustainability-4>

¹¹[21] LEED® Certification Process. *Canada Green Building Council: Every Building Greener* [online]. [cit. 2019-11-30]. Available from: https://www.cagbc.org/CAGBC/Programs/LEED/LEED_Certification_Process.aspx

¹² [23] SBToolCZ for administrative buildings. *Czech Green Building Council* [online]. [cit. 2019-10-25]. Available from: <http://www.czgbc.org/certification/sbtoolcz>

5 AIR QUALITY

Air quality is described as a level of exterior air pollution. Air pollution is caused by emissions from various sources. Most of these sources are of the anthropogenic origin such as transportation, industrial production, combustion of fossil fuels, agriculture, household heating etc. Polluted air may affect human health and well-being, vegetation, entire ecosystems and materials. Pollutants emitted into the atmosphere can affect the air quality in both the immediate vicinity of the pollutant source and the border territory. Therefore, air pollution is considered the main environmental issue. [24]

The fundamental legal regulation in the Czech Republic covering air quality assessment and management is Act no. 201/2012 Coll. on air protection, as amended.[24], [53]

5.1 AIR POLLUTION

Air pollution occurs when harmful substances are introduced into Earth's atmosphere. Pollutants can be biological or of anthropogenic origin. Biological pollutants include volcanic activities, fires, plants' production of polluted substances etc. Anthropogenic pollutants consist of human activities. These activities have led to increased pollution of the air and the soil all over the world. We can divide pollution into primary pollution and secondary pollution. Primary pollution means introducing contaminated substances directly into the atmosphere and the secondary pollution originate as a result of physical and chemical reactions in the atmosphere, for instance: ozone, SO_x, majority of NO₂, secondary aerosols etc. [25]

Pollutants may have a negative effect even on the vegetation. They can affect the growth of agricultural crops. Also, they can cause eutrophication and soil and water acidification. These toxic substances can accumulate in the environment, and negatively affect the ecosystem and can transfer into the food chain. [25]

In last twenty-five years, there have been implemented measures for significant sources like household heating and transport to reduce air pollution emissions in the Czech Republic. Nevertheless, many agricultural and social activities still produce emissions, which in combination with meteorological and scattering conditions, cause the pollutant emission limits to be exceeded in some regions. Currently, particulate matter (PM) and polycyclic aromatic hydrocarbons bonded to PM represent the main problem. Also, in summer ground-level ozone limit values tend to be exceeded in many localities in the Czech Republic. [25]

However, in most cities, the air quality has improved over the past years. Air pollution has disappeared from many cities due to local, national and European initiatives. At the same time, in many European cities, air quality is monitored because of the higher levels of traffic-related air pollution. [26]

„ Most of our economic activities are concentrated in urban areas where almost 80% of the European population lives. In urban areas transport routes and residential areas are often very close to each other and therefore transport is a major contributor to urban air pollution.”¹³[26]

Air pollution may cause health issues (e.g. respiration problems, cancer) and environmental problems like global warming.

The quality of air depends not only on sources of pollutants but also on the meteorological conditions. They affect the amount of emissions from anthropogenic and natural sources, determine the scattering conditions, influence the production of secondary pollutants in the air, as well as the removal of pollutants from the air.

Meteorological conditions have the most impact on household heating. [25]

5.2 POLLUTANTS OF MAIN CONCERN

Pollutants of main concern are those, which are monitored by EU and Czech Republic institutions. They include particulate matter, nitrogen oxides, ground-level ozone, sulphur dioxide, carbon monoxide, and VOC. All of these are emitted into the atmosphere by burning fossil fuels, industrial activity or other. They are mostly of anthropogenic origin.

They are monitored because they can be harmful to human health and the environment. They can cause many health issues, in some cases leading to premature death. Each of these pollutants have their own limit they can reach. If the levels of concentration are higher than normal the institutions alert about these conditions and should take actions against these abnormal values.

5.2.1 Particulate matter PM10 and PM2,5

Fuel combustion and industrial activity generate aerosol emissions, they can be solid, liquid or mixed. These emissions are called Total Suspended Particulate Matter (TSP). In terms of the health effects of TSP on humans, there are two size groups called PM – Particulate Matter. These PMs contain particles with an aerodynamic diameter of less than $x \mu\text{m}$ (micrometre). These emissions have different size and chemical composition, they may also contain heavy metals and are a carrier medium for volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH). Size fraction PM10 and PM2,5 are most often distinguished. [25]

PM10 and PM2,5 are very small particles, the fraction of particles in the air are $<10\mu\text{m}$ and $<2,5 \mu\text{m}$. PM2,5 are so small that can be carried deep into the lungs; therefore, these particles can cause inflammation and heart and lung diseases. Larger particles are not easily inhaled and can be removed from the air quite

¹³[26] Pollution Basics. *Air Quality in Europe* [online]. [cit. 2019-11-30]. Available from: http://www.airqualitynow.eu/pollution_home.php

effectively. The main source of airborne particulate matter in EU cities is road traffic emissions. [26]

5.2.2 Nitrogen oxides NO_x

Nitrogen oxides describe a mixture of nitric oxide (NO) and nitrogen dioxide (NO₂). These inorganic gases are formed by combination nitrogen and oxygen from the atmosphere.

When the fuel is being burned e.g. in transport the NO_x is emitted. The NO_x can affect soil and vegetation in the form of acid rains. These rains increase nitrate level in soils and surface waters, which causes eutrophication. [26]

„ Nitrogen oxides (NO_x) are formed in the combustion of fuels in dependence on the temperature of combustion, nitrogen content of the fuel and excess of combustion air and are also formed in some chemical-technological processes (production of nitric acid, ammonia, fertilisers, etc.).”¹⁴ [25]

In the atmosphere, nitrogen oxides react with water vapour and solar radiation to form nitric acid (a component of acid rain), and ground-level ozone (a component of smog). [27]

„ In addition to creating significant respiratory system problems, both acid rain and smog damage forests, streams, and agricultural products. If transported over a wide area by prevailing winds, nitrogen oxides can create regional air quality issues.”¹⁵[27]

5.2.3 Ground-level ozone O₃

Ground-level ozone O₃ is a secondary pollutant and does not have a significant source in the atmosphere. It is produced by reaction between nitrogen dioxide (NO₂), hydrocarbons and sunlight. O₃ is not emitted into the atmosphere directly. It increases the urban heat island effect due to the high temperatures in summer. Ground-level ozone can affect the lungs and may cause asthma. [31]

5.2.4 Sulphur dioxide SO₂

SO₂ is produced when fossil fuels are burnt, majority of sulphur dioxide emitted to the air is from power generation. Moderate concentrations may cause decreasing of lungs in asthmatic. From atmospheric reactions sulphur acid is generated creating the acid rain, which affects soil and vegetation. [26]

¹⁴ [25] Znečištění ovzduší na území České republiky v roce 2018: Air pollution in the Czech Republic in 2018. Edited by H. Škáchová, L. Vlasáková. Praha: Český hydrometeorologický ústav, 2019. 303 s. ISBN 978-80-87577-95-0

¹⁵ [27] FERGUSON, Colin R. and Allan KIRKPATRICK. *Internal combustion engines: applied thermosciences*. Third edition. Chichester, West Sussex, United Kingdom, 2015. ISBN 978-1-118-53331-4.

„ Sulphur dioxide pollution is considered more harmful when particulate and other pollution concentrations are high”¹⁶[31]

5.2.5 Carbon monoxide CO

It is gas produced by incomplete burning of materials which contain carbon, including transport fuels. This is caused by burning fuels with lack of oxygen and low temperatures in the combustion mixture. When fossil fuels are burnt the carbon monoxide can be transformed in the carbon dioxide CO₂ which is the most abundant greenhouse gas in the atmosphere. [30]

When CO reacts with haemoglobin it reduces the capacity for oxygen transport in blood, therefore is fatal for humans. However, in busy urban areas, CO concentration does not usually exceed health-related levels. [30]

5.2.6 Volatile organic compounds VOC and Hydrocarbons HC

HC are compounds of hydrogen and carbon only while VOC may contain other elements.

Volatile organic compounds affect the condition and quality of air because of its oxidative power in the atmosphere. The reaction between VOCs and nitrogen oxides produces ground-level ozone and other photo-oxidising pollutants as a result. According to the Act No. 201/2012 Coll. on air protection, the volatile organic compound is any organic substance, which has at 20°C vapour pressure of 0,01 kPa or more or has under particular conditions corresponding volatility. According to the extension of reactivity of individual VOCs and their amounts, no limit value of emissions was set for these substances.

„ Volatile organic compounds (VOCs) are low-molecular-weight organic compounds that easily evaporate at room temperature.”¹⁷[29]

They are present in our daily lives and we can find them from numerous sources such as fragrance, indoor furniture, biological matter, industrial chemicals like benzene, solvents such as toluene and xylene etc. VOCs are also released from burning fuel – gasoline, wood, coal, natural gas. They are also found in paints, glues, and other products used at home. Many organic compounds in our air are man-made. [28]

The most recognizable and the most health-hazardous hydrocarbons compounds are polycyclic aromatic hydrocarbons (PAH). PAH bound to particulate

¹⁶ [31] Health effects. *Air Quality in Europe* [online]. [cit. 2019-11-30]. Available from: http://www.airqualitynow.eu/pollution_home.php

¹⁷ [29] PENNERMAN, K.K., H.S. AL-MALIKI, S. LEE a J.W. BENNETT. Fungal Volatile Organic Compounds (VOCs) and the Genus *Aspergillus*. *New and Future Developments in Microbial Biotechnology and Bioengineering* [online]. Elsevier, 2016, 2016, s. 95-115 [cit. 2019-11-30]. DOI: 10.1016/B978-0-444-63505-1.00007-5. ISBN 9780444635051. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9780444635051000075>

matter; therefore, they are considered the most dangerous to human health. As they bound to the PMs they become easy to inhale in and irritate the lungs. There are many PAH distinguished like benzene, which is the most recognised, benzo[a]pyrene, benzo[a]anthracene and others. [30]

5.2.7 Smog

Smog is caused by extreme air pollution which causes low visibility. The term 'smog' was originally used to describe smoke and fog. Smog was common in industrial areas, nowadays it is common in big cities with lot of industry and traffic. [33]

Smog situation

According to the Act. no. 201/2012 Coll. a smog situation is a condition of extremely polluted air where the level of pollution by sulphur dioxide, nitrogen dioxide, PM10 particles or tropospheric ozone exceeds one of the thresholds set out in annexe 6 to Act. no. 201/2012 Coll.

In Table 2. The values of informative thresholds and regulative thresholds [53]

	PM10	Interval	NO ₂	Interval	SO ₂	Interval	O ₃	Interval
	µg.m ⁻³	[h]	µg.m ⁻³	[h]	µg.m ⁻³	[h]	µg.m ⁻³	[h]
Informative	100	12	200	3	250	3	180	1
Regulation	150	12	400	3	500	3		
Alert announcement							240	1

5.3 GREENHOUSE GASSES

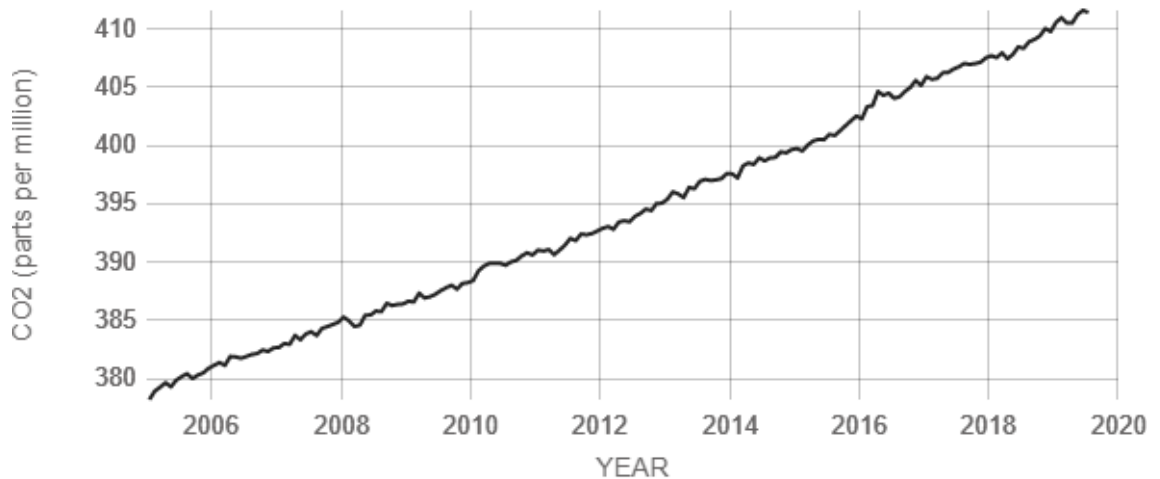
Greenhouse gasses (GHG) cause a greenhouse effect by absorbing infrared radiation produced by solar warming. GHG includes CO₂ carbon dioxide, CH₄ Methane, N₂O nitrous oxide, O₃ ozone and water vapour. These gasses occur in the atmosphere naturally; however, due to human activities such as the burning of fossil fuels, deforestation, agriculture etc., they have increased rapidly in recent years. Gasses of anthropogenic origin include, besides mentioned above, hard and soft freons, hydrofluorocarbons, sulphur hexafluoride, halons and other gases. This leads to the increasing Earth temperatures and leads to climate change. [34], [36]

5.3.1 Carbon dioxide CO₂

Carbon dioxide is odourless, tasteless gas that occurs in the atmosphere naturally. It is produced by perfect combustion, by breathing or by fermentation. Its density is 1,98 kg.m⁻³ and is approximately 1,5 x heavier than air.

„ Carbon dioxide (CO₂) is an important heat-trapping (greenhouse) gas, which is released through human activities such as deforestation and burning fossil fuels, as well as natural processes such as respiration and volcanic eruptions.”¹⁸[35]

The concentration of CO₂ in the atmosphere has increased since the 18th century by more than 31%. [34]



Source: climate.nasa.gov

Figure 4 CO₂ concentration during years. Source:[35]

People spend nearly 90 % of their time indoors, therefore, the indoor air quality is essential to people's lives. The most vulnerable population like elderly and the infirm spend indoors entire days. Usually, indoor CO₂ concentration range from 600 – 1000 ppm (offices, schools, homes). However, they can exceed 2000 ppm, depending on room occupants and building ventilation, whether there is one or not. Also, people spend one-third of their lives sleeping and the CO₂ concentration in bedrooms can exceed 2500 ppm when windows and doors are closed, for privacy and energy conservation. [7]

It is indispensable to keep the indoor CO₂ concentrations on low levels because the elevated carbon dioxide concentrations in the indoor environment have been associated with headaches, lower work performances, higher stress levels, decreased cognitive performance, sleep deprivation etc. [7]

The best way to keep the CO₂ concentrations in the indoor environment at diminished levels is by regular ventilation through windows or via sufficient ventilation system.

On the other hand, increasing building ventilation may be less effective than alternative strategies, because of the energy requirements and the increase of CO₂ indoors through greater use of AC especially in summer.[7]

¹⁸ [35] Carbon dioxide. In: *Global Climate Change: Vital Signs of the Planet* [online]. [cit. 2019-12-09]. Available from: <https://climate.nasa.gov/vital-signs/carbon-dioxide/>

Outdoor CO₂ concentration sets 'floor' for the indoor environment. „ *Continued atmospheric CO₂ increases will require more demanding mitigation strategies to prevent a concomitant rise in indoor concentrations—especially in cities.*”¹⁹

High-rise buildings, narrow streets, densely populated cities can trap atmospheric CO₂ because reduced airflow generates lower wind speeds, thus less air dispersion. [7]

5.3.2 Methane CH₄

Another major greenhouse gas is the methane. It is mostly produced by agriculture, more specifically by raising of livestock. It is also emitted by natural sources e.g. natural wetlands. One tonne of methane is equivalent to 34 tonnes of carbon dioxide. [37]

5.3.3 Nitrous oxide N₂O

Nitrous oxide, as well as the carbon dioxide and methane, belong to the group of greenhouse gases. However, N₂O has greater consequences because one tonne of nitrous oxide is equivalent to 298 tonnes of carbon dioxide. Moreover, the nitrous oxide is also ozone destroyer, because the process that removes N₂O from the atmosphere also depletes ozone. [38]

Origin of this compound comes primarily from nitrogen-based fertilisers used in agriculture. N₂O is also emitted from transportation, industry and other activities. [39]

5.4 NOISE POLLUTION

Noise pollution is considered a major environmental health concern in Europe. A noise comes from a variety of sources and is widely present not only in the busiest urban areas but also in natural environments.

The most widespread source of noise is road traffic. Railways, air traffic and industry are also major sources of noise, however, not as significant as road traffic.

Noise is a significant public health concern. The long-term exposition has negative impacts on human health and well-being. It can cause many health issues such as sleep deprivation, reduced cognitive performance in children, etc. [40]

¹⁹ [7] JACOBSON, Tyler A., Jasdeep S. KLER, Michael T. HERNKE, Rudolf K. BRAUN, Keith C. MEYER a William E. FUNK. Direct human health risks of increased atmospheric carbon dioxide. *Nature Sustainability* [online]. 2019, 2(8), 691-701 [cit. 2019-11-24]. DOI: 10.1038/s41893-019-0323-1. ISSN 2398-9629. Available from: <http://www.nature.com/articles/s41893-019-0323-1>

„ Prolonged exposure to environmental noise can lead to negative cardiovascular and metabolic effects, reduced cognitive performance in children as well as a severe annoyance and sleep disturbance.”²⁰ [40]

Czech Republic

In the Czech Republic, the limits of noise pollution and vibrations are considered in Government Regulation No. 272/2011 Coll., on health protection from adverse effects of noise and vibration. [58]

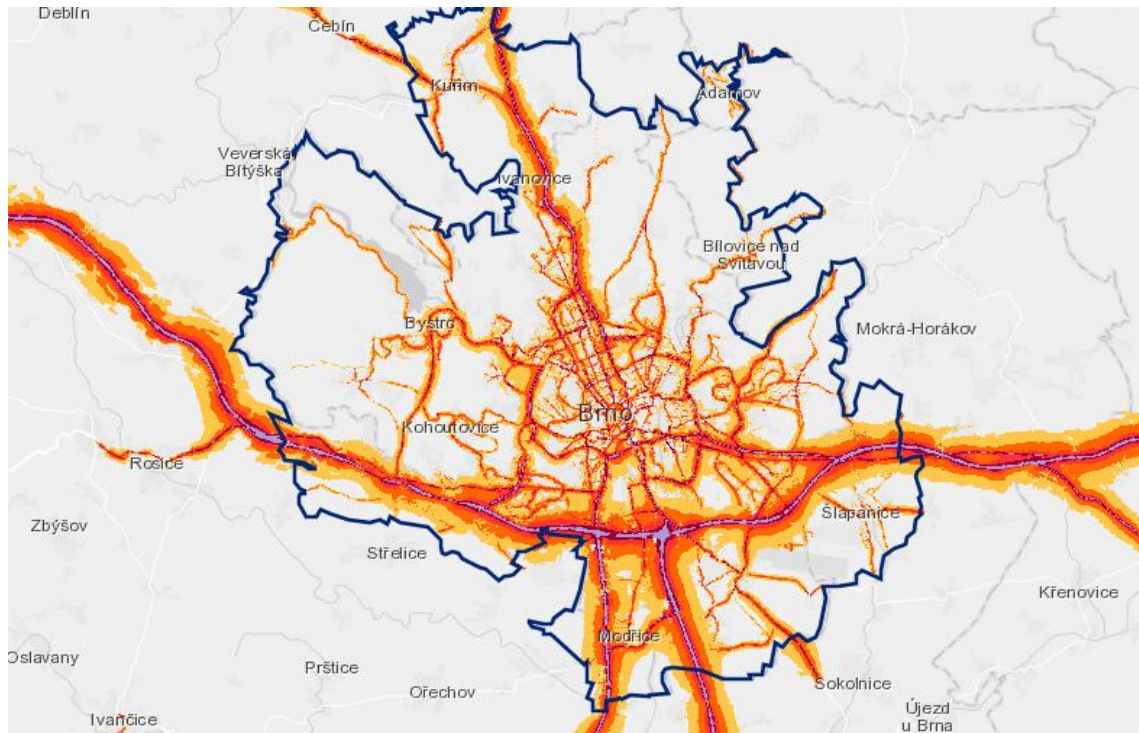


Figure 5 Noise pollution – Roads, Brno. The figure shows noise pollution during the daytime. Source :[41]

5.5 MONITORED INDICATORS IN CZECH REPUBLIC

There are several indicators monitored in the Czech Republic, which present major air pollution problem. The data on the air quality in the Czech Republic is published by the Czech Hydrometeorological Institute (CHMI).

Monitored indicators include Benzo[a]pyrene, suspended particles of PM10 and PM2,5, ground-level ozone, carbon monoxide, sulphur dioxide and nitrogen oxides. The level of polluted air depends on the amount of emissions and prevailing weather and scattering conditions.

²⁰ [40] Noise. In: *European Environmental Agency* [online]. [cit. 2019-12-09]. Available from: <https://www.eea.europa.eu/themes/human/noise>

In the past 25 years, the emissions in the Czech Republic have decreased due to the implementation of measures that significantly reduce air pollution. However, many economic and social activities still produce a number of emissions, which, in combination with meteorological and dispersive conditions, are causing the over pollution of harmful substances, especially in some regions. Currently, suspended particles and the polycyclic aromatic hydrocarbons bound to them present the biggest problem of the monitored pollutants. In the summertime, ground-level ozone limits are exceeded in a number of locations.

The Act No. 201/2012 Coll. on air protection divides the Czech Republic territory into zones and agglomerations for assessments and evaluation of air pollution levels. Main agglomerations are Prague, Brno and Ostrava/Karvina/Frýdek-Místek. These areas are mainly polluted due to traffic and industrial actions. Moreover, in these areas there is high population density. Therefore, the part of a population exposed to over-the-limit concentration is not negligible.

5.5.1 Brno Agglomeration

Brno city is situated in the south of the Czech Republic, in the middle of a South Moravian region. It is the second-largest city in the Czech Republic with a population of nearly 400 000 people and covered area of 230 km². There are several important sources that are affecting the air quality in the city, like significant traffic or household heating.

The most polluted areas in agglomeration Brno are those with the busiest traffic. Large numbers of cars passing through the city; therefore, the air quality is poor. The highest values for 24-hour PM10 concentration and average annual NO₂ concentration, which have exceeded in the long term are in built-up areas, with high traffic and reduced airflow. On the other hand, in the open areas with the similar traffic, the concentrations are lower, and the limit values are not exceeded in the long run. [25]

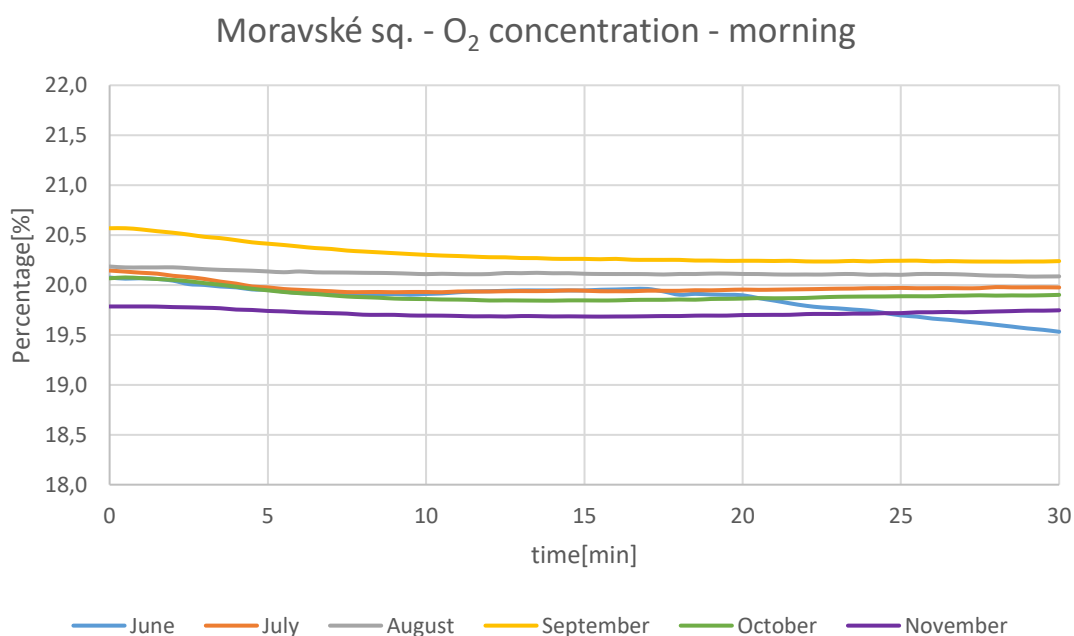
There are ten monitoring stations in Brno city, which track pollutants in the air in chosen locations. The stations trace suspended particles PM10 and PM2,5, nitrogen dioxide NO₂, ground-level ozone O₃, sulphur dioxide SO₂, and carbon monoxide CO. [44]

6 MEASURING

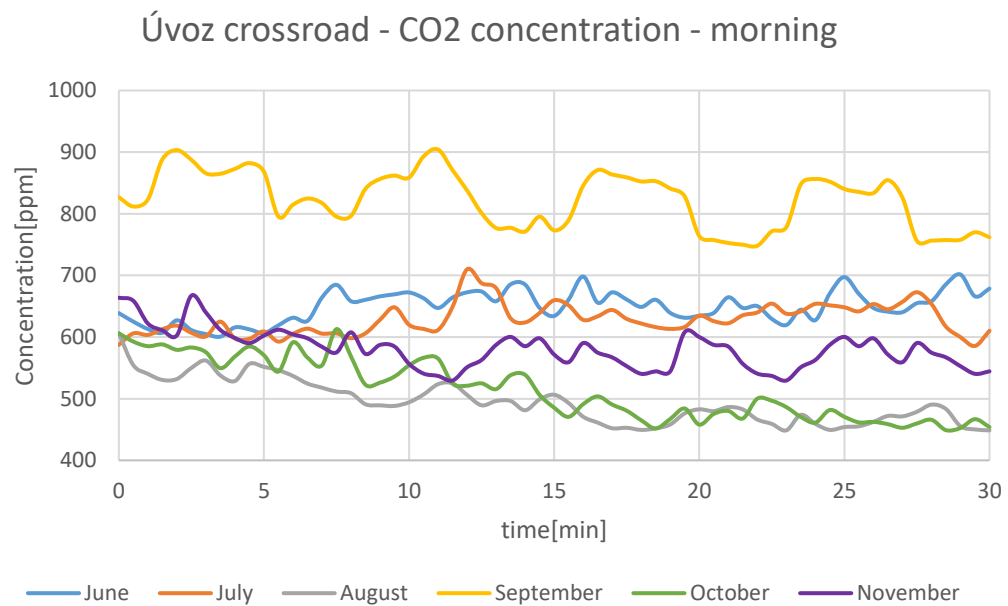
The practical part of this master thesis was to measure the carbon dioxide and oxygen levels, as well as the temperature levels and humidity for six months period, to find out how does the values of CO₂ and O₂ changes within day or month. Furthermore, to find out whether the temperature, humidity or wind speed influences the values of CO₂.

Measurements were made within six months, from June to November 2019, during different periods of the day. In the morning, noon and the afternoon. Morning is considered time between 7 am and 9 am, noon from 11 am to 1 pm and afternoon from 3 pm to 5 pm. The data were collected within one week each month to eliminate weather changes. Also, each measurement was taken for thirty minutes to eliminate deviations in measurements, to diminish changes in weather conditions etc. The collected data were then averaged out.

Temperature, humidity and wind-flow were also collected as a secondary data. These data were collected to include weather conditions and to find out, whether these measurements have any impact on CO₂ concentration.



Graph 1 The comparison of the 30-minute progress of O₂ concentration, in six months



Graph 2 The comparison of the 30-minute progress of CO₂ concentration, in six months

Measuring devices

The data were collected with CO₂ and O₂ sensors. These sensors are made by Vernier company, which is focused on easy-to-use data-acquisition products.

The sensors were placed approximately 60 – 100 centimetres above ground to collect the data properly.

The CO₂ concentration is measured in ppm units. The abbreviation stands for 'parts per million'. The air composes of several gases, the most dominant are oxygen (approx. 21%) and nitrogen (approx. 78%). Carbon dioxide is among the rest one per cent because it is represented in a small amount in the atmosphere, thus the ppm units. 1 ppm unit equals 0,0001% of air. Therefore, any little deviation in CO₂ concentration is not negligible in relation to human health. On the other hand, the oxygen concentration may fluctuate in a much greater range in comparison to carbon dioxide and it would not have a negative effect to human health, unlike CO₂. [42], [43]

6.1 LOCATIONS

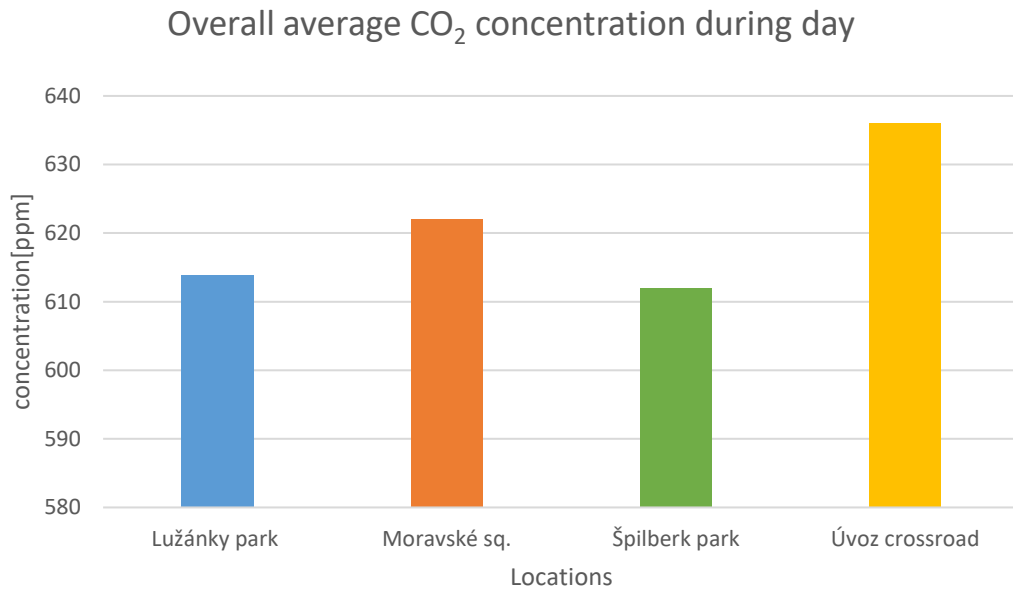
Measuring took place in four locations in Brno city. The areas were chosen according to their composition. The aim was to find sites with a lot of greenery and vegetation and compare them with densely built-up areas or areas with high traffic. To represent places with a lot of greenery and vegetation was chosen park Lužánky and Špilberk castle's surrounding park. As a built-up area with high traffic was chosen crossroad on Úvoz street and Údolní street and crossroad near Moravské square, as seen in Figure 6.



Figure 6 Map of monitored locations in Brno, orange colour signifies monitoring station
source: [52]

The overall average concentration of CO₂ in these four places differ only within approx. 24 ppm, as seen in Graph 3. The measured data are less likely to be different in a wider range, within one town. A more significant difference could be probably measured, for instance, between an urban area and rural area (forest, suburbs etc.). Nevertheless, according to the measured data, densely built-up areas with high

traffic loads does show worse results than areas with vegetation. According to the measurements, the overall average CO₂ concentration in Brno city is 620,97 ppm.



Graph 3 Overall average CO₂ concentration comparison in monitored locations

Lužánky Park

Lužánky Park is situated in Brno-city district and it is the oldest and the biggest public park in Brno. It was based in 1786 as a first public park in central Europe. Currently, the park covers an area of 20 hectares. It is a favourite place for Brno's

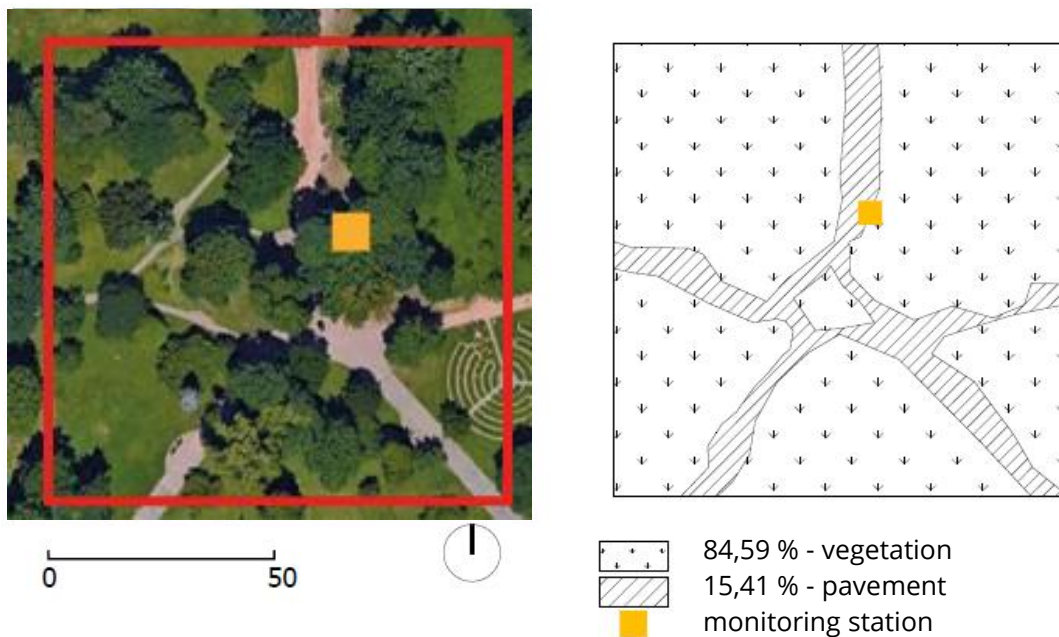


Figure 7 Surface coverage – Lužánky park [52], customised

citizens who come here for recreational or sports activities. The park is surrounded from each side by streets with relatively high traffic loads.

On a selected area of 1 hectare, greenery covers approximately 85 % of the park, the rest 15 % is covered by pavement or hard surfaces – Figure 7. From measurements collected turns out that overall average CO₂ concentration in this park is 613,84 ppm which is the second-lowest concentration compared to the other three places.

Špilberk Castle's surrounding park

Špilberk Park is situated on a hill about 1500 m far from Lužánky park. The park covers an area of approx. 13 hectares. On the top of the hill, in the middle of the park, there is a Špilberk Castle – one of the most visited tourist places in Brno. The park is, as well as the Lužánky park, a favourite site for Brno's citizens.

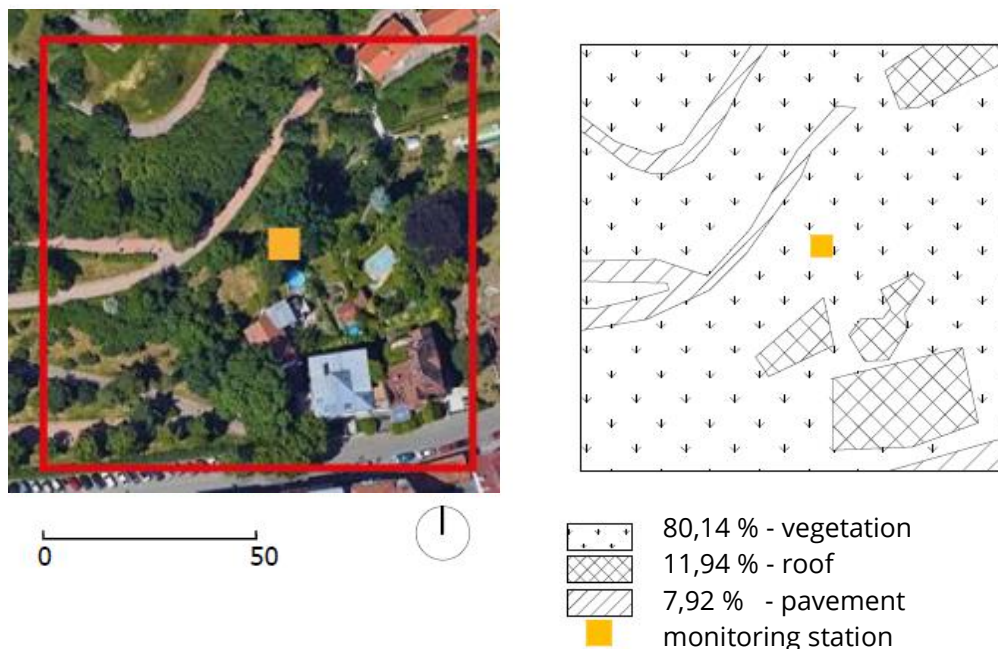


Figure 8 Surface coverage – Špilberk park [52], customised

The overall average CO₂ concentration in the Špilberk park is 611,93 ppm, which is the lowest concentration monitored in comparison to the rest three places, as seen in Graph 3. On an area of 1 hectare, 80,14 % is covered by greenery and the rest 19,86 % is covered by hard surfaces – roofs and pavement, as seen in Figure 8.

The crossroad on Úvoz street and Údolní street

The crossroad is situated approx. 500 m far from Špilberk park. Úvoz street is considered to be the most polluted street in Brno city. This is caused by busy traffic

and relatively high-rise buildings. In addition, the crossroad is situated in densely built-up area.

The overall average CO₂ concentration in this area is 636,04 ppm, which is the highest overall CO₂ levels of measured areas, as seen in Graph 3.

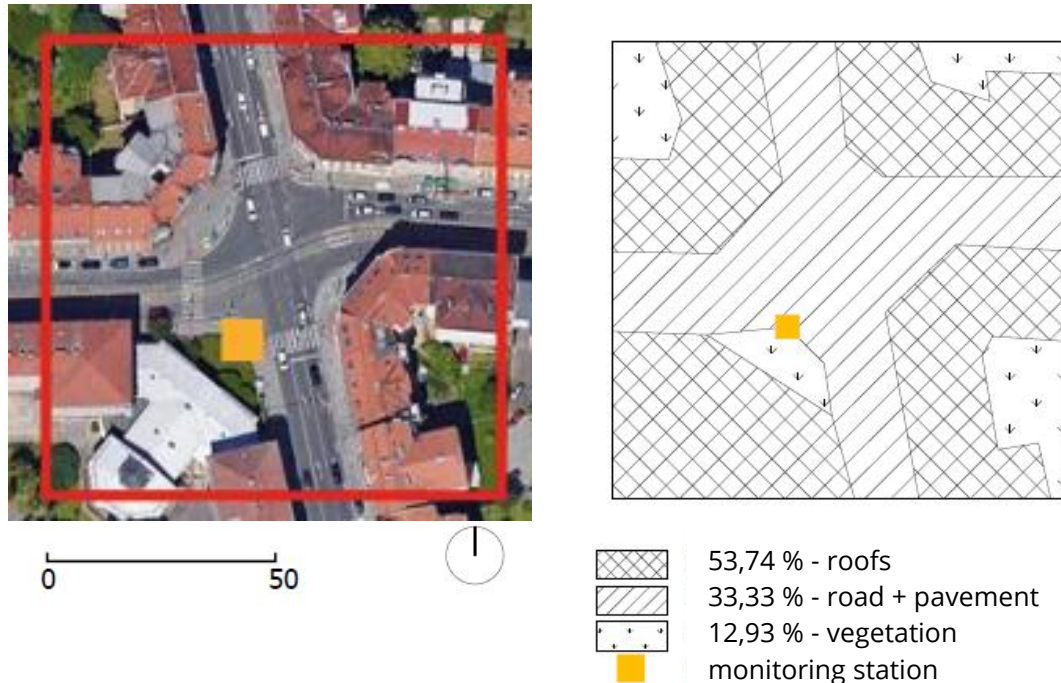


Figure 9 Surface coverage – Úvoz crossroad [52], customised

As seen in Figure 9, the selected area is covered by 53,74% of roofs and 33,33 % by road and pavement, the rest is covered by greenery. Hard surfaces cover 87,07 % of selected area in total.

The crossroad near Moravské square

Unlike the crossroad on Úvoz street and Údolní street, the crossroad near Moravské square (Moravské sq.) is situated in a lot more open area. The density of buildings is lower. The crossroad is one of the main traffic hubs in Brno city, where different types of vehicles like cars and trams meet.

As seen in Figure 10, the area is covered by 48,50 % of roads and pavement and 33,63 % by roofs, hard surfaces cover 82,13% in total. The rest 17,87 % is covered by greenery.

The overall average CO₂ concentration measured in the Moravské sq. was 622,07 ppm, as seen in Graph 3, which is the second-highest concentration compared to other three locations.

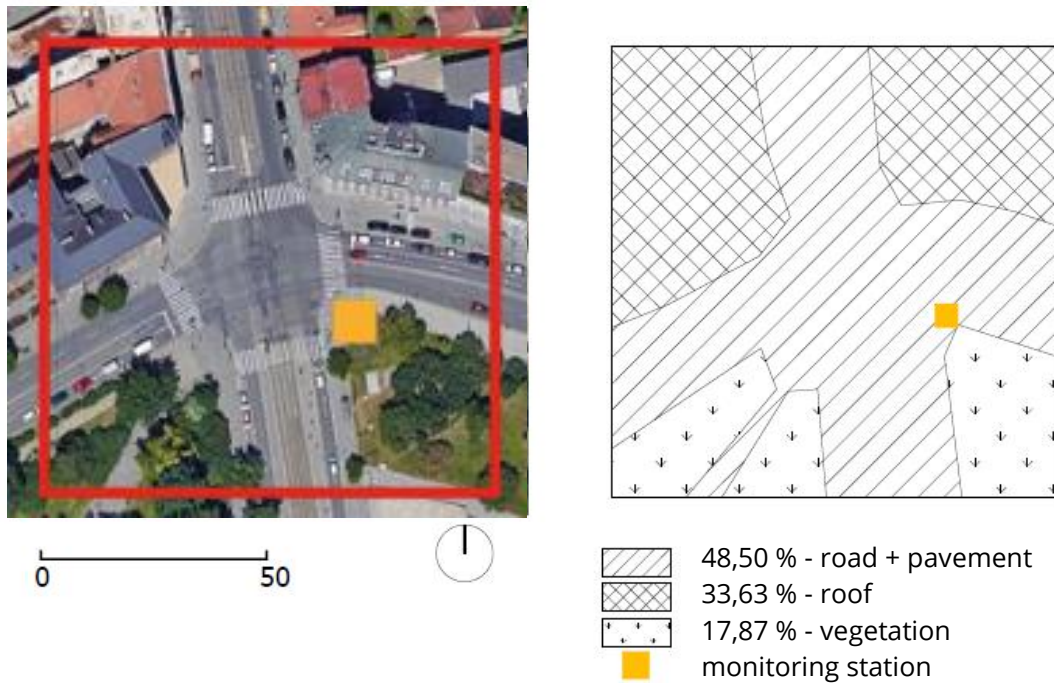


Figure 10 Surface coverage – Moravské sq. [52], customised

6.2 PRECONDITIONS

1. Areas with a lot of greenery and vegetation are going to report better results of CO₂ concentration than built-up areas with high traffic.
2. The worst results of CO₂ levels are going to be during the afternoon (in the morning the conditions would show better results).
3. Temperature, humidity or windspeed would influence carbon dioxide concentration levels (e.g. lower CO₂ concentration would be while higher wind speeds).
4. Oxygen levels would be at a relatively constant level, approx. 20 %

6.3 CO₂ SOURCES

We can divide the CO₂ sources according to the area they affect. For instance, global measure, urban measure or rural measure. Each of these views have its biggest CO₂ source which affects the area the most. In a global measure, it would be industry and traffic, the traffic and household heating in urban areas and primarily household heating in rural areas.

In cities like Brno, the main source of CO₂ is traffic and household heating.

At the ground floor level, in the urban areas, the CO₂ concentration is crucial for people. In this case, the biggest CO₂ source is considered traffic. The high-rise buildings in urban areas do not have that big impact on ground-floor level CO₂ concentration because they usually have their chimneys high above the urban streets. The buildings still produce carbon dioxide and other pollutants; however, the concentrations do not affect the street level unlike the vehicles.

In rural areas and suburbs, the main CO₂ source is household heating and traffic. Houses in such areas are lower than urban buildings. Also, the sources used for heating in rural areas tend to be more diverse than those in the cities. For instance, in the suburbs, households may use natural gas, coal, wood, or electricity as a heating source. On the other hand, in cities is usually one source of heating. Cities usually have one main distributor of heat. In Brno city, the biggest thermal distributor is Teplárny Brno.

Teplárny Brno (TB) supply around 100 000 households. Also, TB produces more than 85% of heat in cogeneration way. The cogeneration of electricity and heat enables the maximum efficient use of input fuel by simultaneously producing the heat supplied to customers, and electricity delivered to the distribution system in one production process. [45]

Reference examples

The production of carbon dioxide is different according to the source. For purpose of this thesis were created reference examples of CO₂ sources which would show the differences between them.

The amount of CO₂ produced by vehicles depends on how many kilometres would someone commute to work. In Table 2 there are three reference examples of how many kilometres does a person commute to work. The values are for two different types of vehicles – one produce 95 g/km of CO₂ and the second one 147 g/km. These values are taken from the Regulation of the European Parliament and of the Council for the year 2020 for every new car registered in EU. [57]

From the 1st of January 2020 each new passenger car registered in EU would have emission limit of CO₂ concentration 95 g CO₂ per one kilometre, and the emission limit for light commercial vehicles is going to be 147 g CO₂ per one kilometre. However, currently, the vehicles' emissions in European union are higher at least half of the amount than in Table 2. [57]

Table 2 The CO₂ production dependency on the type of vehicle [57]

km	Passenger cars			Light commercial vehicles		
	CO ₂ [g/km]	CO ₂ [kg]	CO ₂ [t/year]	CO ₂ [g/km]	CO ₂ [kg]	CO ₂ [t/year]
50	95	4,75	1,7	147	7,35	2,7
100		9,5	3,5		14,70	5,4
20		1,9	0,7		2,94	1,1

The amount of CO₂ produced by households depends on how economical the house is, e.g. how sufficient is the house's thermal insulation, what source of heat is used in the house etc. The difference between an economic house with a low thermal loss would be enormous in comparison to an old house with high thermal loss and insufficient thermal insulation and thermal bridges. Also, the amount of CO₂ produced by households depends on the source of heating.

According to the Czech Decree No. 425/2004 Coll. there are different emission factors for different types of fuel used for heating. The emission factor describes the calorific value of a selected fuel. For the reference examples, three of these emission factors were chosen - emission factor of natural gas, coal and electricity - as seen in Table 3 and Table 4.[56]

Table 3 The CO₂ production of an economical household

Economic household	Heat source	Emission factor	Thermal loss	Production
	[-]	CO₂ [t /MWh]	[MWh/year]	CO₂ [t/year]
3 kW - thermal consumption of an object	natural gas	0,2	14	2,8
	coal	0,36		5,0
	electricity	1,17		16,4

Thermal consumption of an economical detached house with four family members can be approximately 3kW. On the other hand, the thermal consumption of an old detached house can be 15 kW. As seen in Table 3 and Table 4, the CO₂ production in old household might be three times higher than the production of an economic household. ²¹

Table 4 The CO₂ production of an old household

Old household	Heat source	Emission factor	Thermal loss	production
	[-]	CO₂ [t /MWh]	[MWh/year]	CO₂ [t/year]
15 kW – thermal consumption of an object	natural gas	0,2	41,5	8,3
	coal	0,36		14,9
	electricity	1,17		48,6

One person produce approximately 20 litres per hour of CO₂ by breathing. The production depends on human's activity and can range between 10 litres and 75

²¹ Note: The 'thermal loss' per year, in Table 3 and Table 4, is total annual energy need for heating and hot water heating for Brno city, calculated at the website: <https://vytapani.tzb-info.cz/tabulky-a-vypocty/47-potreba-tepla-pro-vytapani-a-ohrev-teple-vody>

litres. One person can produce approximately 0,33 – 1,15 tons of CO₂ per year by breathing. The density of gaseous CO₂ under normal conditions is 1,9768 kg.m⁻³. [49]

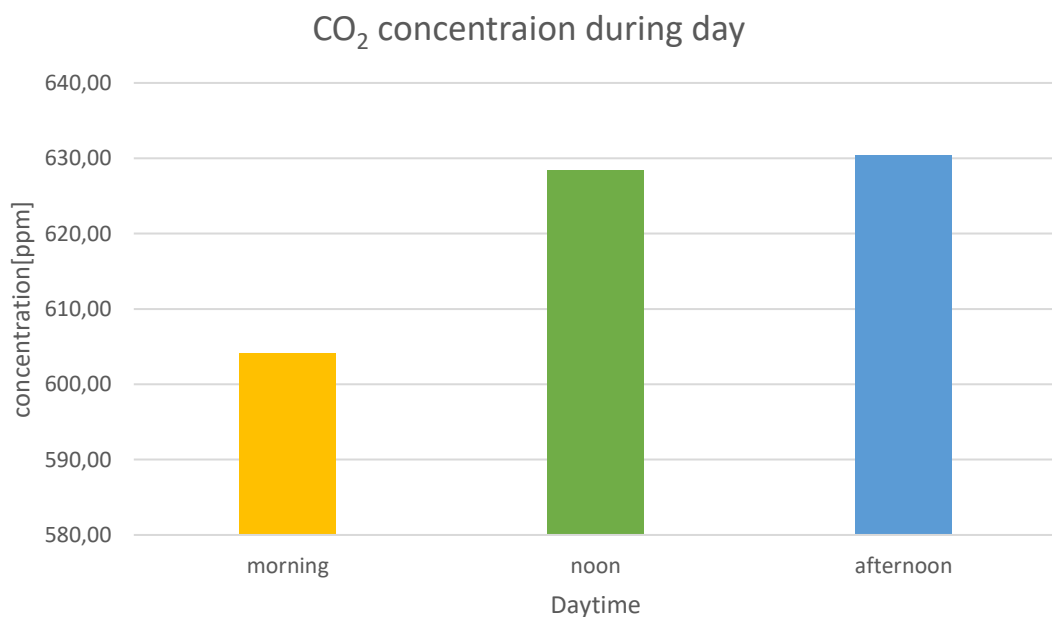
Table 5 The person's CO₂ production by breathing according to the physical activity

physical activity	CO ₂ [l/h]	ρ [kg/m ³] CO ₂	V [m ³ /h]	CO ₂ [kg/day]	CO ₂ [t/year]
low	20	1,977	0,02	0,95	0,35
medium	45		0,045	2,14	0,78
high	70		0,07	3,32	1,21

6.4 CO₂ CONCENTRATION RESULTS

6.4.1 Daytime comparison

The lowest overall average CO₂ concentration is reported in the morning, on the other hand, the highest value of CO₂ is reported in the afternoon. The morning overall average concentration is 604,15 ppm, the noon average concentration is 628,42 ppm and the afternoon average concentration is 630,34 ppm, as seen in Graph 4. The difference between morning and noon concentration is 24,27 ppm and between morning and afternoon the difference is 26,19 ppm. Nevertheless, those differences are negligible.



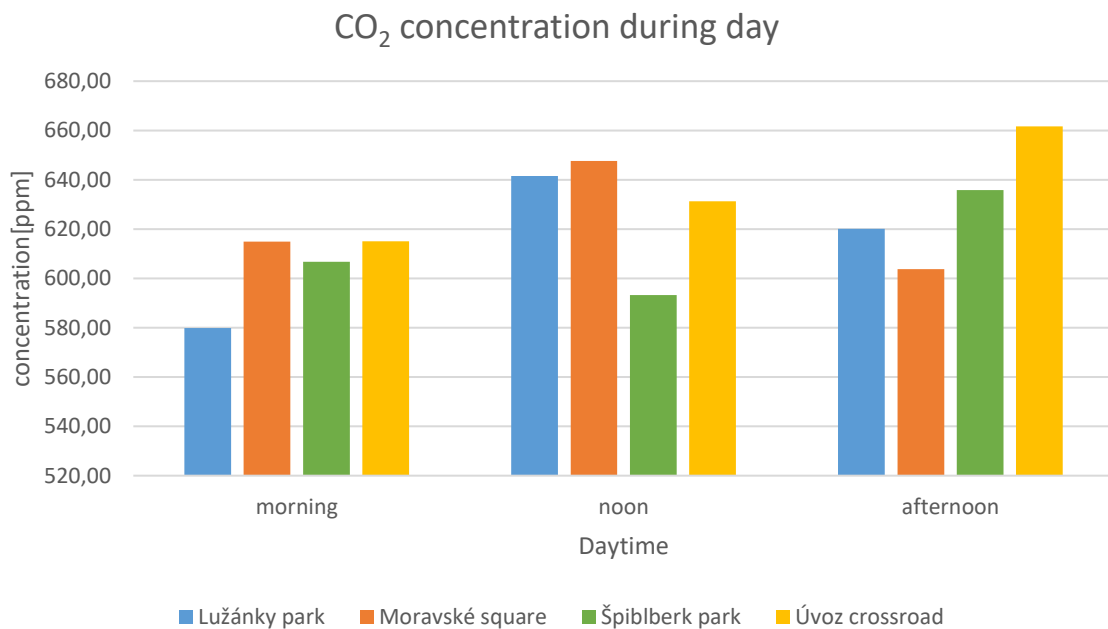
Graph 4 The overall average CO₂ concentration comparison during the day in all places

As seen in Graph 5, the lowest CO₂ concentration in the morning reports Lužánky park with the concentration of 579,90 ppm, on the other hand, the highest morning concentration reports Moravské sq. – 614,90 ppm. The difference between morning extremes is 35 ppm.

In the noon the highest CO₂ concentration reports Moravské square with a value of 614,51 ppm and the lowest carbon dioxide concentration was measured in Špilberk park – 593,23 ppm. The difference between noon lowest and the highest concentration is 21,38 ppm.

In the afternoon the highest CO₂ concentration shows Úvoz crossroad with a value of 661,69 ppm and the lowest concentration shows Moravské sq. – 603,73 ppm. The difference between afternoon extremes is the most significant of the day measurements – 57,96 ppm.

The difference between the lowest and the highest concentration during the day is 81,79 ppm (Lužánky park in the morning and Úvoz crossroad in the afternoon). The difference is probably caused by different traffic intensity in the morning and in the afternoon and simultaneously the difference may be caused by the nature of the monitored locations.



Graph 5 The overall average CO₂ concentration comparison during day

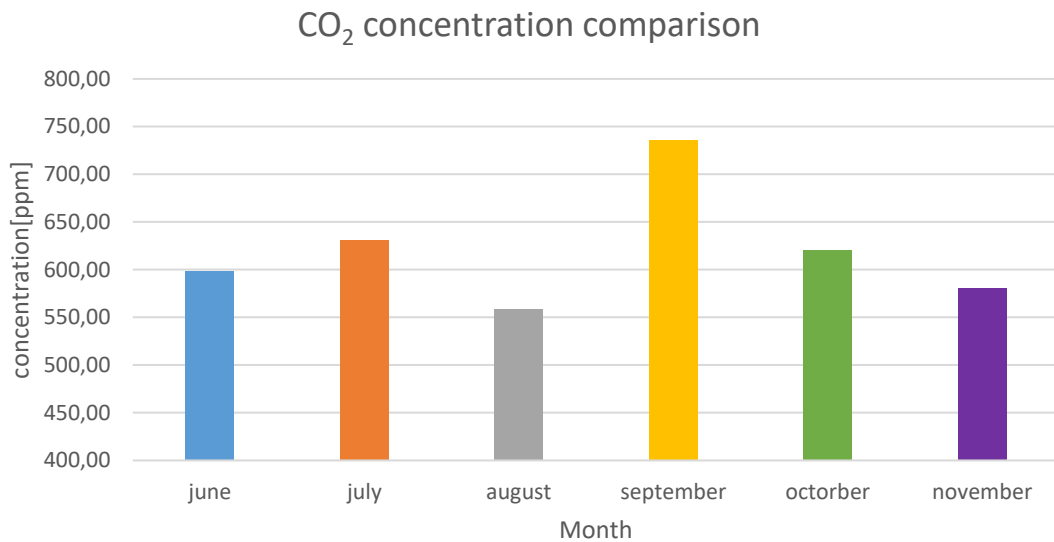
6.4.2 Months comparison

As seen in Graph 6, the highest CO₂ concentration was measured in September, exactly 736,03 ppm. The lowest concentration was measured in August – 558,74 ppm. The difference between September and August is 177,29 ppm, which is not a negligible value. As well as the August measurements, the November and June measurements are below the value of 600 ppm. The October and the July values are between 600 ppm and 650 ppm. The September values, therefore, seem like an anomaly.

Nevertheless, according to the Czech Hydrometeorological Institute (CHMI), the scattering conditions in September exceeded the norm in comparison to the long-

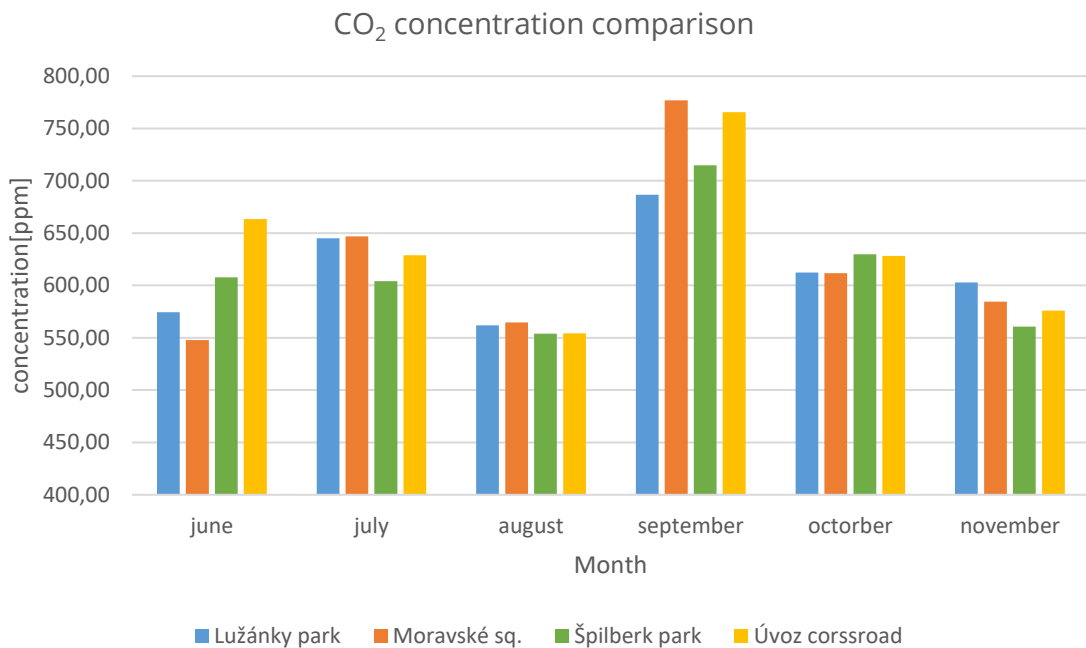
term average values of 2007-2018 in the Czech Republic. In the Brno agglomeration, the scattering conditions were significantly better in comparison to the long-term average values. The temperature in September in the Czech Republic was in normal values, with the exception of the first day in September. The temperature was 6,7°C higher than the daytime average. [46]

In September the maximum daily 8-hour O₃ concentration exceeded the value of emission limit (120 µg.m⁻³) at urban and rural stations in Brno agglomeration. The particulate matter PM₁₀ concentration did not exceed the value of emission limit (50 µg.m⁻³) in Brno agglomeration. Other substances like nitrogen oxide, sulphur oxide etc did not exceed emission limits. Also, in September no smog situation had been declared. [46]



Graph 6 The overall average CO₂ concentration comparison in all places

As seen in Graph 7, the lowest average CO₂ concentration was measured in June at Moravské square, 547,72 ppm even though the lowest overall average CO₂ concentration was measured in August. The other three locations report the lowest CO₂ concentration in August. The highest CO₂ level was measured in September at Moravské square as well, 776,86 ppm. The difference between those measurements is 229,14 ppm, which is a significant difference. According to the measurements, the highest values of CO₂ concentration were measured in September in all monitored locations. Špilberk park, Moravské sq. and Úvoz crossroad exceeded the concentration value of more than 700 ppm, unlike Lužánky park, which did not exceed this value.

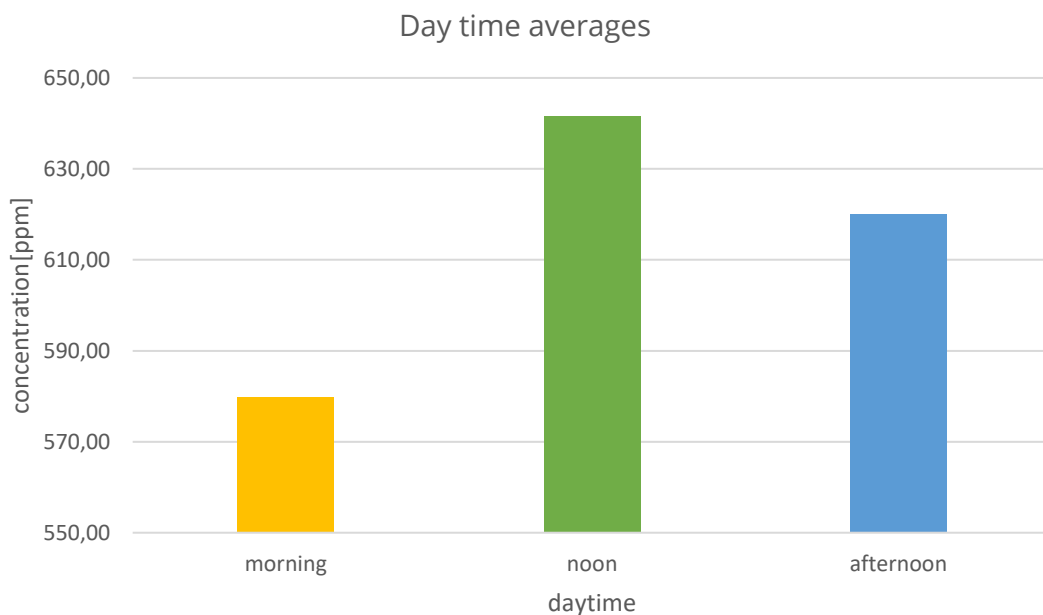


Graph 7 The overall average CO₂ concentration comparison

6.4.3 Locations

Lužánky park

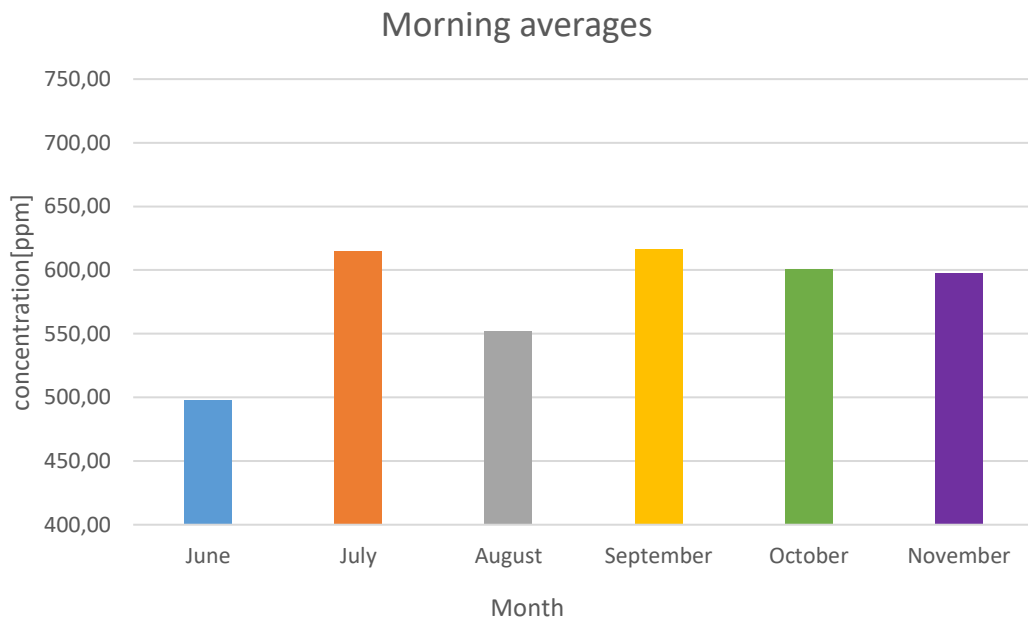
Lužánky park reported the second-lowest CO₂ concentration result compared to the other three locations, as seen in Graph 3.



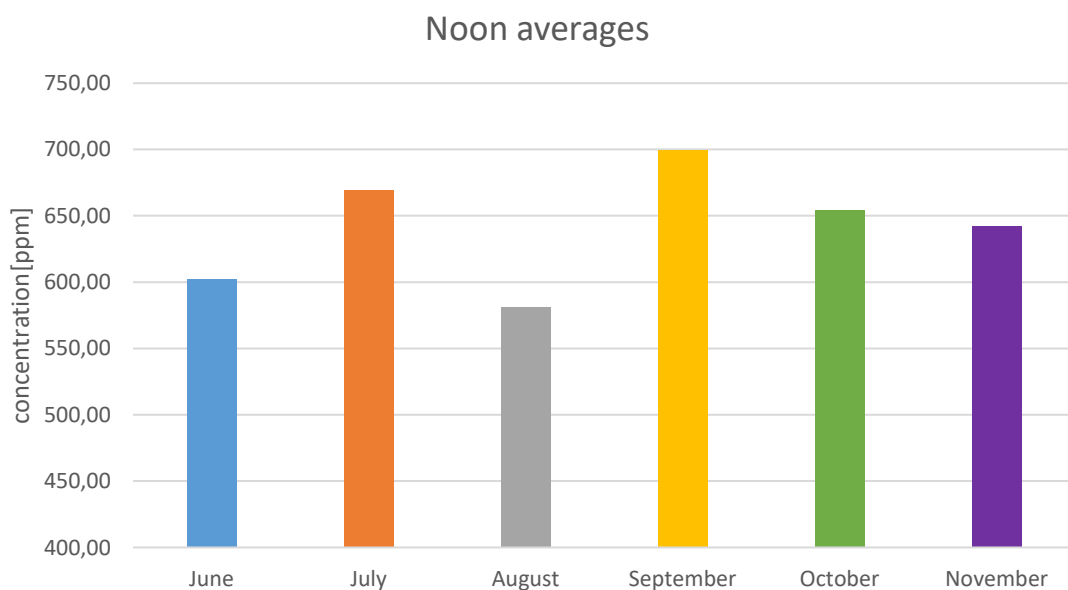
Graph 8 Overall daytime average CO₂ concentration in Lužánky park

The lowest CO₂ concentration was measured in the morning. The average value of carbon dioxide concentration in the morning is 579,90 ppm, in the noon the concentration is 641,51 ppm and 620,10 ppm in the afternoon, Graph 8.

As seen in Graph 9, the value of more than 600 ppm was exceeded in July, September and October. In June the CO₂ concentration did not even exceed the value of 500 ppm. The concentration in August and November was between 550 and 600 ppm.

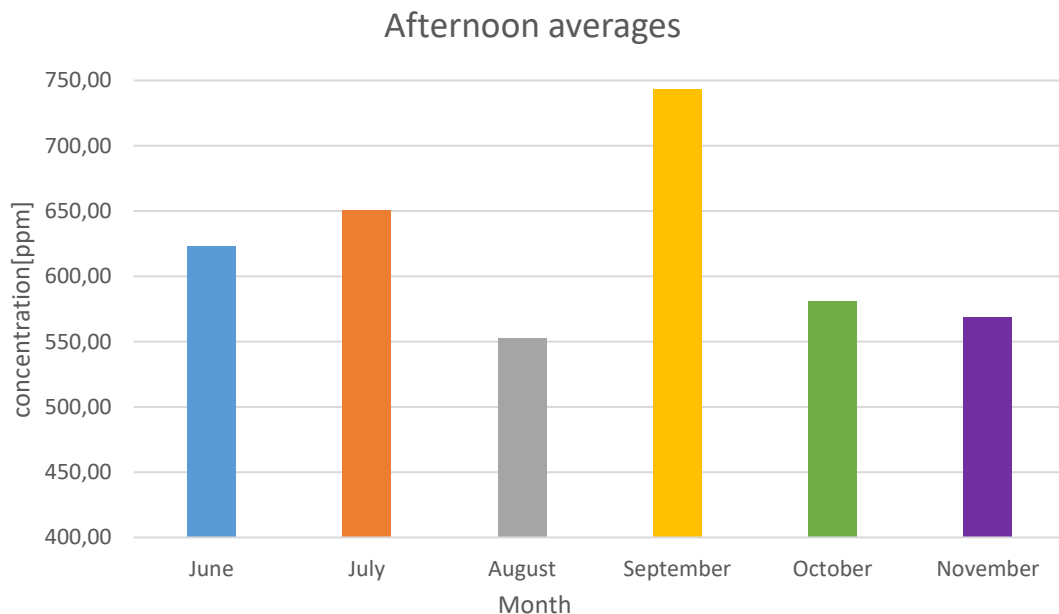


Graph 9 Months comparison of CO₂ concentration in Lužánky park - morning



Graph 10 Months comparison of CO₂ concentration in Lužánky park - noon

Unlike morning measurements, every month in the noon the measurements at Lužánky park reached at least 550 ppm CO₂ concentration. The lowest concentration was measured in August – 581,14 ppm. The highest CO₂ concentration was recorded in September, it almost reached the 700 ppm, as seen in Graph 10. The difference between the lowest and the highest concentration is 118,36 ppm. The average concentration in the four remaining months was between 600 ppm and 700 ppm.



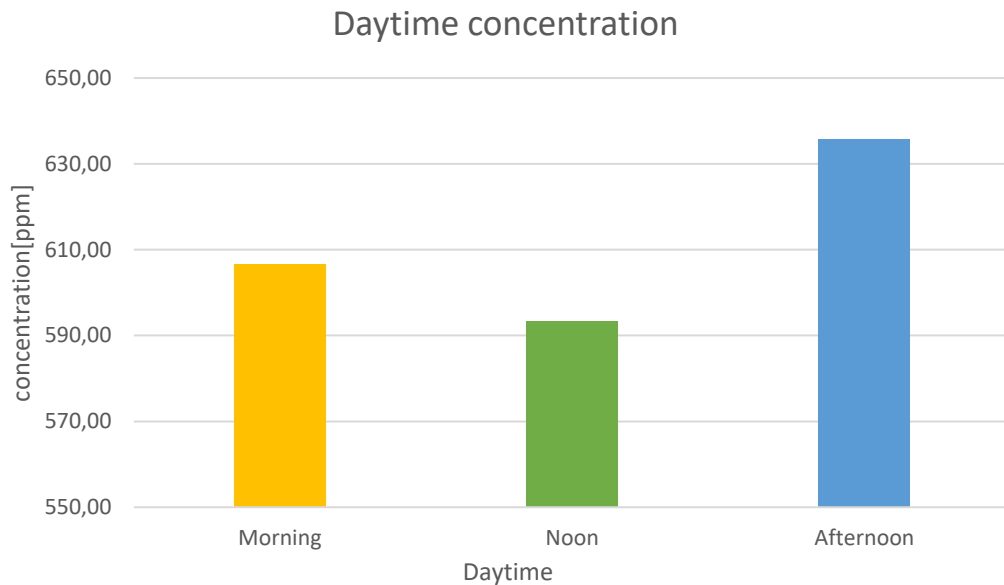
Graph 11 Months comparison of CO₂ concentration in Lužánky park - afternoon

As seen in Graph 11, there is almost 200 ppm difference in the afternoon averages between August and September concentration: exactly 191,14 ppm. The summer concentration in June and July is higher than the autumn concentration in October and November. The summer concentration is between 600 and 650 ppm value and the autumn concentration is between 550 and 600 ppm.

Špilberk park

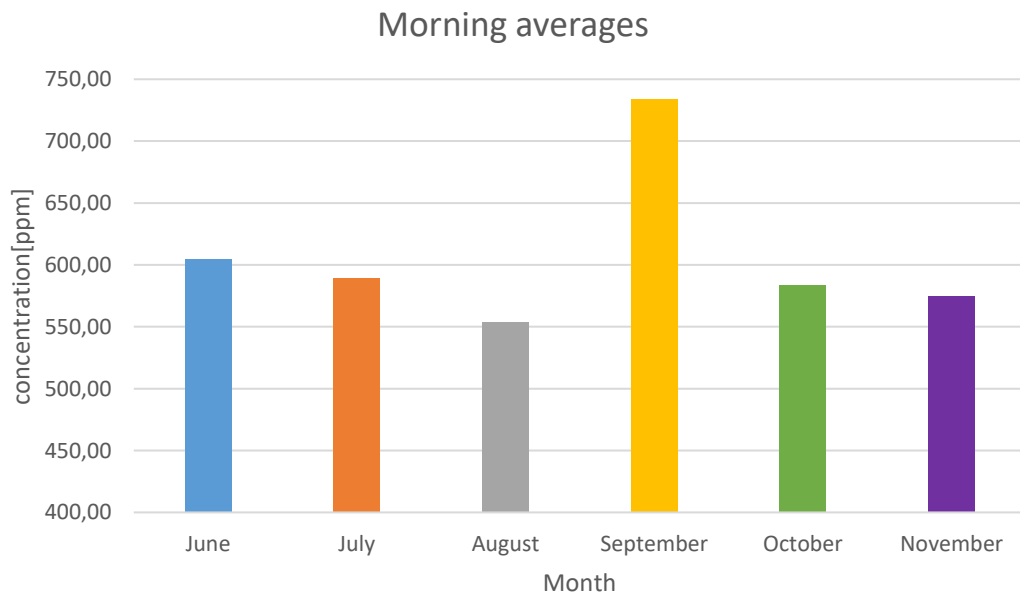
Špilberk park reported the lowest results of CO₂ concentration compared to other locations, Graph 3. This is probably caused by its elevated position, with no huge traffic-hub in the vicinity of the park, or a significant source of household heating.

The lowest concentration was measured in the noon. The overall average CO₂ concentration in the noon is 593,23 ppm, in the morning 606,71 ppm and 635,85 ppm in the afternoon, as seen in Graph 12.

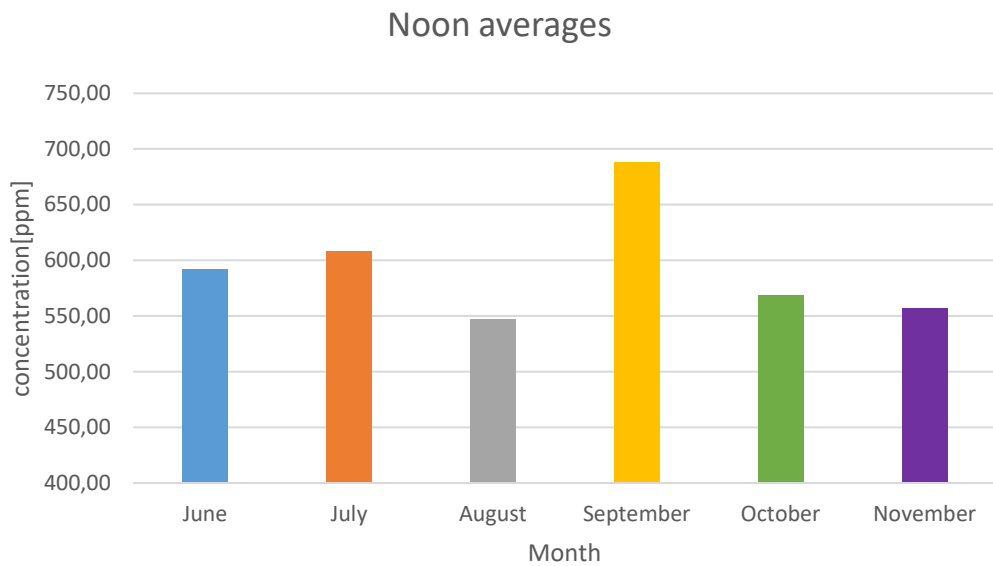


Graph 12 Overall daytime average CO₂ concentration in Špilberk park

As seen in Graph 13, the lowest CO₂ concentration at Špilberk park in the morning was measured in August – 553,92 ppm, and the highest average CO₂ value was in September – 734,26 ppm. The difference between those two months is 180,34 ppm. The concentration in July, October and November is between 550 ppm and 600 ppm. June concentration is slightly above 600 ppm value.

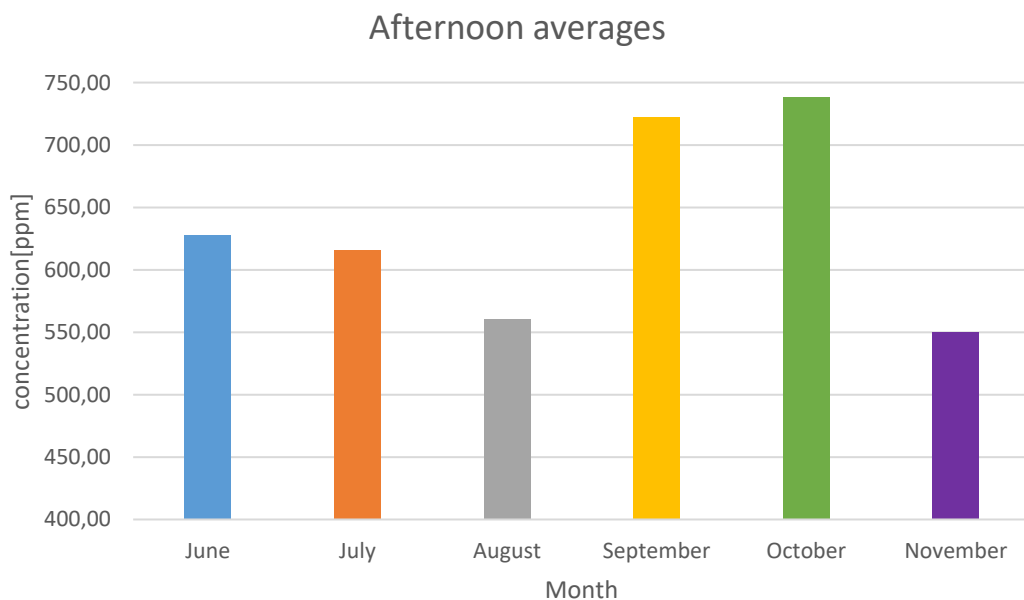


Graph 13 Months comparison of CO₂ concentration in Špilberk park – morning



Graph 14 Months comparison of CO₂ concentration in Špilberk park - noon

The concentration did not reach the value 700 ppm in the noon measurements in Špilberk park, as seen in Graph 14. The biggest difference was between August and September measurements – 140,74 ppm. In June, October and November the CO₂ concentration was between 550 ppm and 600 ppm. July concentration was slightly above 600 ppm.



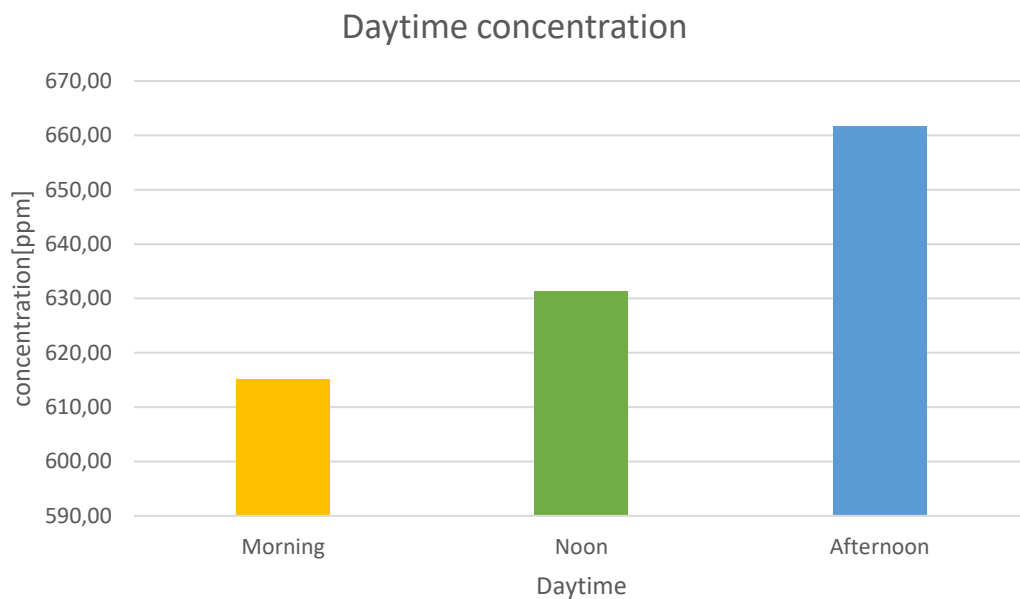
Graph 15 Months comparison of CO₂ concentration in Špilberk park - afternoon

As seen in Graph 15, the lowest CO₂ concentration was measured in November – 550,42 ppm, and the highest concentration in October – 738,05 ppm. The difference between those two months is 187,63 ppm. The difference between September and

October concentration is only 15,39 ppm and between August and November only 10,48 ppm. In June and July, the concentration was somewhat above 600 ppm.

Úvoz crossroad

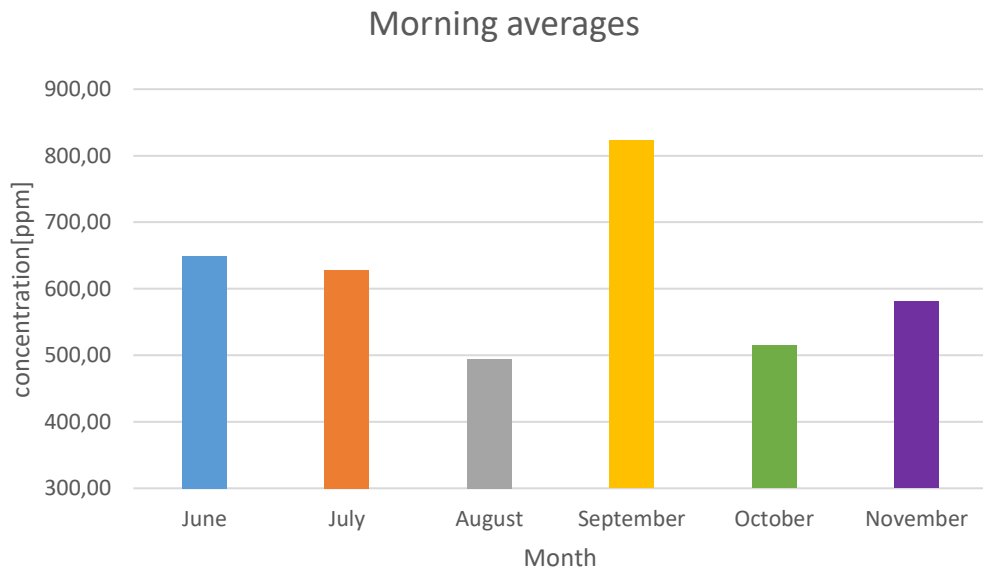
Úvoz crossroad reported the highest overall carbon dioxide concentration in comparison to other three monitored locations. This is probably caused by the nature of this location – important traffic hub, with usually high traffic intensity, thus traffic jams.



Graph 16 Overall daytime average CO₂ concentration in Špilberk park

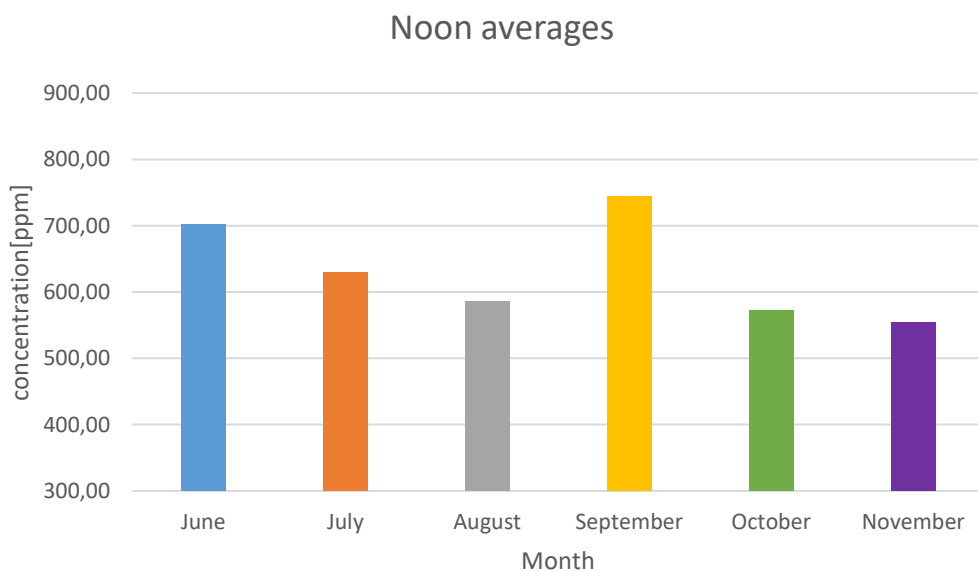
As seen in Graph 16, the lowest average concentration was measured in the morning. The average CO₂ concentration value in the morning is 615,09 ppm, in the noon 631,35 ppm and 661,69 ppm in the afternoon.

As seen in Graph 17, the lowest CO₂ morning concentration was measured in August – 494,49 ppm and the highest morning concentration in Úvoz was in September with the value of 822,76 ppm. The difference between those two measurements is 328,27 ppm. The October's concentration is slightly above 500 ppm value. In June, July and November the concentration is between 550 ppm and 650 ppm.

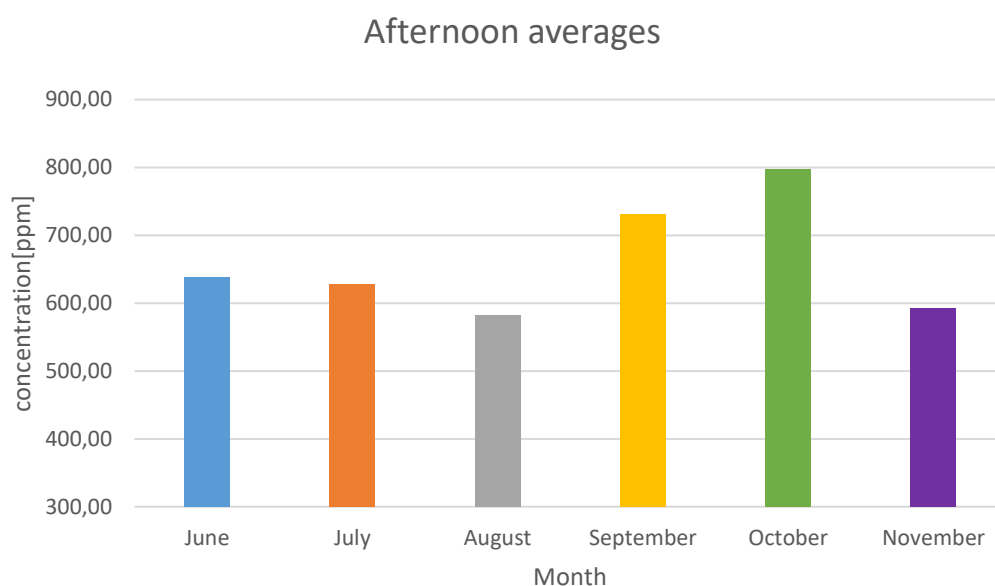


Graph 17 Months comparison of CO₂ concentration in Úvoz crossroad - morning

The highest CO₂ concentration in the noon shows September measurements 743,54 ppm and the lowest CO₂ concentration was monitored in November – 554,08 ppm, as seen in Graph 18. The difference between these two months is 189,45 ppm. June concentration reached the value slightly above 700 ppm. In June, August and October the average concentration was between 550 ppm and 650 ppm.



Graph 18 Months comparison of CO₂ concentration in Úvoz crossroad - noon



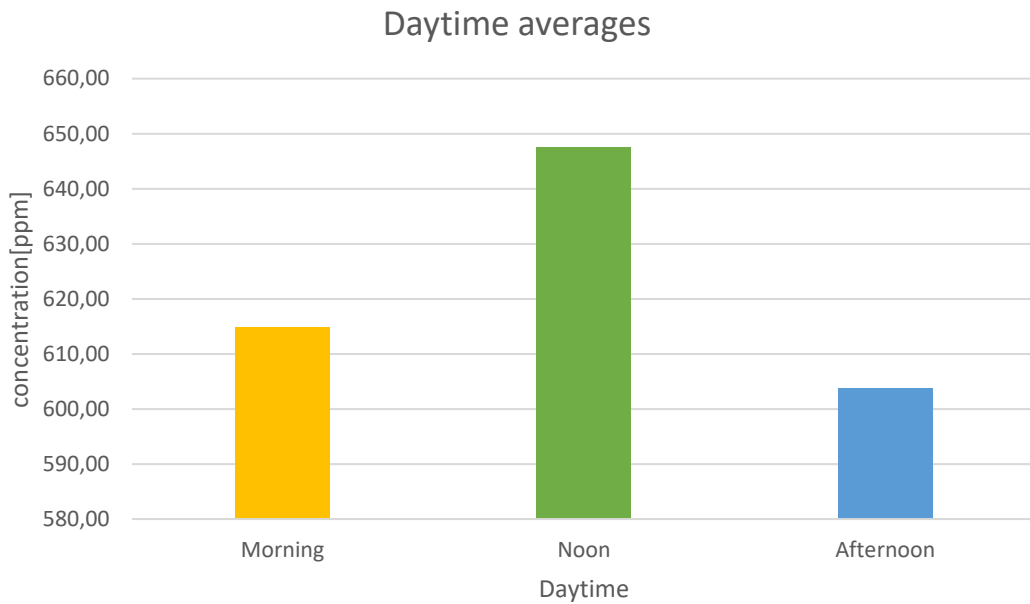
Graph 19 Months comparison of CO₂ concentration in Úvoz crossroad - afternoon

The highest value of CO₂ concentration in the afternoon is reported in October. The average concentration reached 797,10 ppm. The lowest CO₂ concentration was measured in August – 582,94 ppm. The difference between those two months is 214,16. In June, July and November the afternoon concentration did not even reach the 650-ppm value, as seen in Graph 19.

Moravské square

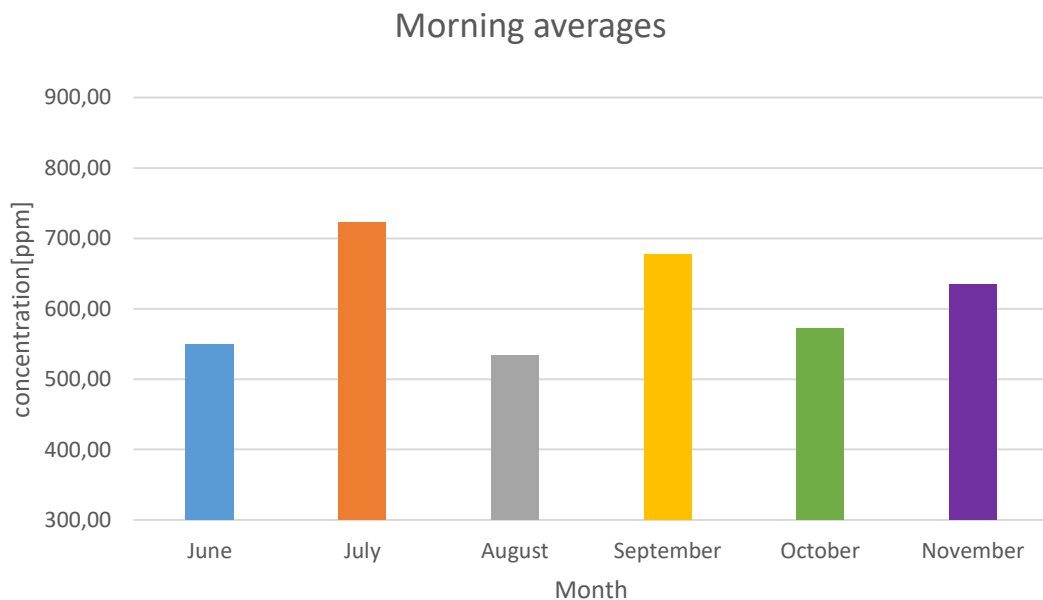
At the crossroad near Moravské square, the values of CO₂ were the second-highest compared to the other three locations. The crossroad is an important traffic hub with quite high traffic loads. Unlike Úvoz crossroad, the crossroad at Moravské square is located in open space, which is framed by buildings from one side and by park and vegetation from the other side.

The lowest CO₂ concentration at Moravské sq. is reported in the afternoon. The highest concentration is reported in the noon. The average morning CO₂ concentration at Moravské sq. is 614,90 ppm, in the noon the average value of CO₂ is 647,57 ppm and 603,73 ppm in the afternoon. The difference between noon and afternoon concentration is 43,84 ppm., as seen in Graph 20.

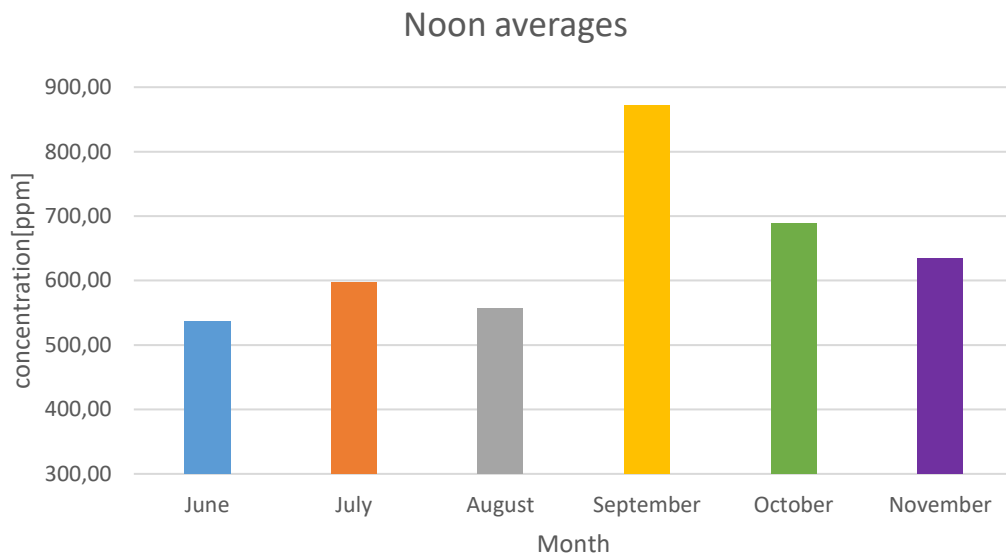


Graph 20 Overall daytime average CO₂ concentration in Špilberk park

As seen in Graph 21, the highest morning CO₂ concentration was measured in July – 722,37 ppm. The lowest morning concentration was measured in August – 532,96 ppm. The difference between those two months is 189,41 ppm. The September concentration was between 650 ppm and 700 ppm. In October and November, the values of CO₂ are between 550 ppm and 650 ppm. The June concentration did not even reach the 550-ppm concentration.

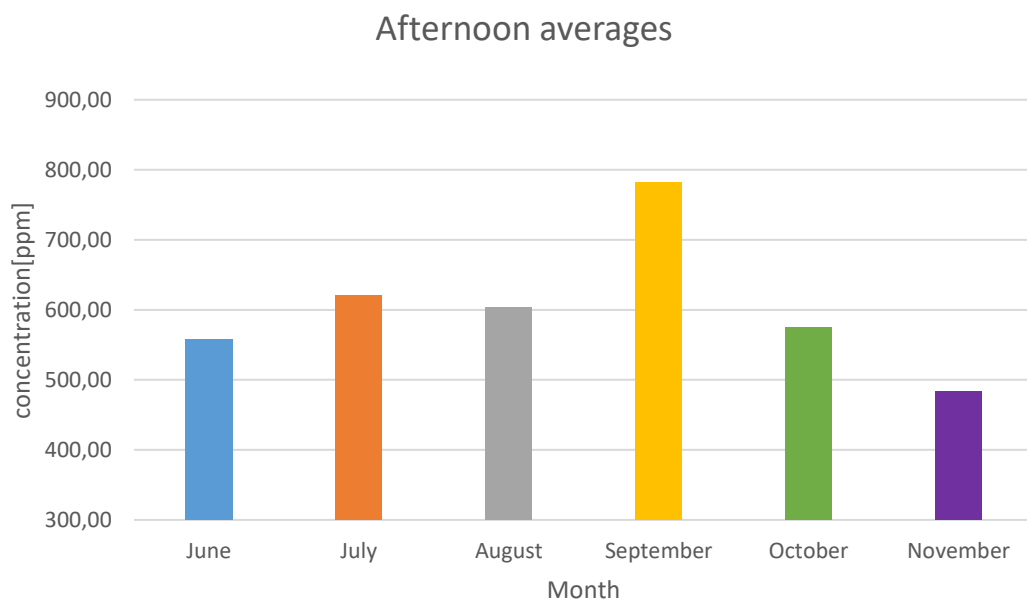


Graph 21 Months comparison of CO₂ concentration at Moravské sq. - morning



Graph 22 Months comparison of CO₂ concentration at Moravské sq. - noon

According to Graph 22, the highest CO₂ concentration in the noon at Moravské sq. was in September – 871,36 ppm. This value is the highest average CO₂ concentration monitored from all locations, for six months. The lowest noon CO₂ concentration at Moravské sq. was measured in June – 537,02 ppm. The difference between June and September concentration is 334,34 ppm. In July and August, the average CO₂ concentration was between 550 ppm and 600 ppm. In October and November, the average CO₂ concentration was between 600 ppm and 700 ppm.



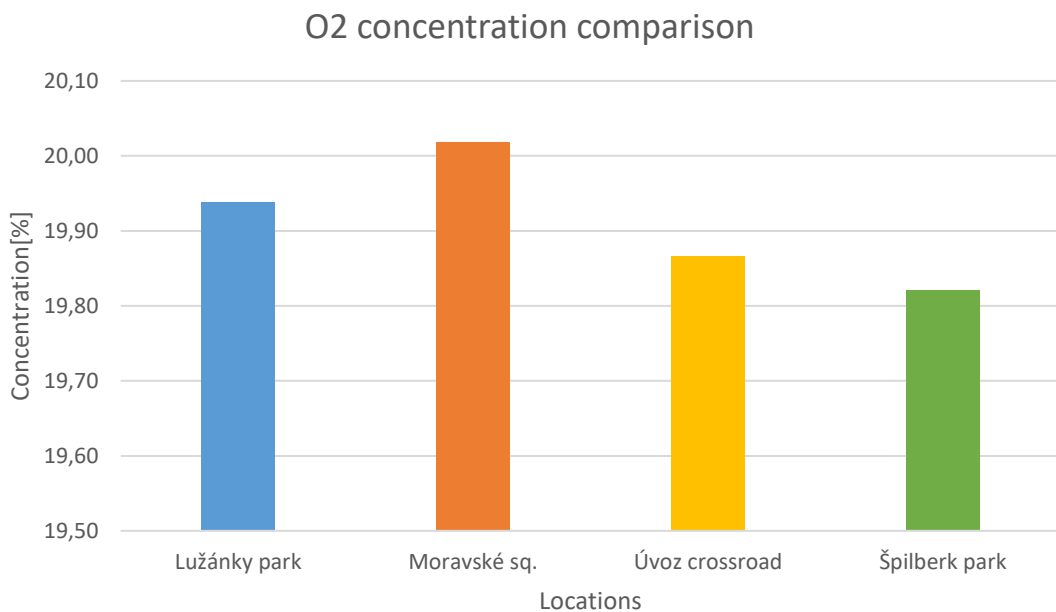
Graph 23 Months comparison of CO₂ concentration at Moravské sq. - afternoon

As seen in Graph 23, the highest afternoon CO₂ concentration was measured in September – 781,50 ppm. The lowest CO₂ concentration was measured in November – 484,03 ppm – which is the lowest average CO₂ concentration monitored from all locations, for six months. The difference between the afternoon extremes is 297,47 ppm. In June, July, August and October the CO₂ concentration ranged around 600 ppm.

6.5 O₂ CONCENTRATION RESULTS

According to the measurements, the overall average oxygen concentration in Brno city is 19,91 %. Even though the concentration is 1 per cent lower than the global average, the value of approx. 20 % is still a normal value. The 1 % difference could be caused by device damage or measuring mistake. The oxygen concentration would have to be lower than 15 per cent to feel any adverse effects on human health. [43]

As seen in Graph 24, the oxygen values at monitored locations differ in tenths of the percentage, which are insignificant values.



Graph 24 Average oxygen concentration at monitored locations

According to Table 6, the concentration between 15 – 19 % is still sufficient to human health. However, intellectual or physical performance is reduced, as well as coordination. Also, thinking and attention are impaired. The hazardous oxygen concentration is below the 15 % value. [43]

The values in open space – outdoors and indoors – cannot get below the 15 % concentration at normal circumstances.

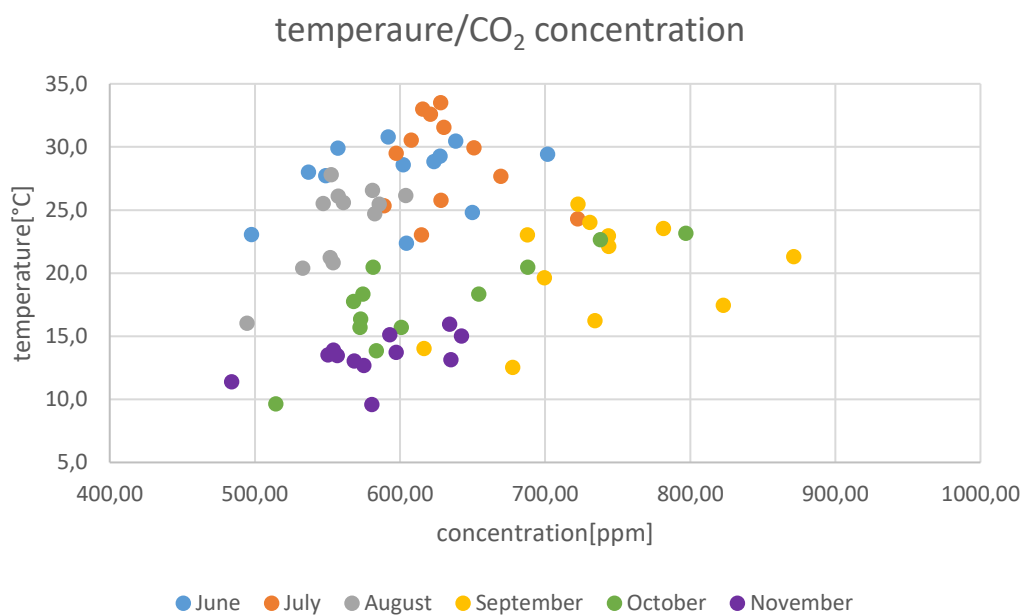
Table 6 Effects of Oxygen-Deficient Exposure [43]

Oxygen concentration [%]	Health effects on person at rest
19	Some adverse physiological effects occur, but they may not be noticeable
15-19	Impaired thinking and attention. Increased pulse and breathing rate. Reduced coordination. Decreased ability to work strenuously. Reduced physical and intellectual performance without awareness.
12-15	Poor judgment. Faulty coordination Abnormal fatigue upon exertion. Emotional upset.
10-12	Very poor judgement and coordination. Impaired respiration that may cause permanent heart damage. Possibility of fainting within a few minutes without warning. Nausea and vomiting.
<10	Inability to move. Fainting almost immediate. Loss of consciousness Convulsions. Death.

6.6 TEMPERATURE, HUMIDITY, WINDSPEED

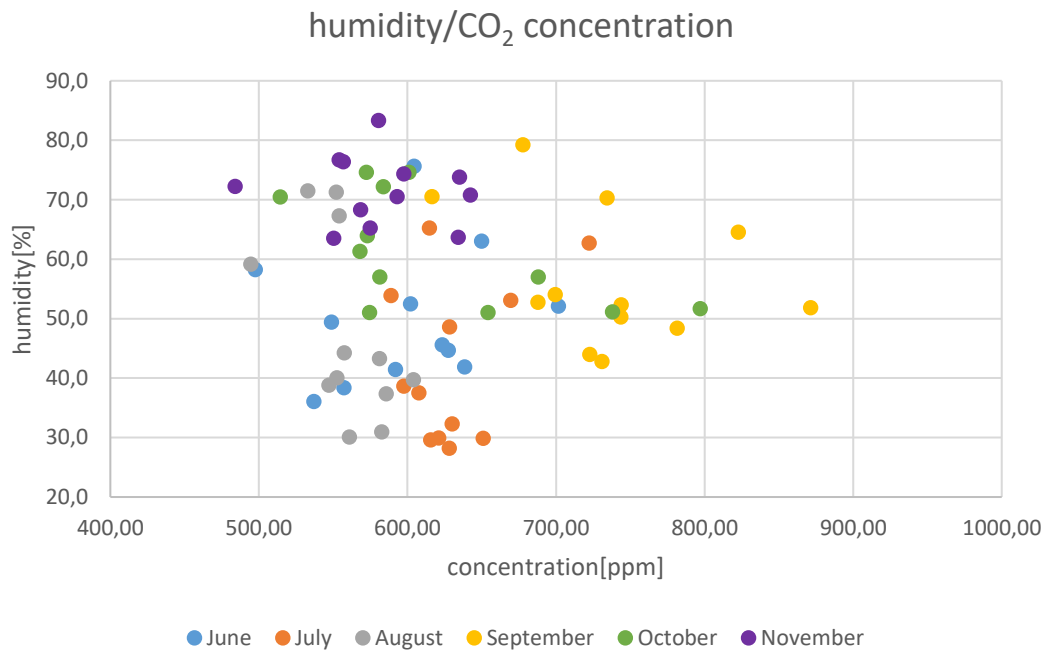
6.6.1 Months comparison

According to the measurements, the warmest month was July. The average overall temperature in July was 28,9 °C. Also, the humidity in July was the lowest of all monitored months – 42,4%. On the other hand, the lowest temperature was measured in November 13,2 °C and the highest humidity was measured in November as well – 71,5 %.

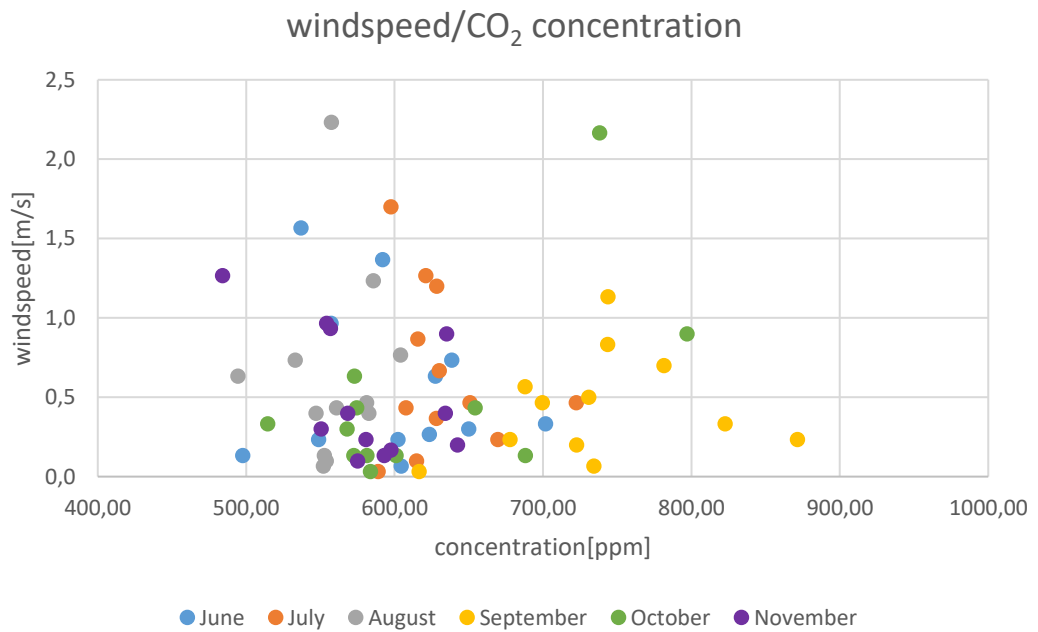


Graph 25 Temperature and CO₂ concentration dependency

As seen in Graph 25, Graph 26 and Graph 27, the concentration is around the value 600 ppm.

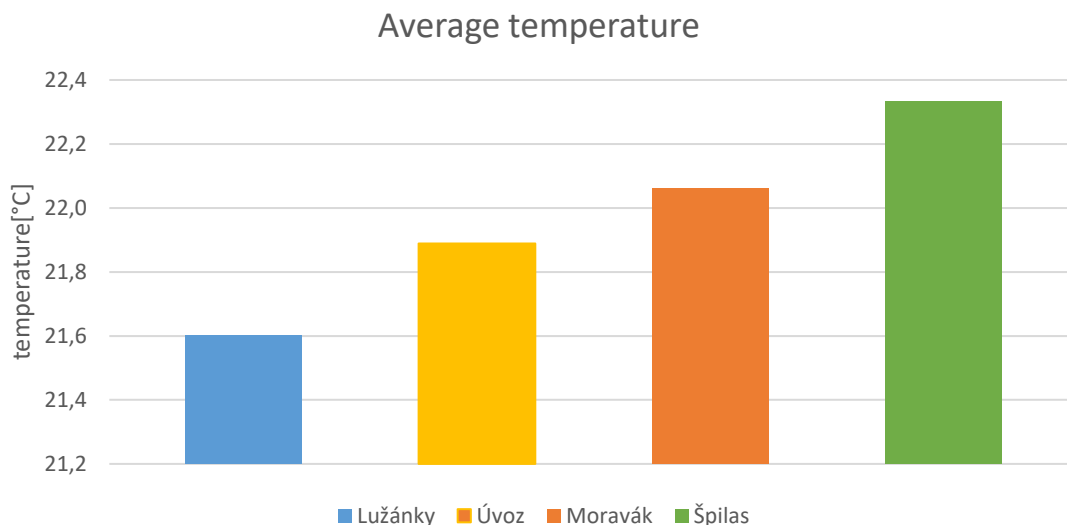


Graph 26 Humidity and CO₂ concentration dependency



Graph 27 Windspeed and CO₂ concentration dependency

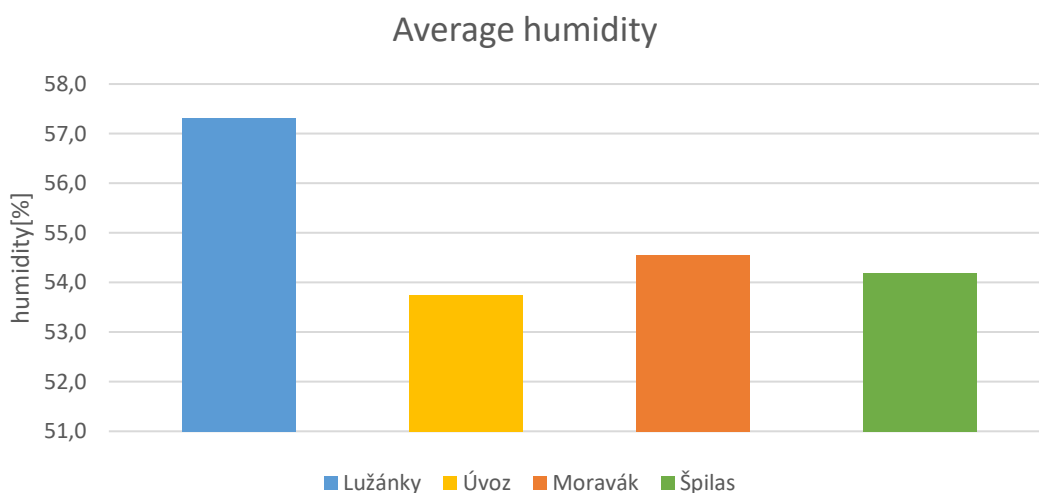
6.6.2 Locations



Graph 28 Average temperature in monitored locations

The lowest average temperature from measured locations was in Lužánky park 21,6 °C and the highest average temperature was measured in Špilberk park, as seen in Graph 28.

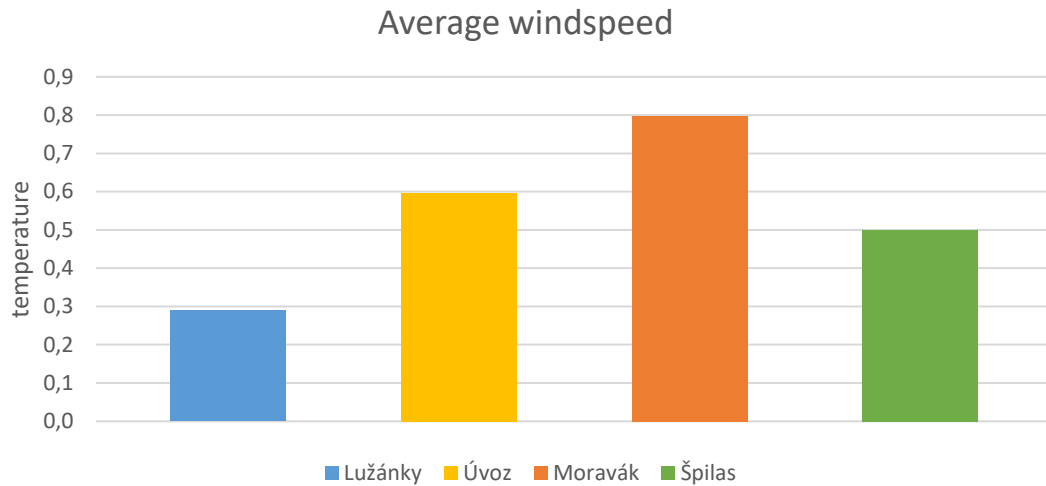
The highest overall average humidity was measured in Lužánky park 57,3 % and the lowest overall average humidity reported Úvoz crossroad 53,7 %, as seen in Graph 29.



Graph 29 Average humidity in monitored locations

According to the measurements, the highest overall wind speed was measured in Moravské sq., as seen in Graph 30. On the other hand, the least windy location is Lužánky park. This is probably caused by the nature of the locations. The crossroad

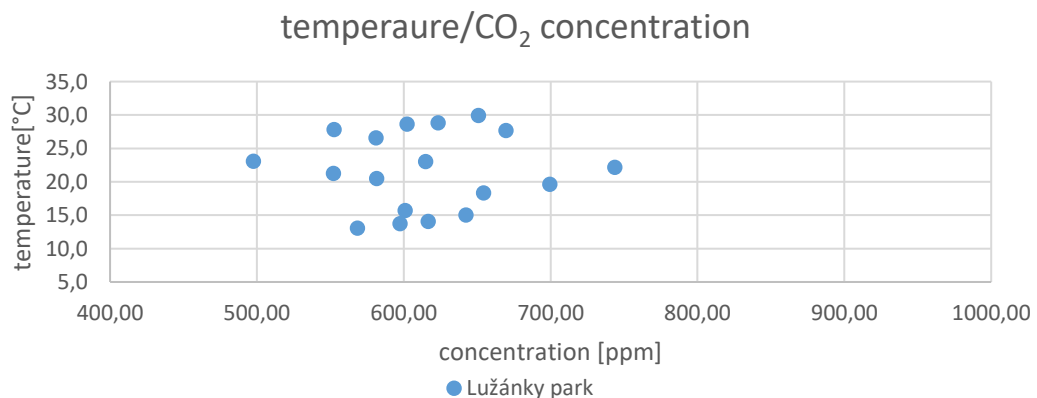
near Moravské square is open space framed by buildings on one side and by trees on the other side. Lužánky park, however, is a location with grown trees and lot of vegetation which may create windbreaks, thus low wind speeds.



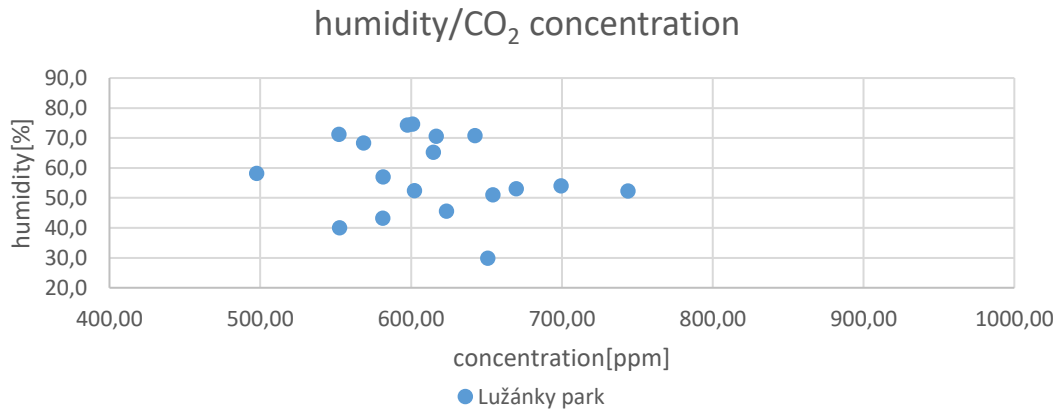
Graph 30 Average wind speed in monitored locations

Lužánky park

The average temperature in Lužánky park was the lowest from all monitored locations. Also, the measured CO₂ concentration dependency on temperature and humidity did not fluctuate that much in comparison to Úvoz crossroad and Moravské sq. The park is able to maintain the carbon dioxide concentration at relatively constant level unlike Úvoz crossroad or Moravské sq., as seen in Graph 31, Graph 32. The CO₂ concentration is between 550 ppm and 700 ppm.

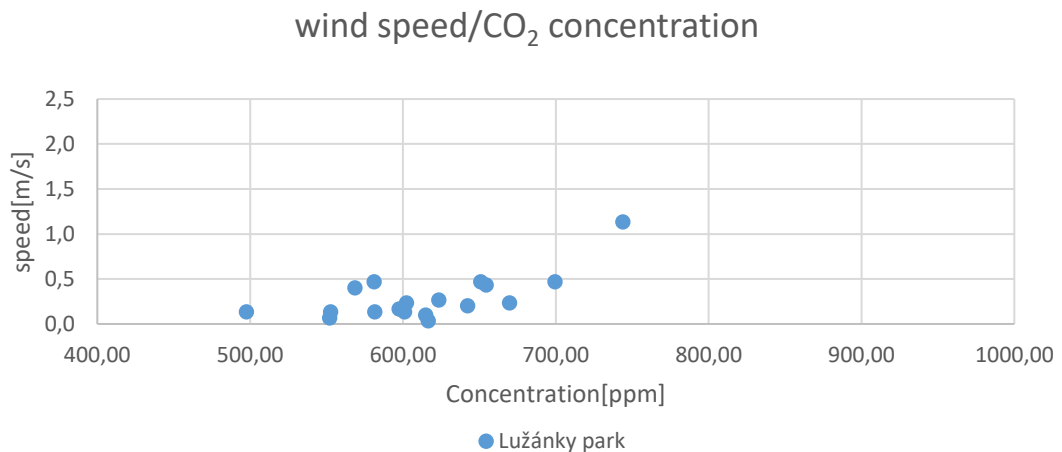


Graph 31 Temperature – concentration dependency – Lužánky park



Graph 32 Humidity – concentration dependency – Lužánky park

The average wind speed in Lužánky park was the lowest in comparison to the other three locations. This is probably caused by grown trees, which create windbreaks.

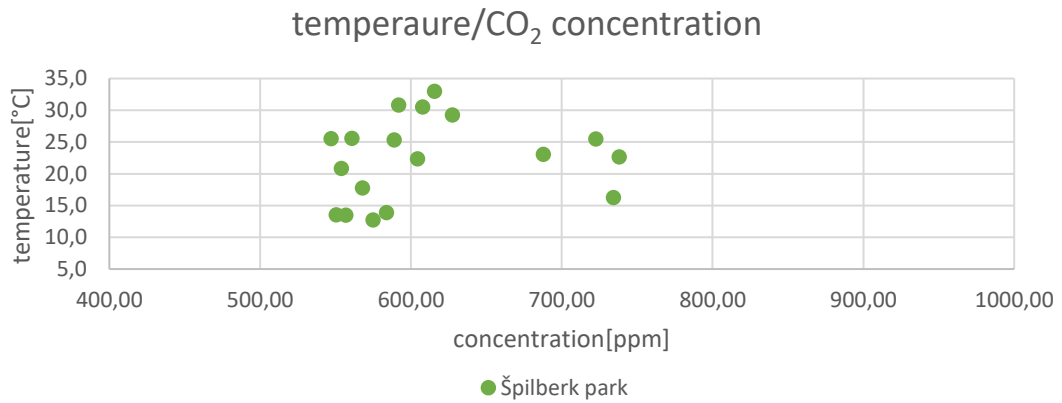


Graph 33 Wind speed – concentration dependency – Lužánky park

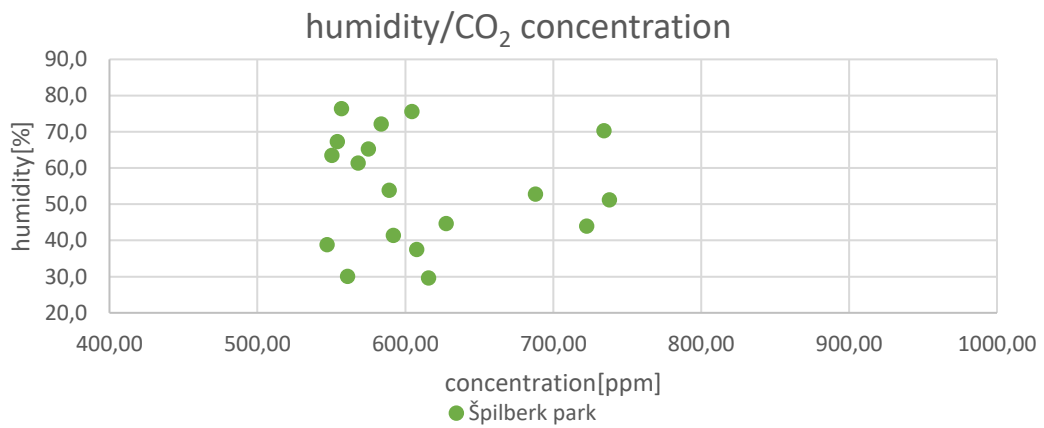
Špilberk park

The CO₂ concentration dependency on temperature and humidity in Špilberk park did not fluctuate that much in comparison to Úvoz or Moravské sq. Like Lužánky park, the Špilberk park is mostly covered with grown vegetation and trees which is able to maintain relatively constant CO₂ values, as seen in Graph 34 and Graph 35. The concentration is between 550 ppm and 650 ppm.

Also, the vegetation creates windbreaks, and the windspeeds in Špilberk park are therefore at low speeds, like in Lužánky park.

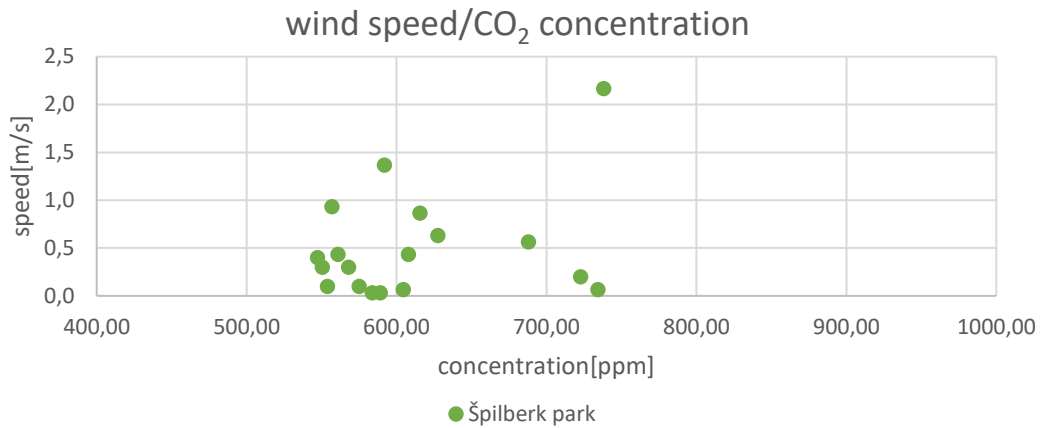


Graph 34 Temperature – concentration dependency – Špilberk park



Graph 35 Humidity – concentration dependency – Špilberk park

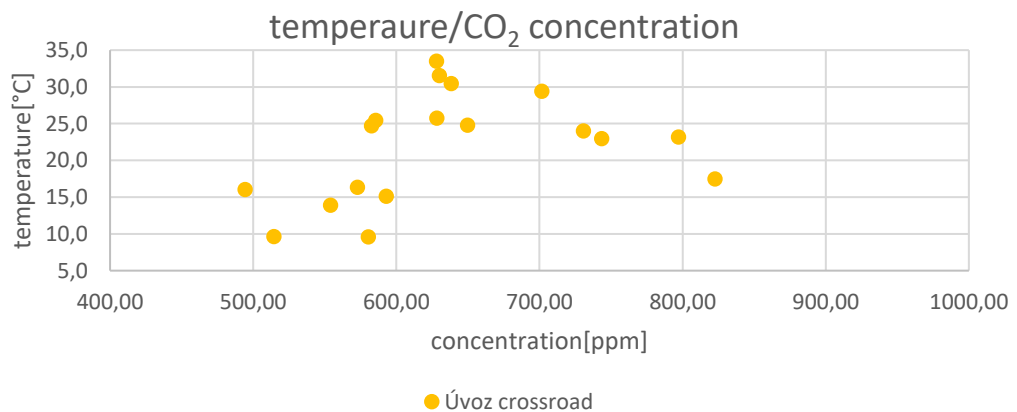
The windspeeds in Špilberk park are higher than in Lužánky park. Špilberk park is not that closed space, unlike Lužánky park, due to the elevated position and not that dense vegetation.



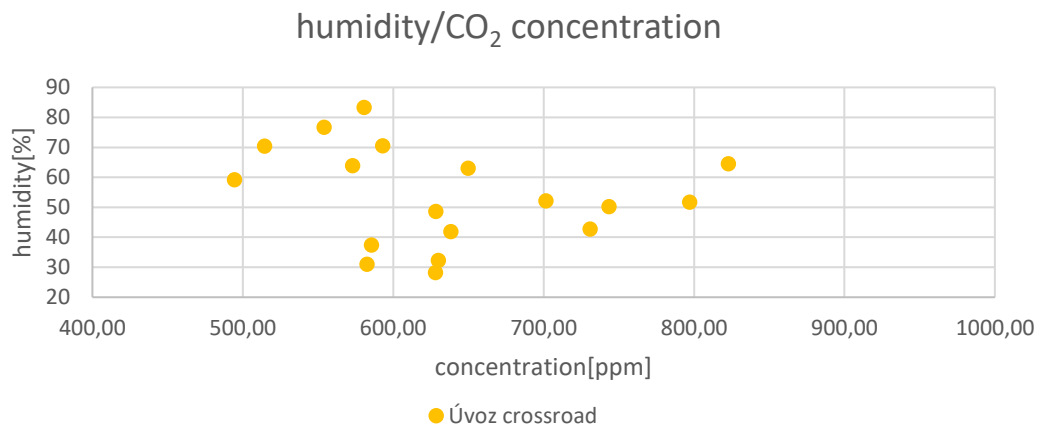
Graph 36 Wind speed – concentration dependency – Špilberk park

Úvoz crossroad

The CO₂ concentration dependency on temperature and humidity at Úvoz crossroad fluctuate in wider range, unlike temperature and humidity in Lužánky park or Špilberk park. This is probably caused by the nature of the location. There is not a big area covered with vegetation that could keep the temperature and humidity at a constant level. The concentration vary between 500 ppm and 800 ppm, as seen in Graph 37 and Graph 38.

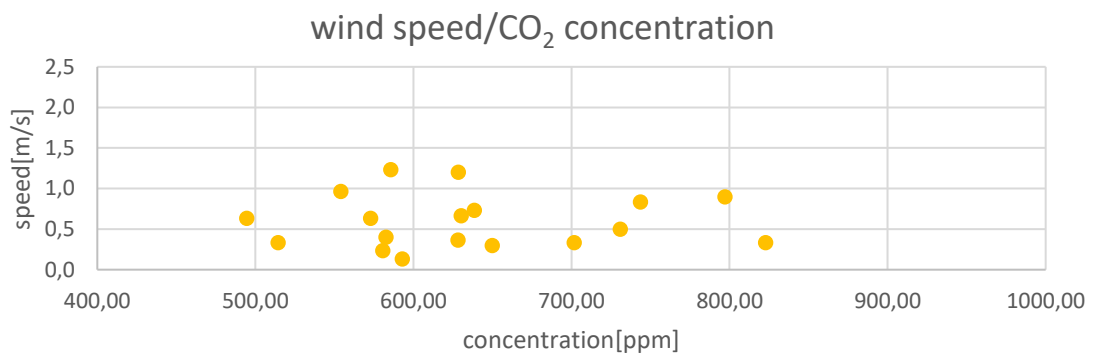


Graph 37 Temperature – concentration dependency – Úvoz crossroad



Graph 38 Humidity - concentration dependency - Úvoz crossroad

The wind speed at Úvoz crossroad is the second-highest from monitored locations, probably because the location is at open space without any trees that could create windbreaks.

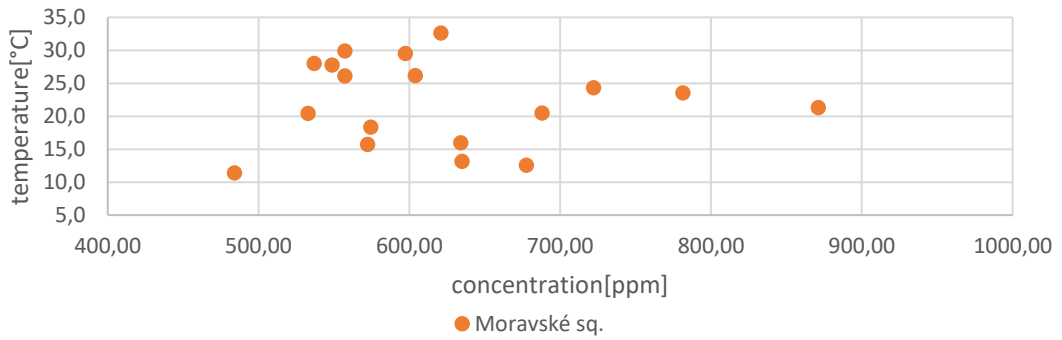


Graph 39 Wind speed - concentration dependency - Úvoz crossroad

Moravské square

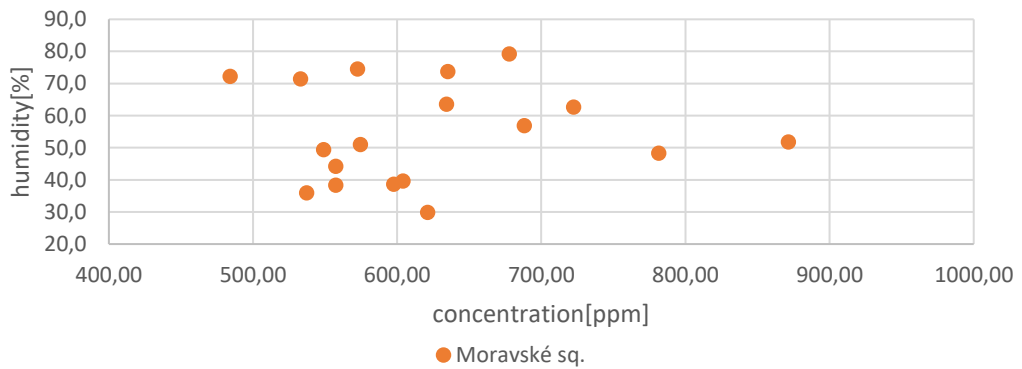
The CO₂ concentration dependency on temperature and humidity at Moravské sq. fluctuate, like at Úvoz crossroad. This is probably caused by the nature of the location – open space framed by buildings, with a small area covered with vegetation or trees. The concentration fluctuates between 500 ppm and 800 ppm.

temperaure/CO₂ concentration



Graph 40 Temperature – concentration dependency – Moravské sq.

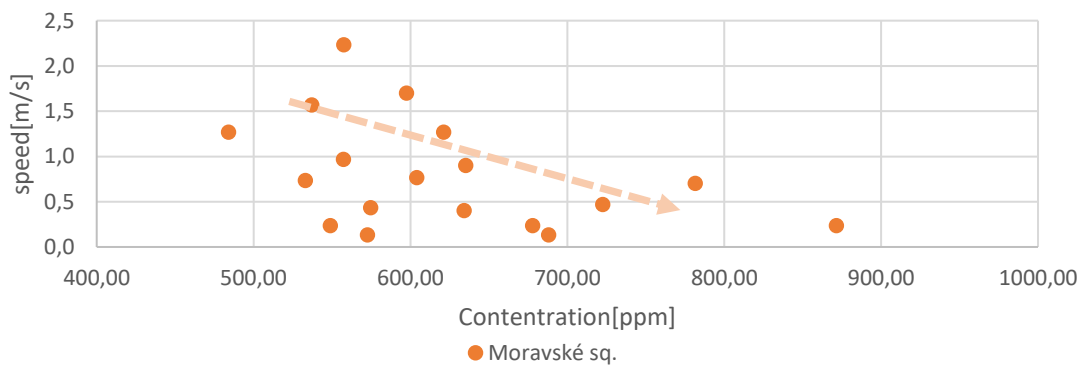
humidity/CO₂ concentration



Graph 41 Humidity – concentration dependency – Moravské sq.

According to Graph 42, the wind speed at Moravské sq. show that with higher wind speed the CO₂ concentration is lower and with low wind speed the CO₂ concentration tend to be higher.

wind speed/CO₂ concentration



Graph 42 Wind speed – concentration dependency – Moravské sq.

6.7 SUMMARY

According to the measurements, the overall average CO₂ concentration in Brno city is 620,97 ppm.

The overall average concentration in monitored locations differs only within approx. 24 ppm, because they are situated near Brno city centre. If the monitored locations were further from each other, the data would probably show a larger difference. However, this paper is mainly focused on urban areas.

According to the measurements, the lowest overall average concentration of CO₂ report locations with more vegetation. The highest overall average CO₂ concentration tends to report build-up areas with high traffic loads. According to Graph 6 and Graph 7, the concentration values differ within the daytime, month and location – not every time, the lowest concentration measured reported 'green areas'.

The lowest overall daytime average CO₂ concentration is in the morning, and the highest overall daytime average CO₂ concentration is in the afternoon. Nevertheless, each location has different daytime extremes. For example, the lowest overall average concentration in the morning report only Lužánky park and the highest overall averages in the afternoon report Špilberk park and Úvoz crossroad - Graph 5.

The highest CO₂ concentration was measured in September in all monitored locations. According to the CHMI, the scattering conditions exceed the norm. The overall average CO₂ concentration measured in September was 736,03 ppm. The lowest overall concentration was measured in August, the average CO₂ value measured was 558,74 ppm.

The highest average CO₂ concentration was measured at Moravské sq. in September – 871,36 ppm, at noon. The lowest average CO₂ concentration was measured at Moravské sq. as well – 484,03 ppm, in the morning. The difference between these two measurements is 387,33 ppm.

According to the measurements, the green areas are able to maintain the CO₂ concentration at a relatively constant level. In addition, the carbon dioxide concentration in Lužánky park and Špilberk park did not fluctuate that much in comparison to Úvoz crossroad and Moravské sq.

7 GREEN MEASURES DESIGN

According to the measurements, the areas with vegetation report better results in CO₂ concentration than those without vegetation, thus the design of green measures is a reasonable solution for keeping the air cleaner or to create a better environment. In addition, the green measures can cool the environment in its vicinity due to the evaporation, thus are able to reduce urban heat island effect.

Also, another reason why green measures implementation is coherent is that green measures can keep the indoor temperatures at a constant level, especially in summer. Green roofs can exchange the Sun's energy into the evaporation process, creating a cooling effect. By this energy exchange, the Sun's energy is not able to get through the roof construction, keeping the indoor environment in the highest floors at liveable level, especially in summer. In winter, however, the contribution of the vegetation on the roof is insignificant. The soil tends to be humid and wet, due to the cooler weather. Nevertheless, sufficient thermal insulation is indispensable.

According to the solar map, the average solar energy in summer in Brno city is approx. 1080 W/m². For purpose of the solar energy distribution differences, in reference examples, the value of 800 W/m² is used. This value incorporates external influences like atmosphere, weather conditions or clouds, which may reduce the actual solar energy shining on the Earth's surface. [47]

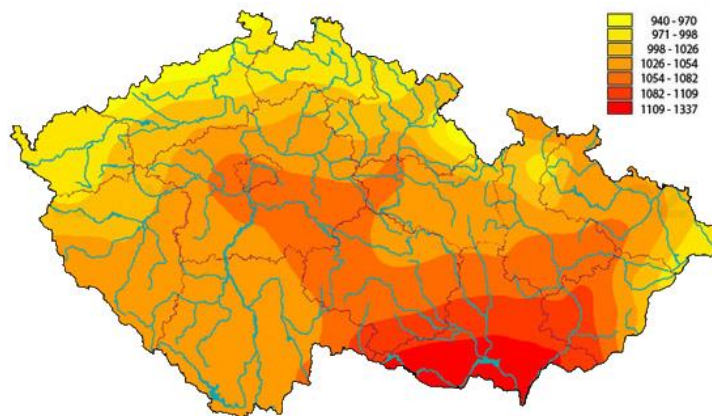


Figure 11 Solar energy map in the Czech Republic [W/m²] [47]

As seen in Figure 12 and Figure 13, the difference between Sun's energy distribution, depending on roof's surface, is shown. As seen in Figure 12, the roof construction with asphalt or metal surface can absorb a lot of Sun's energy, thus introducing heat from the outside indoors. On the other hand, the energy on the roof with vegetation surface is mainly used to water evaporation, thus cooling the nearby area, as seen in Figure 13. In addition, the heat from the outside may not even be introduced indoors.

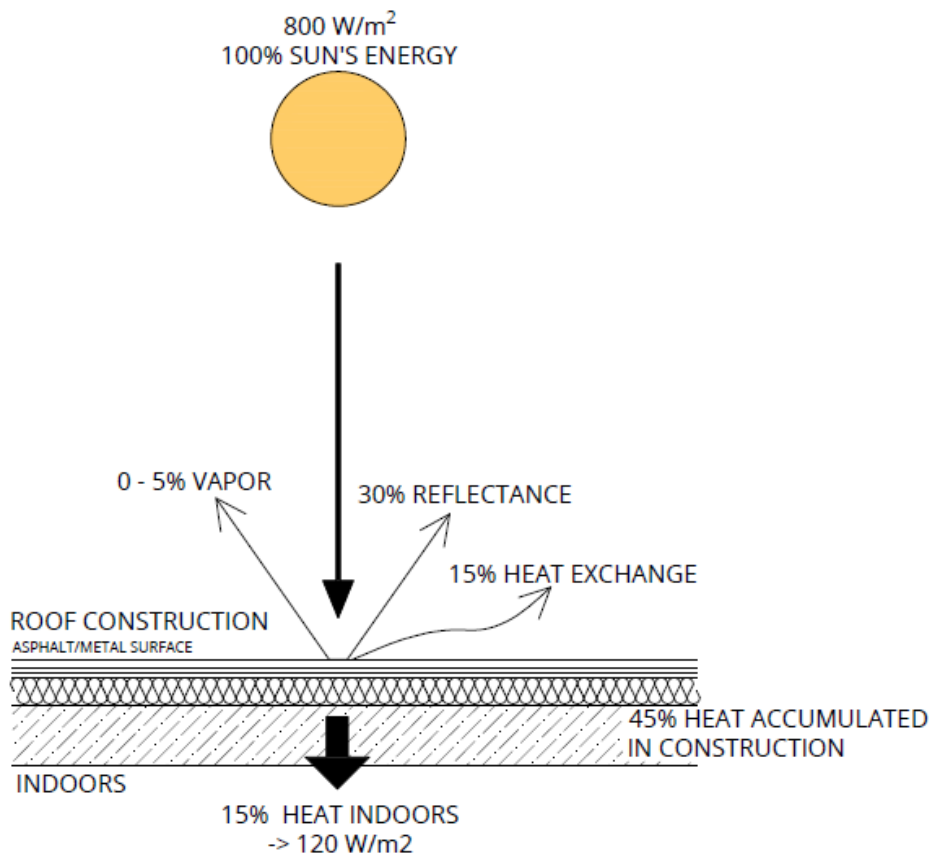


Figure 12 Solar balance during summer – asphalt or metal roof

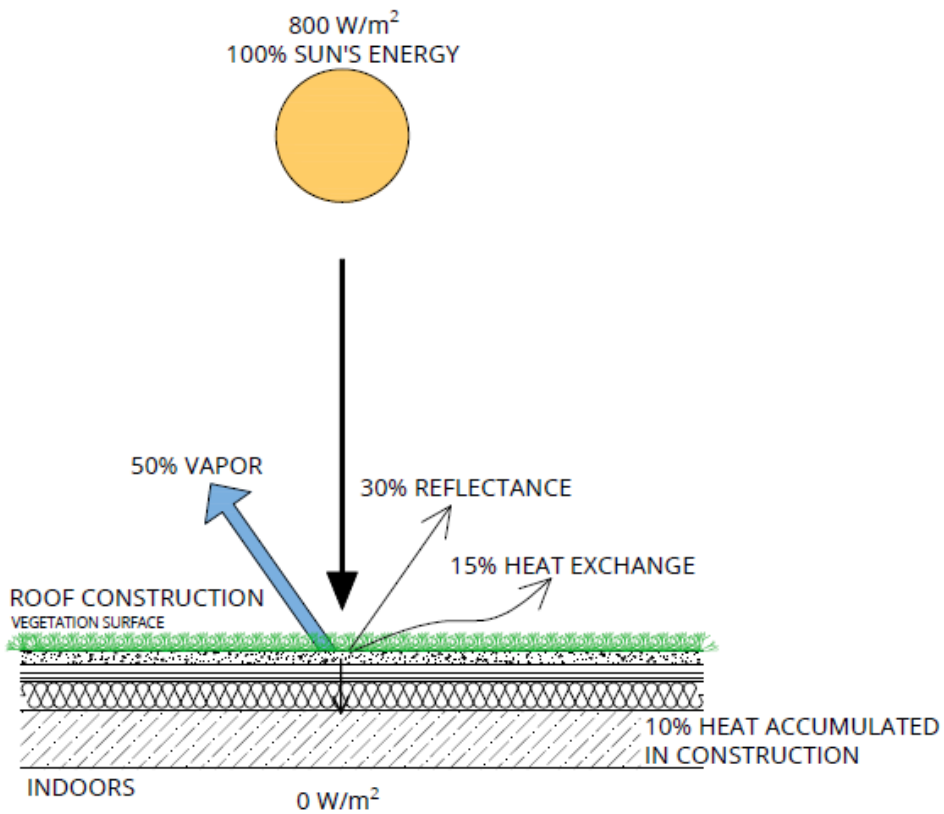


Figure 13 Solar balance during summer – green roof

7.1 DESIGN

The design consist of implementation of the green measures on selected roofs in chosen areas in Brno city. Two areas were chosen for this purpose. The first location is in the centre of Brno, in the Brno-Zábřdovice district. The second location is in the Brno's industrial area, particularly in Brno-Černovice district.

Both of these locations have been chosen because there are flat roofs on which the green measures can be applied. In the design, the extensive roofs are implemented. The reason why the extensive roofs were chosen is because, firstly, the implementation is on the existing roofs. It would be difficult to design the intensive green roof on existing building because of the existing building's statics. The existing roof structure should have sufficient loadbearing capacity for the added load of an extensive roof. Loads of intensive roofs would be greater than the extensive roof loads. Secondly, because extensive roofs do not need that much care unlike intensive roofs.

For purpose of this paper is assumed that all existing roofs, on which the green measures are applied, have sufficient loadbearing capacity even after adding other elements on the existing roofs.

There are two reference examples of extensive roof design and their use. The first one is on the concrete roof construction and the second one is the design of extensive roof on the trapezoidal metal sheet roof construction. It is assumed that in the city centre the buildings tend to have either concrete or brick roofs. On the other hand, the warehouses in Brno's industrial area would rather have metal roof constructions.

The soil mass of the designed roof is 40 mm, and the weight is 80 kg/m². The vegetation used is Sedum, as seen in Figure 14, which is an ideal plant for the extensive roofs (a plant with thick leaves, able to store more water).



Figure 14 Sedum plants on a green roof, [48]

7.1.1 Brno-Zábrdovice district

Brno-Zábrdovice district represents Brno's city centre. The location is quite densely built-up with a little to no vegetation area nearby. In addition, in the vicinity of the selected location, there is an important traffic hub – Koliště.

The high-rise buildings in this area have approximately four to six floors. The estimated buildings' construction is concrete or brick. The skeleton construction, however, is possibility as well. Currently, the selected area is 35,01 % covered by roads and pavement, 52,13 % is covered by roofs and only 12,86 % by vegetation, as seen in Figure 15.

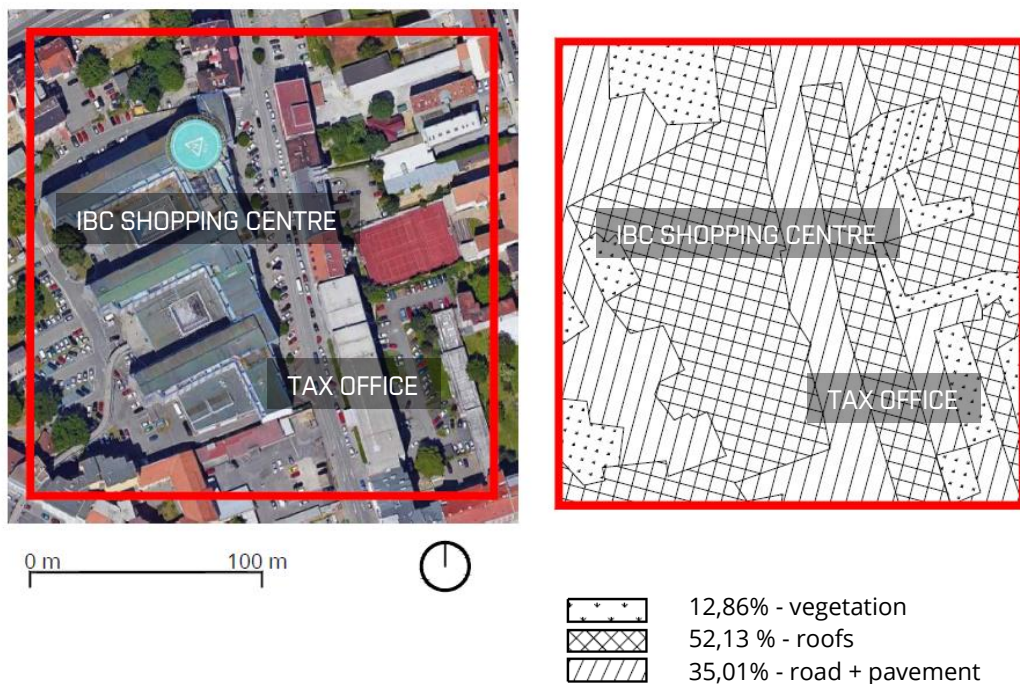


Figure 15 Brno-Zábrdovice district – current state, left figure source [52], customised

The green roof implementation in this area is designed on three roofs on an IBC shopping centre, and on the tax office. The design area is 4 hectares large. In addition, the area covered by vegetation increased by 10,97 %, which is about 0,51 hectares, as seen in Figure 16 and 17.



Figure 16 Brno-Zábrdovice district – green roof design

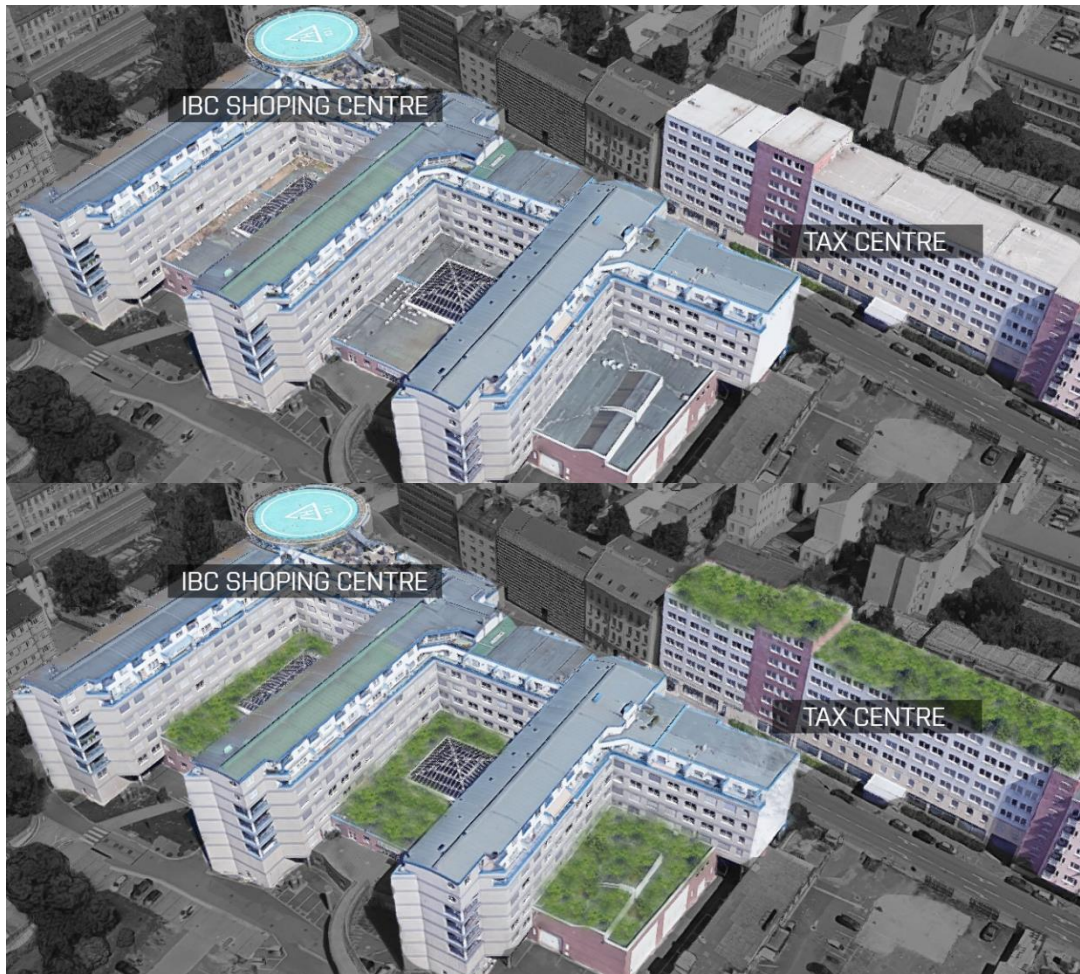


Figure 17 Brno-Zábrdovice district – current state / design; source [52], customised

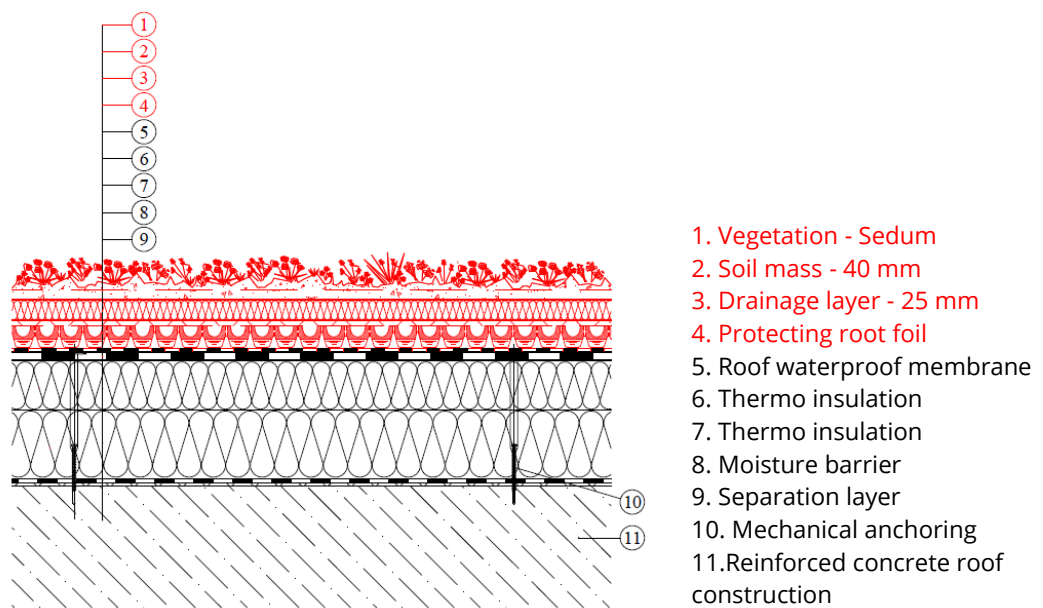


Figure 18 The green roof composition, reinforced concrete roof [50], customised

7.1.2 Brno-Černovice district

Brno-Černovice district represents Brno's industrial area. In this district, there are warehouses with skeleton constructions. These buildings are typically one-floored buildings with tall ceilings, covering large areas. In the vicinity of these warehouses, there are vast fields covered with grasses and herbs. Because of the nature of the area and the nature of warehouse buildings, the implementation of extensive green roofs is on point. The selected area is approx. 36 hectares large.



Figure 19 Brno-Černovice district, selected location, area approx. 36 hectares, [52], customised

Currently, the selected location is covered by 34,13 % of roads and pavement, 39,18 % by roofs and 26,69 % by vegetation, as seen in Figure 20.

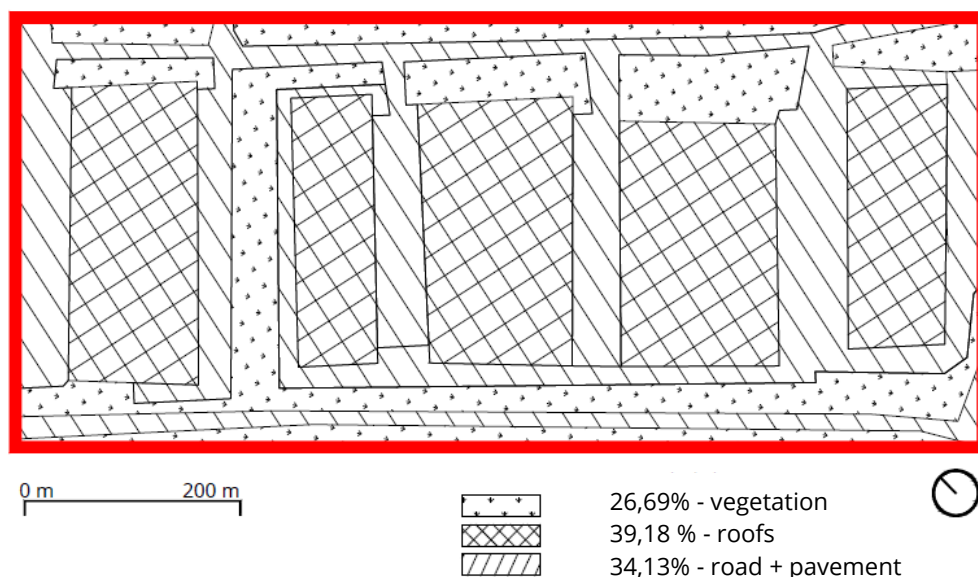


Figure 20 Brno-Černovice district, current state

The design consist of covering all roofs with vegetation in a selected area. Due to the design, the vegetation area increased by 39,18 %, which is about 14,1 hectares (for example the Lužánky park covers area of 20 ha). The design is mainly for technical purpose – the greenery on the roofs may help with the cooling demand especially in summertime. Unlike in Brno- Zábřovice design, where the design has also the aesthetic aspect to it.

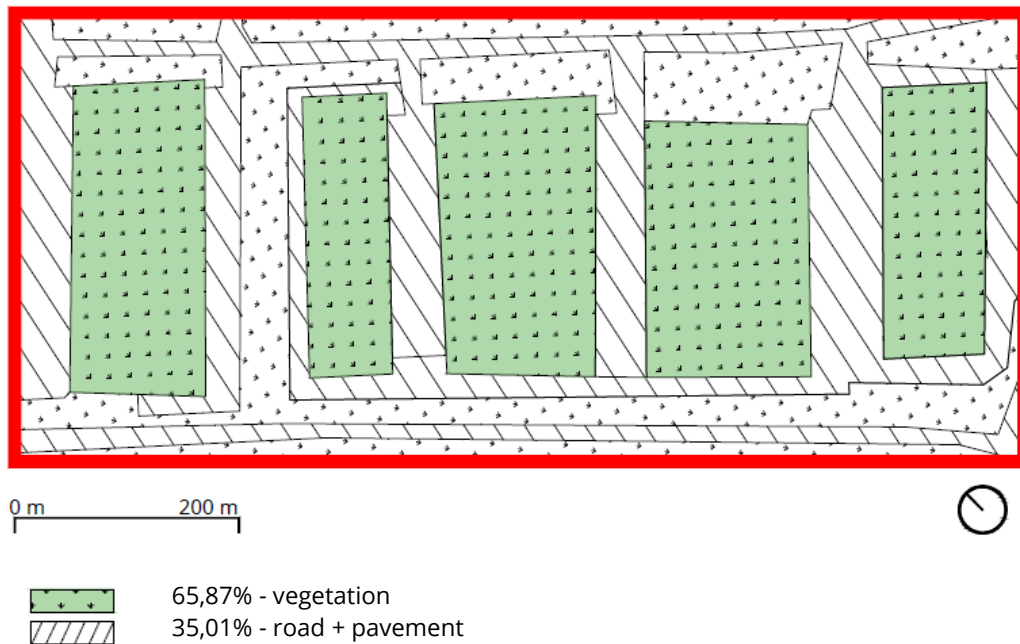


Figure 21 Brno-Černovice district, design

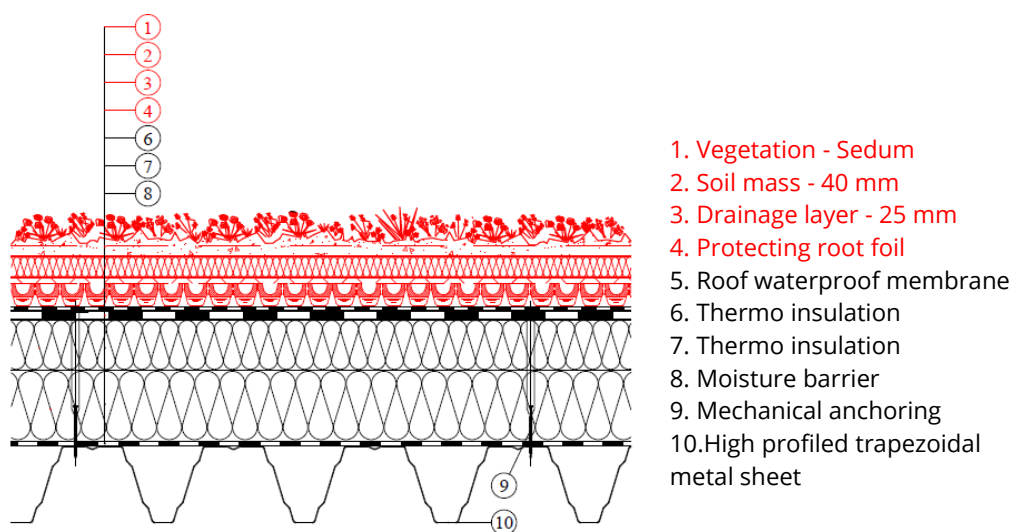


Figure 22 The Green roof composition, trapezoidal metal sheet roof construction [51], customised

CONCLUSION

Urban greenery is an indispensable factor in sustaining the healthy environment in the cities. Not only it is an aesthetically pleasing element, but also, greenery in the urban areas contribute to better living environment. It can clean the air from pollutants by collecting them. Also, greenery keeps the temperature and humidity values at a constant level, it can cool down the urban centres by process of evaporation, thus reducing the urban heat island effect, also, it contributes to stress level reduction.

Vegetation is also excellent in removing the carbon dioxide from the air and creating the oxygen instead. It is crucial to keep the outside CO₂ concentration at a low level because the outside environment sets 'floor' to the indoor environment, where people spend most of their time. According to the measurements, the carbon dioxide exceeded the value of 871,36 ppm, which is not a negligible value. Values higher than 800 ppm tend to be indoors and can exceed even higher concentrations. It is important to maintain outdoor values at a low level so that the CO₂ concentration indoors could be reduced when needed, e.g. by air exchange or ventilation.

Measurements show that the areas with a lot of vegetation report better results in comparison to built-up areas with high traffic loads. In addition, green areas are able to maintain the CO₂ concentration at a relatively constant level, unlike built-up areas. The overall CO₂ concentration changed during the daytime, with the lowest values in the morning and the highest in the afternoon.

As a positive influence of greenery was confirmed by the measurements, an example of such green implementation was designed. The selected green measure was an extensive green roof. Two suitable areas were selected in Brno city. A choice of the used plant was made as well as the building's roof structure.

Incorporation of more vegetation into the cities and towns can lead to sustainable building and development and better living conditions. By making urban areas more attractive to its residents, people would not be pressured to leave the urban centres to find greenery, and towns would not be depopulated. Green measures can contribute to a better living environment outdoors and indoors, by trapping the carbon dioxide and creating oxygen, by cooling the urban centres and also by lesser energy demands for cooling the indoors, especially in the summer. The implementation of green measures inside the cities is therefore important, not only for people, but also for urban nature and encouraging biodiversity.

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LIST OF ABBREVIATIONS

AC	Air conditioning
CHMI	Czech Hydrometeorological Institution
CO ₂	Carbon dioxide
O ₂	Oxygen
NO _x	Nitrogen oxides
SO _x	Sulphur oxides
CO	Carbon monoxide
O ₃	Ground-level ozone
HC	Hydrocarbons
VOC	Volatile organic compounds
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
TSP	Total Suspended Particulate matter
GHG	Greenhouse gases
CH ₄	Methane
TSES	Territorial System of Ecological Stability
EU	European Union
No.	Number
Coll.	Collection
Avg.	Average
e.g.	Exempli Gratia (for example)
etc.	Et cetera (and the rest)
µm	micrometre
m ²	square metre
sq.	square

LIST OF FIGURES

Figure 1 World Population Growth, source [6]	14
Figure 2 Greenery in the streets [8].....	17
Figure 3 comparison built-up area with the rural area, evapotranspiration, [14]	22
Figure 4 CO ₂ concentration during years. Source:[35].....	32
Figure 5 Noise pollution – Roads, Brno. The figure shows noise pollution during the daytime. Source :[41].....	34
Figure 6 Map of monitored locations in Brno, orange colour significates monitoring station source: [52]	38
Figure 7 Surface coverage – Lužánky park [52].....	39
Figure 8 Surface coverage – Špilberk park [52].....	40
Figure 9 Surface coverage – Úvoz crossroad [52].....	41
Figure 10 Surface coverage – Moravské sq. [52]	42
Figure 11 Solar energy map in the Czech Republic [W/m ²] [47].....	69
Figure 12 Solar balance during summer – asphalt or metal roof	70
Figure 13 Solar balance during summer – green roof.....	70
Figure 14 Sedum plants on a green roof, [48]	71
Figure 15 Brno-Zábrdovice district – current state, left figure source [52], customised.....	72
Figure 16 Brno-Zábrdovice district – green roof design	72
Figure 17 Brno-Zábrdovice district – current state / design; source [52], customised.....	73
Figure 18 The green roof composition, reinforced concrete roof [50].....	73
Figure 19 Brno-Černovice district, selected location, area approx. 36 hectares, [52], customised.....	74
Figure 20 Brno-Černovice district, current state.....	74
Figure 21 Brno-Černovice district, design.....	75
Figure 22 The Green roof composition, trapezoidal metal sheet roof construction [51]	75

LIST OF GRAPHS

Graph 1 The comparison of the 30-minute progress of O ₂ concentration, in six months	36
Graph 2 The comparison of the 30-minute progress of CO ₂ concentration, in six months ..	37
Graph 3 Overall average CO ₂ concentration comparison in monitored locations	39
Graph 4 The overall average CO ₂ concentration comparison during the day in all places ...	45
Graph 5 The overall average CO ₂ concentration comparison during day	46
Graph 6 The overall average CO ₂ concentration comparison in all places.....	47
Graph 7 The overall average CO ₂ concentration comparison	48
Graph 8 Overall daytime average CO ₂ concentration in Lužánky park	48
Graph 9 Months comparison of CO ₂ concentration in Lužánky park - morning.....	49
Graph 10 Months comparison of CO ₂ concentration in Lužánky park - noon	49
Graph 11 Months comparison of CO ₂ concentration in Lužánky park - afternoon.....	50
Graph 12 Overall daytime average CO ₂ concentration in Špilberk park	51
Graph 13 Months comparison of CO ₂ concentration in Špilberk park – morning.....	51
Graph 14 Months comparison of CO ₂ concentration in Špilberk park - noon	52
Graph 15 Months comparison of CO ₂ concentration in Špilberk park - afternoon.....	52
Graph 16 Overall daytime average CO ₂ concentration in Špilberk park	53
Graph 17 Months comparison of CO ₂ concentration in Úvoz crossroad - morning.....	54
Graph 18 Months comparison of CO ₂ concentration in Úvoz crossroad - noon	54
Graph 19 Months comparison of CO ₂ concentration in Úvoz crossroad - afternoon.....	55
Graph 20 Overall daytime average CO ₂ concentration in Špilberk park	56
Graph 21 Months comparison of CO ₂ concentration at Moravské sq. - morning	56
Graph 22 Months comparison of CO ₂ concentration at Moravské sq. - noon	57
Graph 23 Months comparison of CO ₂ concentration at Moravské sq. - afternoon.....	57
Graph 24 Average oxygen concentration at monitored locations	58
Graph 25 Temperature and CO ₂ concentration dependency.....	59
Graph 26 Humidity and CO ₂ concentration dependency.....	60
Graph 27 Windspeed and CO ₂ concentration dependency	60
Graph 28 Average temperature in monitored locations	61
Graph 29 Average humidity in monitored locations	61
Graph 30 Average wind speed in monitored locations	62
Graph 31 Temperature – concentration dependency – Lužánky park	62
Graph 32 Humidity – concentration dependency – Lužánky park	63
Graph 33 Wind speed – concentration dependency – Lužánky park	63
Graph 34 Temperature – concentration dependency – Špilberk park	64

Graph 35 Humidity – concentration dependency – Špilberk park	64
Graph 36 Wind speed – concentration dependency – Špilberk park.....	65
Graph 37 Temperature – concentration dependency – Úvoz crossroad	65
Graph 38 Humidity – concentration dependency – Úvoz crossroad	66
Graph 39 Wind speed – concentration dependency – Úvoz crossroad.....	66
Graph 40 Temperature – concentration dependency – Moravské sq.	67
Graph 41 Humidity – concentration dependency – Moravské sq.	67
Graph 42 Wind speed – concentration dependency – Moravské sq.....	67

LIST OF TABLES

Table 1 The emission limits declared for the protection of human health and a maximum number of overrun according to the Act. no. 201/2012 Coll. on air protection [53]	12
Table 2 The CO ₂ production dependency on the type of vehicle [57]	43
Table 3 The CO ₂ production of an economical household	44
Table 4 The CO ₂ production of an old household.....	44
Table 5 The person's CO ₂ production by breathing according to the physical activity	45
Table 6 Effects of Oxygen-Deficient Exposure [43].....	59