Urban thermodynamics

Course project

Salomé Pierre (342281)
Aurora Villain (344202)
Manon Siebenmann (344835)
Alia Boughaleb (328692)
Gabin Robbe (341285)

Professor

Dolaana KHOVALYG

Teacher assistant

Kun LYU

EPFL

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1 Introduction

Urbanization is reshaping cities worldwide, leading to significant challenges for urban microclimates. Among these, the urban heat island (UHI) effect, intensified by anthropogenic activities and global warming, poses critical risks to human health, energy consumption, and overall thermal comfort.

This project investigates the thermodynamic interactions between urban elements and their effects on the microclimate of the EPFL Innovation Park.

By employing ENVI-met simulations, the study aims to analyze current site conditions, evaluate specific mitigation strategies, and propose integrated solutions to improve the site's thermal environment. This report outlines the project's objectives, methodology, and findings, providing actionable insights for sustainable urban design.

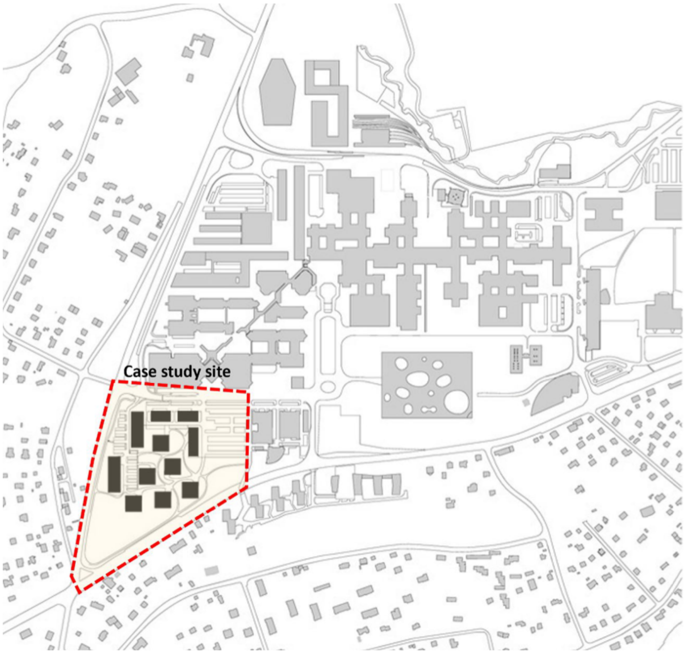


FIGURE 1 – Case study site

2 Site analysis

2.1 Site description

EPFL Innovation Park was established as a community of start-ups, scale-ups, research units, and established tech firms. The site, as shown in Figure 1, is located close to Lake Geneva to its south and in the southwest part of the EPFL campus, adjacent to residential areas on its west and south sides. It features a cluster of rectilinear office buildings, a parking lot, and an urban woodland bordered by roads on three sides. It has an area of around 11 hectares [1]. The microclimate of EPFL innovation Park is influenced by its surroundings (for example Lake Geneva causing wind flows and higher humidity), but also by the human activities from the traffic and the infrastructures, which contributes to anthropogenic heat generation. It is also mainly influenced by its characteristics.

The simulation is conducted on the hot day of the 18/08/2021, from 6a.m. to midnight. The initial model is shown bellow.

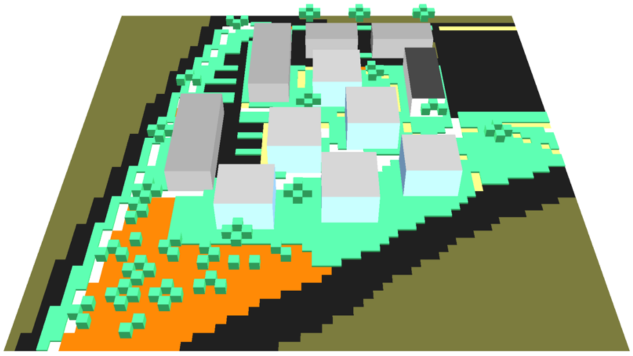


FIGURE 2 – Base case - model

2.2 Site characteristics

Here can be found some key characteristics of the site along with hypothesis on how they might influence the local microclimate. These hypothesis will then be analyzed in the next part to be confirmed or refuted.

Sky View Factor : Building density is pretty low (LCZ 5, open mid-rise), and canyon aspect ratio is very variable (varies between 0.3 to 0.6). It is visible in figure 73 of the appendix that the sky view factor is generally pretty high, even inside the park in between buildings. A high SVF affects radiation exchanges and thermal comfort. It can be expected to cause :

- more direct shortwave solar radiation to reach the ground and people during daytime because of the lack of shadow, causing rise of the Mean Radiant Temperature, which is determinant for thermal comfort, especially in sunny conditions.
- increased longwave radiation loss at night, which allows faster cooling of the environment at night.

Materials : Thermal properties of the materials used in the facades and the roofs can be found in tables 1 to 3 of the appendix. Here are some important information that we can take out :

- Building Group A : The facade uses prefabricated concrete walls with plaster and insulation. Concrete has a high thermal mass, which means it absorbs and stores more heat at daytime, and releases it slowly at nighttime, contributing to UHI effect. The roof features gravel cover (0.05 m) and insulation (XPS) with reinforced concrete, with a very high thermal mass, and thus, the same problematic as the facade.
- Building Group B : Uses plaster, expanded polystyrene insulation, and heavyweight plywood. Expanded polystyrene has good insulation properties but low thermal mass. Lower external surface temperatures during sunny conditions can be expected compared to Group A. The roof uses thicker gravel (0.1 m) than roof A, and reinforced concrete, which increases the thermal inertia and allows more heat storage at night.
- Building Group C : Uses fiber cement board and aluminum. Aluminum is highly reflective, with low emissivity : at Daytime, it reflects more solar (shortwave) radiation, likely showing lower surface temperatures. Its low emissivity also means lower longwave radiation in the surroundings. This group might display lower facade temperatures in direct sunlight but contributes indirectly to UHI. The roof C also has gravel (though thinner layer) and concrete slab. However it has minimal insulation compared to Groups A and B. Higher surface temperatures can be expected during the day and faster cooling at night compared to the other groups.

Ground Cover : The ground cover of the site consists of four types of material, including asphalt road, sandy soil, cement concrete pavement, and loam soil. There is also urban woodland.

- Asphalt roads, or parkings lots have a low albedo (dark surface), meaning it absorbs lots of solar radiation during the day. This should mean higher surface temperature during the day around the lot, and a high mean radiant temperature. The heat stores in the surface will then be released at night time, leading to higher air temperature. Asphalt contributes to urban heat island effect.

— Cement concrete pavement : Its albedo depends on its color. It has a high thermal mass, meaning it will store heat during the day in the surface and release it at night in the air.
— sandy / loam soil : it is covered in grass so it has a higher albedo than asphalt. This means it stores less heat and contributes less to the UHI effect. It is also, in the contrary of the two previous materials, not impervious. It can thus hold more water and have a cooling effect due to evaporation. It should also cool faster than concrete at night due to lower thermal mass.
— Woodland : It provides shape, which reduces the absorption of shortwave radiations of the surface. Vegetation provides evapotranspiration, which actively cools the air. All in all the forest provides cooler surface and air temperatures due to shading and moisture release. They provide a better thermal comfort and we should thus observe lower UTCI there. However it is important to keep in mind that the vegetation changes with the season, and may not hold the same properties throughout the whole year.

Buildings layout : The relative placement of buildings change the wind flow patterns. Factors are : their spacing, alignment, rotation and height. Here is what we can take out from EPFL innovation park.
— Low aspect ratios (short buildings, wide streets) : The buildings are very scattered. They allow for better wind circulation, which enhances cooling. But in another hand it reduced shading, increasing solar radiation exposure, raising daytime surface and air temperatures. Here it isn't relevant to talk about urban canyon.
— The buildings are not aligned, which "breaks" the windflow, meaning some spots could be protected from the wind, despite the wide streets.
— Variation in building heights : the taller buildings are placed on the south, facing the direction of the lake. The buildings behind them are gradually smaller. These tall buildings can act as windbreaks, reducing airflow at ground level. Buildings blocking prevailing winds create zones of stagnant air, leading to heat buildup[9]. The heights of the buildings is shown in figure 74 of the appendix.

2.3 Climate analysis

In this part different parameters will be analyzed from the simulations. For those to which it is relevant, there will be a daytime vs nighttime comparison. Daytime simulation is chosen at 2p.m. and nighttime at 10p.m.

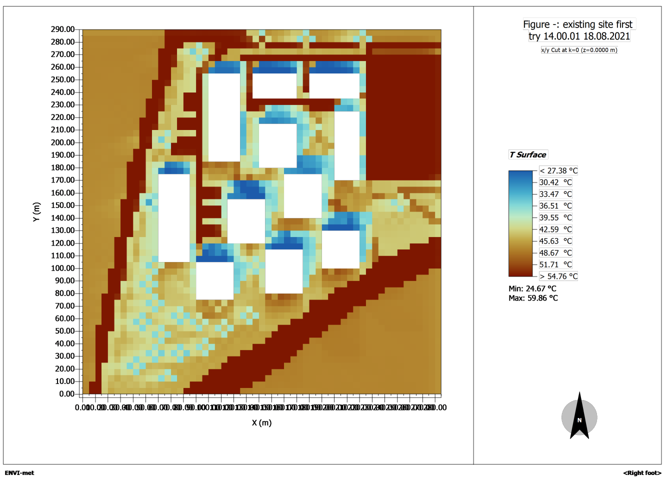


FIGURE 3 – Surface Temperature - Daytime

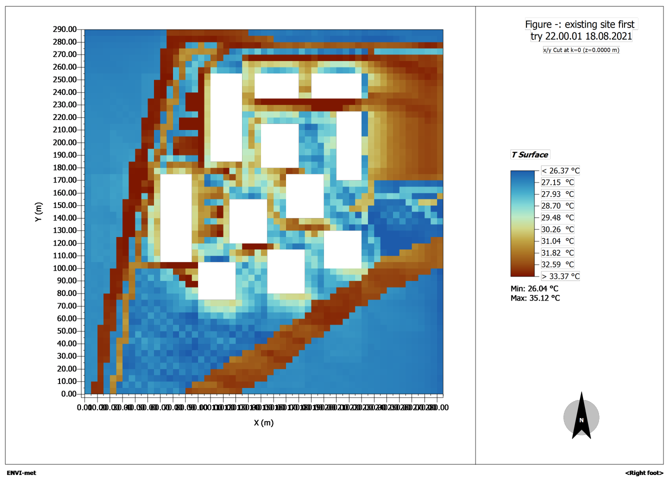


FIGURE 4 – Surface temperature - Nighttime

At daytime, asphalt has a high surface temperature. It is because it is a dark material, which absorbs a lot of solar radiation and reflects little (see figure 67). There is a lack of shade between the buildings, leading to

9. On the day of the simulation, the wind doesn't come from the south but from the north-east. This hypothesis thus doesn't apply on our simulation but is more of a general statement.

high temperatures there too. The urban woodland and vegetated areas are cooler, due to evapotranspiration and shade. At nighttime, the forest and vegetation covered areas are already cooled, when the pavement paths and asphalt still hold lots or heat. This is due to their high thermal inertia, which causes them to retain heat even at night, leading to prolonged warmth.

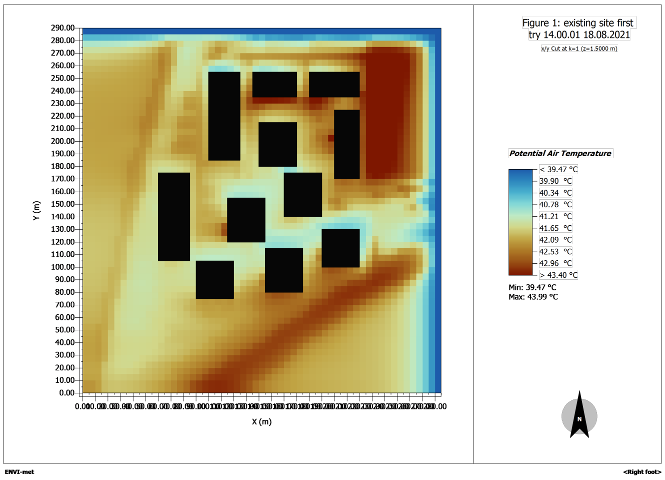


Figure 5 – Air Temperature - Daytime

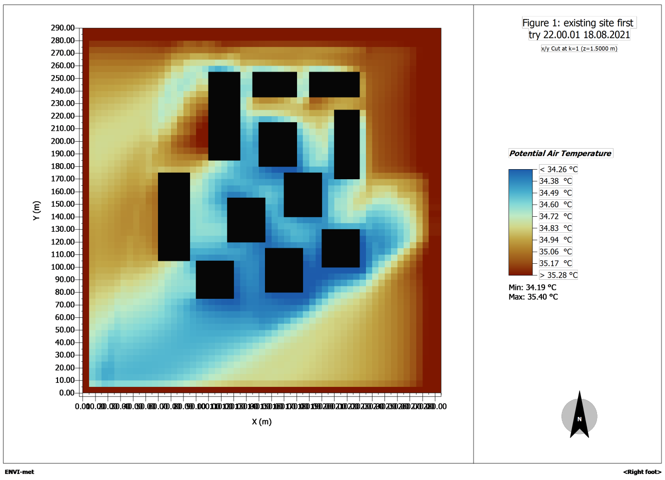


Figure 6 – Air Temperature - Nighttime

At daytime the air temperature above asphalt is a bit lower than the surface temperature, but still very high. At nighttime it is the other way around for asphalt, which releases very slowly its heat into the atmosphere (high thermal mass). Same observations as for the surface temperature can be done about the vegetated areas. They are much cooler and cool much faster at night.

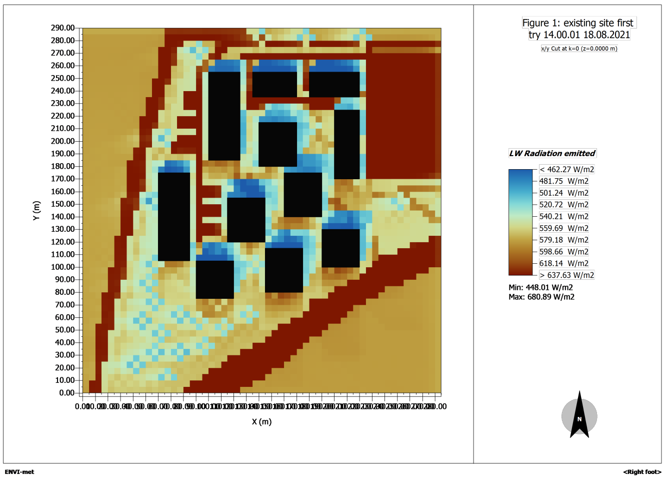


Figure 7 – Longwave Radiation emitted - Daytime

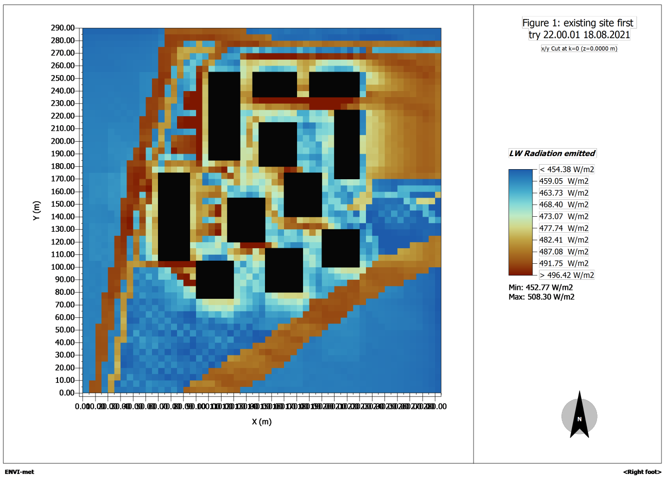


Figure 8 – Longwave Radiation emitted - Nighttime

Asphalt emits significant longwave radiation during both the day and night, contributing to elevated air temperatures in the surrounding area, as well as increasing UTCI around it (see figure 15 and 16). Vegetation and shaded areas have lower LW radiation emissions. This is because the vegetation has lower thermal conductivity as concrete for example.

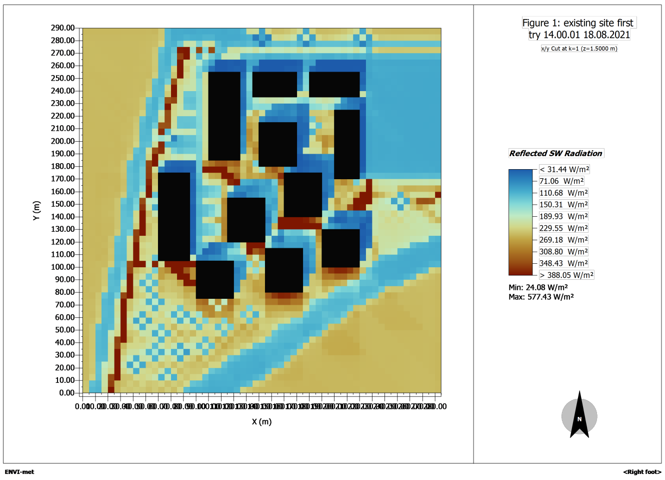


FIGURE 9 – Reflected Shortwave Radiations

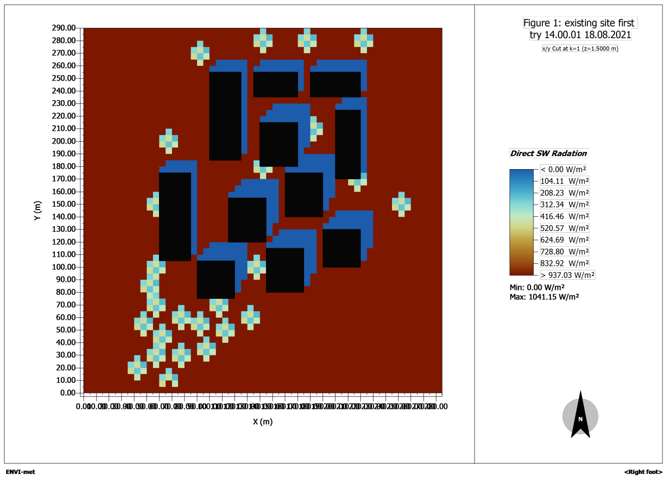


FIGURE 10 – Direct Shortwave Radiations

The areas with vegetation, the pavement, and some buildings facades of group B reflect SW. These materials have a higher albedo than asphalt, which, in the contrary, don't reflect SW and absorb it. During the day direct SW hits everywhere but in the shadow of the trees and the buildings. The shaded areas block direct solar radiation, reducing as well the reflected amount of shortwave. This allows the surfaces and materials in the shade to absorb less heat. It would be profitable to increase the number of trees between the building to provide shaded areas in the wide space between the buildings. Areas dominated by low-albedo materials (like asphalt in the parking lot, and dark roofs) absorb most of the SW radiation, leading to higher temperatures and contributing to the Urban Heat Island effect. Conversely, vegetation, light-colored surfaces, and shaded areas mitigate this effect.

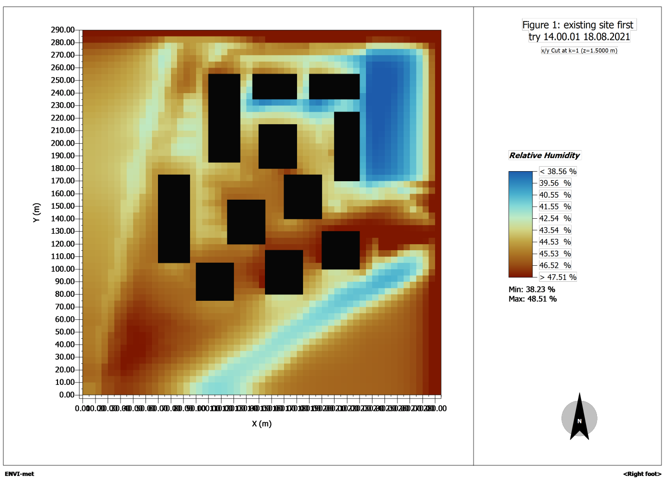


FIGURE 11 – Relative Humidity - Daytime

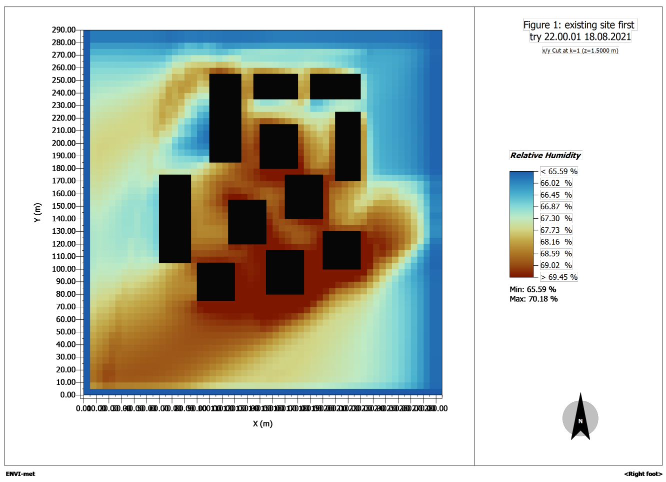


FIGURE 12 – Relative Humidity - Nighttime

The vegetated area including the forest hold more relative humidity. This is due to the bare ground properties and the increased shading. This higher humidity allows evaporative cooling, helping to reduce the UHI effects. We can observe in figure 5 that the air temperature is in consequence lower in the urban woodland than elsewhere. Asphalt road and parking lot hold little humidity due to being impervious. This translates into higher surface and air temperature. At night the humidity in general increases but the same pattern is observable.

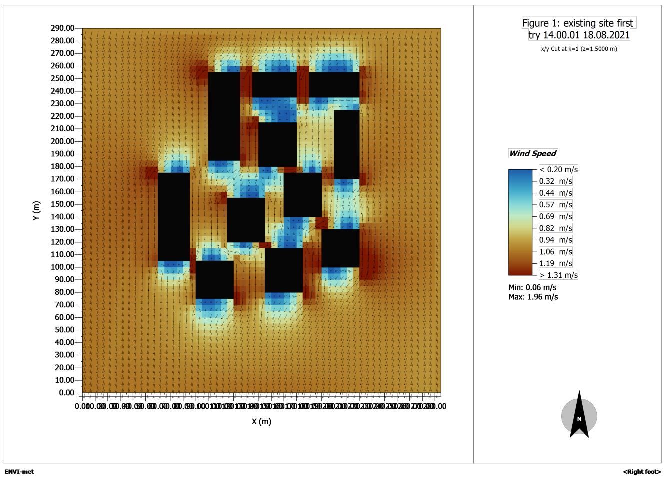


FIGURE 13 – Wind Speed and Direction - Top view

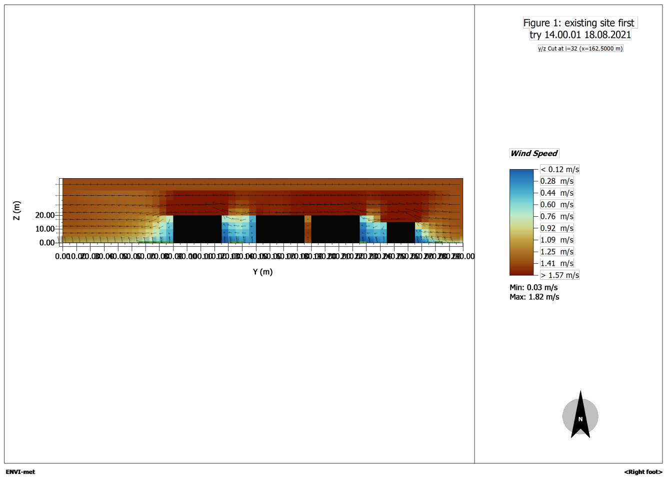


FIGURE 14 – Wind Speed and Direction - Side view

There are some spots with low wind speed behind the tall buildings, and very high wind speeds around other spots. Wind tunneling isn't really relevant here due to the scarcity of the buildings and their non regular placement. We can however see on figure 14 that that when the wind enters with the right direction an area where the buildings are close, it creates some pretty strong wind speeds at human height. Otherwise the wind is quite fast at the top of the buildings, but it doesn't really impact the human experience in the Innovation Park, as the wind mostly struggles to penetrate inside the Park.
Vegetated area and woodland were expected to have lower wind speed than parking lot for example, but it is not the case here. This could be due to the actual lack of trees in the model.
About the direction, the wind comes diagonally, from the North-East, creating areas with good ventilation, and areas with blocked wind, leading to higher heat retention, and reduced air exchange, as explained before.

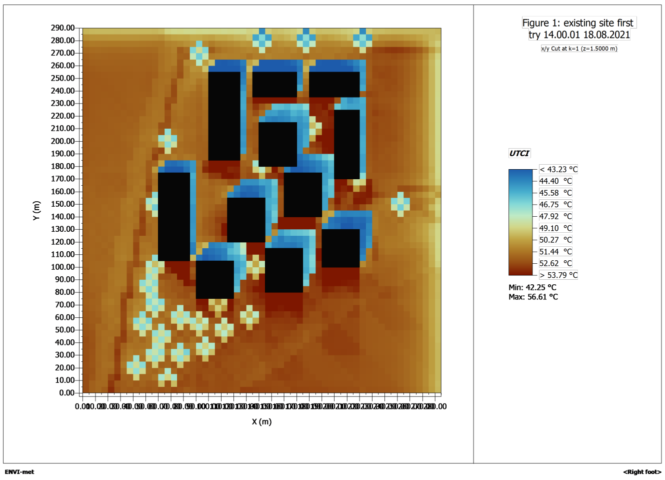


FIGURE 15 – UTCI - Daytime

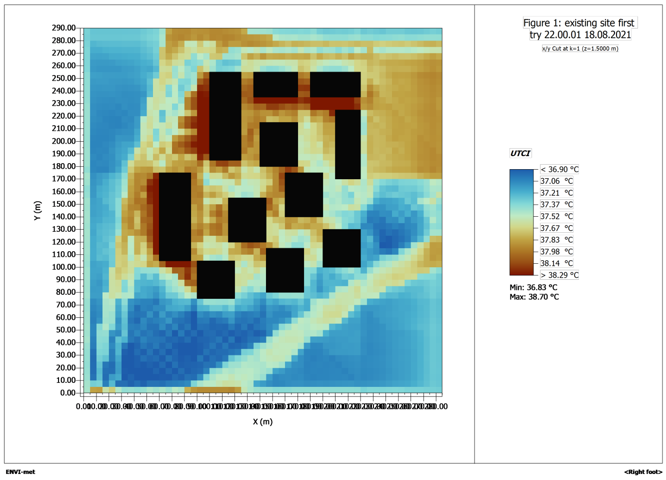


FIGURE 16 – UTCI - Nighttime

The Universal Thermal Climate Index (UTCI) is a thermal comfort metrics, and studying it can help to imagine what a pedestrian would feel like walking through the innovation park. It takes into account lots of parameters such as the temperature, air velocity, relative humidity, air pressure, activity of the human and clothing of the human.
The human we chose to analyze is a standard male in summer clothes whoses characteristics can be found in the appendix (figure 75). During daytime, the UTCI is only low (better thermal comfort) in the direct shadow of the buildings and a bit in the urban woodland. The parking lot and pavement path show high

UTCI. At night the UTCI is worst around some buildings due to their high thermal mass, which keeps the air temperature high. It is also bad above the asphalt roads and parking lots, and pavement paths. The areas with vegetation held way less heat and are more comfortable at nighttime.

The primary hotspots of the site are the asphalt roads and parking lots. Due to low albedo and high thermal mass, they store heat and contribute to UHI effect. It was said previously that the site has a high sky view factor. Thus can be listed as hotspots open, unshaded spaces between buildings with high solar exposure and poor ventilation, along with wind shadows behind tall or clustered buildings where airflow is obstructed. These areas are exacerbated by limited shade, poor ventilation, heat-retaining materials, and lack of vegetation that could provide shading and cooling by evapotranspiration.

3 Urban microclimate exploration

First of all, it is important to make one clarification for the simulations. As in the previous section, the time of day is 2pm and the time of night 10pm. For the atmospheric parameters, the values were taken at 1.5 m (human height). For the first model, it was difficult to compare the two models directly because the buildings were not in the same place, so we have included the simulations for the two models separately in the report each time. However, for subsequent models, we directly used the 'comparison' function. This feature computes Set A - Set B. It will be precised at the beginning of each part which model is which set.

3.1 Building-Environment interactions

In order to analyze the interactions of the buildings with their environment, we created three models where we tried different building layouts. Analyzing the results from these simulations allowed us to make our ideas evolve and we eventually decided to present in this report only one of these models. None of the layout we tried really showed good results in term of reducing the UHI effect, and they all showed quite similar results. The model we will present to you in the next part is thus not the model that showed the best performance, but rather the more extreme layout, which allowed us to highlight the most clearly the effects of bringing the buildings closer.
Despite not being analyzed, the two extra models are left on display in the appendix (see figures 76 and 78).

3.1.1 Model 1 - Change in the configuration of buildings [10]

In this model we decided to move all the buildings closer together and align them. The main reason for this was to increase the shaded areas, as there would be an increase in mutual shading between the buildings, and therefore a reduction in the ground temperature in the shaded areas. The reason for this reduction in temperature is that the amount of direct solar radiation reaching the ground decreases. This hypothesis is not really confirmed by the simulations (see Figures 17 and 18). In fact, as expected, where there are shadow zones (mainly between buildings) the direct shortwaves are at 0 W/m^2. However, in the initial model the shadow zones are larger because they are not intersected by other buildings. In fact, to optimise this parameter, it would be necessary to space the buildings at a distance corresponding precisely to the maximum extent of the shadow zone (which changes during the day). The positive point of this model is that surface temperatures are slightly lower overall during the day (see Figure 19).

10. Set A : base model, Set B : modified model

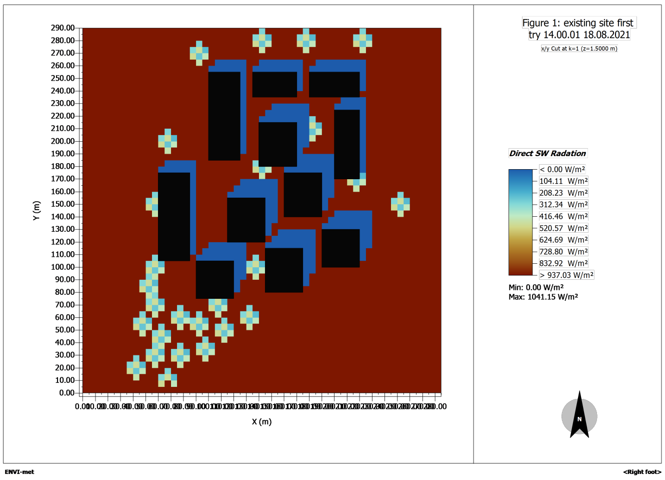


FIGURE 17 – Direct SW during the day for the base model

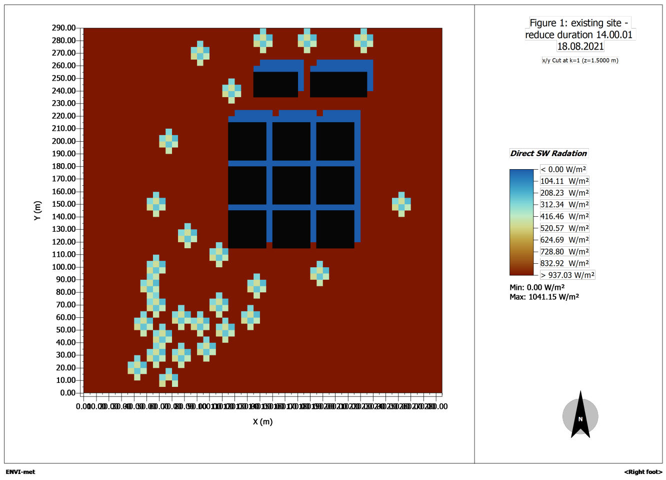


FIGURE 18 – Direct SW during the day for the modified model

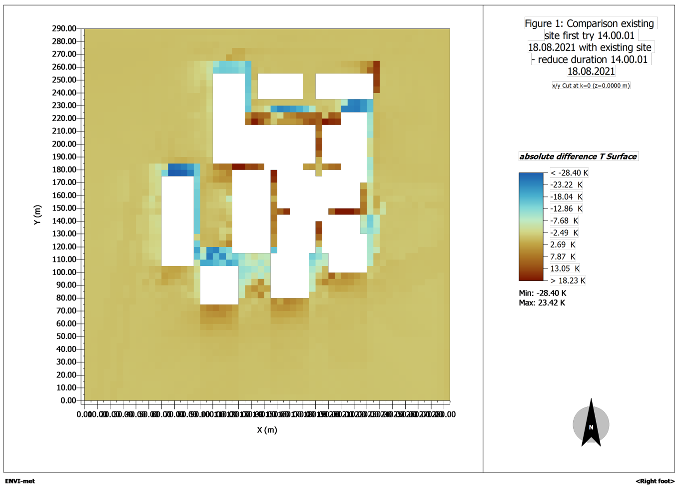


FIGURE 19 – Comparison of surface temperature during the day between the base model and the modified model. The white areas are the places where there are buildings.

However, the fact that buildings are placed closer together creates poor air circulation, because this layout creates zones where the air tends to stagnate. This leads to poorly ventilated spaces and increased heat on exposed facades. Using Figure 21, we can see that in the entire perimeter where there are buildings, the wind speed is almost zero. Indeed, the wind does not flow at all in an East-West direction, but there does seem to be some unfavorable wind tunneling in a North-South direction. In comparison, the basic model (see Figure 20) has more zones where air circulates in the perimeter, which is better.

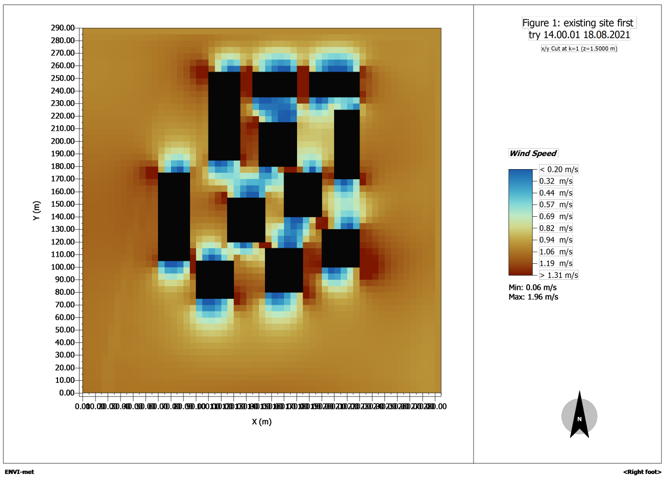


FIGURE 20 – Wind speed during the day for the base model

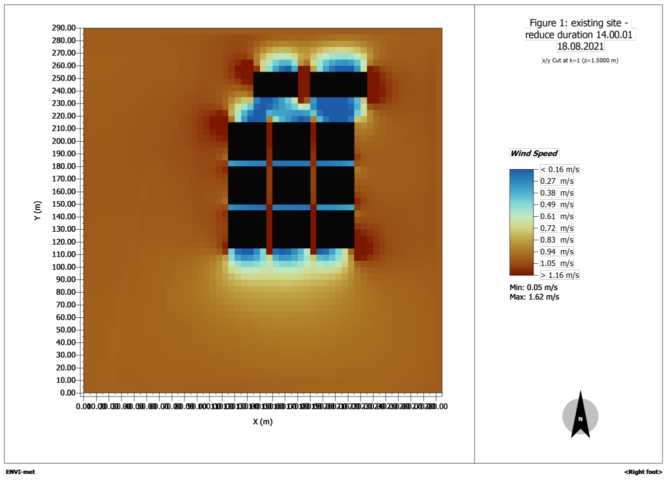


FIGURE 21 – Wind speed during the day for the modified model

Another disadvantage of this model is the slowdown in night-time cooling. This is because there is a reduction in the thermal radiation emitted into the atmosphere at night (much lower sky view factor). As a result, air temperatures at night are higher with this new arrangement of buildings, as we can see from Figures 22 and 23.

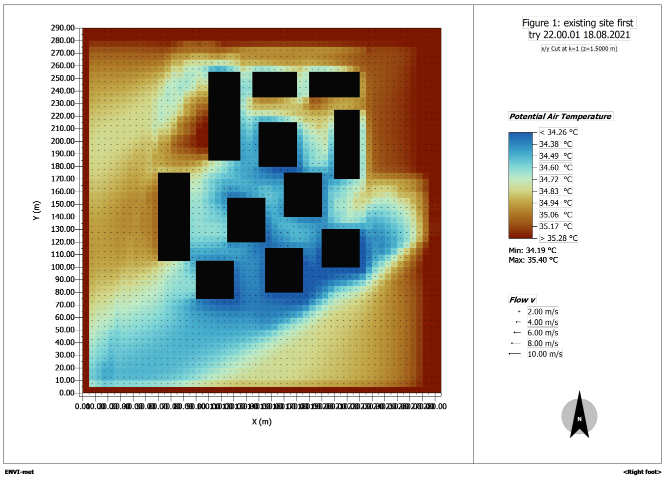


FIGURE 22 – Night-time air temperature for the basic model

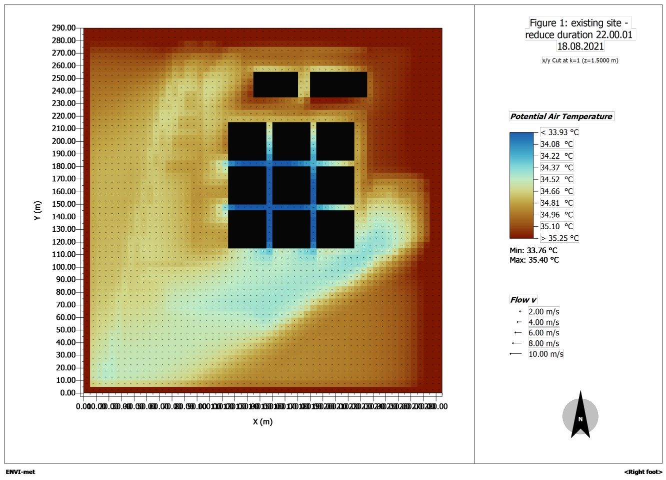


FIGURE 23 – Night-time air temperature for the modified model

In short, despite the slight reduction in surface temperatures during the day, this model has more disadvantages due to the canyon urban effect. That is why, from a building layout point of view, Innovation Park is very good.

3.2 Ground-Environment interactions

3.2.1 Model 2 - Change of soil type [11]

For the second model, we looked at ground-environment interactions. Our mitigation strategy was to replace the asphalt in the parking spaces with loam soil. We chose this material because, like most natural materials,

11. Set A : base model, Set B : modified model

It would be more informative to provide the values of these thermal properties

it has low thermal conductivity and poor heat storage capacity (unlike asphalt). As a result, there will be a reduction in surface temperatures during the day and a more gradual release of heat at night. This is verified by the simulation results. We can see from Figure 24 that the parking lot areas are where the absolute difference in temperature surface is greatest, at 7.31 [K]. This shows that the change in surface has a positive impact on the environment. However, this impact is very local because it only occurs in the changed areas and not really in the surrounding area. Logically, we can see that these changes are significant during the day, but less so at night (Figure 25). At 10pm, the maximum absolute difference temperature surface is only 1.48 [K] (in the parking lot areas).

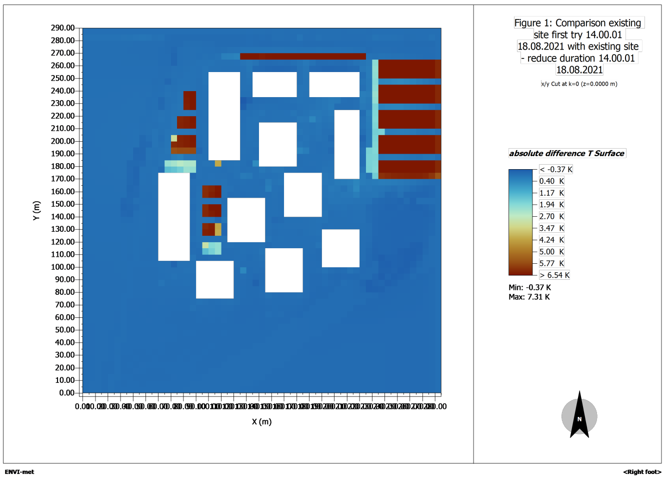


FIGURE 24 – Comparison of surface temperature during the day

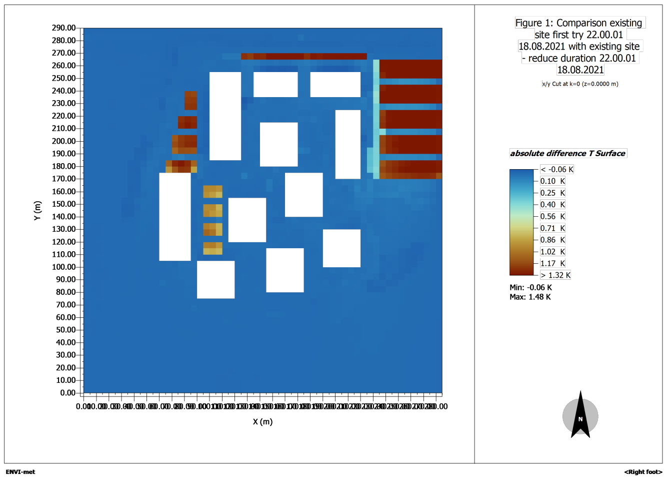


FIGURE 25 – Comparison of surface temperature during the night

How is humidity linked to CO2 level?

Another hypothesis that would reduce the effect of urban heat islands thanks to this change in pavement would be better air quality. Indeed, permeable soils promote better water infiltration and increased evaporation compared to impermeable surfaces, resulting in slightly higher relative humidity. Higher humidity can help trap certain fine particles in the air, causing them to fall to the ground. This hypothesis is also confirmed by the simulation (Figures 26 and 27), where relative humidity has increased. As before, logically this effect is greater during the day (absolute difference Relative Humidity min = -3,23 %) than at night (absolute difference Relative Humidity min = -0,15 %) and this is a local phenomenon. For air quality, we can also look at the quantity of CO2. With Figures 28 and 29 we can see that the change in pavement has a slightly positive effect. The air temperature is also a good parameter to observe, and Figures 30 and 31 show a slight drop, more visible during the day than at night, which is conducive to better thermal comfort and the reduction of heat islands. This is because a higher relative humidity allows evaporative cooling.

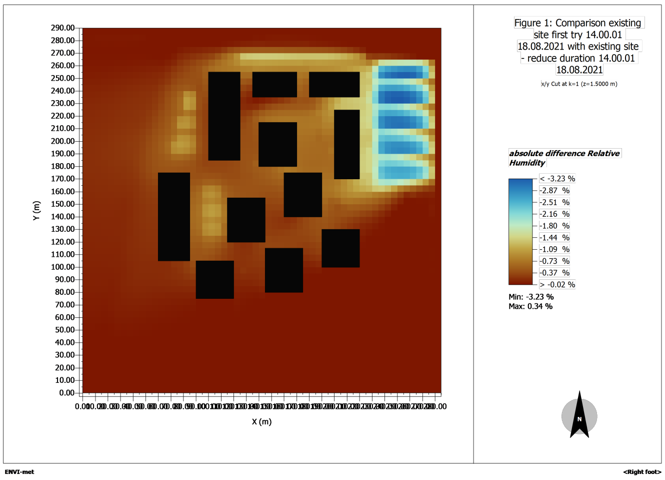


Figure 26 – Comparison of relative humidity during the day

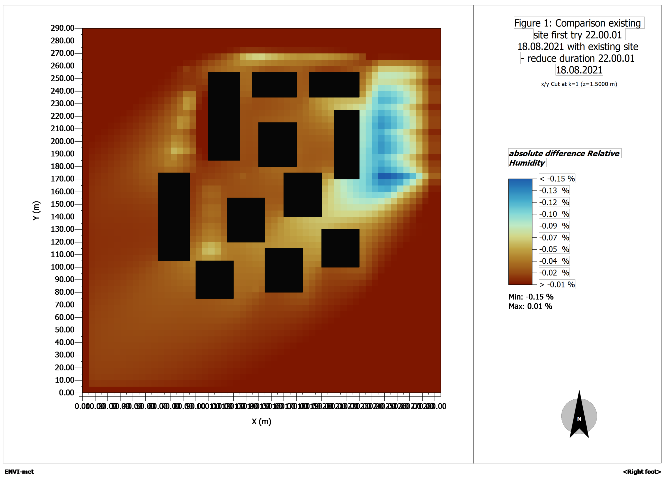


Figure 27 – Comparison of relative humidity during the night

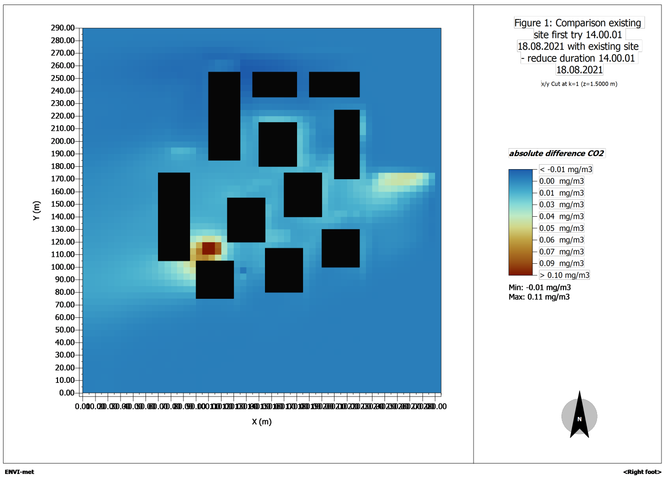


Figure 28 – Comparison of CO2 during the day

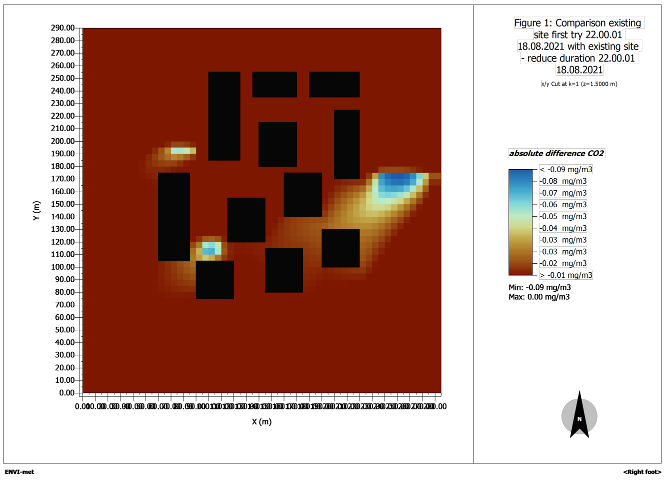


Figure 29 – Comparison of CO2 during the night

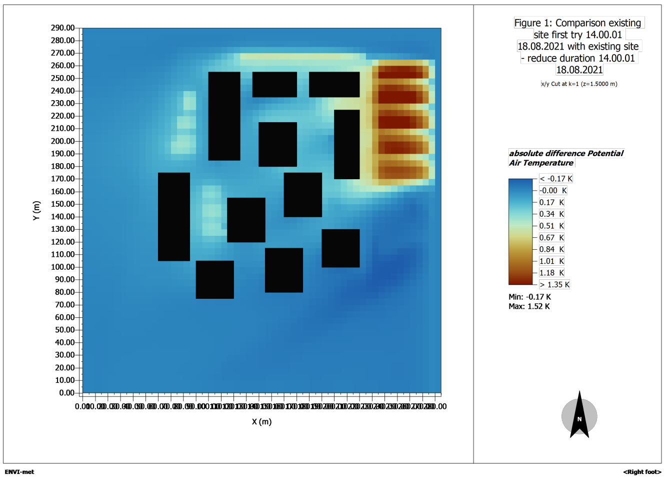


FIGURE 30 – Comparison of air temperature between the base model and the modified model during the day

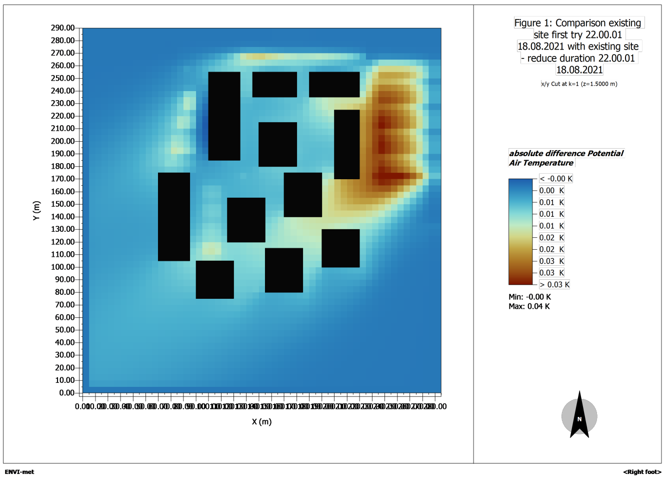


FIGURE 31 – Comparison of air temperature between the base model and the modified model during the night

The simulations also allow us to compare short-wave radiation during the day. In Figure 32, we can see that this reflected radiation has increased by a maximum of 240.56 W/m^2 , which indicates that more solar radiation is reflected by loam soils. This suggests better thermal regulation thanks to the loam soil. In Figure 33 where we have compared the basic model with the model where the surface of the parking spaces has been modified, we can see that the longwave radiation has decreased by a maximum of 58.87 W/m^2 during the day. This is a positive thermal impact because it indicates that the loam soil stores less heat, which can help to reduce the urban heat island effect. This result is favorable because it helps to stabilize the ambient temperature, particularly at night (see Figure 34), by limiting the heat flows emitted by the soil. A reduction in LW radiation can also mean greater thermal comfort for pedestrians and the immediate environment, as less heat is emitted towards buildings and people. This parameter is also linked to relative humidity (see above), which confirms that loam soil encourages better evaporation.

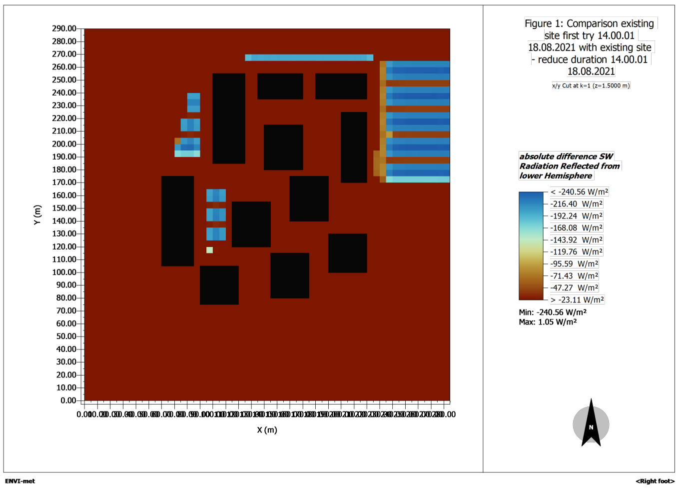
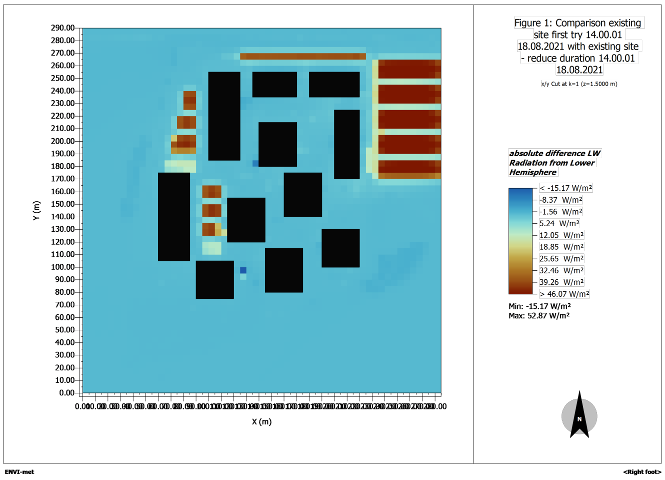


FIGURE 32 – Comparison of reflected SW radiation during the day between the base model and the modified model



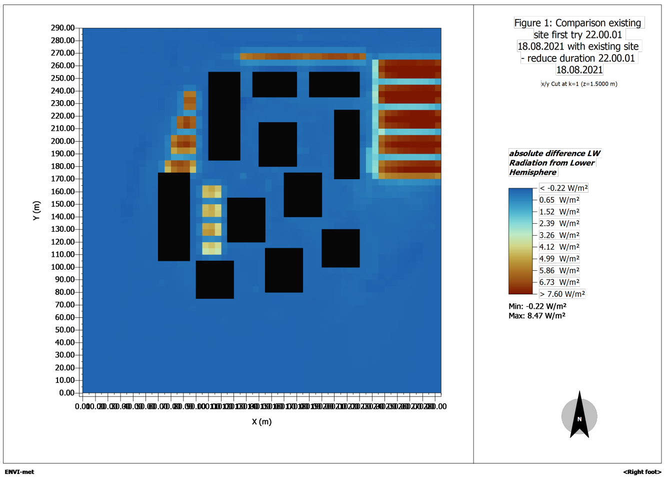
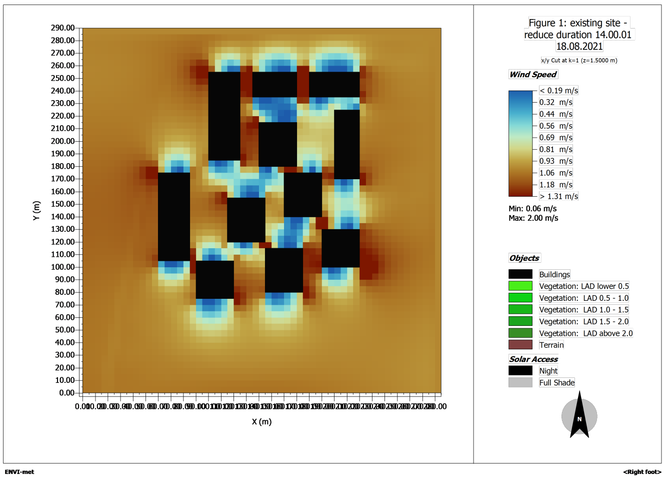


FIGURE 33 – Comparison of LW radiation during the day between the base model and the modified model

FIGURE 34 – Comparison of LW radiation during the night between the base model and the modified model

However, despite the advantages of having loam soil parking spaces, there is also a disadvantage. Loam soil, especially when exposed to wind, can produce fine particles that disperse into the air. These particles are respiratory pollutants. In our simulation, carried out on 18 August, this disadvantage does not affect us too much because the maximum wind speed is 2 m/s during the day (See Figures 35 and 36). However, on certain days of the year, this speed is higher and this disadvantage can be a problem. One solution to this problem would be to add vegetation to limit the spread of these particles.



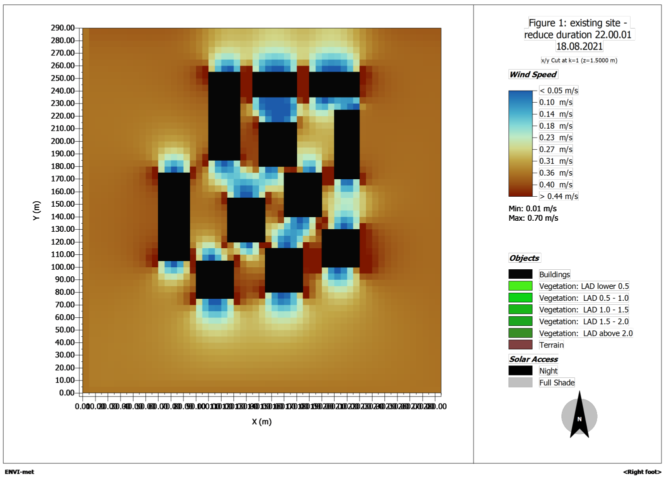


FIGURE 35 – Wind speed during the day

FIGURE 36 – Wind speed during the night

To sum up, this strategy of changing the floor of parking spaces to loam soil is positive (if the wind is moderate) because it reduces surface temperature and improves air quality, but it remains very local.

3.3 Water bodies-Environment interactions

3.3.1 Model 3 - Water Body Addition [12]

Explanation of the choice of mitigation strategies and relevant parameters are needed, as well as the cooling mechanism

For the third model, we analyzed the effect of adding a water body on **surface temperature** compared to the Base Case during the daytime (14 :00) and nighttime (22 :00).

12. Set A : modified model, Set B : base model

At 14 :00, the water body significantly reduced surface temperatures in its immediate surroundings, with a maximum decrease of **-9.57 K**. This reduction is due to the cooling effect of water evaporation and the lower heat absorption of water compared to other surfaces. Some areas farther from the water body show slight temperature increases, potentially caused by heat redistribution.

At 22 :00, the surface temperatures near the water body are still slightly lower, with a maximum decrease of **-7.35 K**. However, the cooling effect is less pronounced at night as the water gradually releases the heat it absorbed during the day, which reduces the temperature gradient between the water and its surroundings.

Overall, the results demonstrate the water body's capacity to lower surface temperatures, especially during the day, aligning with its role in mitigating urban heat islands through evaporative cooling.

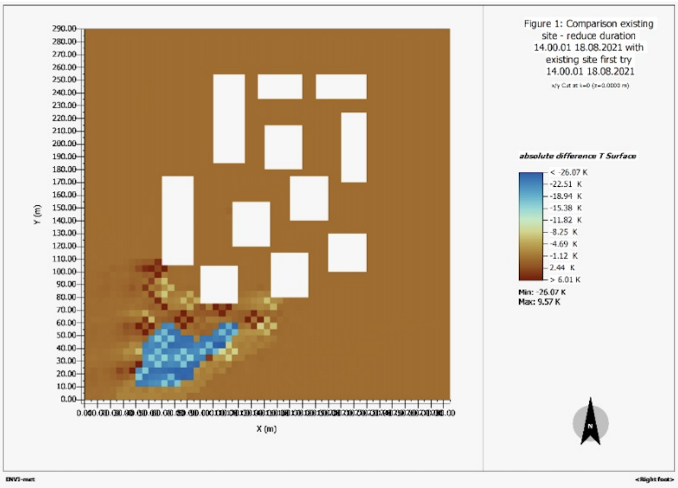


FIGURE 37 – Surface temperature during the day

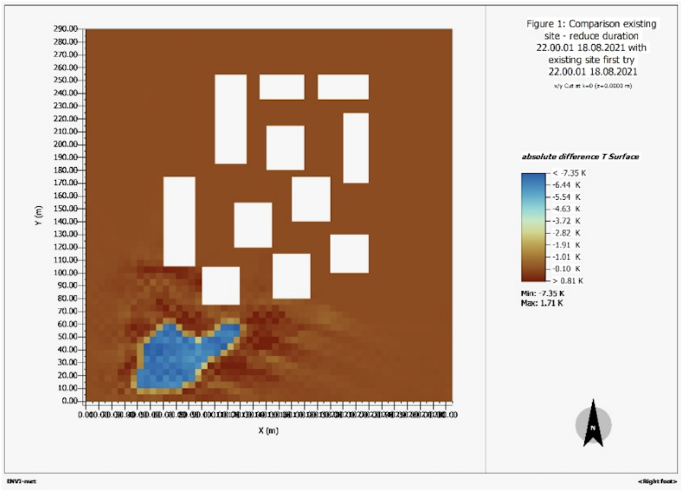


FIGURE 38 – Surface temperature during the night

We also examined the impact of introducing a deep pond on the relative humidity of the surrounding environment during both daytime and nighttime. This analysis evaluates how the evaporative properties of the water body influence local humidity levels at different times.

During the day at 14 :00, the addition of the pond results in an increase in relative humidity in its immediate surroundings, with a maximum absolute difference of **+1.05%**. This effect is caused by the evaporation of water, which adds moisture to the air. The process of evaporative cooling not only reduces surface temperatures but also increases the amount of water vapor in the atmosphere, leading to higher relative humidity. However, this effect remains highly localized and is concentrated around the pond area, with minimal impact observed farther away.

At night at 22 :00h, the influence of the pond on relative humidity diminishes, with a maximum absolute difference of **+0.11%**. This reduction is expected as the evaporation rate slows down due to the lower temperature gradient between the water surface and the surrounding air. The thermal inertia of the pond helps maintain a stable moisture level, but the overall effect on relative humidity at night is less pronounced compared to daytime.

In summary, the comparison highlights the pond's effectiveness in increasing relative humidity during the day through evaporation, while its nighttime impact is relatively minor. These findings underscore the role of water bodies in improving urban microclimates by enhancing localized humidity levels, particularly during warmer periods.

What about the heat capacity of water body for regulating temperature?

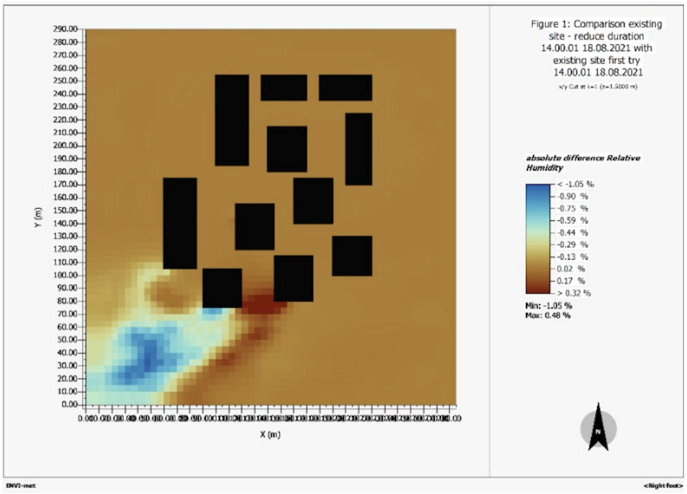


FIGURE 39 – Relative humidity during the day

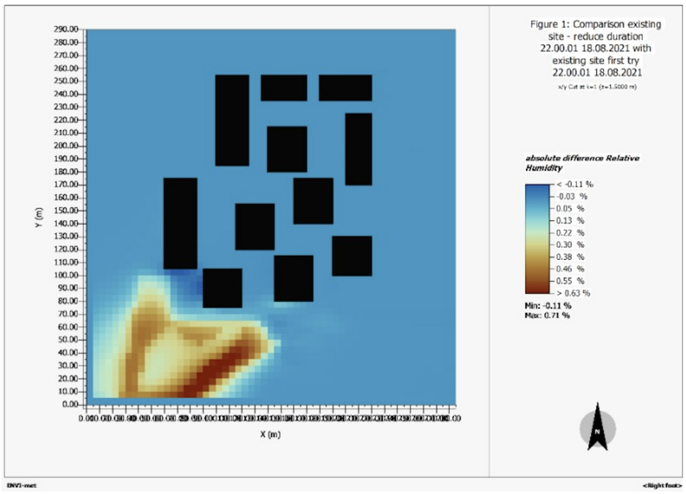


FIGURE 40 – Relative humidity during the night

3.3.2 Model 4 - Fountain addition [13]

For the fourth model, we analyzed the effect of adding fountains on **relative humidity (RH)** compared to the Base Case. This analysis was conducted for both daytime (14 :00) and nighttime (22 :00) conditions.

At 14 :00, the fountains increased relative humidity in the immediate vicinity, with a maximum rise of **3.37%**. This effect is concentrated around the locations of the fountains, as the evaporation of water contributes to localized cooling and moistening of the air. Some minor decreases in RH, reaching **-1.29%**, are observed in adjacent areas, likely due to shifts in air circulation.

At 22 :00, the impact of the fountains on relative humidity is less pronounced, with a maximum increase of **0.31%** near the fountain locations. This reduced effect at night can be attributed to lower evaporation rates due to cooler ambient temperatures, which limit the fountains' ability to add moisture to the air.

Overall, these results illustrate how fountains can enhance relative humidity during the day, particularly in their immediate surroundings, while their nighttime impact remains minimal. These findings align with the course concepts on water features' contribution to urban cooling and humidity management.

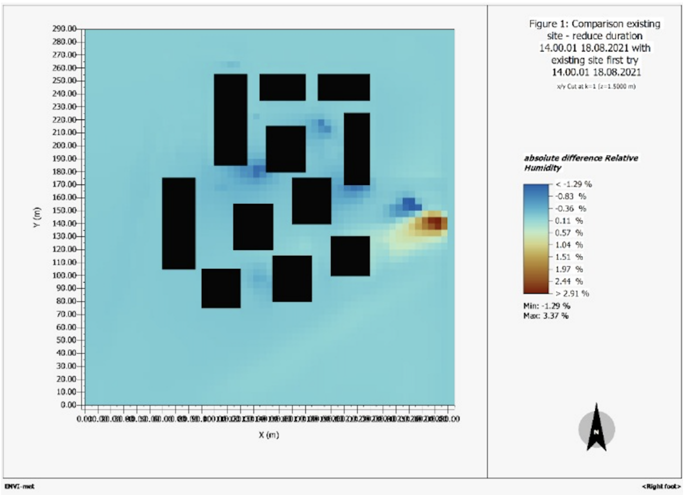


FIGURE 41 – Comparison of RH during the day

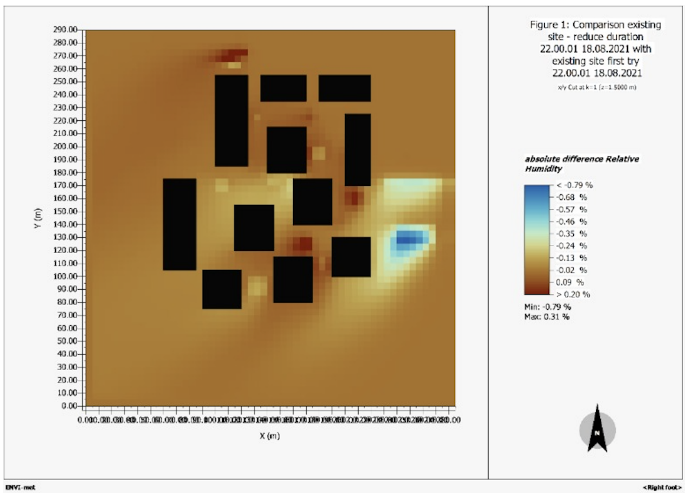


FIGURE 42 – Comparison of RH during the night

We also evaluated the impact of adding fountains on air temperature. At 14 :00, the fountains caused a maximum cooling effect of **-0.93 K**. This reduction is due to evaporative cooling, where heat from the

13. Set A : modified model, Set B : base model

surrounding air is absorbed to evaporate water. The cooling is strongest in the immediate vicinity of the fountains and decreases with distance. At 22 :00, the impact is smaller, with a maximum reduction of **-0.20 K**. This is because evaporation rates are lower at night due to reduced thermal gradients and ambient temperatures. Overall, the results show that fountains are effective in reducing air temperatures during the day while maintaining stable conditions at night. This aligns with course concepts on the role of water features in mitigating urban heat and improving thermal comfort.

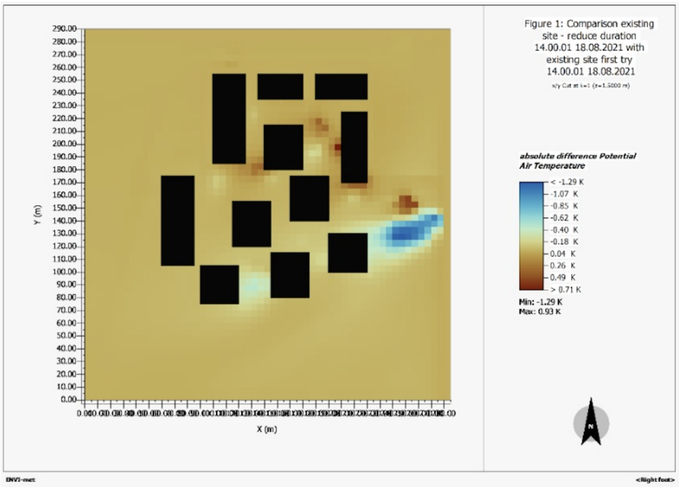


FIGURE 43 – Comparison of air temperature during the day

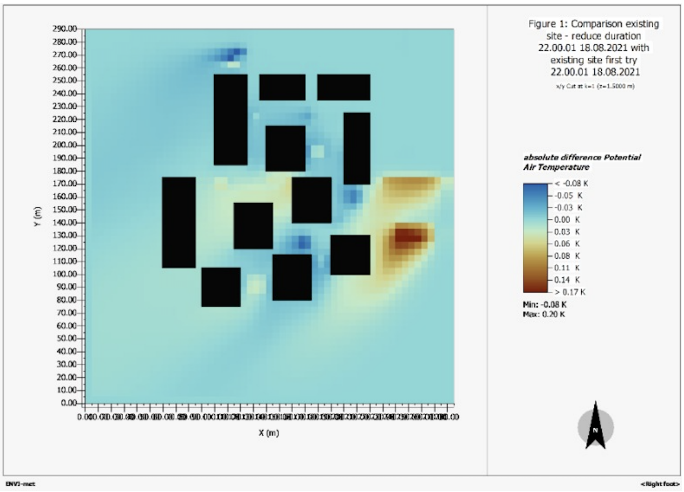


FIGURE 44 – Comparison of air temperature during the night

3.4 Vegetation-Environment interactions

3.4.1 Model 5 - Conifer Tree Replacement [14]

For the fifth model, we analyzed the impact of replacing existing trees with conifer trees on CO2 levels. During the day at 14 :00, CO2 levels significantly decrease near the conifers, with a maximum reduction of **-0.58 mg/m^3**, due to their high photosynthetic efficiency and ability to actively absorb CO2 during daylight hours. This aligns with principles from the course, where vegetation is shown to act as a natural carbon sink, especially in urban environments with limited airflow. At night, the impact is minimal, with a maximum increase of **0.01 mg/m^3** due to tree respiration, consistent with the concept that photosynthesis halts in the absence of sunlight while respiration continues. This comparison highlights the dual role of conifers in improving air quality during the day and maintaining stable CO2 levels at night, making them effective for urban climate mitigation strategies discussed in the lectures [2].

14. Set A : modified model, Set B : base model

Change of CO2 level is not related to cooling effect and not the focus of this project.

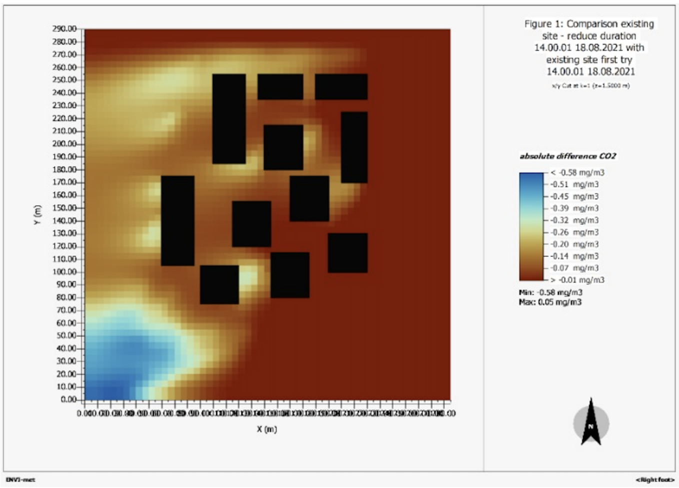


FIGURE 45 – CO2 level during the day

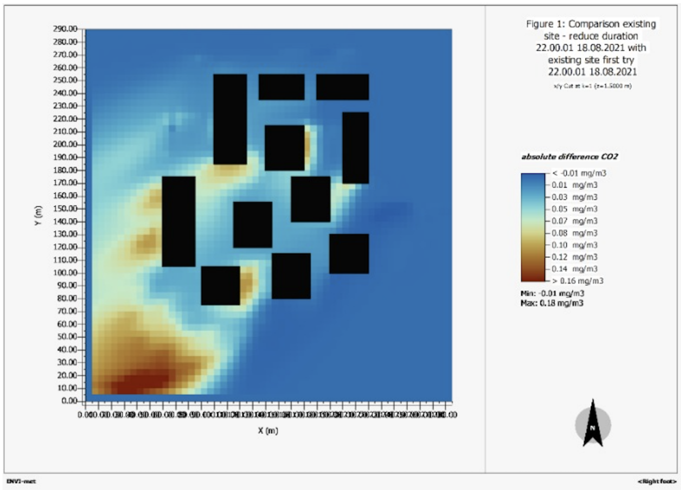


FIGURE 46 – CO2 level during the night

Replacing existing trees with conifers caused slight reductions in wind speed. At 14 :00, wind speed decreases by a maximum of **-0.04 m/s** near the conifer zones due to their denser foliage, which increases drag. At 22 :00, the impact is minimal, with a maximum difference of **-0.01 m/s**, as reduced convective activity limits airflow. This demonstrates that conifers have a localized and minor effect on wind speed, aligning with course principles on vegetation as a physical barrier to airflow.

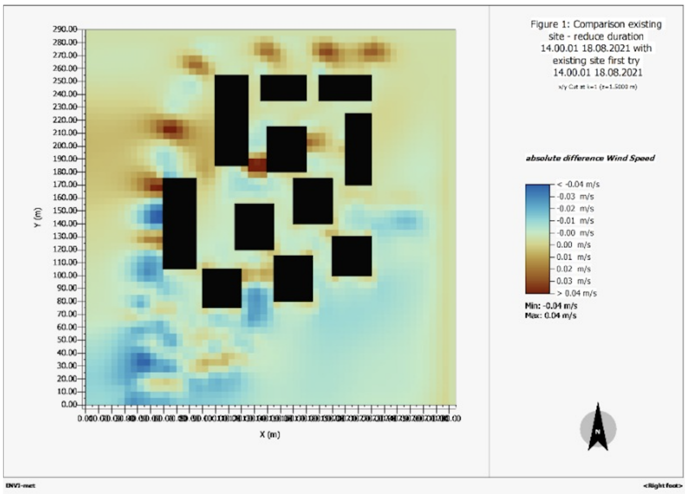


FIGURE 47 – Wind speed during the day

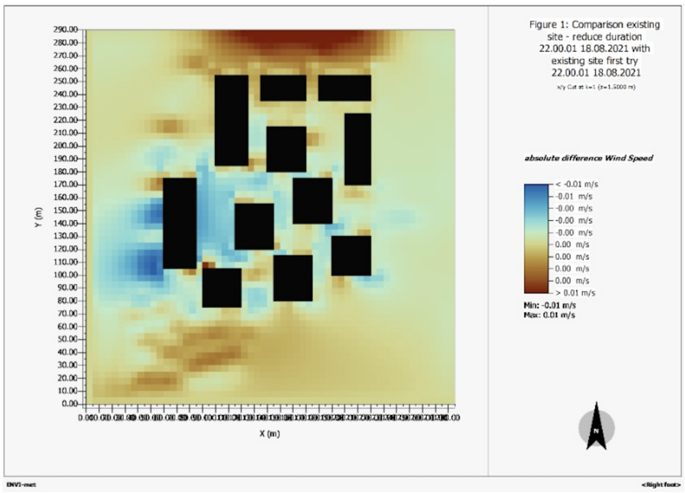


FIGURE 48 – Wind speed during the night

What about shading effect and evapotranspiration ?

However what is observed is that globally the change in type of tree has a minimal impact on wind flow and CO2 levels. It seems that the presence of trees is what matters more rather than the type of them and the shape of their leaves. It would maybe be interesting to compare the effect of the type of trees throughout the year because conifers change less with the seasons than other types of trees.

3.4.2 Model 6 - Model with green roofs [15]

For this model, we made another change for the vegetation-environment interactions where the roofs of all the buildings were vegetated. We didn't plant the walls because there are so many windows that it wouldn't be worth it.

15. Set A : base model, Set B : modified model

The project to install green roofs was chosen because of a major advantageous assumption, that of improved comfort inside the buildings (and of course also for ecological reasons). Indeed, green roofs play an important role in regulating temperatures thanks to their capacity for evapotranspiration and their high thermal inertia. In other words, these roofs absorb and slowly store the sun's heat during the day, then gradually release this heat at night. To put it another way, the vegetation acts as an insulator, limiting heat transfer to the buildings. This keeps the interior cooler, reduces the use of air conditioning and helps to reduce the temperature in the urban environment.

The simulations allow us to verify the evapotranspiration capacity of green roofs. Figure 49 shows that the relative humidity at night is higher with this new model. This is clearly visible to the south-west, in the blue zone, where relative humidity has risen by a maximum of 2.58 %. This confirms that green roofs increase ambient humidity, even slightly, through evapotranspiration. Another parameter that is interesting to look at at night is long wave radiation. Figure 50 shows that the flux is lower, which means that green roofs store heat better and release it more slowly, thus stabilizing the night-time temperature in the surrounding area (see Figure 51). Again, the places where this is most noticeable are around the buildings to the south and south-west. We can also see that even if the temperatures are uniform, they are very warm for one night (even in the middle of summer).

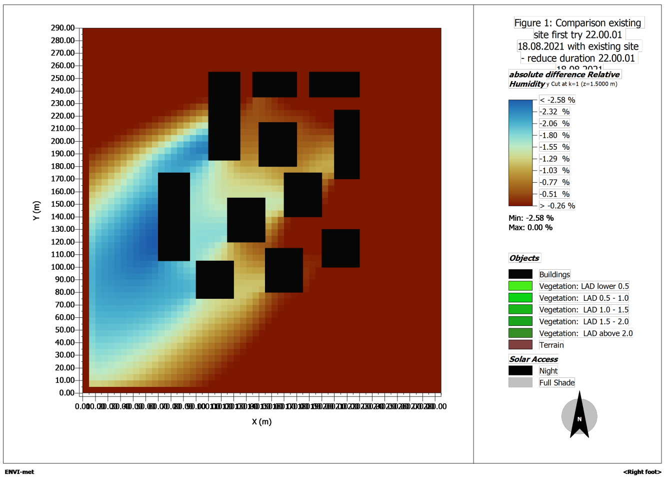


FIGURE 49 – Comparison of relative humidity during the night

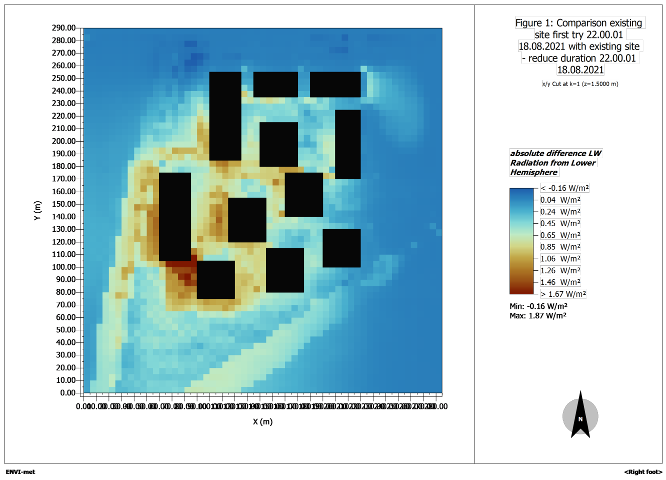


FIGURE 50 – Comparison of long wave radiation during the night

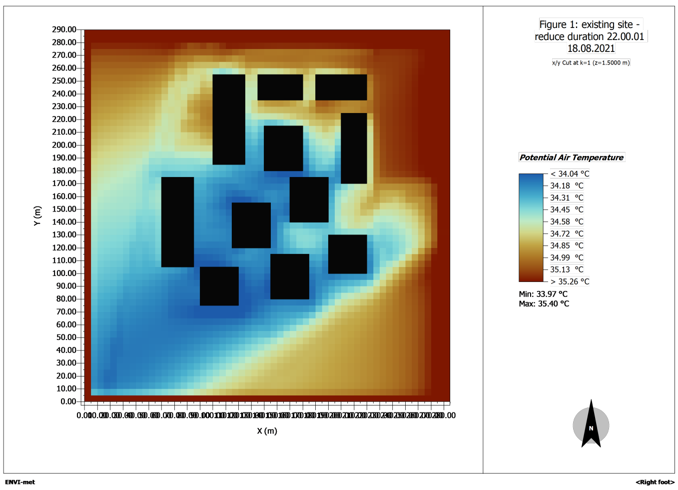


FIGURE 51 – Air temperature for the model with green roofs during the night

The simulations also shows us the benefits of green roofs during the day. To better observe these changes, we made cross-sections at x=112.5 [m] and x=207.5 [m]. For example, Figures 52 and 53 show that the air temperature decreases on the roofs (and slightly around them) by a maximum of 1.52 [K] and 1.04 [K] respectively. This means that the temperature inside the buildings is certainly lower, which reduces the need for air conditioning. With the cross-sections in the same places as before (see Figure 54 and 55), we can see that air circulation is better. A low wind speed can lead to thermal stagnation and, conversely, a wind that is too strong can reduce the insulating effect of the vegetation.

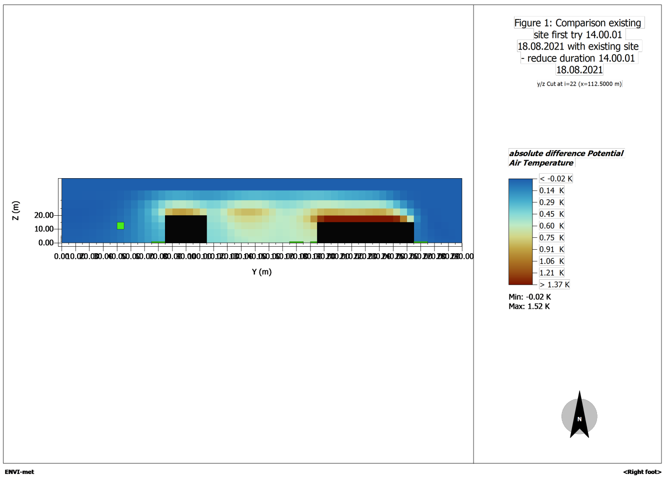


FIGURE 52 – Comparison of daytime air temperature between the base model and the model with green roofs, for section x=112 [m]

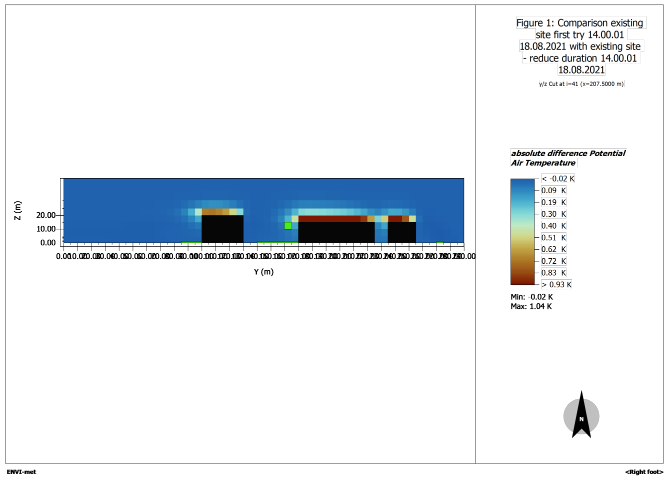


FIGURE 53 – Comparison of daytime air temperature between the base model and the model with green roofs, for section x=208 [m]

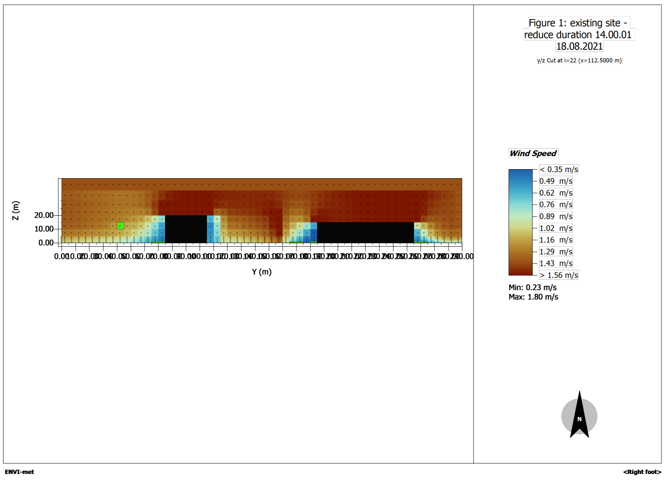


FIGURE 54 – Comparison of wind speed during the day between the base model and the model with green roofs, for section x=112 [m]

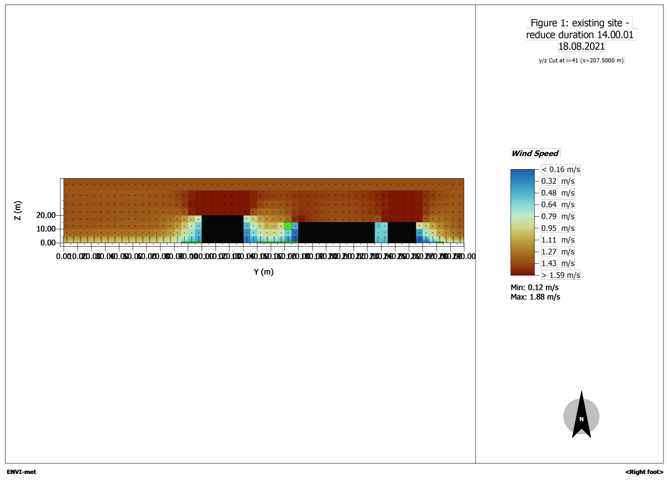


FIGURE 55 – Comparison of wind speed during the day between the base model and the model with green roofs, for section x=208 [m]

In short, adding vegetation to roofs is an asset, because it improves thermal comfort, reduces heat accumulation through evapotranspiration, and stabilizes temperatures.

3.4.3 Model 7 - Addition of Deciduous Trees on Parking [16]

This model combines the effect of loam soil (instead of asphalt in the parking lot) with the addition of trees. This is especially interesting to combine two mitigation strategies in the parking lot because it is the worst hotspot that we had identified.

Let's start by evaluating the impact of adding deciduous trees on the parking area on the **Sky View Factor (SVF)**. This metric measures the proportion of the sky visible from the ground and is influenced by obstructions such as trees and buildings.

The addition of deciduous trees significantly reduces the Sky View Factor in the parking areas, with a maximum decrease of **-0.34**. This reduction is due to the canopy of the deciduous trees, which blocks a portion of the sky from view. The impact is localized to the areas directly beneath the trees, with little to no change observed in uncovered areas.

This decrease in SVF is beneficial in urban climates, as it reduces direct solar exposure, thereby mitigating heat buildup during the day. This aligns with the course concepts on shading strategies, where tree canopies act as a natural barrier to solar radiation, improving thermal comfort in open spaces like parking areas.

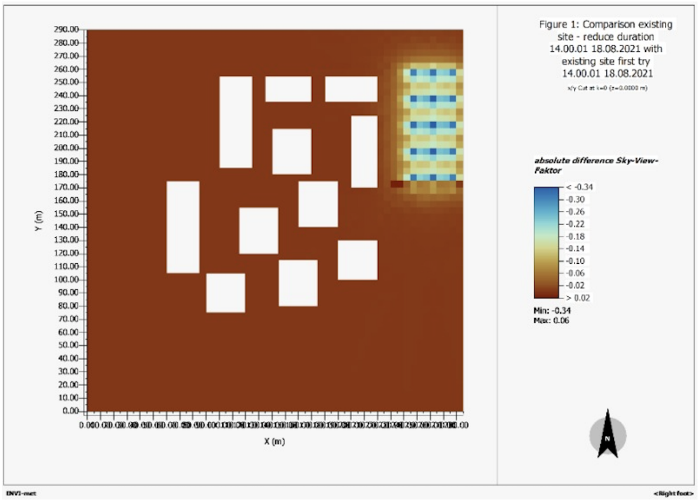


FIGURE 56 – Comparison of the sky view factor

We also analyzed the impact of adding deciduous trees on parking areas on long wave radiation (LWR) compared to the Base Case.

At 14 :00, the addition of trees leads to a significant reduction in long wave radiation in shaded areas, with a maximum decrease of **-140.36 W/m²**. This reduction is most likely due to the soil change than to the addition of trees.

At 22 :00, the long wave radiation difference is much smaller, with a maximum reduction of **-22.85 W/m²**. This is because at night, surfaces radiate stored heat, and the impact of shading diminishes. However, the trees still contribute to slightly cooler conditions by limiting heat radiation from the covered surfaces.

This comparison highlights the dual role of deciduous trees in reducing daytime heat through shading and moderating nighttime heat release. These results align with the course principles on vegetation's role in improving thermal comfort and mitigating urban heat island effects.

16. Set A : modified model, Set B : base model

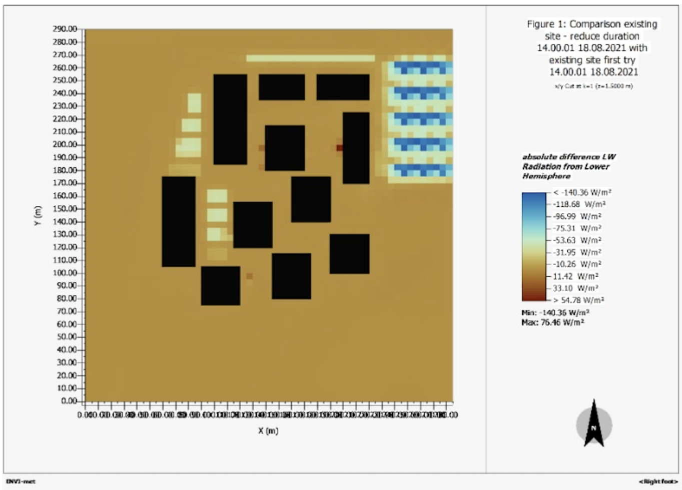


FIGURE 57 – Comparison of the long wave radiation during the day

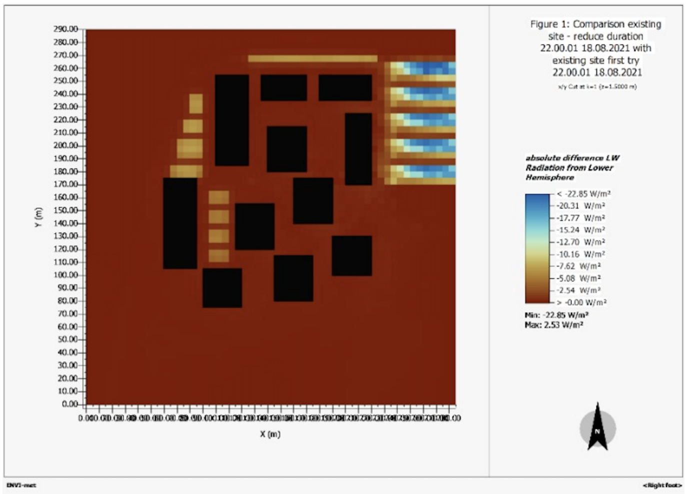


FIGURE 58 – Comparison of the long wave radiation during the night

For the seventh model, we analyzed the impact of adding deciduous trees on parking areas in terms of **shortwave radiation** (SWR) reflected from the lower hemisphere. This comparison focuses solely on the daytime effects.

The addition of trees leads to a significant increase in reflected shortwave radiation in areas directly adjacent to the tree canopies, with a maximum increase of **231.79 W/m²**. This is due to the reflective properties of the tree leaves and the light-colored surfaces beneath them, which scatter more sunlight compared to the darker asphalt of the Base Case. Conversely, areas directly under the tree canopy exhibit lower SWR values, with a maximum reduction of **-31.87 W/m²**, as the trees provide shading and reduce direct solar radiation.

Overall, the results highlight the dual effect of deciduous trees on shortwave radiation : increasing reflection in adjacent areas while reducing direct exposure in shaded zones. These findings align with the course concepts on urban vegetation's role in altering solar radiation distribution and improving thermal comfort in urban settings.

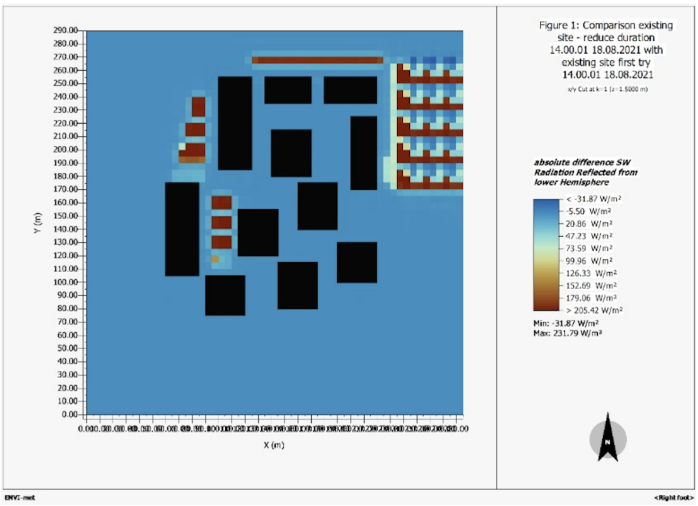


FIGURE 59 – Comparison of the short wave radiation

4 Integrated microclimate solution [17]

Finally, let's combine all the most effective mitigation strategies analyzed previously into a final model. Here is what we decided to do and why :

- We decided to keep the same building layout as in the Innovation Park. The other layout we tried out did not show good results, and it was difficult for technical reasons for us to model other building layouts. However the current layout is not so bad for several reasons.
  A small aspect ratio λ allows ventilation and promotes night time cooling. However it lets sun shine and provides little shelter. A high aspect ratio λ provides shade and provides shelter, but it limits night time heat loss and weakens ventilation. Values of $0.4 < \lambda < 0.6$ offer a compromise for both [2]. In this layout, the shortest buildings have a height H of 13m and the highest ones a height of 22m. The distance between the buildings is very variable, but is somewhat around 25 to 30 m. This keeps the canyon aspect ratio
  $$\lambda = \frac{H}{W}$$
  in between 0.43 and 0.73. The canyon aspect ratio is actually very variable in the Innovation Park because the buildings are placed in a non rectilinear way, but all in all what we can say is that the current layout is a good compromise between shadow and ventilation. By increasing the canyon aspct ratio, we would also take the risk of increasing the UHI.
- We are adding green roofs, as they showed good results in the previous analyze in decreasing the air temperature above the roofs and increasing humidity.
- The parking lot, which was the worst hotpsot, will combine several mitigation strategies :
  we started off by changing the asphalt into loam soil. This material has the advantage of being more porous. It thus can hold more humidity and the latent heat of vaporization helps reduce the surface temperature.
  Covered in grass, the loam soil also has a higher albedo than asphalt. This allows to reflect more of the shortwave radiation that reaches the group and also emits less longwave radiation, helping to reduce the surface and air temperature.
  Finally, some trees are added along the parking spots. They help reduce the sky view factor by providing shade (thus preventing solar radiations to reach the ground where they would be stored) and help cool the ambient air thanks to evapotranspiration.
- In between the buildings, in the areas that are unshaded during the day, some fountains are added. They provide a localized cooling effect thanks to latent heat of vaporization which is enough for the local unshaded areas inside the buildings. These fountains are placed in windy spots to help clear away the stagnant water vapor above the fountain and help boughten their cooling effect a little bit.
- In the smaller parking areas, and in the paths where there is more traffic, the asphalt is replaced by white concrete with a 0.6 albedo. This highly reflective material allows to store very little heat because it reflects most of the incoming shortwave.
- The urban woodland is left untouched as it is showing very good performances already, being a very shaded area and allowing cooling by evapotranspiration.

The image bellow shows a 3D representation of the new Innovation Park we imagined.

17. Set A : modified model, Set B : base model

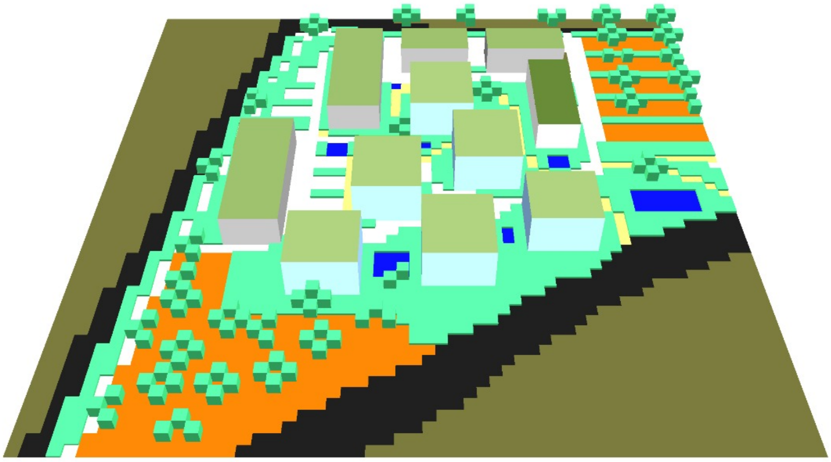


FIGURE 60 – Final Model

We can compare the results of the simulation in more details, to quantify how much the combined mitigation strategies chosen allowed to decrease the temperature and to improve thermal comfort.

Let's start by comparing the surface and air temperature between the final model and the initial one.

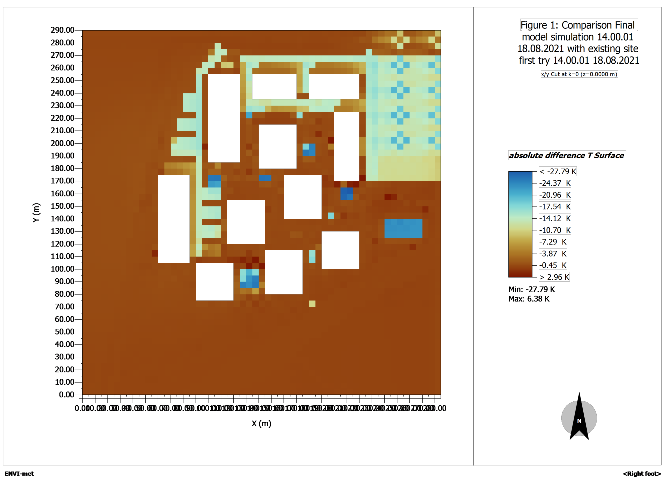


FIGURE 61 – Surface Temperature Comparison - Daytime

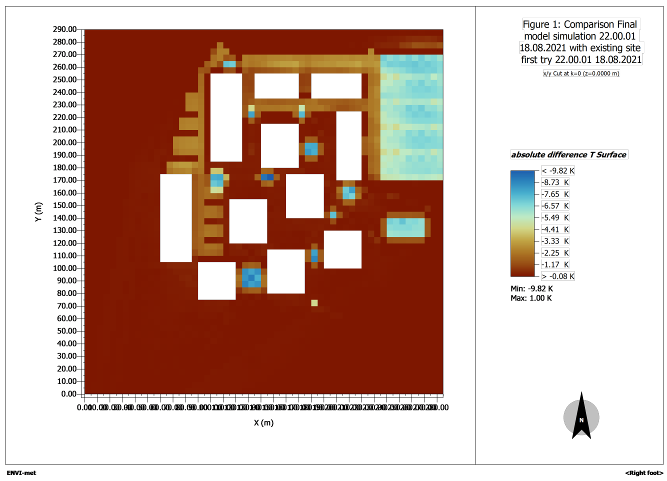


FIGURE 62 – Surface temperature Comparison - Nighttime

At daytime, we can observe a decrease in surface temperature in the small parking spots of around 15°C. The effect of the mitigation strategies is especially impressive in the big parking lot where it is reduced between 10 to 20°C (under the trees). The maximum decrease in temperature is worth 27.8°C, but its only where the fountains are located (naturally water is colder than the ground present in the initial model).
At nighttime, the temperature difference is still visible, meaning we successfully managed to use materials that store less heat during the day and tend to diminish the UHI effect at night. This difference is especially visible in the big parking lot, where the temperature difference at 10p.m. with the original asphalt is around 8°C. [18]

18. An absolute difference of 1 K is equivalent to an absolute difference of 1°C.

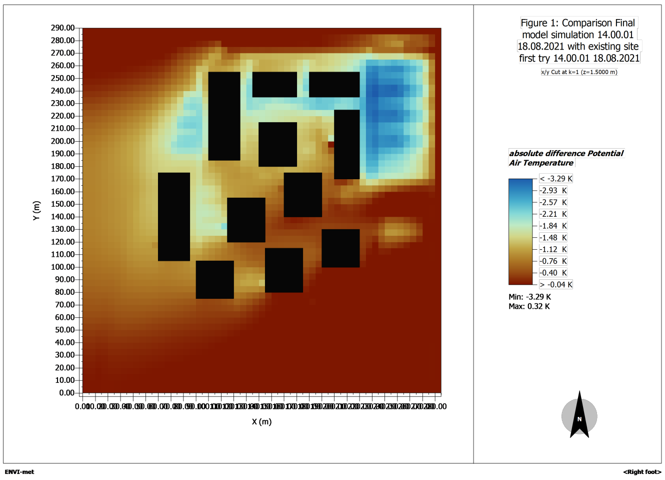


FIGURE 63 – Air Temperature Comparison - Daytime

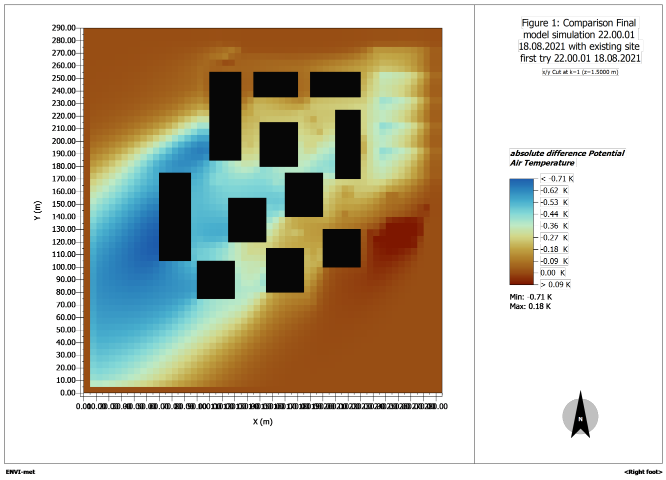


FIGURE 64 – Air Temperature Comparison - Nighttime

A global temperature decrease is again visible at 1.5m above the ground. At the big parking lot, the decrease at daytime reaches 3°C. The fountains also seem to play their (local) role alright as they provide a 1.5°C decrease in air temperature at 2p.m. The same pattern is observable at night for the parking lot, in a lesser degree. In addition we can see what seems to be the effect of the green roofs, manifesting itself by a 0.7°C decrease in temperature in the whole south west section of the Park. This effect is likely due to the green roofs, as we observed it previously in the "vegetation - environment interaction" section of this report. The green roofs help to keep a higher relative humidity, as it can be seen in figure 70.

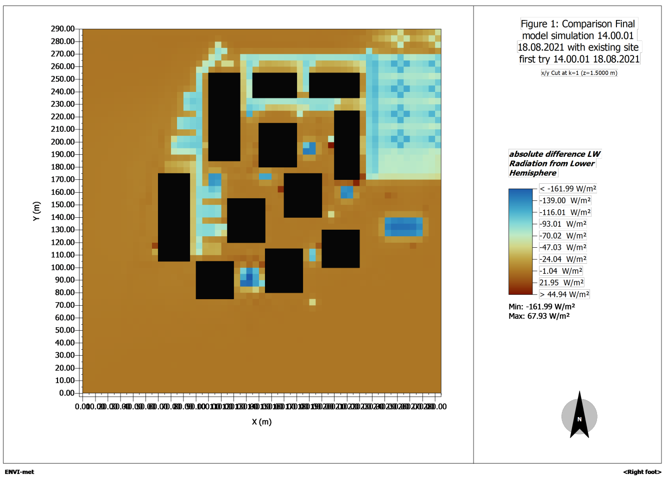


FIGURE 65 – Longwave Radiation comparison - Daytime

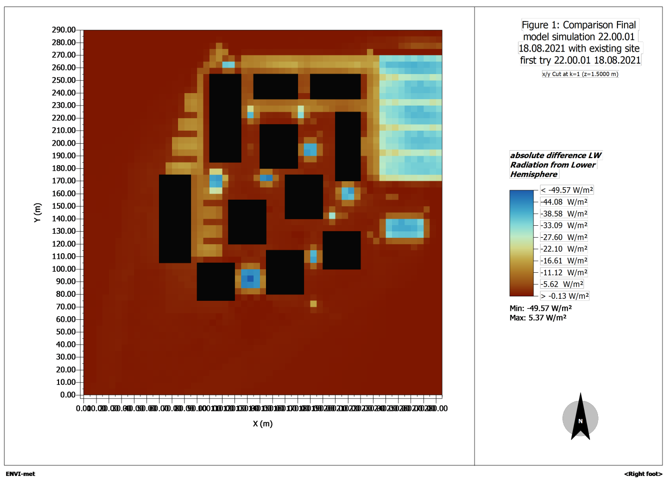


FIGURE 66 – Longwave Radiation Comparison - Nighttime

As expected, the asphalt being replaced by vegetation allowed significant LW emission reduction of around 100 W/m^2 in the big parking lot. The white concrete parking spots also helped reduce the LW emission of a similar amount at daytime. At night otherwise, the vegetated loam soil of the north-east parking lot allows a reduction of the LW emission more than twice more important than the white concrete.
This plays a role in the lower air temperature encountered with the new model and helps reduce the UTCI (see figures 71 and 72).

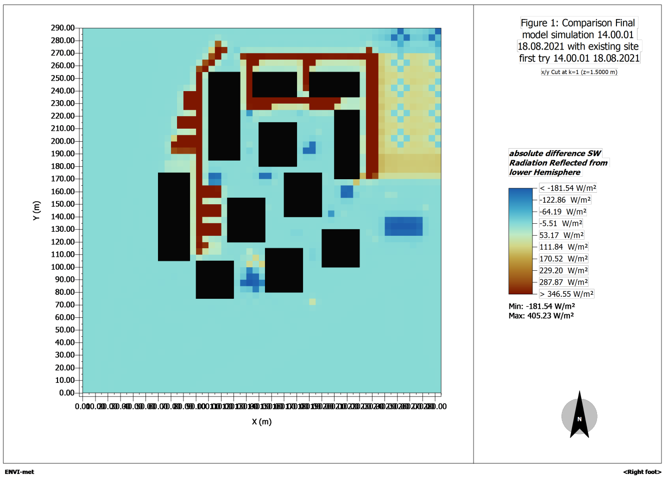


FIGURE 67 – Reflected Shortwave Radiations Comparison

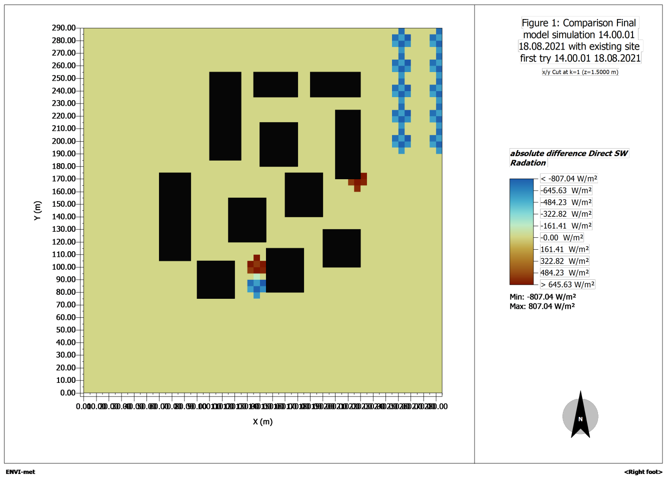


FIGURE 68 – Direct Shortwave Radiations Comparison

Firstly we can see the the small parking spots in white concrete allow as expected to reflect much more SW radiation than asphalt due to its high albedo of 0.6. The white concrete reflects in average 400 W/m^2 more than the asphalt (see the albedo comparison in the appendix figure 79).
Secondly the direct shortwave radiation is decreased in the parking lot where there is a difference of around 700 W/m^2 under the trees. This means the trees play their role of reducing the sky view factor and help the surfaces keep a lower temperature (see the SVF comparison in the appendix figure 80).

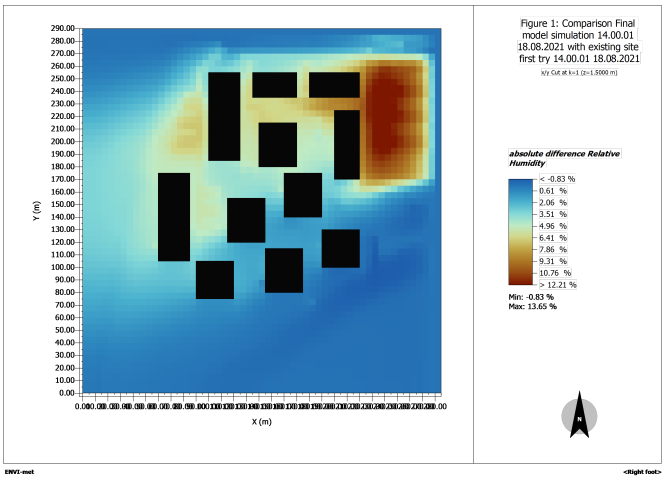


FIGURE 69 – Relative Humidity Comparison - Daytime

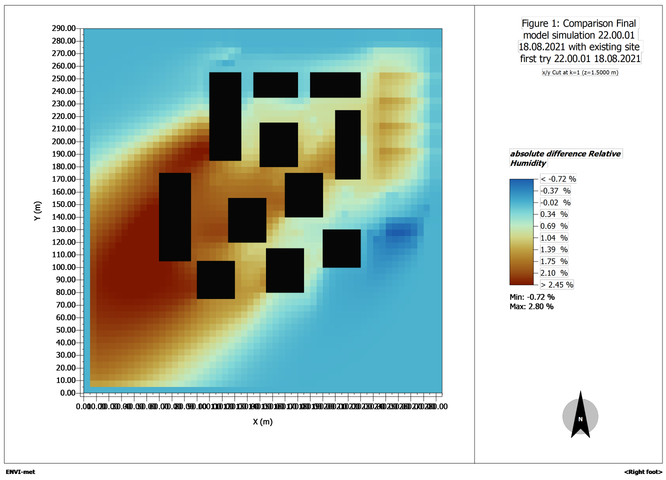


FIGURE 70 – Relative Humidity Comparison - Nighttime

We observe that both during daytime and nighttime the relative humidity is higher in the parking lot, due to adding the more porous loam soil and to the presence of grass and trees. The increase is worth around 13% during daytime and 1.5% during nighttime. At nighttime we also observe an increase of about 2.5% of the relative humidity in the south west part of the Park, due to the green roofs. All this vegetation and humidity allows the cooling of the air observed in figure 63, thanks to vaporization of latent heat and evapotranspiration. There is interestingly no flagrant increase in humidity above the fountains.

The wind direction and speed should be mostly unchanged since the building layout is kept as in the initial model.

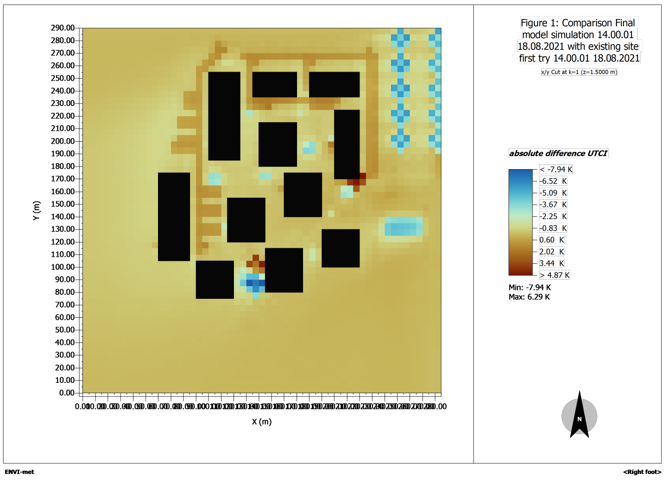


FIGURE 71 – UTCI Comparison - Daytime

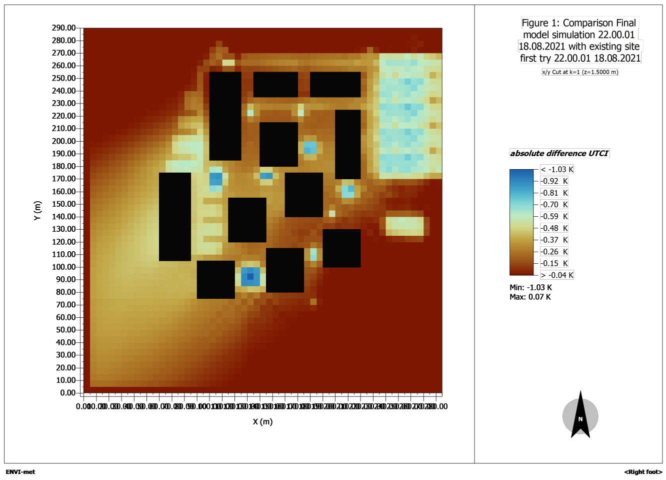


FIGURE 72 – UTCI Comparison - Nighttime

Finally, the UTCI has globally decreased, which is a good thing and means that the mitigation strategies chosen have worked properly. In what used to be the worst hotspot of the innovation park, I name the parking lot, the UTCI has decreased by 2°C in the unshaded areas and up to almost 8°C under the trees. In the small parking spots it has decreased less (around -0.8°C). A local important decrease in UTCI is also effective at the fountains location.
The same pattern can be seen at night, in a lesser way, where the building's surrounding and the parking lots are now more comfortable to human. We can see that at night the small parking spots made of white concrete show better performances, comparable to the big parking lot. This is simply due to the fact that the white concrete rejected most of the upcoming shortwave during the day and is thus not releasing its heat into the atmosphere at night the way asphalt does.

All in all, we managed to drastically reduce temperatures and UTCI in the hotspots of the innovation park (parking lots), by combining positive effects of vegetation on humidity and shade with localized water spots and material changes. These combined mitigation strategies helped to reduce the UHI effect.

5 Conclusion

Through this project, we investigated the thermodynamic interactions within the EPFL Innovation Park, using simulations on ENVI-MET to evaluate current conditions and propose mitigation strategies. The eleven models we created ans analyzed helped us show the significant role that urban elements like building layout, materials, vegetation, and water bodies play in the microclimate.

We identified key hotspots, particularly the parking areas, which suffered from high thermal retention and low humidity. By combining strategies, such as introducing green roofs, replacing asphalt with loam soil, incorporating vegetation, and adding fountains, we successfully managed to reduce the UHI effect and improve thermal comfort. These strategies were based on different albedo materials, evapotranspiration, and shading to limit the absorption of shortwaves.

Références

[1] Kun LYU Dolaana KHOVALYG. Civil -309 “urban thermodynamics” course project, 2024.

[2] Dolaana KHOVALYG. Civil -309 “urban thermodynamics”, 2024.

6 Appendix

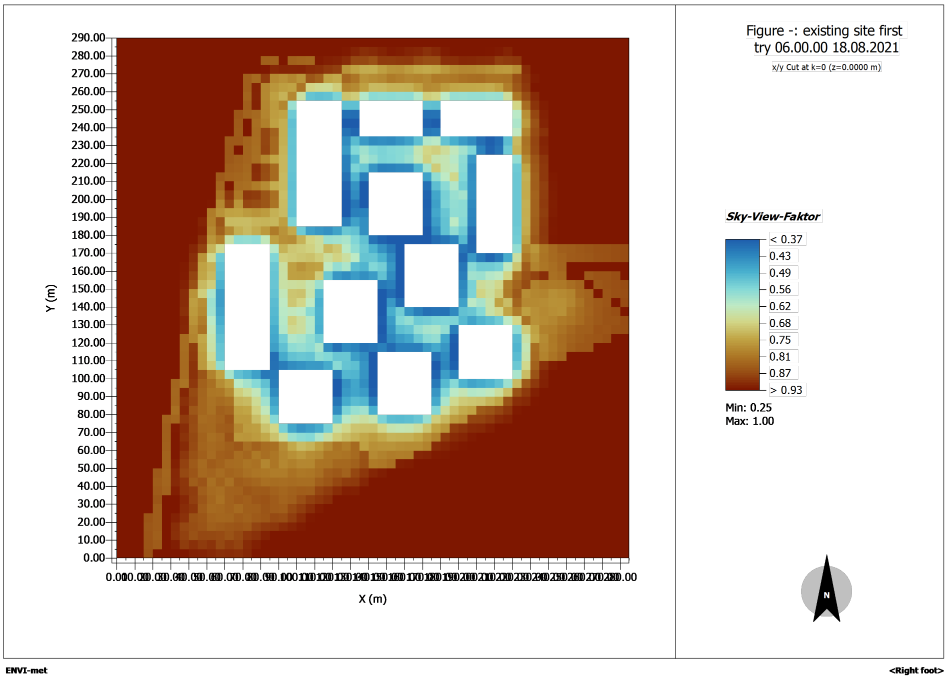


FIGURE 73 – base case - Sky View Factor

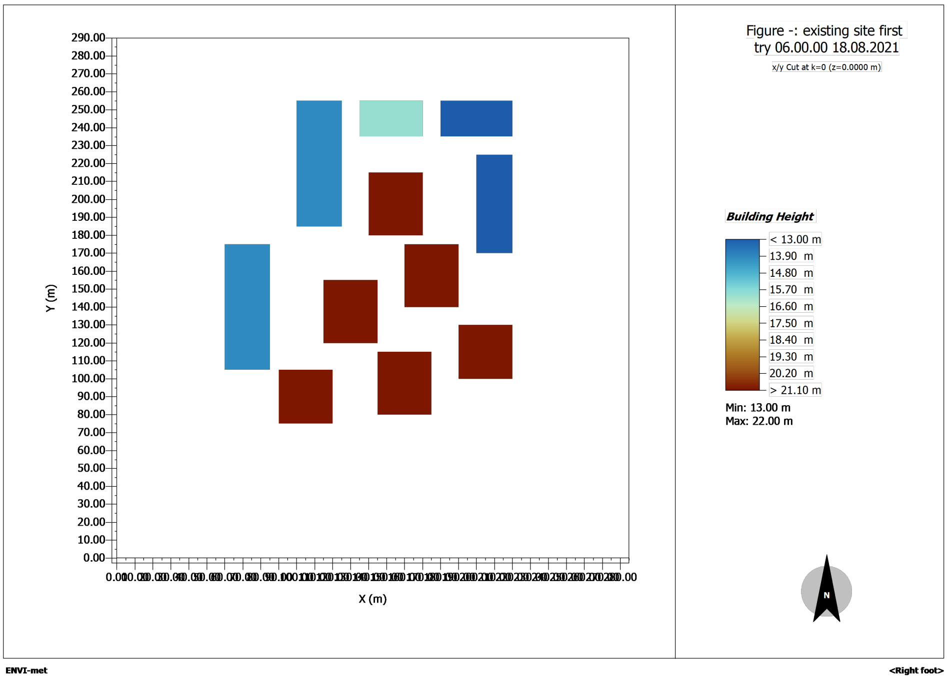


FIGURE 74 – Building's heights

TABLE 1 – Material Properties (Part 1)

Property	Prefabricated Concrete	Insulation	Plaster	Plywood
Absorption (-)	0.7	0.5	0.6	0.6
Reflection (-)	0.3	0.5	0.4	0.4
Emissivity (-)	0.9	0.9	0.93	0.82
Specific Heat (J/kg·K)	850	1500	850	170
Thermal Conductivity (W/m·K)	1.6	0.07	0.6	0.3
Density (kg/m^3)	2220	400	1500	700

TABLE 2 – Material Properties (Part 2)

Property	Mineral Wool	Aluminium	Fiber Cement	Polystyrene
Absorption (-)	0.5	0.2	0.7	0.5
Reflection (-)	0.5	0.8	0.3	0.5
Emissivity (-)	0.9	0.1	0.94	0.68
Specific Heat (J/kg·K)	1500	880	840	1315
Thermal Conductivity (W/m·K)	0.07	203	0.86	0.03
Density (kg/m^3)	400	2700	930	50

TABLE 3 – Material Properties (Part 3)

Property	Reinforced Concrete	Concrete + XPS	Gravel
Absorption (-)	0.5	0.6	0.5
Reflection (-)	0.5	0.4	0.5
Emissivity (-)	0.9	0.812	0.28
Specific Heat (J/kg·K)	1000	1126	500
Thermal Conductivity (W/m·K)	2.3	1.392	1
Density (kg/m^3)	2520	1532	1700

FIGURE 75 – Default Male for UTCI

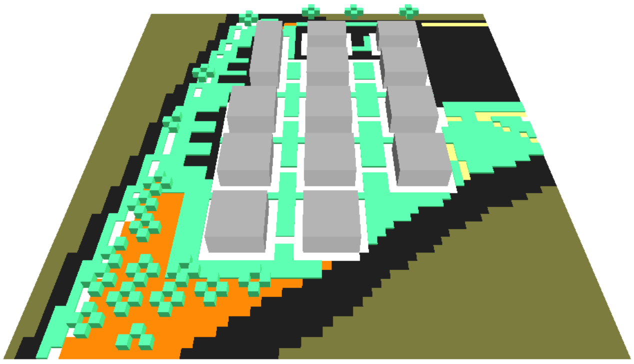


FIGURE 76 – Model 8 - Rectilinear building layout

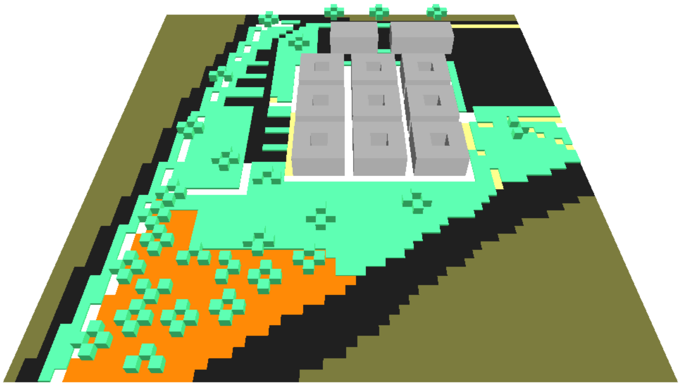


FIGURE 77 – Model 9 - Close buildings with inner courtyard

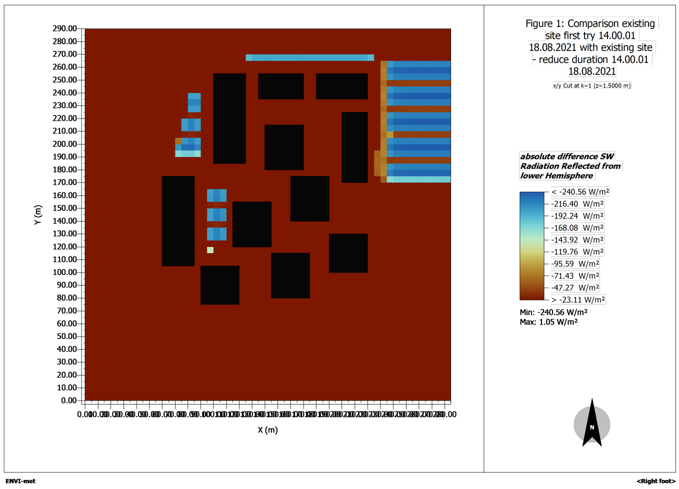


FIGURE 78 – Comparison of reflected SW radiation during the day between the base model and the modified model

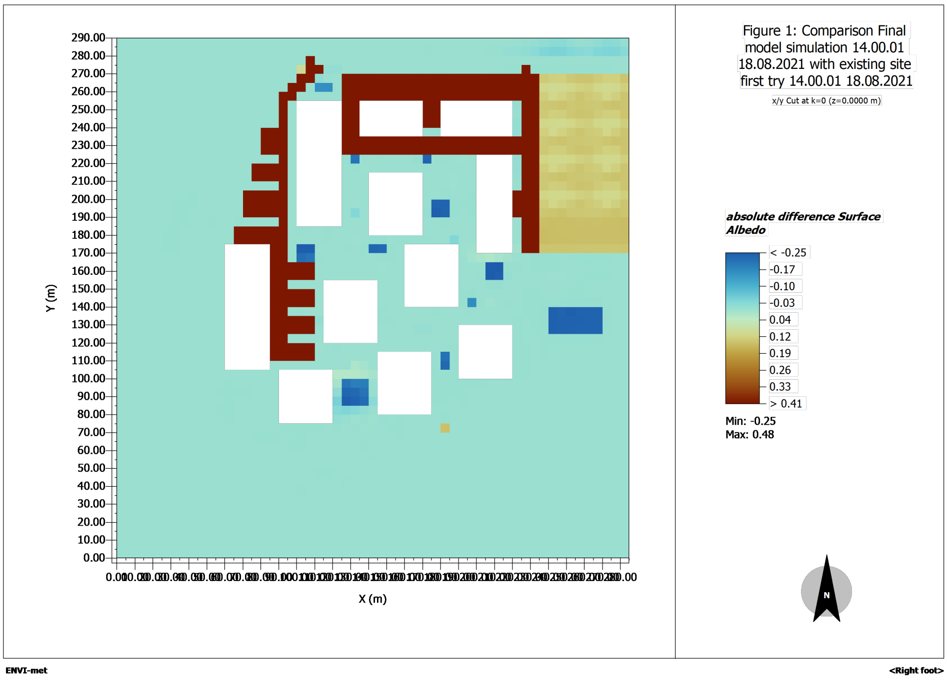


Figure 79 – Albedo comparison between final and base model

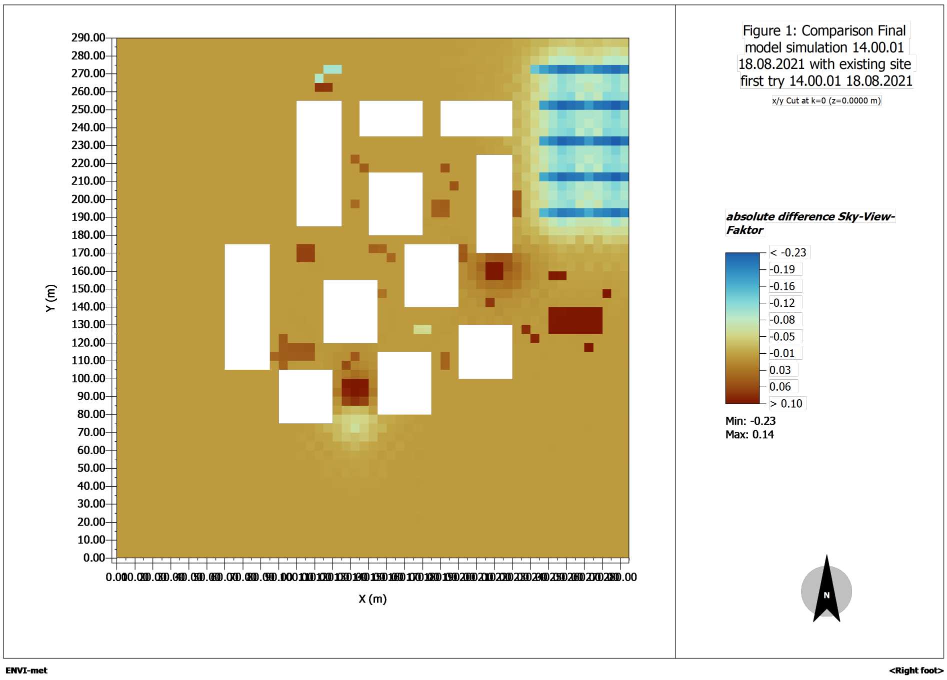


Figure 80 – Sky View Factor comparison between final and base model