Urban Thermodynamics

Course Project

Group 9

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1 Introduction

Nowadays, cities are increasingly challenged by environmental issues, particularly the urban heat island (UHI) effect, where urban areas experience higher temperatures than their suburban surroundings. This phenomenon is driven by the density of urban infrastructure, the use of materials that retain heat, and intensified by human activity. In the context of global climate change, the UHI effect is a danger for urban residents as it causes heat-related illnesses, greater energy demands for cooling, and adverse impacts on urban biodiversity. Addressing these issues is essential to make cities more sustainable and livable.

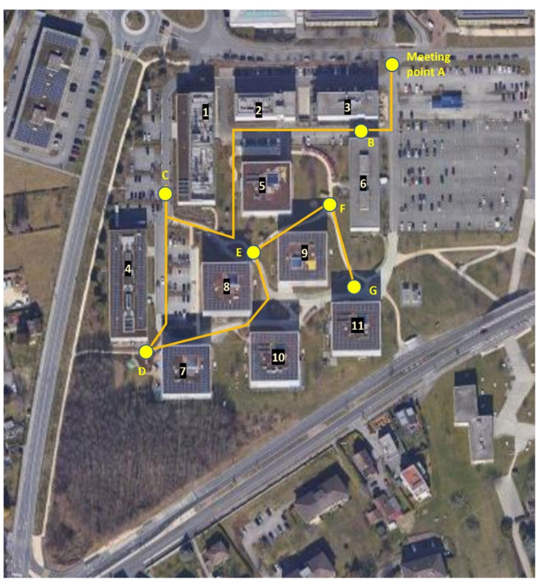
This project aims to investigate the microclimate of EPFL Innovation Park, a site on the EPFL campus that includes office buildings, parking areas, and wooded spaces. Our objective is to analyze how various urban elements—such as buildings, ground materials, vegetation, and water features—influence the site's microclimate. By using ENVI-met simulation software, we will explore the thermodynamic interactions between these elements to understand both their individual and combined impacts on local climate conditions.

The results of this analysis will guide the development of targeted strategies to mitigate overheating and improve thermal comfort, tailored specifically to the unique characteristics of EPFL Innovation Park. This report is organized into three main sections: an analysis of the site's current conditions, an exploration of microclimate interactions across different scenarios, and a final section presenting an integrated solution designed to enhance outdoor thermal comfort on the site.

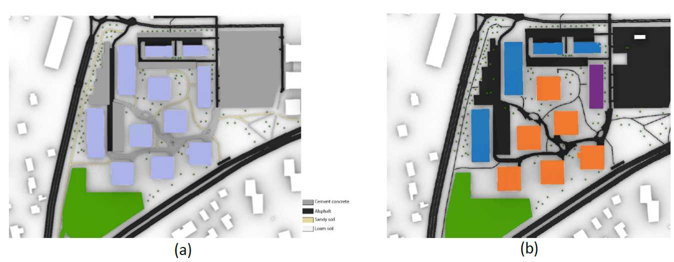
1.1 Site analysis

The site analysis is a crucial step in understanding the specific characteristics of the EPFL Innovation Park and their impact on the urban microclimate. This analysis will inform the implementation of climate-sensitive strategies in urban design, addressing both current and future environmental challenges.

Located near Lake Leman, the EPFL Innovation Park features a diverse environment, with varying surface materials, urban geometry, and green and blue infrastructure. These elements directly influence the local climate and, consequently, the urban overheating issue. A thorough understanding of these conditions will help in identifying targeted solutions to mitigate urban heat islands (UHI). The figures below show the details of the site.



(a) EPFL Innovation Park



(b) Details of the site: (a) ground cover, (b) building material group

Figure 1

The *Site Analysis* section will focus on the following areas:

- **Climate Analysis**: Examine the site's climate using current and projected data for 2100, focusing on air temperature, humidity, and heatwave predictions.
- **Thermal Properties of Urban Materials**: Assess how materials like asphalt, soil, and concrete store and release heat, influencing local microclimates.

- **Urban Morphology**: Analyze factors like sky view, building density, and street aspect ratio to identify areas with exacerbated thermal conditions.

- **Base Case Simulation with ENVI-met**: Model the existing microclimate to identify overheating areas, considering factors like temperature, humidity, radiation, and wind.

These analyses will help identify the causes of urban overheating at EPFL Innovation Park and guide sustainable solutions to mitigate urban heat islands.

Firstly, to learn more about our site, we visited the location and analyzed several key elements that are important for the urban microclimate, such as the sky view factor, building heights, and the various materials used. We have summarized our findings in the following table.

Location	Natural elements	Ground cover material	Surrounding building material	Surrounding building-height [m]
A	Grass, Vegetation, Trees	Asphalt	Concrete, Steel, Grass	14
B	Vegetation, Grass	Asphalt	Concrete, Steel, Grass	14
C	Grass, Vegetation, Trees	Asphalt	Concrete, Glass, Plastic	14
D	Grass, Vegetation, Trees, Sandy Soil	Gravel, Sand	Concrete, Glass, Plastic	14 to 22
E	Bushes, Grass, Trees, Sandy Soil	Gravel, Sand	Concrete, Glass (a lot), Plastic	22
F	Bushes, Grass, Trees, Sandy Soil	Gravel, Sand	Concrete, Glass, Plastic	13 to 22
G	Bushes, Grass, Trees, Sandy Soil	Asphalt, Grass	Concrete, Glass, Plastic	22

Location	Anthropogenic heat source	Aspect ratio [-]	Sky view factor [-]	Shading sources
A	Cars, People	-	0.9	Buildings
B	Cars, People, Building	1.6	0.90	Buildings, Trees
C	Cars, People, Building	-	1	Buildings, Trees
D	People, Building, Kindergarten	1.25	0.80	Buildings, Trees
E	Building, People	1	0.7	Buildings, Trees
F	Building, People	0.5 - 0.6	0.8	Buildings, Trees, Bike shelter
G	Building, People	-	0.90	Buildings, Trees

Figure 2: Collected data on site

Based on the data collected, we have highlighted the following key aspects that influence the site's microclimate:

- **Thermal Resistance and Conduction:** The thermal resistance of surfaces, such as asphalt and concrete, dictates how well they store heat. Materials like concrete, steel, and glass (commonly found in the surrounding buildings of the site) have high thermal conductivity, meaning they retain heat during the day and slowly release it at night. In the analyzed locations (A, B, C, D, E, F, G), materials like asphalt (used for ground cover) and **c**oncrete (building material) have a significant thermal mass, absorbing and storing heat. The sand and gravel ground cover in some locations, on the other hand, offers less thermal storage.

- **Radiation**: Radiation refers to the transfer of heat through electromagnetic waves. In urban areas, this is mainly associated with solar radiation absorbed by surfaces and the subsequent re-radiation of infrared energy. The surfaces with lower albedo (such as asphalt) absorb more solar radiation and subsequently re-emit infrared radiation, contributing to higher surface temperatures

- **Convection**: Convection is the transfer of heat through air or another fluid, driven by temperature gradients. Forced convection can occur in urban areas due to wind or artificial ventilation. Locations like C, with lower building height, may experience better airflow compared to more densely built locations like A and E.

- **Transport of Water Vapor and Bowen Ratio** : **Bowen Ratio** (the ratio of sensible heat flux to latent heat flux) is a useful indicator of the balance between heat stored in the atmosphere and the cooling effect of evaporation. Locations with more vegetation, like B, C, and D, will likely have a higher Bowen ratio, indicating more cooling via evaporation.

- **Sky View Factor (SVF)**: The SVF is crucial in determining how much of the sky is visible from the ground, which affects the ability of the area to cool down at night. Locations with a higher SVF (like Locations C and G, with an SVF of 1 and 0.9 respectively) will experience better nighttime cooling as they can radiate heat away more efficiently. In contrast, areas with lower SVF (such as Location F with an SVF of 0.8) may experience reduced cooling, leading to more prolonged heat retention.

- **Aspect Ratio**: The aspect ratio, which is the ratio of building height to street width, helps assess the potential for solar radiation and shading. Locations with a higher aspect ratio, such as Location B (with an aspect ratio of 1.6), may experience more shade and less direct solar radiation, reducing heat accumulation. On the other hand, areas with a lower aspect ratio, such as Location F (0.5–0.6), may see higher exposure to the sun and increased heat buildup.

- **Building Density and Shading**: Locations with taller buildings (such as Locations B, E, F, and G with building heights of 16m) offer more shading for the surrounding streets, potentially mitigating the urban heat island effect. However, this shading may also result in limited airflow and restricted cooling, especially in areas where buildings are tightly packed together, as seen in Locations B, C, and G.

- **Ground Cover Materials**: The areas with more *gravel, sand*, and *sandy soil* (Locations D, E, F, G) likely have lower thermal mass compared to those with *asphalt* (Locations A, B, C), meaning they will heat up and cool down more quickly. Asphalt, being a dark, heat-absorbing material, will contribute to higher temperatures during the day, particularly in Locations A, B, and C.

- **Building Materials**: The surrounding buildings are made from materials such as *concrete, glass, steel*, and *plastic*. Concrete and steel are known for their high thermal mass, which means they retain heat for longer periods, exacerbating the urban heat island (UHI) effect in areas like Locations A, B, and G. On the other hand, the extensive use of *glass* (in Locations C, D, E, F, and G) can increase heat absorption and reflection, potentially causing higher temperatures in these areas, particularly in sunny conditions.

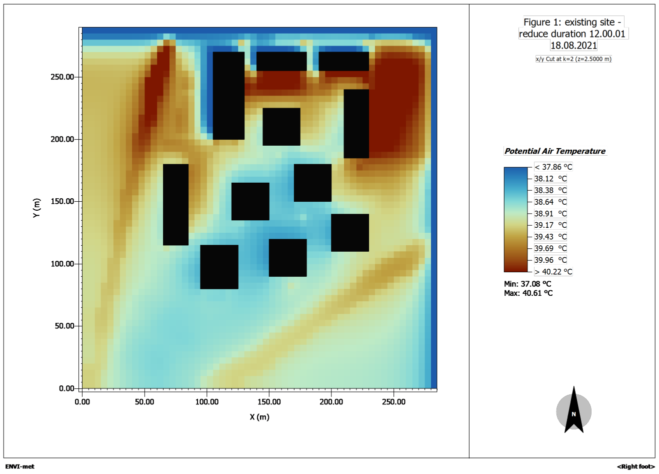
- **Anthropogenic heat sources**, including *cars*, *people*, and *buildings* themselves, also contribute to local warming. Areas with higher human activity, such as *cars* and *buildings* (Locations A, B, and C), will experience higher levels of anthropogenic heat, exacerbating the urban heat island effect, especially during peak activity times.

After analyzing the site on location, we modeled our environment using ENVI-MET. For each building, we assigned the different materials based on the figure 4.

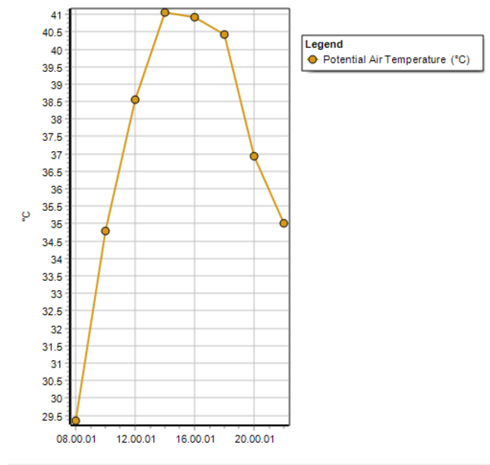
Category	Layer	Building Group A		Building Group B		Building Group C	
		Material	Thickness (m)	Material	Thickness (m)	Material	Thickness (m)
Façade	1	Prefabricated concrete wall	0.14	Plaster	0.01	Fiber cement board	0.008
	2	Insulation	0.1	EPS Expanded Polystyrene	0.18	Sandwich panel mineral wool	0.15
	3	Plaster	0.047	Plywood (heavyweight)	0.14	Aluminum	0.002
Roof	1	Gravel	0.05	Gravel	0.1	Gravel	0.04
	2	Insulation	0.2	XPS Extruded polystyrene CO2 blow	0.2	Mineral wool insulation	0.08
	3	Reinforced concrete slab	0.3	Concrete reinforced with 2% steel	0.3	Reinforced concrete slab	0.35
	4	--	--	EPS Expanded Polystyrene	0.065	--	--

Figure 3: Building facade and roof materials

For this project, weather data in EPW format from the nearby Esplanade weather station has been selected. The simulation uses a future climate scenario for Esplanade in the year 2100 . The simulation happens on 18.08.2021 . We firtsly analyse the atmosphere and key parameters like air temperature, relative humidity, surface temperature, shortwave & longwave radiation, and wind using the application leonardo from envi-met. Here we have a first map showing the mean radiant temperature

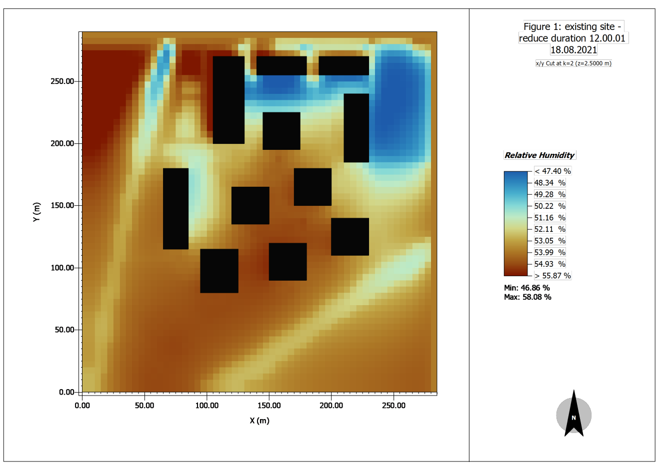


(a) Base case potential air temperature

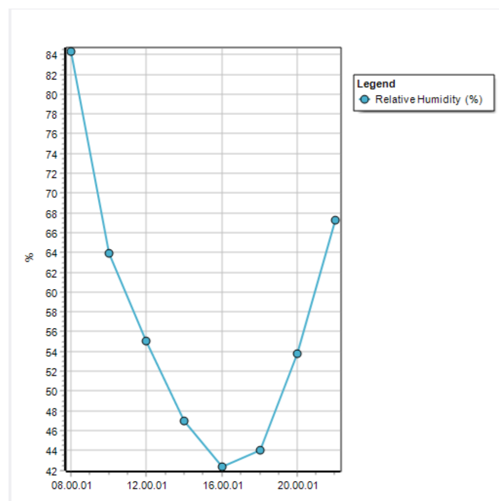


(b) Base case potential air temperature graph

Figure 4

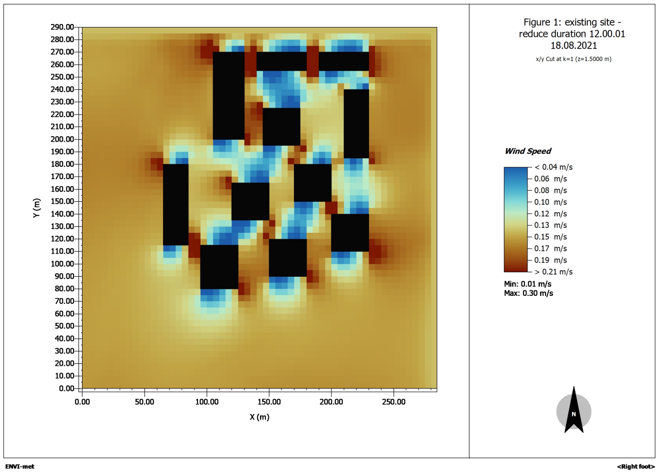


(a) Base case Relative Humidity

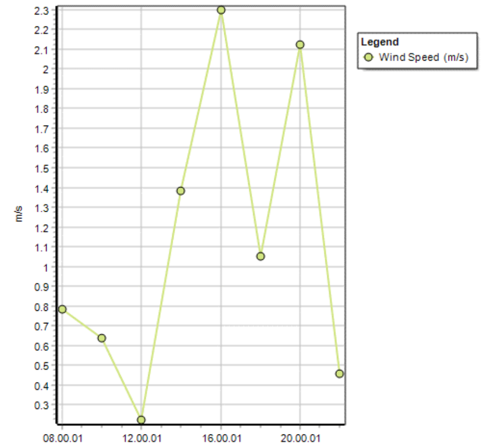


(b) Base case Relative Humidity graph

Figure 5

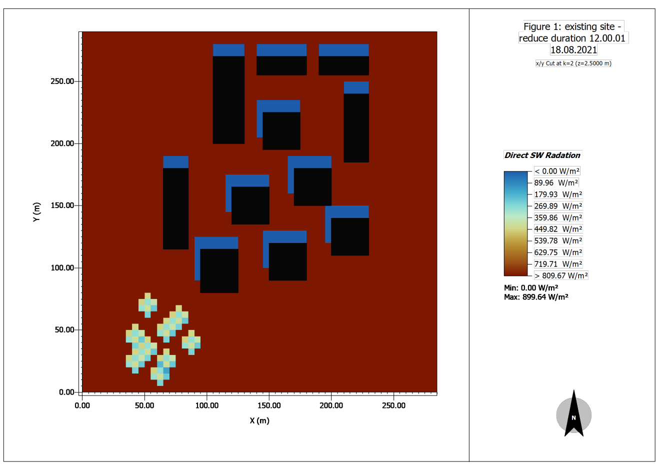


(a) Base case Wind speed

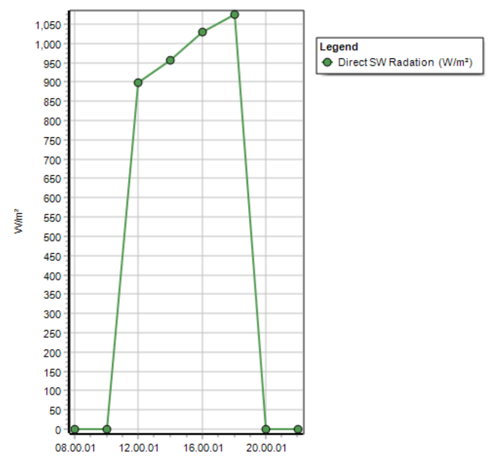


(b) Base case Wind speed graph

Figure 6

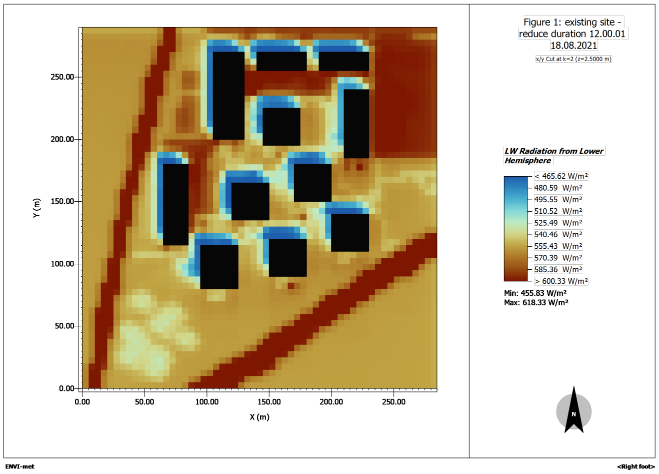


(a) Base case Direct shortwave radiation

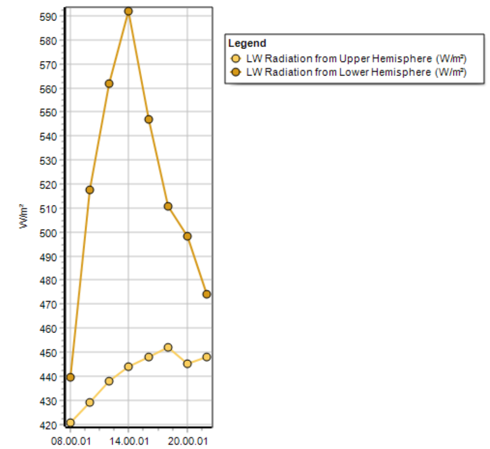


(b) Base case Direct shortwave radiation graph

Figure 7



(a) Base case Longwave radiation from Lower hemisphere



(b) Base case Longwave radiation from Lower hemisphere graph

Figure 8

The ENVI-MET simulation indicates significant diurnal fluctuations in air temperature, with peaks observed around mid-day. Urban materials such as asphalt and concrete, commonly present in the park, absorb and retain heat, contributing to higher temperatures during the day. In contrast, areas with higher vegetation coverage, such as Locations B and D, benefit from evapotranspiration, resulting in relatively cooler conditions. However, nighttime cooling efficiency is reduced in areas with lower sky view factors (SVF), such as Location F, which traps heat and prolongs thermal discomfort. Relative humidity inversely correlates with air temperature throughout the day. During peak heating periods, humidity levels drop significantly, particularly in areas dominated by impervious surfaces like asphalt. Locations with higher vegetation and water-permeable surfaces, such as Locations C and D, exhibit slightly higher humidity due to increased evapotranspiration. These conditions underline the importance of integrating more vegetation to balance the Bowen ratio and enhance local cooling effects. Wind speed variations across the site highlight the impact of urban morphology on natural ventilation. Locations with lower building densities or smaller aspect ratios, such as Location C, benefit from better airflow, facilitating heat dispersion. Conversely, densely built areas with higher aspect ratios, such as Location B, experience restricted airflow, intensifying heat accumulation. These findings emphasize the need for urban design strategies that optimize wind corridors to enhance thermal comfort. The site experiences significant radiation disparities due to differences in surface albedo and material properties. Asphalt and concrete surfaces absorb substantial solar radiation, re-emitting it as longwave radiation, thereby increasing localized surface temperatures. Locations with lighter-colored or more reflective materials could mitigate this effect. Additionally, higher albedo materials, particularly on rooftops, and increased shading from trees or structures would further reduce radiative heat gain.

2 Urban microclimate exploration

In this section, we explore different modifications to the base case microclimate scenario to evaluate their effects and understand how different strategies influence key environmental parameters. By comparing these interventions, we aim to analyze the variations in microclimate behavior and identify effective approaches to mitigate urban overheating.

2.1 Building environment interactions

Buildings are not isolated entities but integral components of the urban environment. Their design, structure, and layout significantly influence and are influenced by the surrounding microclimate. The complex interplay between buildings and environmental factors—such as solar radiation, wind, temperature, and humidity—shapes not only the performance and comfort within the buildings but also the broader urban climate.

In this study, we focused on analyzing a dense, compact urban layout where building heights were increased to between 22 and 25 meters. The aim was to understand how this specific urban morphology influences microclimatic parameters, such as air temperature, surface temperature, wind patterns, and thermal comfort. By modifying building heights within this compact layout, we sought to explore the thermodynamic and aerodynamic effects of tall structures in a dense urban environment.

2.1.1 Modifications

1. **Building Height:**
   In the modified scenario, I decided to increase building heights to 22–25 meters to simulate a denser urban environment with taller structures. This choice was made supposing that it could introduce significant shading effects on ground surfaces, reducing direct solar radiation during the daytime. However, the increased building height also reduced the sky view factor (SVF), limiting radiative cooling at night and intensifying heat retention in narrow urban canyons. Additionally, taller buildings influenced wind patterns, leading to localized wind deflections, stagnant zones, and turbulence in certain areas. These aerodynamic and thermodynamic changes directly impacted the urban microclimate, particularly near ground level.

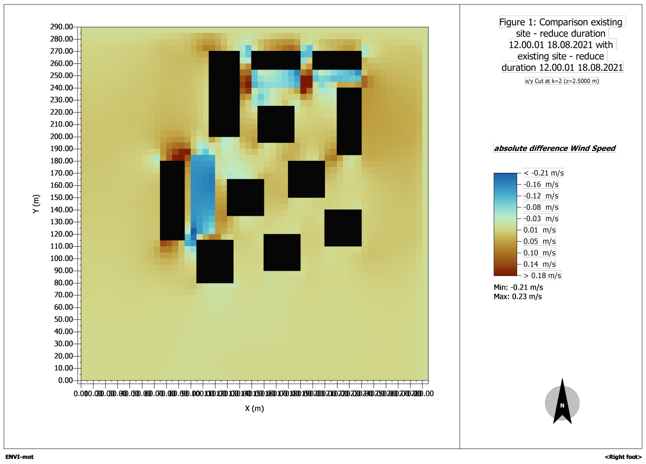
2. **Footprints:**
   The building footprint was also modified by reducing the size of individual buildings while decreasing the spacing between them, creating a more compact urban layout. This configuration increased surface coverage by impervious materials, restricted open spaces, and amplified the urban heat island (UHI) effect by trapping heat in narrow streets. The smaller footprints, however, provided opportunities for integrating cooling mechanisms such as vegetation or permeable surfaces in the unbuilt areas, which could help mitigate heat accumulation. The combination of a compact layout and reduced spacing also altered airflow dynamics, restricting natural ventilation and further influencing microclimatic parameters like air temperature and thermal comfort.

2.1.2 Hypothesis

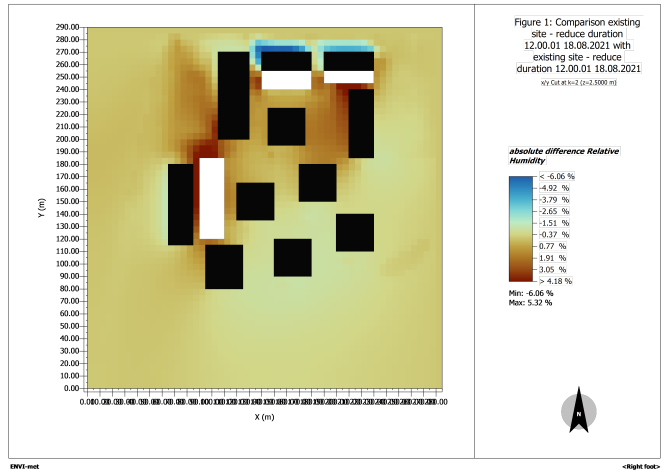
We hypothesized that increasing building heights in a dense, compact layout would lead to:

- Higher localized air and surface temperatures due to restricted ventilation and greater heat retention.
- Reduced wind speeds at ground level, with potential turbulence or accelerations near building edges.
- Increased challenges for maintaining thermal comfort, particularly during daytime hours.

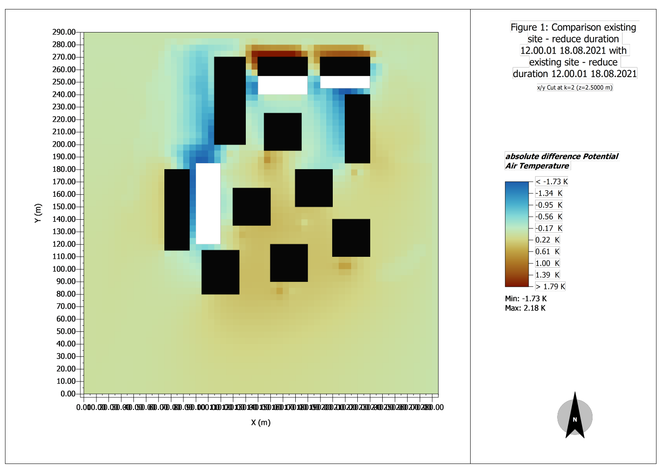
2.1.3 Simulations



(a) Wind Speed



(b) Relative humidity



(c) Potential Air temperature

2.1.4 Analysis of Simulation Results

Relative humidity:
From our results, we can see that there are some regions with reduced and increased relative humidity in the modified case compared to the base case. We see that thanks to the color scale interpretation. In fact, the color bar indicates the absolute difference in relative humidity (%), with warm colors (orange to red) representing an increase in relative humidity in the modified case compared to the base case, and cool colors (blue) representing an decrease. The scale ranges from <-6.06% (deep blue) to +5.32% (darkest red).

Significant reductions in relative humidity are observed in areas near tall buildings, as indicated by the blue zones. This is likely due to increased heat retention, higher surface temperatures, and reduced evaporation in the modified case. These areas may correspond to locations where compact urban layouts and increased building heights have created heat islands, reducing the availability of moisture in the air.

The blue zones, particularly at the northern edge and around some open areas, indicate a decrease in relative humidity in the modified case. This might be due to shading effects or reduced surface heating, which could preserve moisture in certain areas. The presence of cool zones suggests localized improvements in microclimatic conditions due to reduced solar radiation or airflow patterns that trap moisture in specific areas.

Air Temperature:
The color bar indicates differences in potential air temperature. Blue areas show higher air temperatures in the base case, implying a decrease in air temperature in the modified case. Red areas show higher air temperatures in the modified case, indicating an increase relative to the base case. The scale ranges from <-1.73 K (darkest blue) to >2.18 K (deep orange).

The blue zones suggest cooling effects in the modified case. This might result from increased shading by taller buildings, reduced direct solar heating, or enhanced airflow in specific locations. Most notable decreases are near the southern and western edges and around open spaces, where taller buildings might provide better shading and alter wind dynamics.

The reddish zones highlight regions where air temperature is higher in the modified case. This is likely due to heat trapping and reduced radiative cooling caused by the dense, compact urban morphology with increased building heights. These areas are concentrated near the dense building clusters and intersections where airflow is limited.

Wind speed:
The simulation output illustrates the absolute difference in wind speed for two scenarios: existing and modified building layouts. The color scale indicates areas with reduced (blue) and increased (brown) wind speeds. The range spans from -0.21 m/s to +0.23 m/s, showing localized changes in wind dynamics. Significant reduction in wind speed is observed behind tall buildings, primarily in their wake regions. This is due to increased wind blocking and turbulence induced by the taller structures. The largest reductions occur on the western and northern edges, where the prevailing winds likely interact with the urban geometry. Marginal increases in wind speed are seen in narrow gaps and streets between buildings. This could result from channeling effects, where wind is forced through confined spaces, leading to localized accelerations. Dense layouts inherently create calm zones (low wind speeds) around building clusters due to aerodynamic shadowing, which influences ventilation and thermal comfort.

2.1.5 Mechanisms of Interaction

1. **Building Height and Heat Dynamics:**
   Increasing building heights to between 22 and 25 meters introduces significant shading effects, which can reduce surface temperatures in shaded areas by limiting direct solar radiation. However, the compact layout reduces sky view factors, which restricts radiative cooling, particularly during nighttime. The vertical surfaces of taller buildings also absorb and store solar energy, contributing to heat retention and intensifying the urban heat island (UHI) effect.

2. **Airflow and Ventilation:**
   The compact arrangement of tall buildings alters natural wind patterns. Increased building height can lead to wind deflection and the formation of wind shadows at lower levels, reducing natural ventilation and creating stagnant zones. In some areas, taller buildings may accelerate wind speeds due to funneling effects, but these localized increases are often insufficient to offset the overall reduction in airflow.

3. **Thermal Comfort:**
   The dense configuration of taller buildings limits open spaces and natural cooling mechanisms, such as evaporation and convective heat transfer. This can result in increased perceived temperatures and reduced thermal comfort for pedestrians and residents at street level.

This analysis provides insights into the microclimatic implications of tall buildings in compact urban environments and serves as a basis for designing mitigation strategies to optimize thermal performance and comfort in dense urban settings.

2.2 Ground-environment interactions

Ground-environment interactions significantly influence the thermal behavior of urban areas by affecting surface and subsurface temperatures, ground heat flux, and evaporation rates. Modifying ground materials can play a key role in mitigating urban heat island (UHI) effects and improving the thermal comfort of outdoor spaces. In this project, a single ENVI-met simulation was conducted to evaluate the impact of different ground materials on the microclimate of the EPFL Innovation Park. Two specific modifications were introduced: replacing vegetable zones with permeable ground cover to simulate natural conditions and replacing DP zones with impermeable ground cover to simulate urban pavement. This mixed-material scenario reflects realistic urban conditions and provides insights into the contrasting thermal and hydrological behaviors of permeable and impermeable surfaces.

The simulation involved updating the soil profiles for the specified zones using 19 distinct layers to accurately represent the thermo-physical properties and functional characteristics of the chosen materials. For the vegetable zones, permeable ground cover was applied, designed to mimic a natural, well-drained soil structure. For the DP zones, impermeable ground cover was introduced to replicate urban pavement conditions. These modifications were then compared to the original state of the Innovation Park to assess changes in surface and subsurface temperatures, ground heat flux, and evaporation rates.

2.2.1 Modified Soil Profiles

The soil profiles for the modified zones were designed to improve the microclimate of the EPFL Innovation Park. These modifications replaced the existing materials in the base case to enhance thermal regulation and moisture management.

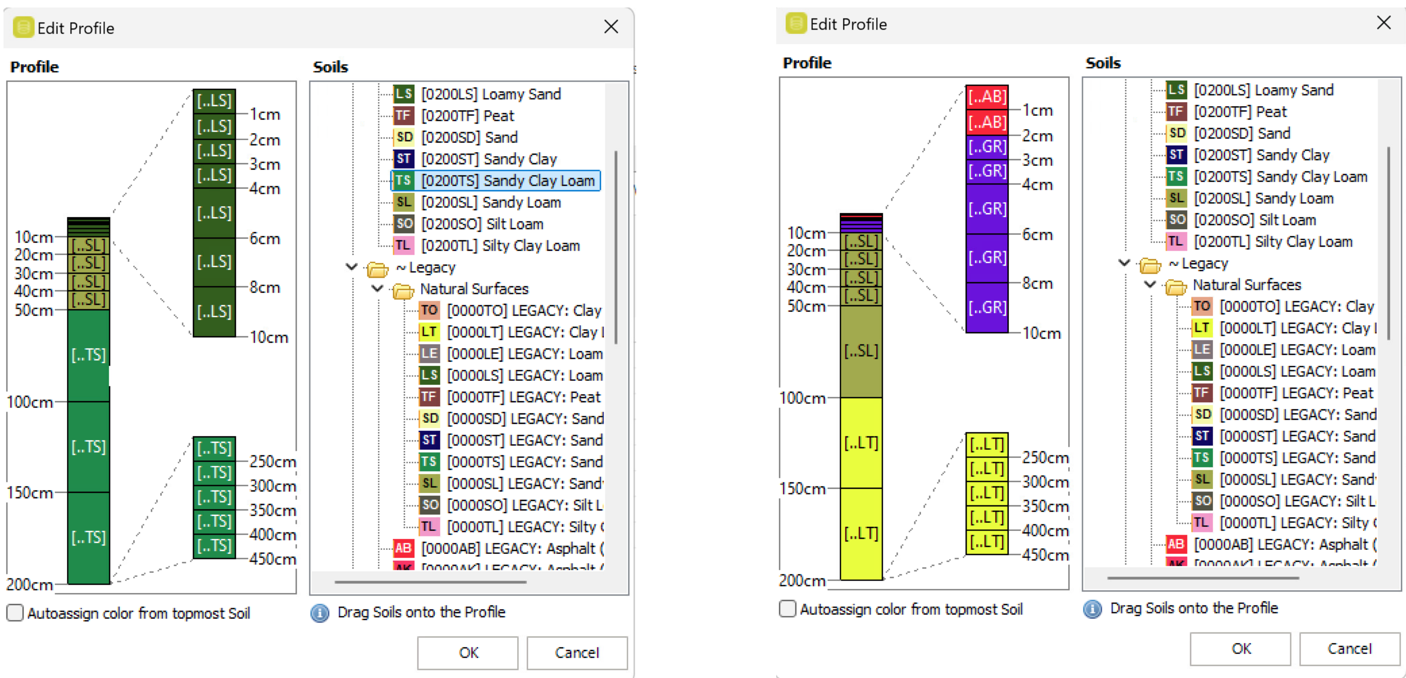
Vegetable Zones → Permeable Ground Cover:

- **Top Layers (1-5, Depth: 0-10 cm):** Loamy Sand (LS) to enhance infiltration and evaporation.
- **Mid Layers (6-10, Depth: 10-50 cm):** Sandy Loam (SL) for moderate moisture retention and structural stability.
- **Lower Layers (11-19, Depth: 50-450 cm):** Sandy Clay Loam (ST) for long-term moisture storage and thermal stability.

Dark Concrete Pavement Zones → Impermeable Ground Cover:

Dark concrete is already an impermeable material.

- **Top Layers (1-2, Depth: 0-2 cm):** Asphalt (AB) to simulate high thermal conductivity and reduced permeability.
- **Subsurface Layers (3-5, Depth: 2-10 cm):** Crushed Gravel (GR) for stability and moderate heat transfer.
- **Mid Layers (6-12, Depth: 10-100 cm):** Sandy Loam (SL) to provide limited permeability for runoff.
- **Lower Layers (13-19, Depth: 100-450 cm):** Clay Loam (LT) to retain moisture and restrict vertical water flow.



(a) New permeable Ground Cover (b) New impermeable Ground Cover

Figure 10: New soil profiles

2.2.2 Justification of Modifications

The modified soil profiles were designed to address the limitations of the base case materials while improving the microclimate:

Permeable Zones: Replacing Sandy Loam with Loamy Sand enhances evaporation rates due to increased water infiltration and surface permeability. This promotes cooling through latent heat flux, while deeper layers provide water retention for long-term thermal stability. These modifications reduce surface temperature peaks and support vegetation growth, which further contributes to cooling.

Impermeable Zones: Replacing Dark Concrete with Asphalt reduces surface heat absorption due to Asphalt's higher albedo. The addition of Crushed Gravel as a sub-layer moderates heat conduction to the subsurface. Deeper layers, such as Sandy Loam and Clay Loam, provide thermal buffering and improve subsurface temperature stability. These modifications mitigate some of the negative thermal impacts associated with impermeable surfaces.

What is the new albedo value for the asphalt?

2.2.3 Comparison Between Base Case and Modified Profiles

The following tables summarize the expected improvements:

Feature	Base Case (Sandy Loam)	Modified Profile (Loamy Sand)
Surface Temperature	Moderate	Lower (due to evaporation)
Latent Heat Flux	Moderate	Higher (enhanced evaporation)
Moisture Retention	Moderate	Better (stratified layers)
Subsurface Stability	Moderate fluctuations	Stable due to deeper layers

Table 3: Comparison of Permeable Zone Modifications

Feature	Base Case (Dark Concrete)	Modified Profile (Asphalt)
Surface Temperature	High	Slightly lower (higher albedo)
Heat Conduction	High	Moderated by Crushed Gravel
Subsurface Stability	Poor (rapid fluctuations)	Improved (layered structure)

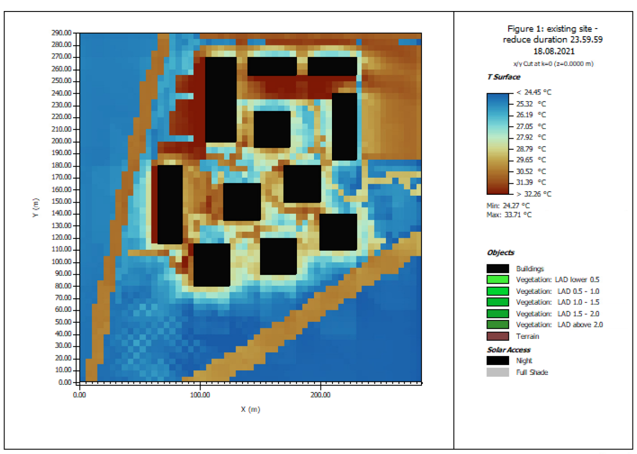
Table 4: Comparison of Impermeable Zone Modifications

2.2.4 Simulation Results and Observations

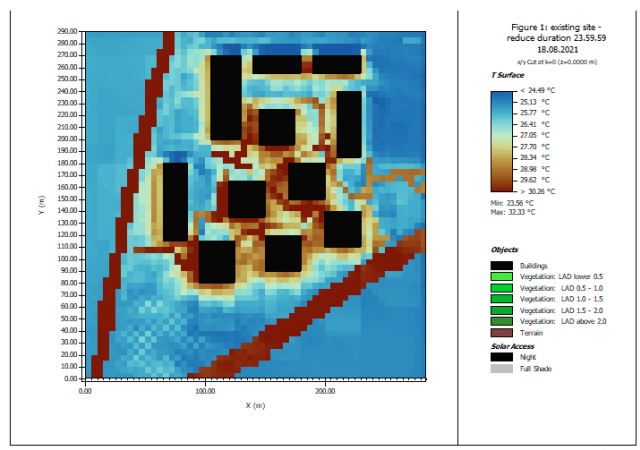
The simulation results were analyzed by comparing key parameters such as surface temperature, subsurface temperature, ground heat flux, latent heat flux, air temperature, and relative humidity.

Observed Improvements:

1. **Surface Temperature:** Permeable zones with Loamy Sand exhibited lower surface temperatures due to enhanced evaporation, while impermeable zones with Asphalt showed a slight improvement compared to Dark Concrete.
2. **Subsurface Stability:** Both zones demonstrated reduced subsurface temperature fluctuations, indicating improved thermal buffering from the stratified layers.
3. **Ground Heat Flux:** Permeable zones had moderate heat flux due to moisture retention, while impermeable zones showed slower heat conduction compared to the base case.
4. **Latent Heat Flux:** Increased in permeable zones, contributing to effective cooling.
5. **Thermal Comfort:** Air temperature and relative humidity indicated localized cooling benefits in permeable zones.



(a) Base case



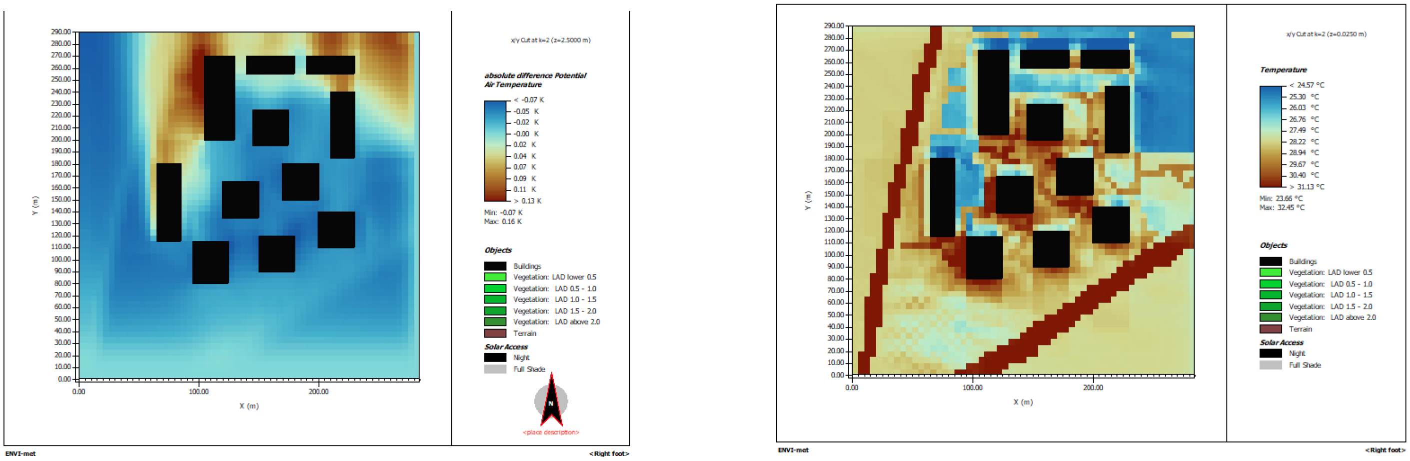
(b) Simulation result

Figure 11: Surface Temperature comparison

2.2.5 Synthesis

The modified profiles effectively improved the microclimate compared to the base case. Permeable zones with Loamy Sand achieved better cooling and thermal stability by enhancing evaporation and providing long-term moisture retention. Impermeable zones with Asphalt demonstrated marginal improvements in surface temperature and subsurface thermal regulation due to higher albedo and moderated heat conduction from the layered subsurface structure. These modifications highlight the potential of optimized soil profiles in mitigating UHI effects and enhancing urban microclimates.

However, while these changes yield a better microclimate in simulation, implementing them in real-life urban environments poses significant challenges. Modifying deep subsurface layers, as suggested in the stratified profiles, may not be practical due to the high costs, labor, and disruption involved in such extensive changes. A more feasible approach would focus on modifying the uppermost layers, such as replacing Dark Concrete with high-albedo materials or Loamy Sand



(a) Potential air temperature of the new case compared to the base case

(b) Subtemperature of the new case compared to the base case

Figure 12: Comparison on Leonardo

for permeable zones. These surface-level interventions can still achieve noticeable microclimate improvements without requiring extensive excavation or restructuring of existing infrastructure.

This practical adjustment emphasizes the importance of integrating surface-level modifications into urban planning to balance cost, feasibility, and environmental impact.

2.3 Water body - environment interactions

Water bodies play a crucial role in influencing the thermal and hydrological dynamics of urban environments, particularly in regulating temperature fluctuations and increasing moisture retention. Their presence can reduce urban heat island (UHI) effects by providing cooling through evaporation, as well as stabilizing subsurface temperatures.

To accurately represent the effects of water bodies, a soil profile was created. This profile was designed with multiple soil layers to capture the complex interactions between water bodies, ground materials, and atmospheric conditions. The results were analyzed to assess how the water bodies influence the cooling effect, soil heat flux, and local humidity, ultimately providing a better understanding of their contribution to the microclimate in urban areas.

2.3.1 Modifications

To represent the effects of water bodies, a layered soil profile was created to reflect realistic hydrological and thermal conditions. Each layer was chosen to optimize water retention, drainage, and thermal stability, essential for understanding the interaction between water bodies and their environment. The top layer consists of pure water (0-50 cm), simulating the open surface crucial for evaporation and thermal exchange. Below this, a peat layer (50-100 cm) provides excellent water retention and slows infiltration, mimicking organic-rich environments.

The next layer, clay loam (100-150 cm), balances water retention with moderate drainage, this way we are sure to have consistent moisture availability and thermal regulation. Finally, sandy clay (150-200 cm) at the base introduces slow drainage, preventing excessive water loss while stabilizing the water table. This configuration of the soil profile effectively captures the cooling effects, soil heat flux, and local humidity interactions, providing valuable understanding into the contribution of water bodies to the urban microclimate. The different profiles were to match the actual or similar to real profile conditions of the soil. For this purpose, we chose to use a layered soil profile that reflects realistic conditions while emphasizing key hydrological and thermal properties.

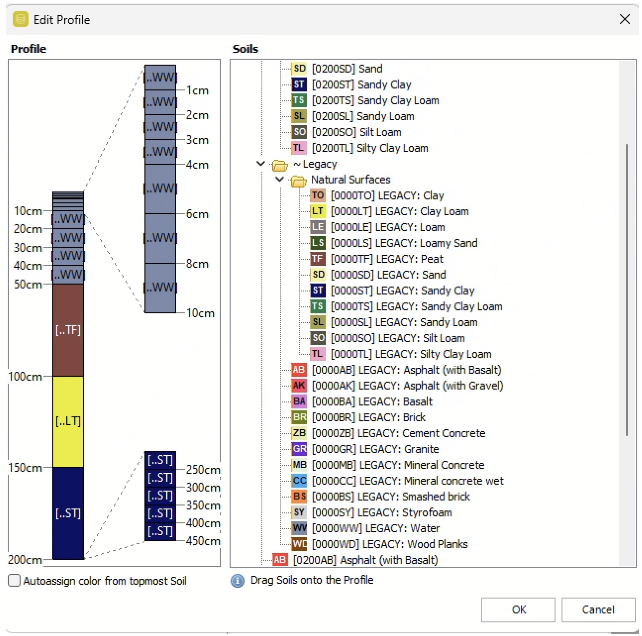


Figure 13: Water body Soil Profile

To ensure that the water bodies will have the most impact on the microclimate studied, we chose to place the newly created soil profile in different regions of the map. Additionally, we varied the size, shape, and surrounding conditions of the water bodies to capture a wide range of interactions with the environment. To effectively capture the best shape for a water body, we often use the LSI (Landscape Shape Index), as the equation 1 shows:

$$LSI = \frac{D}{2\sqrt{\pi + WA}} \tag{1}$$

In this equation, D represents the equivalent diameter of the water body, and WA represents its surface area. A higher LSI value indicates that the water body has a more complex shape with a greater perimeter relative to its surface area, which may lead to more fragmentation and lower efficiency in terms of evaporation and cooling. In contrast, a lower LSI value indicates a more compact shape, which tends to be more efficient for cooling purposes, because it offers a larger surface area relative to the perimeter.

A map showing the placement of different water bodies is shown below.

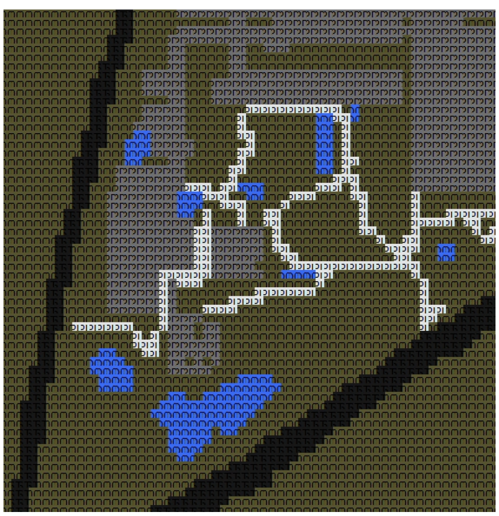


Figure 14: Different Water bodies location

2.3.2 Simulations

In this section, we focus on comparing key parameters to demonstrate the effect of water bodies on the studied climate. These parameters were selected for their influence on cooling effects, soil heat flux, and local humidity distribution. By analyzing these variations, we aim to identify the optimal configurations that can help regulate thermal environmental conditions in urban settings. The simulations give good insights into the role of water bodies in mitigating heat island effects and supporting sustainable urban planning strategies.

Latent heat flux: One of the most important parameters to measure the effect of water bodies on the region is the latent heat flux. This parameter reflects the efficiency of evaporative cooling, as latent heat is used to transition water from its liquid state to vapor. During this process, heat is absorbed from the air, making it effective in cooling the surrounding area. As shown in figure 15, we observe a significant difference in latent heat around the water body, highlighting its cooling effect on the region.

Relative humidity: Similarly, relative humidity indicates the effectiveness of cooling since water vapor is added to the air during evaporation, increasing humidity in areas near the water bodies. As seen in figure 16, the presence of water increases relative humidity significantly in the surrounding areas showing a good cooling process.

Wind speed: Wind speed also plays a crucial role in the cooling effect of water bodies. Strong winds help remove the saturated air near the water's surface, promoting evaporation. This process enhances the cooling effect by enabling the transfer of heat away from the water surface. Measuring wind speed allows us to assess its impact on the rate of evaporation and on the cooling efficiency of the water bodies. Wind speed is a critical parameter in the surface evaporation in the Pennman formula. The results are shown in figure 18.

Mean radiant temperature: Finally, we measure the mean radiant temperature, which is an effective parameter for evaluating the thermal comfort of an area. By analyzing changes in mean radiant temperature, we can observe how the addition of water bodies influences the overall thermal environment, providing a better understanding of their contribution to climate regulation.

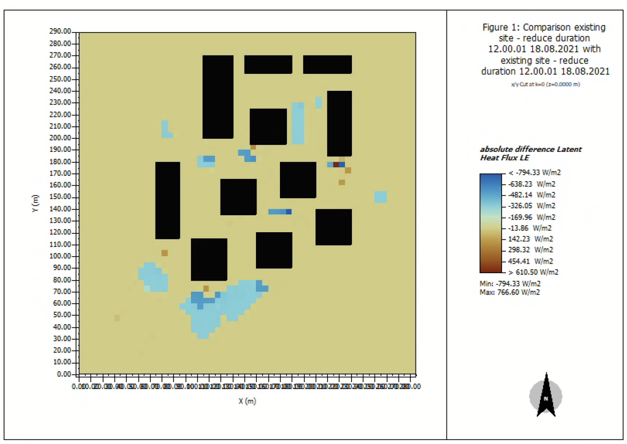


Figure 15: Latent heat flux

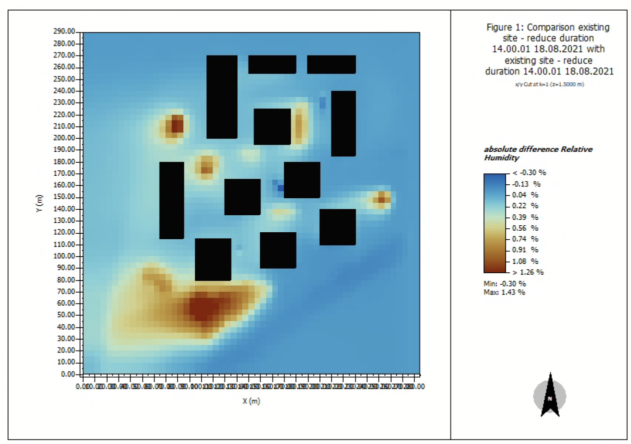


Figure 16: Relative humidity

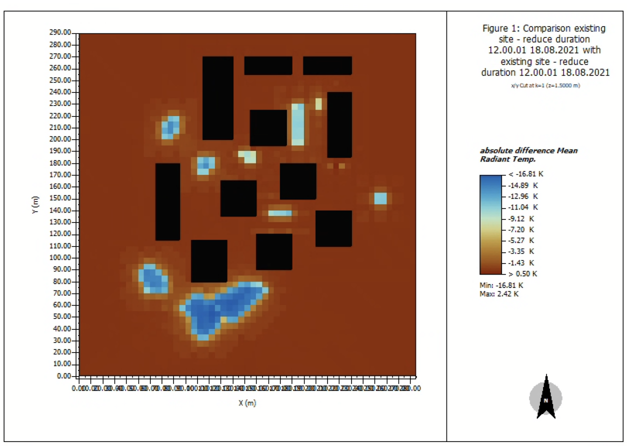


Figure 17: Mean radiant temperature

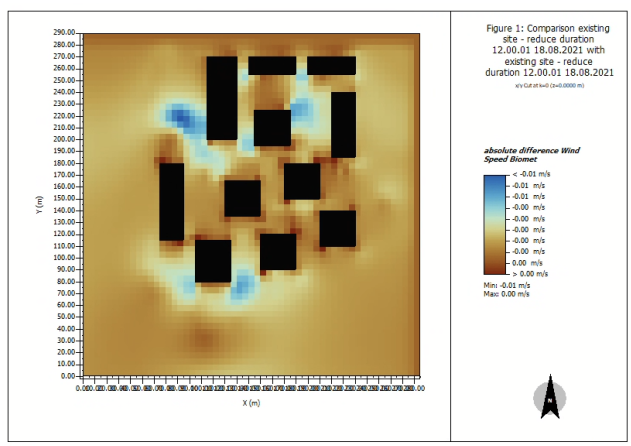


Figure 18: Wind speed

2.3.3 Synthesis

These simulations have demonstrated the impact of water bodies on the microclimate of the studied area. By comparing key parameters, we were able to highlight the effectiveness of the water profiles in regulating the local climate. In general, the presence of water bodies led to a clear decrease in global temperature, as well as a reduction in the overall Urban Heat Island (UHI) effect, which is a key concern in urban environments.

Additionally, by incorporating the Universal Thermal Climate Index (UTCI), we observed a marked improvement in thermal comfort for individuals in areas with water bodies. The UTCI, which integrates temperature, humidity, wind speed, and radiation, showed lower thermal stress in regions near water compared to areas with standard soil or gravel. This reduction in thermal stress indicates a more comfortable environment for inhabitants, making water bodies a valuable tool for enhancing urban livability.

Where did you show the UTCI value?

2.4 Vegetation - environment interactions

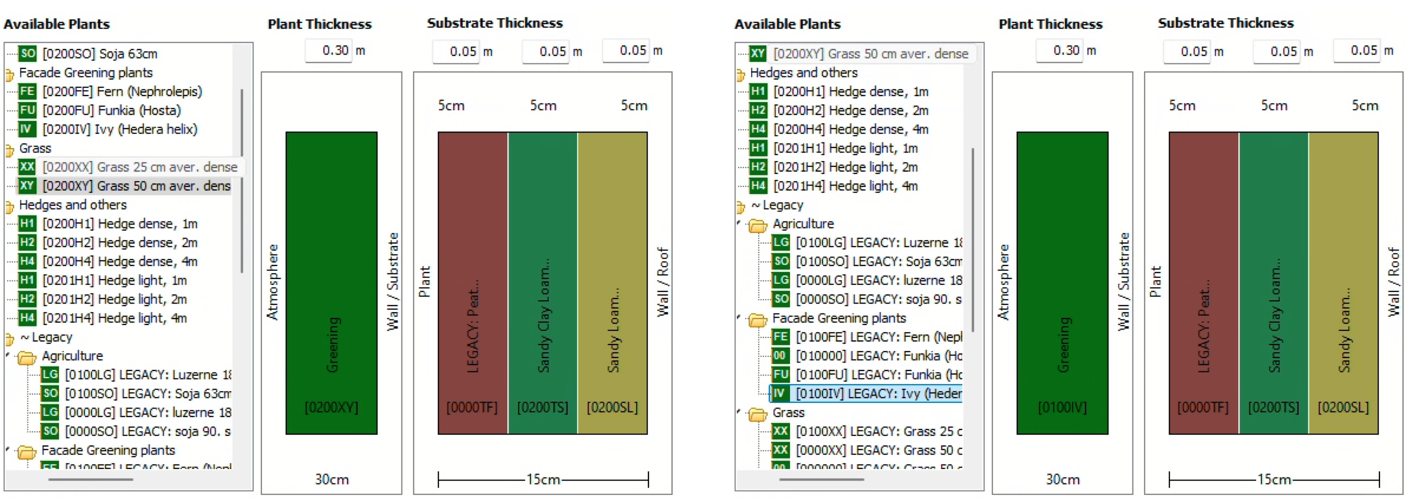
Urban environments face growing challenges related to heat stress, air pollution, and reduced thermal comfort due to the urban heat island (UHI) effect. As a response, integrating vegetation into urban design has become a key strategy for mitigating these effects and enhancing the overall urban microclimate. This section focuses on exploring the impact of vegetation elements, specifically green facades, green roofs, and urban trees placed strategically between buildings.

2.4.1 Modifications

Green facade and roofing:

For the green facades, I selected ivy (Hedera helix) with a Leaf Area Index (LAI) of 1.5. This choice was inspired by observations of similar implementations on buildings in Lausanne, where ivy has been successfully used due to its ability to climb and densely cover facades. Ivy's dense foliage creates an effective barrier that shades building walls, reduces surface temperatures, and contributes to evapotranspiration cooling. The chosen soil type for this application is a classic soil type, suitable for maintaining plant health and supporting the root systems of climbing vegetation. The profile is described in figure 19b.

For the green roofing, I opted for grass with a height of 50 cm and a typical LAI of 0.8. Grass was chosen for its suitability for rooftop installations, requiring minimal maintenance while still providing substantial cooling benefits. Its lower LAI compared to ivy is offset by the extensive coverage it offers on horizontal surfaces. Similar to the facades, a classic soil type was selected, ensuring compatibility with the vegetation and providing adequate water retention and drainage. Again, the profile is described in figure 19a.



(a) Green roofing with 50cm grass

(b) Green facade with ivy

Figure 19: New greenings

Trees:

To further enhance cooling and shading, I incorporated trees into the design. In tighter spaces between buildings, I selected Norway maples, medium-sized trees that thrive in urban environments and can fit into narrower spaces without compromising their functionality. For areas with more open space, I chose linden trees (Tilia) due to their suitability for the Swiss climate and their particularly dense foliage, which provides excellent shading and cooling. To be consistent, the number of trees has been maximized while respecting the constraint of planting them only in areas where grass is present.

Additionally, the site already included existing 15-meter-tall trees. These existing trees complement the newly added vegetation, creating a layered approach to mitigating urban heat. The new disposition of trees on the Innovation Park is explained in the figure 20.

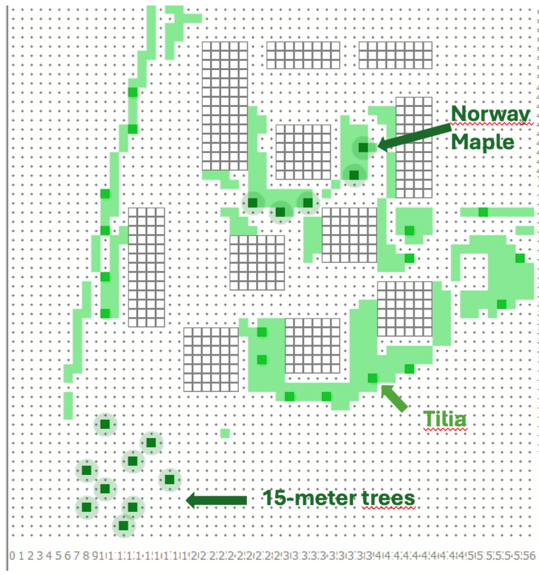
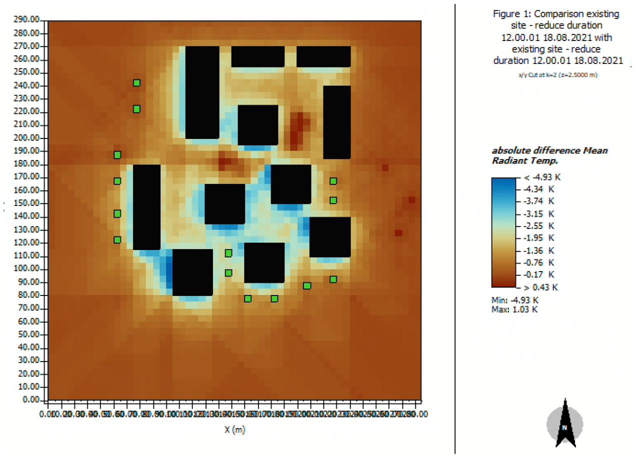
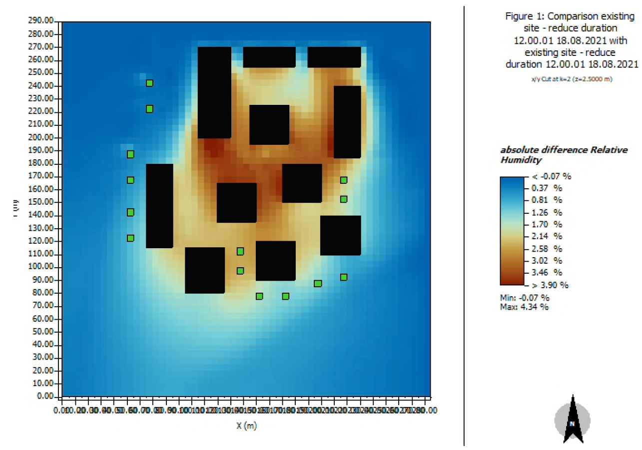


Figure 20: Different trees implementation

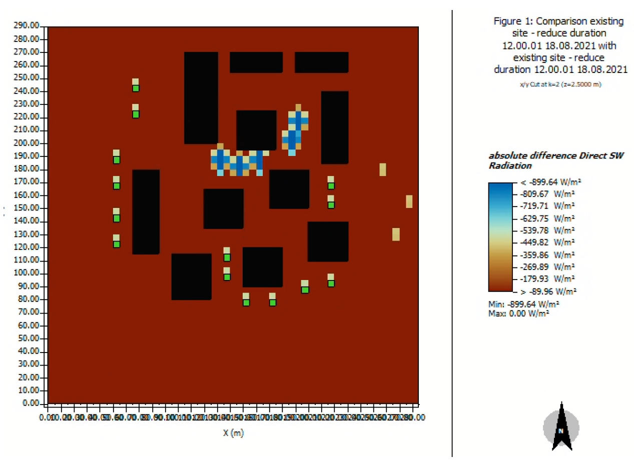
2.4.2 Simulations



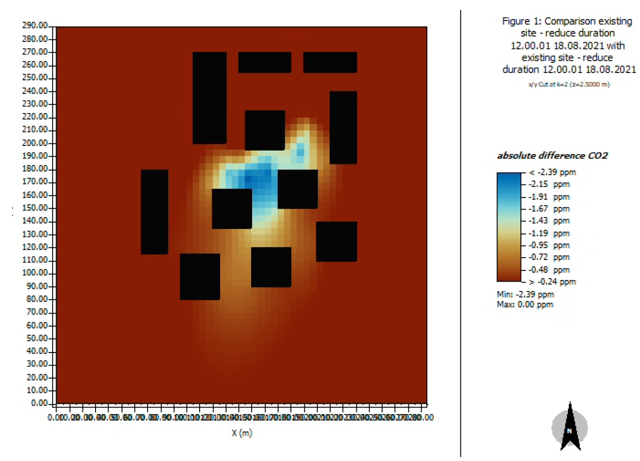
(a) Mean radiant temperature



(b) Relative humidity



(c) Direct shortwave radiation



(d) CO2 levels

Figure 21: Simulations between base case and the case with vegetation

What about air temperature?

2.4.3 Results analysis

Mean radiant temperature: One of the key aspects of my simulations was comparing the mean radiant temperature (MRT) between the base case and the scenario with vegetation. The results demonstrated a noticeable decrease in MRT, ranging from approximately 3 to 5 Kelvin (equivalent to 3 to 5°C). The most significant reductions were observed near the contours of the buildings. This cooling effect is attributed to the implementation of green facades, which provide shading and enhance evaporative cooling, reducing the amount of radiation absorbed and re-emitted by building surfaces. As Tilia trees were planted still pretty close to the buildings, they also contribute to the reduction in mean radiant temperature (MRT). A similar reduction in MRT was observed in the central spaces of the Innovation Park, where Norway maple trees were strategically planted. These medium-sized trees contribute to the cooling effect by shading the ground and reducing the heat radiated from surrounding surfaces.

Relative humidity:

We also compared relative humidity (RH) between the base case and the scenario with vegetation. The results indicated a consistent increase in relative humidity across the entire Innovation Park, ranging from 2 to 4%. The increase in RH was observed throughout the park, with the primary drivers being the green facades and green roofs. These vegetation types enhance evapotranspiration, which adds moisture to the air, raising the local humidity levels. The highest RH values were recorded in the area where Norway maple trees were planted. The trees extensive canopy and shading capabilities, combined with their role in moisture release through evapotranspiration, contributed to this localized peak. This increase in humidity is beneficial for improving thermal comfort, as higher humidity can reduce the perceived temperature. It also contributes to enhancing air quality.

Direct shortwave radiation:

For the direct shortwave radiation, the simulation revealed a significant reduction in direct shortwave radiation, with values decreasing by up to 900 W/m^2. In the base case, the maximum direct shortwave radiation was 900 W/m^2, this means that in the areas with newly planted trees, the direct shortwave radiation was reduced to zero. This highlights the strong shading effect of the vegetation, which completely blocks the incoming solar radiation from reaching the surface. The dense canopies of these trees provide extensive shading, mitigating the solar heat load and contributing to a cooler microclimate.

CO2 levels:

Lastly, we compared the concentration of CO2 in parts per million (ppm). The results showed a modest reduction in CO2 levels, with a decrease of 2.4 ppm observed in the area where Norway maple trees were planted. However, no reduction in CO2 concentration was detected in the area with Tilia trees. After some research, this can be attributed to the relatively low photosynthetic activity of the Tilia trees compared to the Norway maples. To take this further, we could replace them, as the ability of vegetation to absorb CO2 in urban areas plays a crucial role.

2.4.4 Synthesis

The simulations comparing the base case and the vegetation scenario show that the introduction of vegetation has had a positive impact on all studied parameters, contributing to reduce the UHI effect. Additionally, wind speed was also compared, but no significant difference was found (less than 0.03 m/s). This is due to the absence of wind during the simulations, as shown in Figure 6a. Unfortunately, this limitation prevents us from analyzing how wind would react to the changes in vegetation.

3 Integrated Microclimate Solution

To address the challenges posed by urban microclimates within the EPFL Innovation Park, an integrated strategy was implemented. This approach focused on increasing vegetation, modifying building configurations, extending blue infrastructure, and using permeable ground materials. The objective remains to reduce urban heat island effects, improve thermal comfort, and promote a sustainable environment.

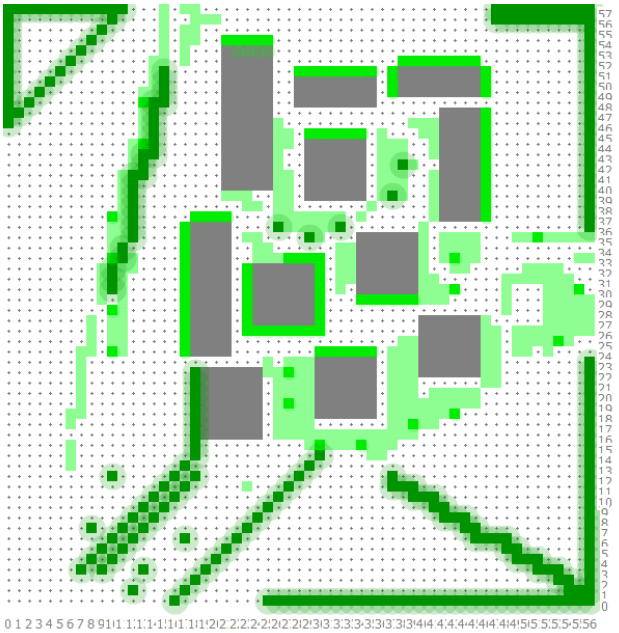
Vegetation and Green Spaces: A significant increase in vegetation density was implemented around buildings and in sparsely built areas, as illustrated in Figure (22). To maximize cooling and shading effects, trees such as Norway maples and linden were strategically added at key locations, including near residences facing the road and in parking areas. The parking zone, due to paved surfaces, exhibited high temperatures requiring targeted interventions.

Furthermore, the green roofs and facades mentioned in section 2.4.1 were implemented, demonstrating positive and significant impacts on temperature reduction.

Water Body : The water profile described in section 2.3.2 was extended over a larger area, as shown in Figure (22), to amplify cooling effects and improve thermal comfort in the affected areas. These elements were strategically placed to maximize their efficiency in persistent hotspot zones.

Building Configuration: Buildings were placed closer together to increase ground-level shading and reduce heat absorption by open surfaces. This compact configuration was chosen to optimize urban space utilization while limiting areas exposed to direct radiation.

Ground Materials : Regarding ground materials, we decided to maintain the modified profile presented in section 2.2.1, which demonstrated positive effects on surface temperature. Permeable and reflective materials contributed to reducing surface temperatures while improving water infiltration and thermal stability.



(a) New configuration

(b) New configuration of soil

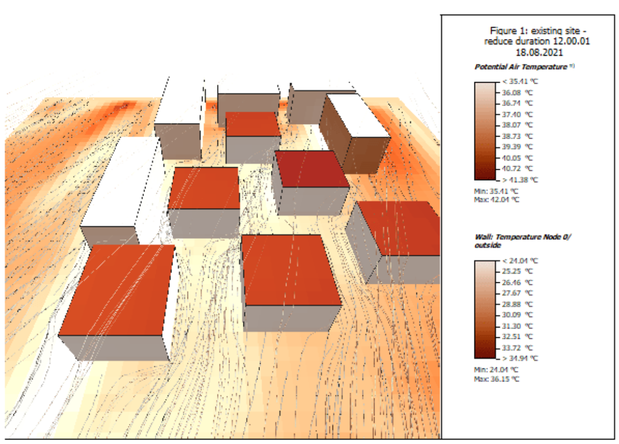
Figure 22: Comparison of vegetation and soil images

3.1 Results and Observations

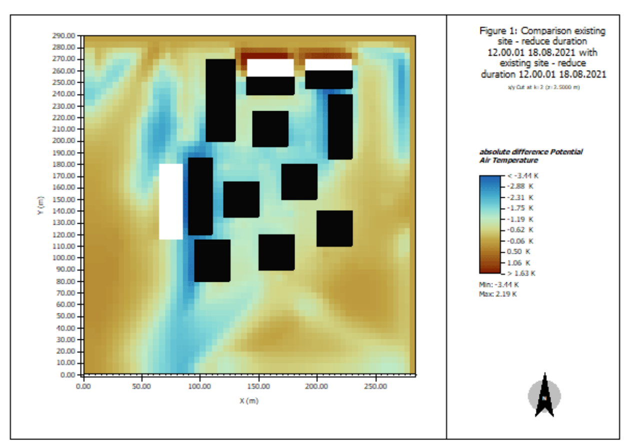
3.1.1 Potential Air Temperature and Wall Temperature

The analysis of the final simulation highlights several key observations:

- **Potential Air Temperature:** The integration of additional vegetation and water significantly reduced potential air temperatures by 2 to 4°C in shaded and vegetated areas. Paved and exposed areas exhibit high temperatures, often exceeding 37°C, especially in zones with limited shading. Vegetation and water body interventions successfully reduced these temperatures in critical areas. The difference maps highlighted significant cooling in areas with combined interventions, particularly between buildings and near water surfaces.
- **Wall Temperature:** South- and west-facing facades exhibit wall temperatures of >36°C due to strong solar radiation absorption by non-reflective materials. This underscores the importance of vegetated facades to mitigate this effect because in the base case the wall temperatures were higher.



(a) Potential Air Temperature and Wall Temperature



(b) Air temperature difference

Figure 23

3.1.2 Relative Humidity

Relative humidity levels increased by 5-8% in areas with dense vegetation and water bodies, contrasting with the base case where impervious surfaces led to significant moisture loss. Enhanced evapotranspiration from vegetation added moisture to the air, improving thermal comfort. The energy balance in these areas shifted as latent heat flux increased, effectively balancing the Bowen ratio and reducing sensible heat flux.

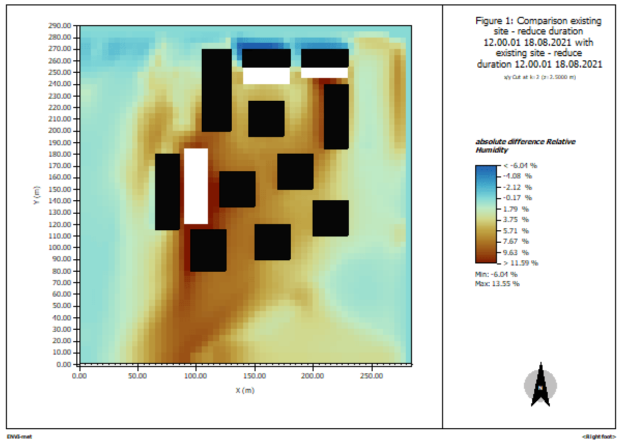


Figure 24: RH

3.1.3 Wind Speed

Wind speed analysis highlighted variations across the site. Compact building configurations resulted in slower wind flows (<0.2 m/s) in corridors, while open areas with water features experienced faster wind speeds (>0.5 m/s). This variation influenced heat dispersion and evaporation rates, with faster airflow near water bodies enhancing evaporative cooling and improving overall thermal comfort.

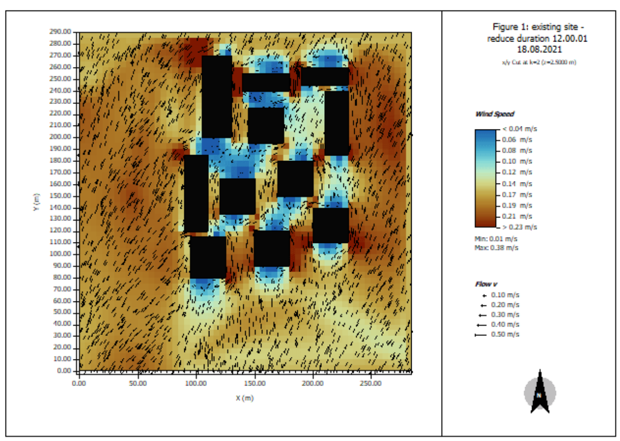


Figure 25: Wind speed

3.1.4 UTCI (Universal Thermal Climate Index)

A notable reduction in UTCI values (5 to 8°C) was observed in areas with integrated vegetation and water bodies, significantly improving outdoor thermal comfort. Vegetation reduced mean radiant temperature by providing shading, while water bodies contributed to localized cooling through increased latent heat flux and reduced sensible heat flux. Comparison with the base case highlighted the importance of combining shading and cooling strategies to manage thermal stress.

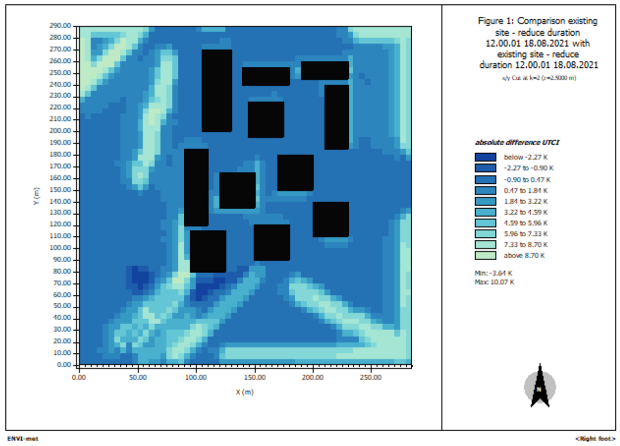


Figure 26: UTCI difference

The comparative analysis of microclimate parameters highlights the distinct contributions of each intervention. Vegetation played an important role in reducing solar radiation absorption, enhancing latent heat flux, and moderating surface temperatures through shading and evapotranspiration. Water bodies further amplified cooling by increasing latent heat flux and improving humidity levels, effectively lowering sensible heat flux in surrounding areas. Adjustments to building configurations increased ground-level shading and reduced radiative heat transfer, although maintaining adequate ventilation remained essential. Lastly, modified ground materials improved albedo and reduced surface heat storage, helping to moderate subsurface heat flux. Together, these interventions synergistically improved the microclimate, demonstrating the value of integrated strategies.

This approach highlights the importance of combining vegetation, water body, and urban planning to create a more sustainable and thermally comfortable urban environment.

4 Conclusion

The EPFL Innovation Park presented a challenging urban microclimate, with initial temperatures reaching critical levels due to factors such as extensive asphalt surfaces, high thermal mass materials (concrete and steel), and limited ventilation in densely built areas. These conditions often exceeded 37°C, creating a stressful thermal environment. Despite these high starting points, the integrated strategies demonstrated significant improvements, even with moderate reductions in temperature.

The combined interventions reduced potential air temperatures by 2 to 4°C and lowered the Universal Thermal Climate Index (UTCI) by 5 to 8°C. While these reductions may seem modest, they represent a substantial improvement in a context where initial conditions were extremely challenging. Vegetation and water bodies played a pivotal role in enhancing shading, evapotranspiration, and localized cooling, while optimized building configurations and ground materials contributed to improved energy balance and thermal stability.

These results highlight that even incremental improvements can have meaningful impacts in highly urbanized and thermally stressed environments. They emphasize the importance of pursuing integrated strategies that combine natural and structural solutions to mitigate the urban heat island effect and enhance outdoor thermal comfort.

For future urban planning, these findings underline the necessity of prioritizing green and blue infrastructure (water body), along with innovative materials and thoughtful urban layouts. In areas where extreme temperatures prevail, even small gains in cooling can significantly improve livability, resilience, and overall quality of life. It is important to keep in mind that this planning includes huge challenges as plenty of solutions are unusual or impossible to realise in real life or may not be practical due to the high costs, labor, and disruption involved in such extensive changes. However,in the context of global climate change, addressing these issues remains essential.