URBAN THERMAL COMFORT STUDY

Kiruna square (68°N 22°E)

WRL (0500478500) - DIGITAL DESIGN AND BIM

2017-06-20
Alejandro Pacheco Diéguez
Christoph Duckart
Silvia Coccolo (EPFL)

Revised: 2017-06-21
Sarah Dahman

Marie-Claude Dubois

The particular aim in this project is to inform urban designers and landscape architects on the best material choices and distribution of trees to attain the best possible outdoor thermal comfort in a very cold climate like this one.

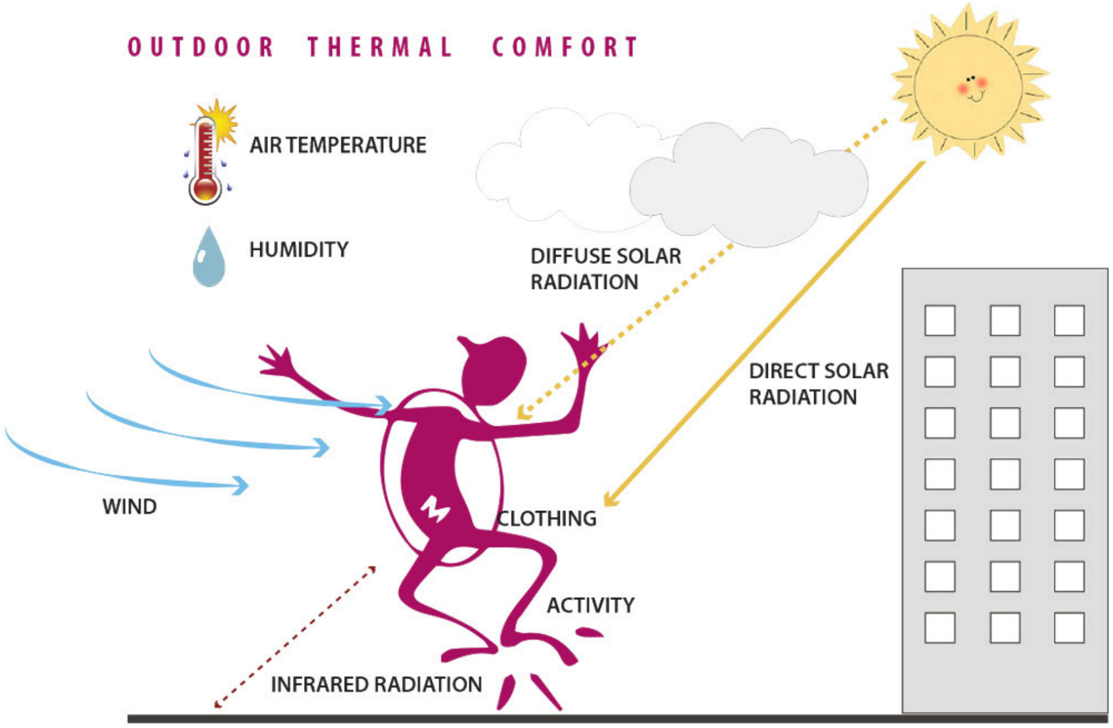


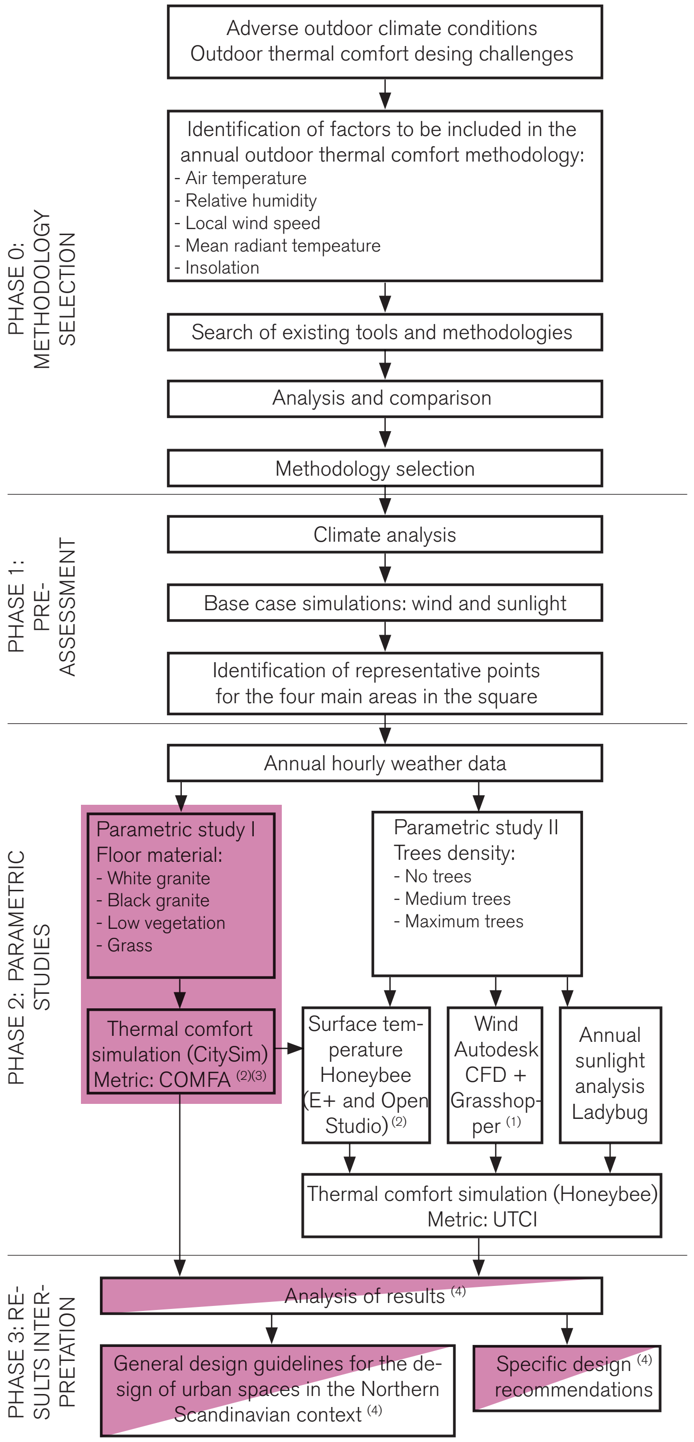
Figure 1: parameters involved in thermal comfort.

ABSTRACT

A new central square is being design in the city of Kiruna (Northern Sweden). Particular emphasis has been placed on creating a comfortable microclimate that mitigates the extreme cold climate. This document presents a methodology developed to evaluate the effect of floor surface material and tree density on the outdoor thermal comfort of the square.

The evaluation of thermal comfort is complex as it involves many parameters: air temperature, radiant temperature from surrounding objects, relative humidity, wind speed, clothing level and activity level (figure 1). Material choice can impact the thermal sensation in areas with a high direct sunlight exposure. The amount of solar radiation (heat) that is reflected by the material is higher with lighter materials. The results show that material choice has an impact for points with a high direct sunlight exposure, especially during the warmer seasons. The results show that 40 more minutes of thermal comfort on average per day during summer are attained using a light granite compared to a dark granite.

Trees reduce both the direct sunlight access and the wind exposure. These two factors have been found to have a significant impact in pedestrian thermal sensation. In this study the average differences per season are of up to 2.5° in winter, 4.5° in spring, 3.5° in summer and 2° in autumn. These values represent “apparent temperature”, wich is the “felt” temperature taking in consideration factors such as air velocity, relative humidity or the radiant temperature of surrounding objects. It is measured according to the Universal Thermal Climate Index (UTCI).



Identify project challenges and define strategy

Find the relevant pre-conditions and tools

Study the base case with site specific conditions

Explore scenarios relevant to the project

Feed your design

Figure 2: flow diagram of the outdoor thermal comfort study.

(1) Methodology under development.
(2) Both these tools calculate Mean Radiant Temperature. Comparison study recommended for validation.
(3) This part of the study was delevoped by Silvia Coccolo (EPFL).
(4) This part of the study was delevoped in collaboration with Silvia Coccolo (EPFL).

BACKGROUND

According to ASHRAE thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. Good outdoor thermal comfort encourage people to spend time outdoors in urban environments, which is beneficial for both physical and social well-being and the local economy. Walking and cycling are healthier than commuting and meeting friends and neighbors foster social cohesion. Lynch (1984) discusses the climate of cities in relation to “vitality”, “the form of the settlement supports vital functions, the biological requirements and capabilities for human beings”.

A wholistic methodology to evaluate outdoor thermal comfort is needed to inform urban planners and urban designers on the best way to make the best design choices. Most research in this field focuses on the urban scale through physical analysis of the urban fabric or specific studies that focus only on one parameters, such as wind and shading studies. The impact of urban design on outdoor thermal comfort hasn’t been completely understood yet, due to the lack of wholistic tools. There is a lack of human perspective focused on the microclimate of outdoor spaces. Outdoor thermal comfort can be assessed by using indicators such as COMFA budget, UTCI (Universal Thermal Climate Index), PET (Physiological Equivalent Temperature) or another similar metric. These indicators take in consideration different parameters involved in outdoor thermal comforwt such as air temperature, Mean Radiant Temperature (MRT), relative humidity, air velocity, clothing leve or methabolic rate (activity level).

The city of Kiruna, in the North of Sweden, lives mainly from its underground iron mine, the largest in the world. The mine is progresively growing underneath the city itself. This has forced the government to progressively relocate the city two kilometers East of its original location. The master plan of the new city, developed by White arkitekter, puts especial enphasis on crating comfortable and pleasant urban spaces. Kiruna, located in a subarctic climate, certainly would benefit from having outdoor spaces designed to attain the best possible outdoor thermal comfort, given its extreme climate. Some wind and solar access studies have already been developed for this project to inform the urban planning in terms of outdoor thermal comfort. At the current point of the project development an more detailed study is required to optimise the outdoor environment.

PURPOSE

This research project aims at taking the outdoor thermal comfort studies one step further from specific studies, such as shading or wind studies, to a more holistic approach that considerers all parameters involved at once and evaluates annual predicted thermal comfort as a whole. The resulting methodology ultimately should serve inform urban plannning and urban design projects in terms of outdoor thermal comfort, annually or by month/season.

The methodology must take in consideration all the different parameters involved in outdoor thermal comfort: Mean Radiant Temperature of surrounding surfaces; typical hourly data on air temperature, cloud coverage, relative humidity and wind speed and direction; local wind shelter and local shading. It should use a suitable metric to evaluate outdoor thermal comfort, in contrast with indoor thermal comfort. In this case two different outdoor thermal comfort metrics were used: the COMFA model and the UTCI (Universal Thermal Climate Index).

Different methodologies were evaluated (see Appendix I). Two of them were selected to carry out each of the two parametric studies. One of them uses a combination of tools (Autodesk CFD, Grasshopper, Ladybug/Honeybee) and the other one was tested in collaboration with the École Polytechnique Fédérale de Lausanne (EPFL). The methodology chosen should be applicable to other urban planning or urban design projects. The latter consists on a beta version of a new microclimate module created by the researcher Silvia Coccolo for the program CitySim. The simulations were performed by Sivia C. herself. The selected methodologies will be used to inform the urban designers of the central square of the new city of Kiruna, in Northern Sweden. This space consists in a 9500-square-meter public space located around the new city hall. The particular aim in this project is to inform urban designers on the best material choices and distribution of trees to attain the best possible outdoor thermal comfort in a very cold climate like this one.

The results should be laid out and summarized in a comprehensible way. Urban planners and urban designers uninitiated in the subject of thermal comfort should be able to easily extract conclusions on the repercusion of different design choices.

Another purpose of this study is to create a collaboration frame with other R&D partners, in this case the EPFL.

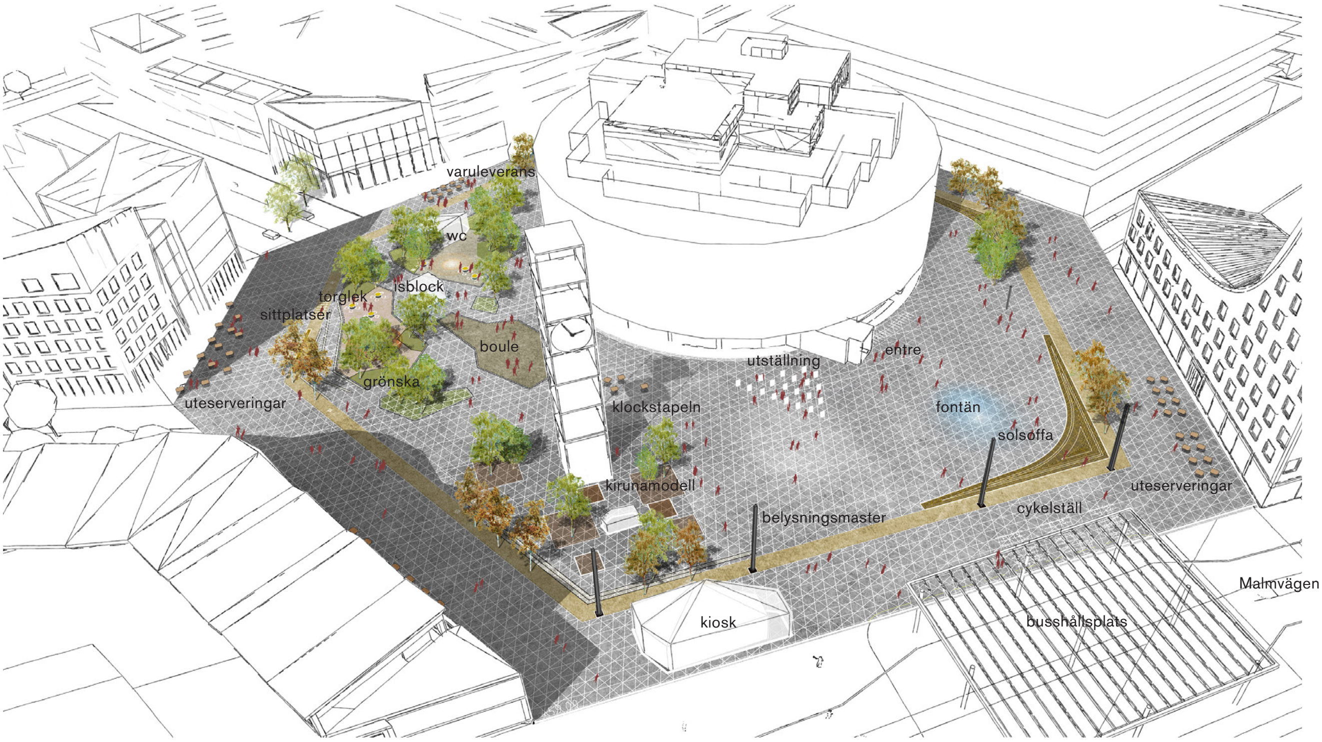


Figure 3: *bird-eye perspective of the square.*

METHOD

A methodology was developed to evaluate the impact of different urban design choices in the annual outdoor thermal comfort in the future central square of the new city of Kiruna. The weather data used corresponds to a climate file produced by ASHRAE using the readings from 1982-1993. Figure 2 shows the flow diagram that summarizes the strategy followed in this study.

A previous study (Phase 0) was done to evaluate the best software to use. This previous study is explained in Appendix I. In this case, given the lack of one single tool that could respond to all the requirements in the different steps, different software were selected and combined for each step.

The methodology is comprised of three phases:
- Phase 1: pre-assessment.
- Phase 2: parametric studies
- Phase 3: results interpretation.

Phase I: Preassessment

Phase I consists on a general analysis of the local climate and the identification of representative points in terms of wind and sun exposure for each of the four main areas of the square.

The physical delimitation of the four focus areas (see Figure 4) and its specific functions and requirements are explained in the following:
- Area 1: small area on the North side of the city hall (round building).
- Area 2: small area on the East side of the city hall.
- Area 3: area on the West side of the city hall and North of the clock tower.
- Aarea 4: large area on the South side of the city hall and the clock tower.

Two simulations (annual wind exposure and annual sunlight hours) were performed in this phase. The results were used to select the representative points at each area by visually selecting points with approximately the average annual sunlight hours and wind exposure for each given focus area. The methodology used in the wind exposure and the sunlight hours simulaitons is detailed further down in this sec-

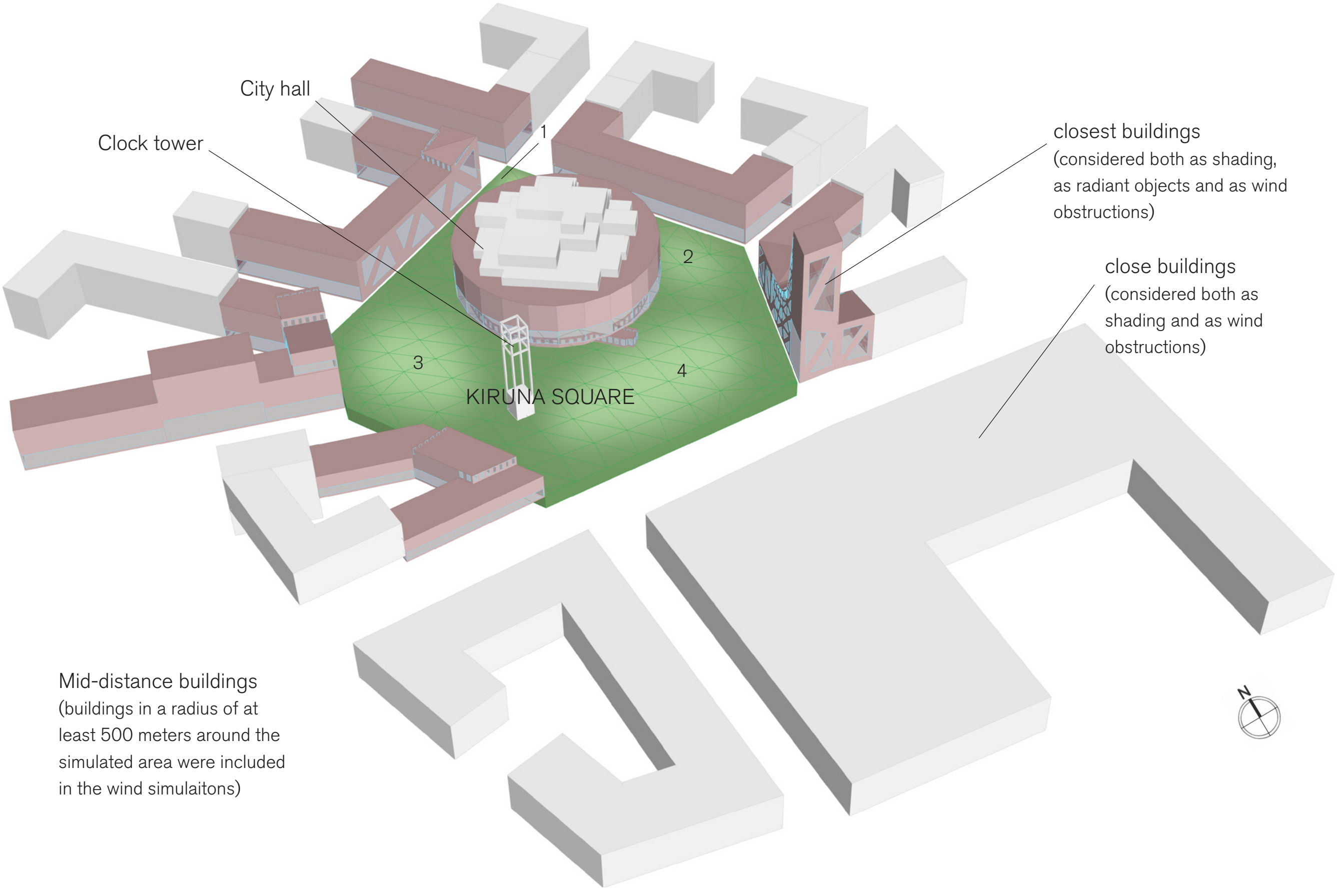


Figure 4: view of the model used in the simulations. Four focus areas are highlighted and numbered.

tion.

Phase II.a: Floor surface material parametric study

A parametric study was carried out to investigate the effect of different floor surface materials (Figure 6) in the square on the thermal comfort. This part of the study was developed by Silvia Coccolo as part of her PhD thesis developing a microclimate module for the program CitySim at the École Polytechnique Fédérale de Lausanne (Switzerland). The following text explaining the methodology is extracted from a repport written by her:

“Based on the informations received from White Architects, the snow is assumed covering the site from the15th of October to the 15th of Mai; as visible in Figure 5, summarizing the snow depth during 2005, the snow events are stronger during the month of December, when the snow depht arrives up to 66 mm hourly.

The model in CitySim is defined by the geometrical informations received by White Architects, as well as the physical informations concerning the outdoor environmental surfaces. The 3D model was realized with CitySim (...): just the buildings facing the square are considered in the analysis, because the others, due to their distance from the points of measurements, do not impact the outdoor thermal comfort.

The neighbor’s buildings present two types of envelope: wood and concrete covering; their glazing ratio ranges between 35 to complete glazing, (...). The physical characteristics of the buildings are summarized in Table 1, as well as the physical characteristics of the ground covering. In order to understand the impact of the ground covering on the pedestrian thermal sensation, five case studies are proposed (as required by White Architect):
- Case study A: white granite
- Case study B: black granite
- Case study C: vegetation, plants of 60 cm height
- Case study D: grass covering
The vegetation is designed as groups of small tree (60 cm high, total are of 2m) placed upon the natural soil (without covering) and each 5 meters each one. Pedestrian are located on the square, upon a grid of 5 m each side; the distance is defined in order to create homogeneous point of measurements, and reduce the mutual shadowing between pedestrians. Totally, 227 points of measurements were defined, (...) the points are divided into 23 rows and up to 17 columns. The thermal budget of a person is defined by the COMFA Budget (COMfort FormulA) in a seven point scale, as expressed in Table 2. The pedestrians located in the outdoor environment are performing light metabolic activities, like standing/relaxed.”

Note that the snow cover was not considered in this study, although it is present during a large part of the year.

Table 1: Thermal properties of the materials of the scene.

Location	Material	Density ($kg \cdot m^{-3}$)	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
Buildings	Concrete	2,400	849	2,1
	Wood	700	1,600	0,18
Square (A)	White granite	2,600	1,000	2,8
Square (B)	Black granite	2,600	1,000	2,8
Square (C)	Vegetation (>50 cm)	1,600	890	0,25
Square (D)	Grass	1,600	890	0,25

Table 2: Thermal sensation as function of the COMFA Budget.

Thermal sensation	COMFA Budget ($W\ m^{-2}$)
Cold	≤ −201
Cool	−200 to − 121
Slightly cool	− 120 to − 51
Neutral	−50 to + 50
Slightly warm	+51 to + 120
Warm	+121 to + 200
Hot	≥ 201

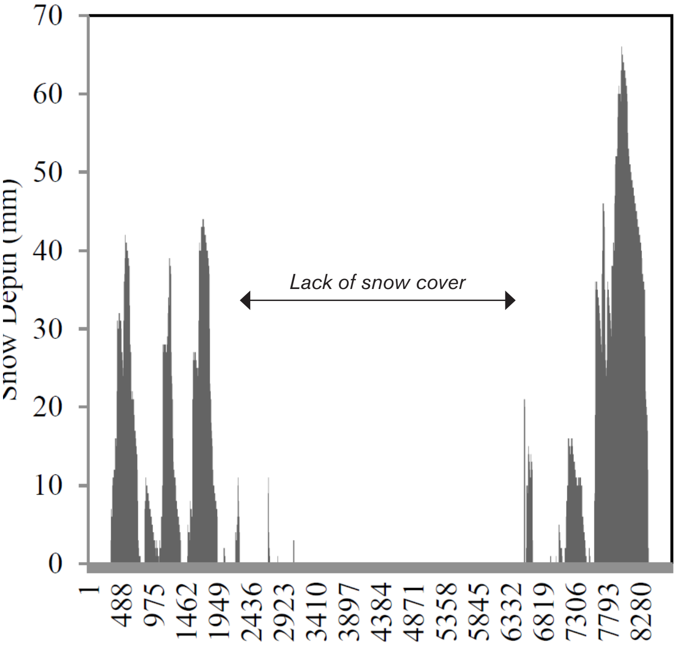


Figure 5: Snow depth, expressed in mm, defined hourly for the city of Kiruna.

Figure 6: assessed floor surface materials

Phase III: Results interpretation

The results of the parametric studies provide detailed information on the effects of material choice and tree density on thermal sensation of pedestrians all year round. This information used to extract general conclusions on the design of outdoor spaces in the Northern Scandinavian context as well as specific design recommendations for the central square of the new city of Kiruna. The data was sorted in four groups (winter, January to March; spring, April to June; summer, July to September and autumn, October to December) to facilitate the interpretation of the repercussions of design choices at each season separately.

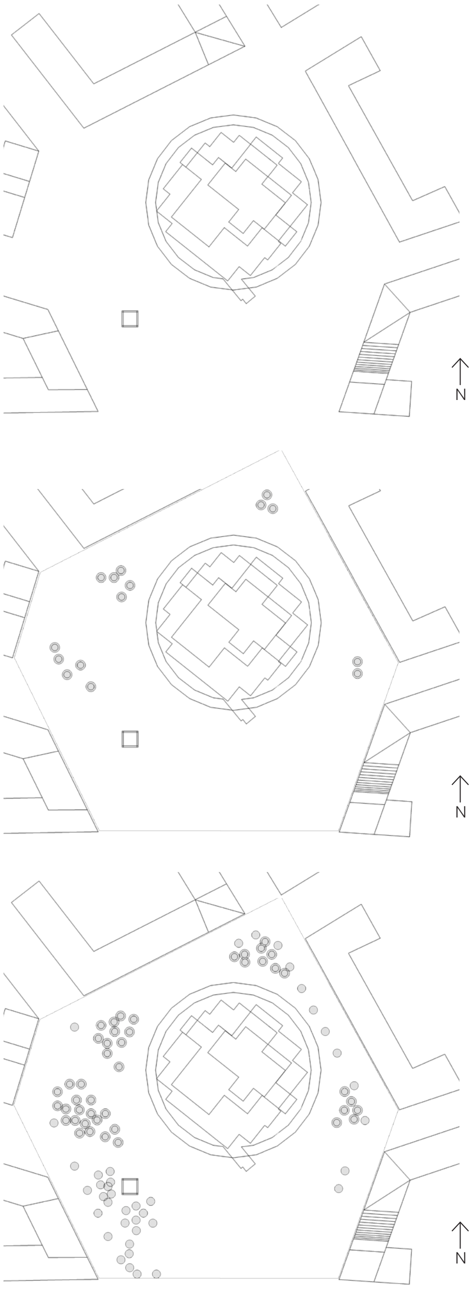


Figure 7: scenarios studied in the tree density parametric study. T1 (no trees, above), T2 (medium trees, middle) and T3 (maximum trees, below)

RESULTS

Phase I: Preassessment

In this phase the general climate of Kiruna was analyzed as well as the particular conditions of the square in terms of sunlight access and wind shelter.

Figure 9 shows the annual distribution of air temperature ranging from -29°C to +23°C. Table 4 shows the temperature distribution in percentages. The average annual temperature is +1°C and 65% of the time the temperature lays between -10°C and +10°C.

Figure 8 shows the wind speeds and directions for the different seasons. It can be seen as South and Southwest are clearly dominant wind directions during the cold seasons (winter and autumn) white as in summer and spring the distribution of wind directions is more homogeneous with a slight predominance of southerly and northerly winds. High windspeeds are concentrated in autumn and to lesser degree in winter and spring. Table 4 shows the distribution of wind speeds in percentages. It shows how more than 80% of the time the wind speed is lower than 6 m/s. The average wind speed in Kiruna is 3,8 m/s, which is a midrange value if we compare it with other Swedish cities such as Stockholm (3,3 m/s), Gothembourg (4,1 m/s) or Malmo (6,1 m/s).

Figures 10 and 11 show the annual number of direct sulight hours (considering only clear skies) and the average wind speed thoughout the square correspondingly. A representative point in terms of sunlight hours and average wind speed was selected for each of the four areas in the square: area 1,175 h and 0,4 m/s; area 2, 470 h and 1 m/s; area 3, 545 h and 0,9 m/s and area 4 775 h and 0,5 m/s. All areas present a low average wind speed, which means that the square is well sheltered by surrounding buildings. However, Areas 2 and 3 have a slightly higher average wind speed than areas 1 and 4. Area 1 is very shaded, while as area 4 is very exposed to direct sunlight. Areas 2 and 3 have a medium number of sunlight hours.

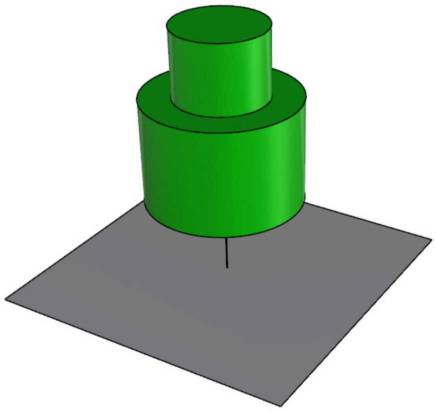


Figure 7: image of one of the trees used in the simulations, simplified as two cilinders. Deciduous trees: Summer permeability, flow-through constant = 150; Winter permeability, flow-through constant = 40. Source: Gromke, C., Buccolieri, R., Di Sabatino, S. and Ruck, B., 2008.

Table 4: Distribution of air temperatures and wind speeds in Kiruna.

	Percentance of time				
Air temp.	Total	Winter	Spring	Summer	Autumn
<-20°	4%	10.2%	0.0%	0.0%	5.2%
-20° to -10°	16%	41.6%	1.2%	0.0%	22.6%
-10° to 0°	31%	47.1%	25.2%	5.0%	47.7%
0° to 10°	34%	1.1%	55.8%	56.7%	24.5%
10° to 20°	13%	0.0%	16.8%	37.1%	0.0%
>20°	1%	0.0%	1.0%	1.2%	0.0%

	Percentance of time				
Wind speed	Total	Winter	Spring	Summer	Autumn
0 to 2 ms^{-1}	25%	22.5%	21.1%	28.8%	14.6%
2 to 4 ms^{-1}	34%	32.1%	36.3%	33.6%	31.9%
4 to 6 ms^{-1}	23%	24.7%	23.8%	20.2%	26.4%
6 to 8 ms^{-1}	11%	7.4%	10.0%	12.1%	14.3%
8 to 10 ms^{-1}	5%	3.7%	4.7%	3.0%	6.5%
>10 ms^{-1}	2%	0.7%	1.8%	0.3%	3.7%

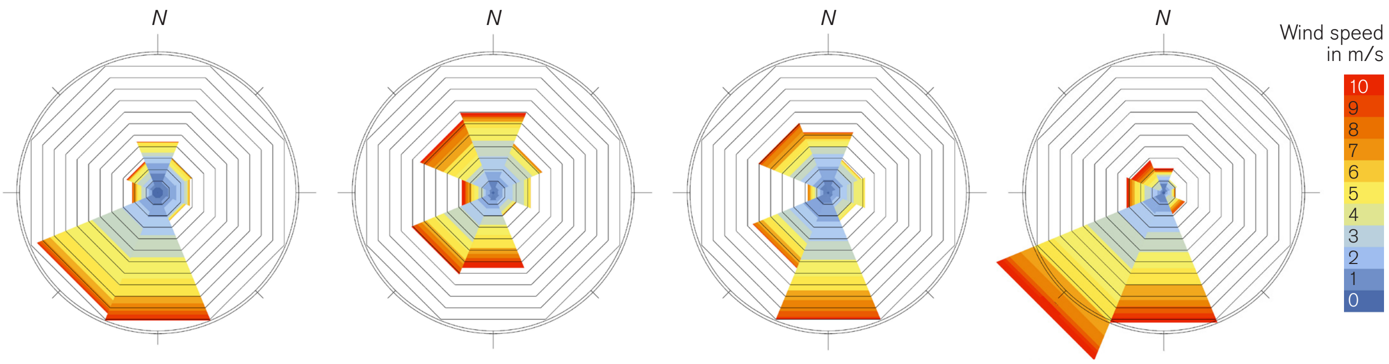


Figure 8: Wind direction and speed, Kiruna airport (Source: Energy + database). From left to right: winter (Jan-Mar), spring (Apr-Jun), summer (Jul-Sep) and autumn (Oct-Dec). Source: IWEC E+ weather file https://energyplus.net/weather-location/europe_wmo_region_6/SWE//SWE_Kiruna.020440_IWEC

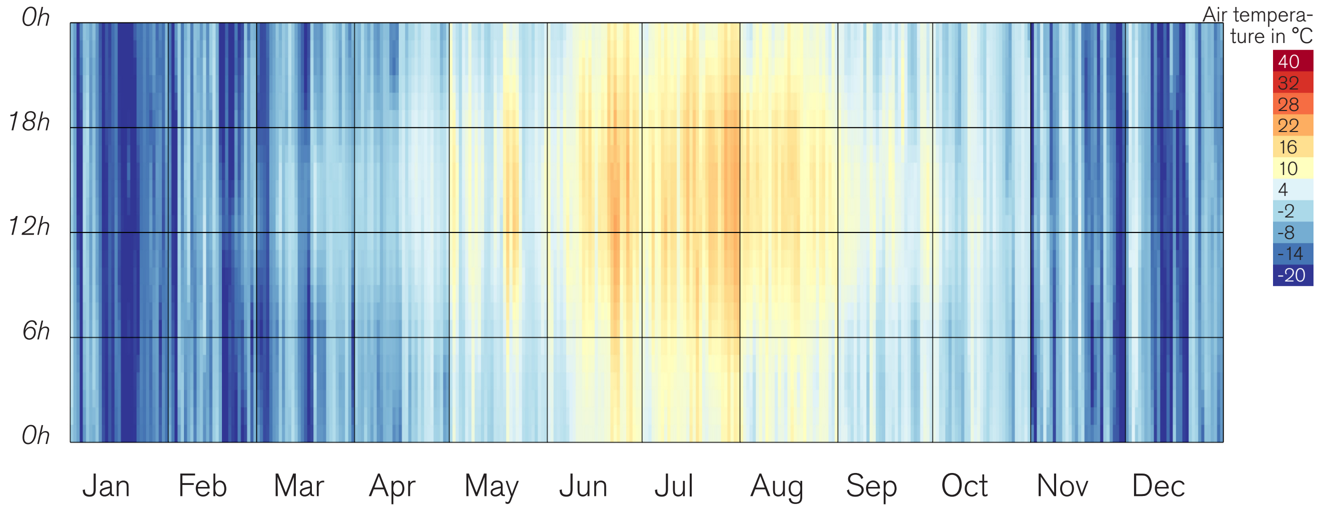


Figure 9: Air temperature, Kiruna airport (Source: E+ database).

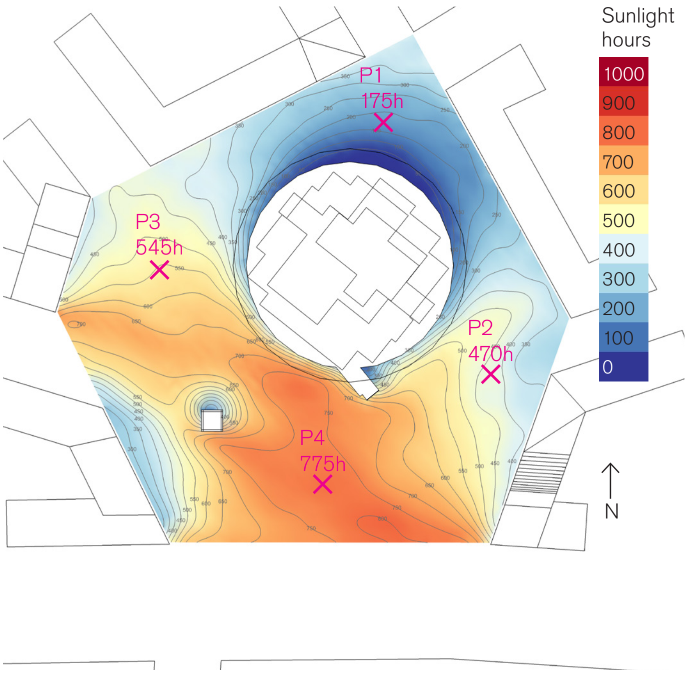


Figure 10: annual hours of direct sunlight using only clear sky for T1(no trees).

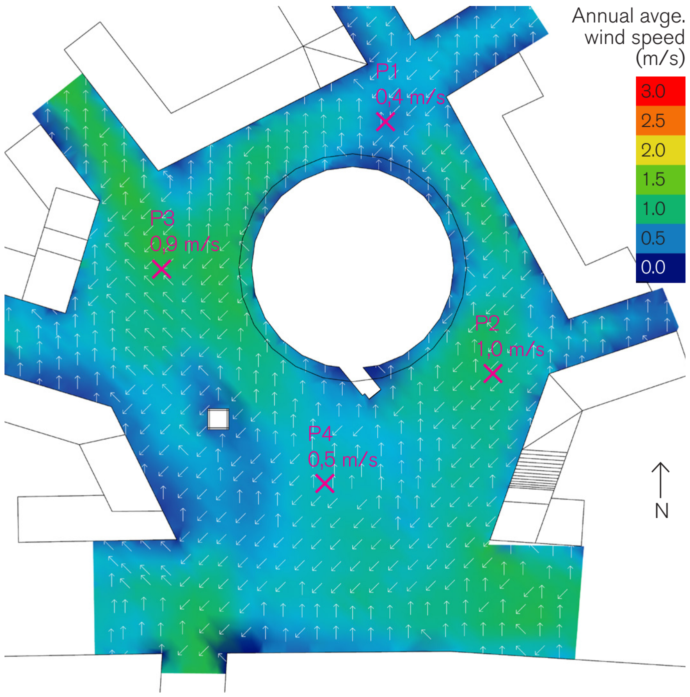


Figure 11: annual average wind speed for T1 (no trees).

Phase II.a: Floor material parametric study

This parametric study, performed by Silvia Coccolo at EPFL (Switzerland), compares the effect of four different floor materials. The effect of materials was found to be directly related to the amount of sunlight hours received. For that reason only the results for points 1 and 4, the two extreme cases in terms of direct sunlight, are shown in this report.

The following text interpreting the results has been extracted from the report written by Silvia Coccolo:

"The surface temperature of the square is directly related to the color of the granite: by varying it from black (albedo equals to 0.05) to white (albedo equals to 0.75), the surface temperature varies drastically. (..) the surface temperature of the ground during the year, according to the three case studies: the average temperature for the white granite corresponds to -0,94°C (...) and 3,97°C the black one. By analyzing the hourly surface temperature during the year, is evident that the black granite could reach up to 80°C during a sunny summer day; the same day the white on would reach just 36°C. Is evident that all the heat received by the black granite is absorbed by the material, on the contrary on the white one, it is reflected to the environment, in this case to the pedestrian. By the way, due to the meteorological characteristics of the site, and the fact that the main part of the summer radiation is diffuse, not direct, the radiation emitted by the ground covering is not affecting the visual perception of pedestrian, which will not probably face glare events. On the contrary, during the winter time, when the sun is mostly absent and the outdoor environment is really cold, the surface temperature of all materials is similar, and under the 0°C; additionally, as clarified by White Architects, the snow covers the square from 15th October to 15th of Mai, consequently the impact of the different covering is low."

Figures 12 and 13 show the differences in thermal sensasion of the different floor surface materials by season for points 1 and 4 correspondingly. It can be seen how in point 1, the one with only 175 hours of direct sunlight per year, the choice of floor surface material does not have a signicant effect in none of the seasons. On the other hand, point 4, with 775 hours of direct sunlight, does show a significantly colder sensation in all seasons for black granite compared to the rest of materials investigated. This results in an average increase of cold sensation (including also cool and slightly cool) of of 1-3 per day. Grass presents slightly better results for summer and spring compared to the other materials at point 4. Similar results can be observed in Table 5, which shows the average COMFA budget.

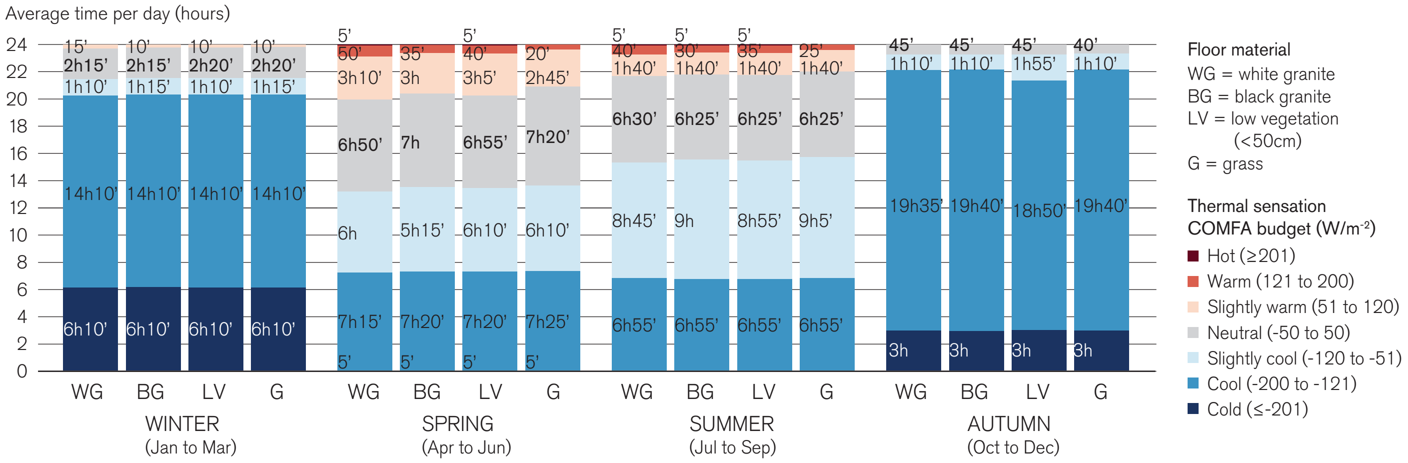


Figure 12: *Thermal sensation in point 1 (mostly shaded, low exposure to direct sunlight).*

Black granite produces a colder sensation for all the seasons in points with a high direct sunlight exposure because it absorbs the heat instead of reflecting it. However, in a larger scale darker materials would contribute to increasing the heat island effect, which in this case would be beneficial.

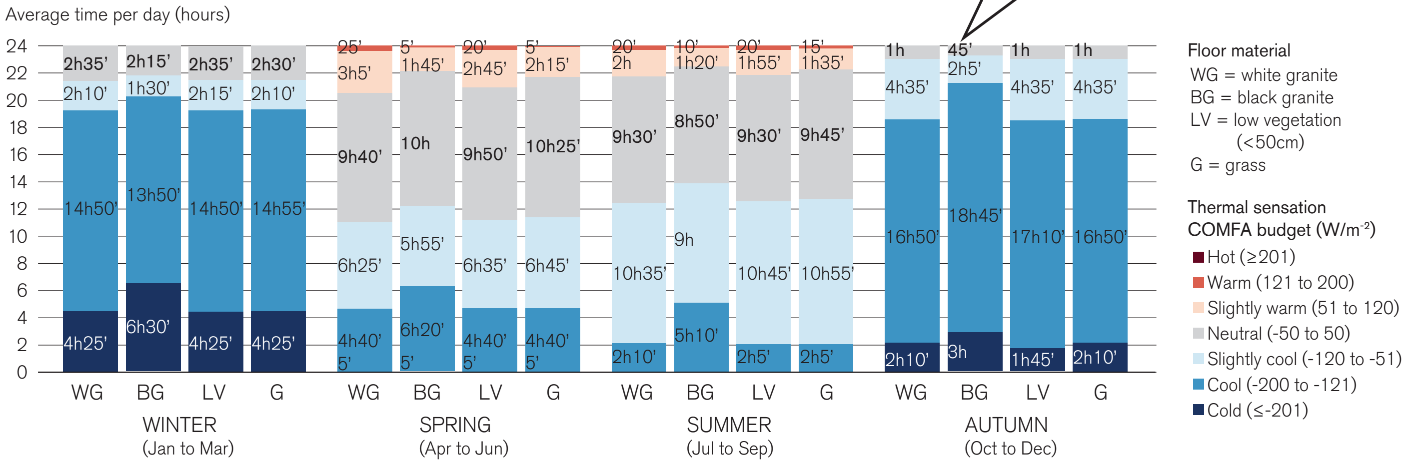


Figure 13: *Thermal sensation in point 4 (open area, high exposure to direct sunlight).*

Table 5: *Average COMFA budget (W/m^2) for different floor materials.*

	Point 1 (low sunlight exposure)				Point 4 (high sunlight exposure)			
	WG	BG	LV	G	WG	BG	LV	G
Winter (Jan-Mar)	-158	-159	-160	-159	-150	-163	-151	-150
Spring (Apr-Jun)	-30	-35	-39	-34	-17	-37	-24	-20
Summer (Jul-Sep)	-49	-52	-55	-52	-26	-46	-31	-28
Autumn (Oct-Dec)	-158	-159	-159	-159	-143	-156	-143	-144

WG = White granite LV = Low vegetation BG = Black granite G = Grass

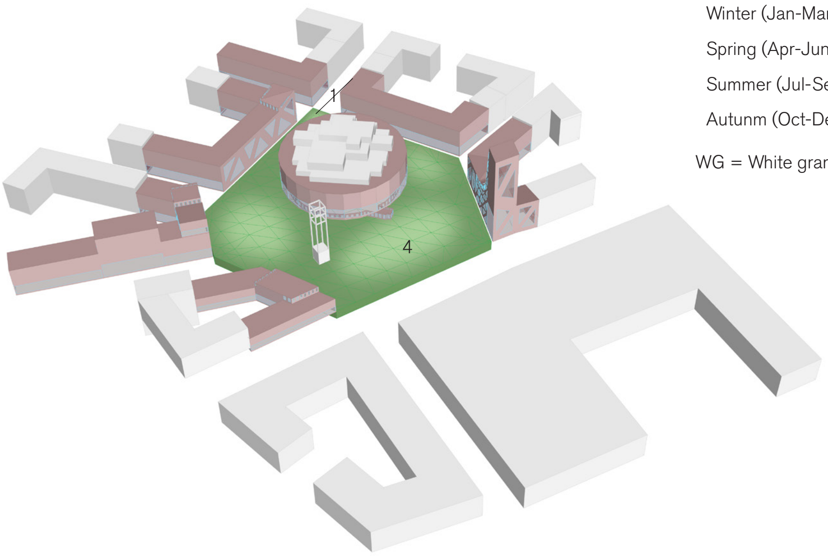


Figure 14: *view of the model used in the simulations. The two points simulated are shown.*

Phase II.b: Tree density parametric study

Wind speed:

This parametric study investigates the differences in terms of annual thermal comfort between three tree scenarios: T1, no trees; T2, medium trees and T3, maximum trees.

Figure 16 shows the variations in average wind speed between the three scenarios. It demonstrates that the trees in scenarios T2 (Figure 17) and T3 (Figure 18) produce significant reductions of wind speeds compared to T1 (Figure 15). Figures 15, 17 and 18 display graphically how much trees are affecting the average wind speeds throughout the square. It can be seen how opints P1 to P3 present significant reductions of the average wind speeds between scenario T1 and T2. The reduction of the average wind speed in the selected points between T2 and T3 is quite small for points P1, P2 and P3. In the case of P4 the wind speed reductions are negligible.

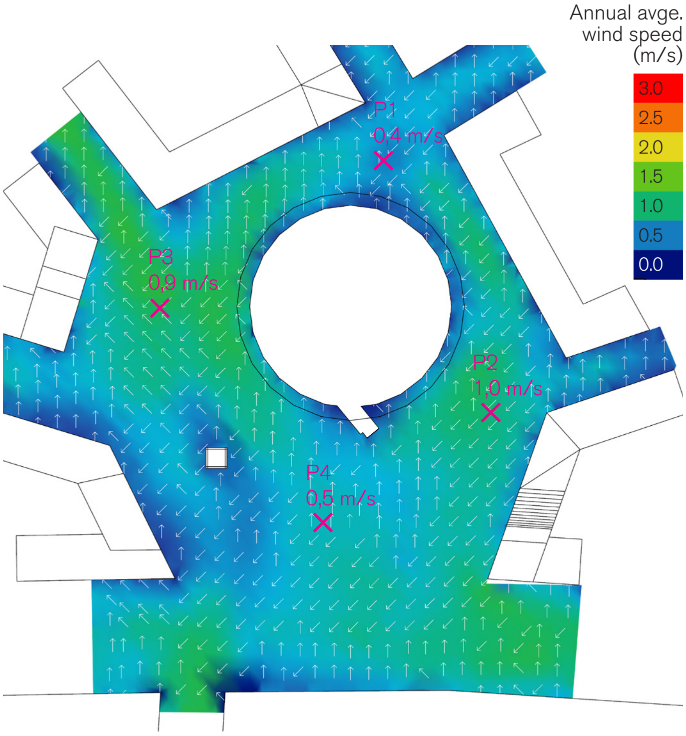


Figure 15: annual average wind speed for T1 (no trees).

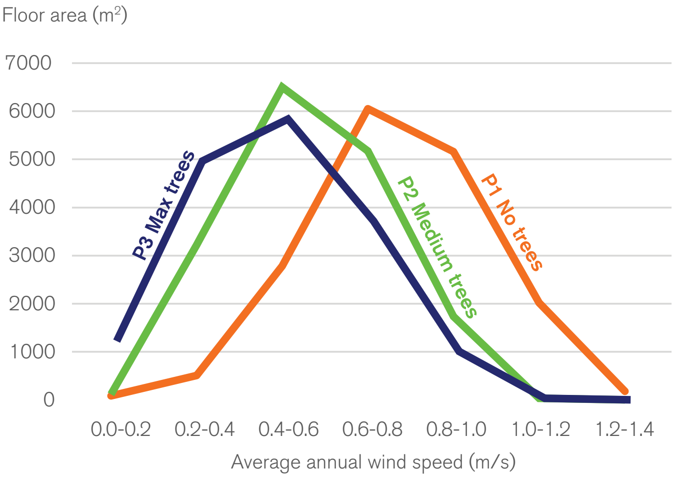


Figure 16: comparison average annual wind speed at each of the three proposals: T1 (no trees), T2 (medium trees) and T3 (maximum trees).

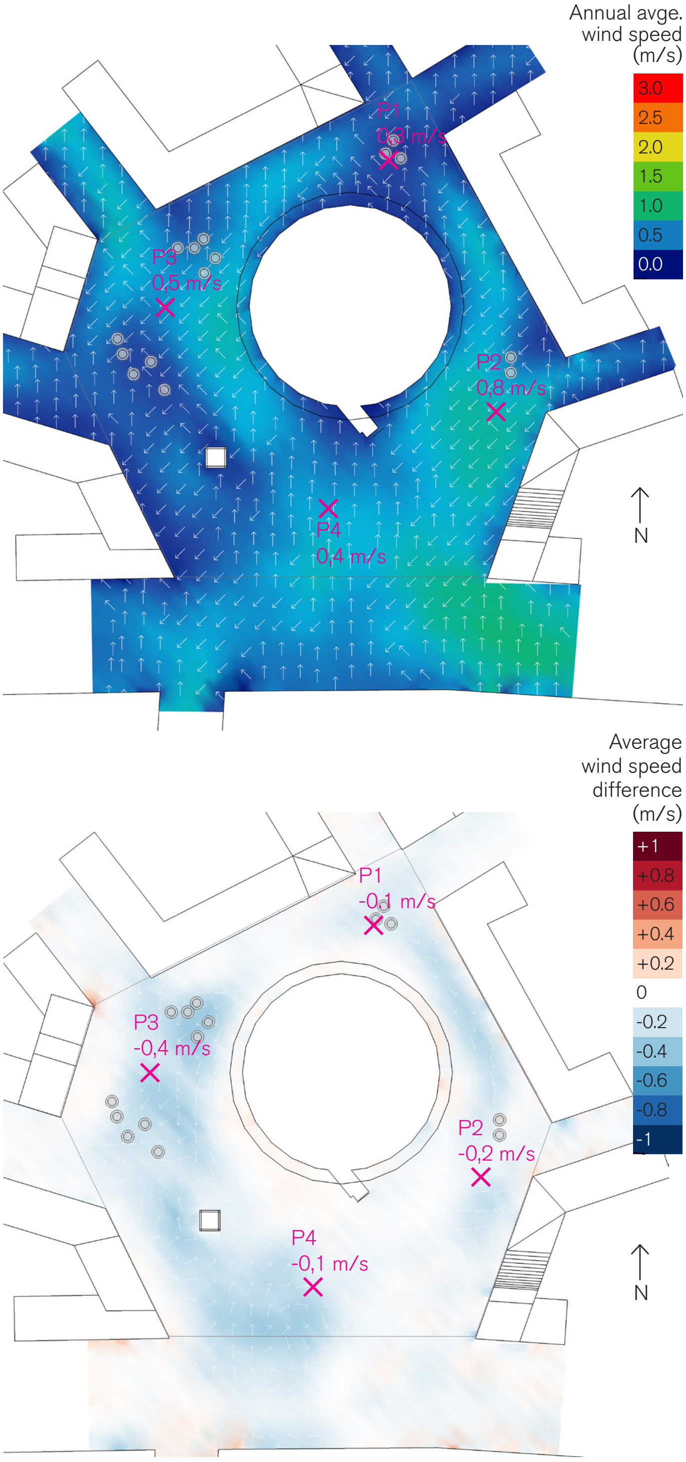


Figure 17: *annual average wind speed for T2 (above) and annual wind speed difference compared to T1 (below).*

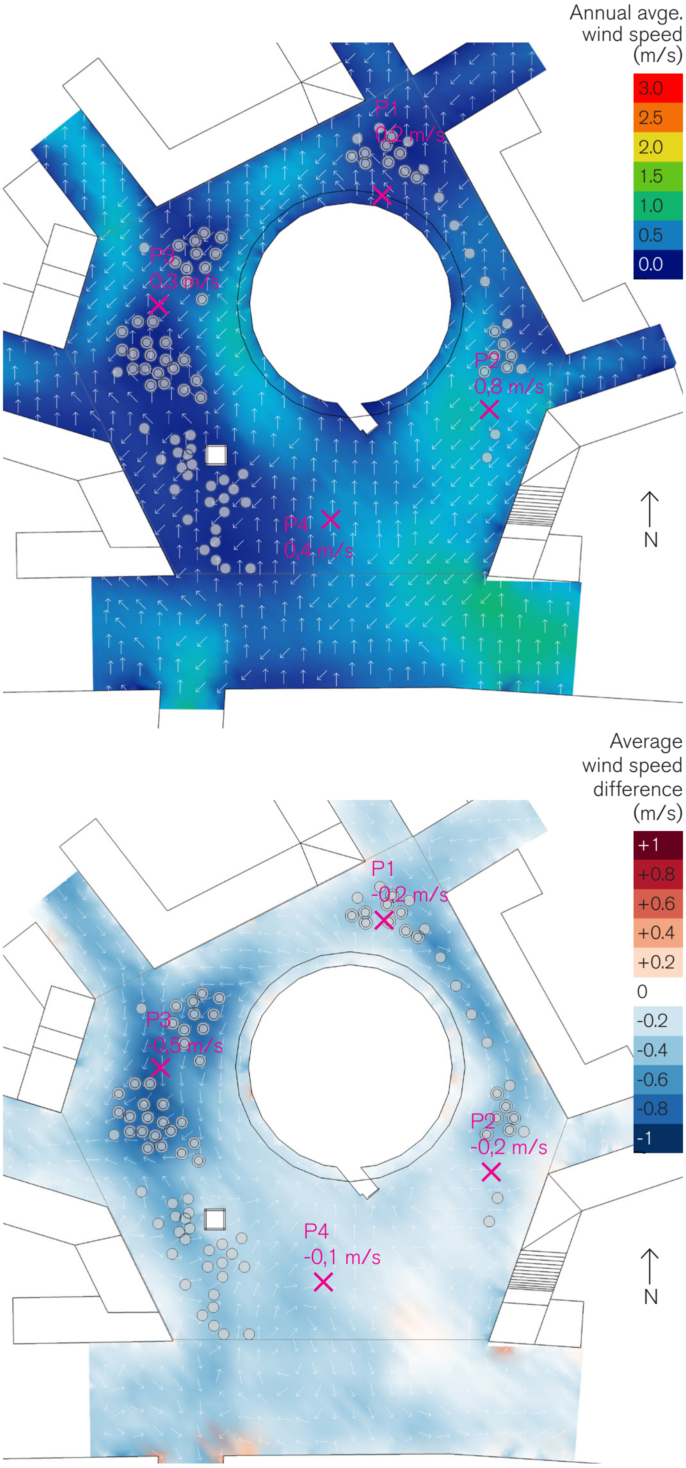


Figure 18: *annual average wind speed for T3 (above) and annual wind speed difference compared to T1 (below).*

Direct sunlight access:

Figure 20 shows a comparison between the three scenarios in terms of solar access in the square. It shows how the presence of trees reduces the area with high direct sunlight access by 5% and 17% for T2 and T3 respectively. At the same time, it increases by 4% and 17% respectively the percentage of areas with a low direct sunlight access. Figures 19, 21 and 22 display graphically the annual direct sunlight hours distribution considering only clear skies for the three scenarios. It shows how point one reduces its annual access to direct sunlight by 15 and 85 hours respectively; point two by 0 and 70 hours; point three by 70 and 240 hours and point four by 0 and 20 hours correspondingly.

Thermal sensation:
(See next page)

Table 6 displays the annual thermal comfort results expressed as UTCI degrees by season for each of the three scenarios. Figures 22 to 25 show a comparison of the average wind speed, direct sunlight hours and the thermal sensation for each of the four investigated points.

Due to the nature of the cold climate of Kiruna, heat stress is negligible. In this study only point 4 presented some slight heat stress during spring and summer for about one hour per day (Figure 25). On the other hand, cold stress is constant for the entire winter and autumn periods and it constitutes roughly 2/3 of the time in spring and 1/3 of the time in summer (Figures 23 to 25).

During the colder seasons (autumn and winter) the results show a clear correlation between the average wind level and the comfort level. P1 and P4 present in general better thermal comfort results compared to P2 and P3 during the cold seasons, winter and autumn. On the other hand, during the warmer seasons, spring and summer, the comfort level are both influenced by the level of wind and by the level of direct sunlight hours. During these seasons point P1, P2 and P3 present similar results. This is due to the fact that even though P1 has a better wind shelter, P2 and P3 have a higher level of sunlight hours. Point 4, with a low wind speed and a high level of sunlight hours present significantly better thermal comfort, in the order of 3°-4° UTCI degrees higher than the rest of the points.

In points P1, P2 and P3 the presence of trees increases the thermal sensation in all seasons (Table 6) by 0,1° to 0,5° UTCI degrees in point 1, by 0,4° to 0,8° in point 2 and by 0,6° to 2,2° in point 3. In most of these points both the wind speed and the sunlight hours are reduced by the presence of trees. However, due to the fact that their direct sunlight access is limited the reduction in the wind speed becomes the dominant factor that explains the warmer thermal sensation produced by the trees.

In contrast to points P1, P2 and P3, in P4 the presence of trees produces a colder sensation of up to 3,2° UTCI degrees for all seasons except autumn, where it produces a slight reduction. This point is not significantly affected by the trees, neither in terms of wind speed nor in terms of shading. The fact that the trees are creating a colder sensation can be due to the fact that even though trees are not casting shade on P4 itself they are shading surrounding objects such as the square floor surface material or the surrounding buildings. The shading decreases the temperature of these objects and therefore also decreases the heat radiated by them.

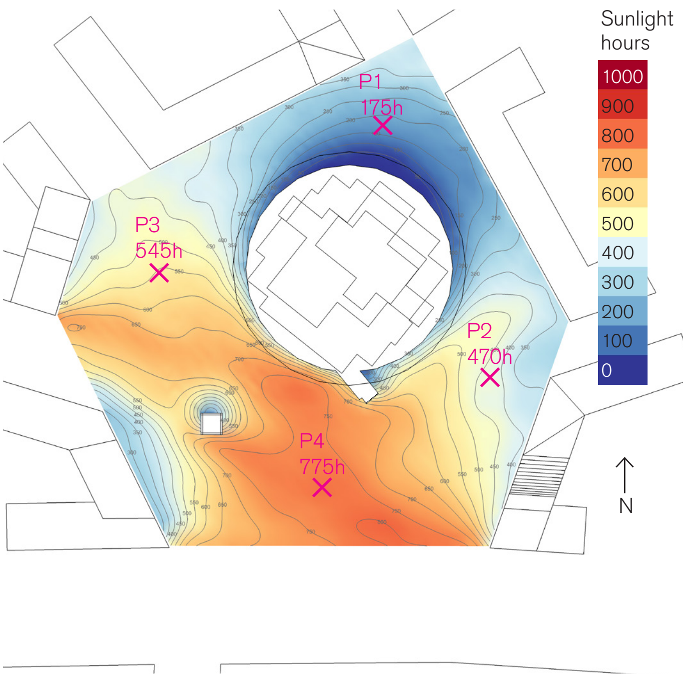


Figure 19: annual hours of direct sunlight using only clear skies for T1(no trees).

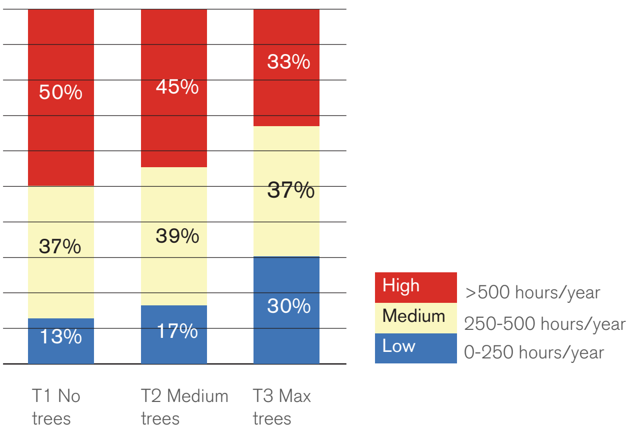


Figure 20: comparison direct sunlight access at each of the three proposals: T1 (no trees), T2 (medium trees) and T3 (maximum trees).

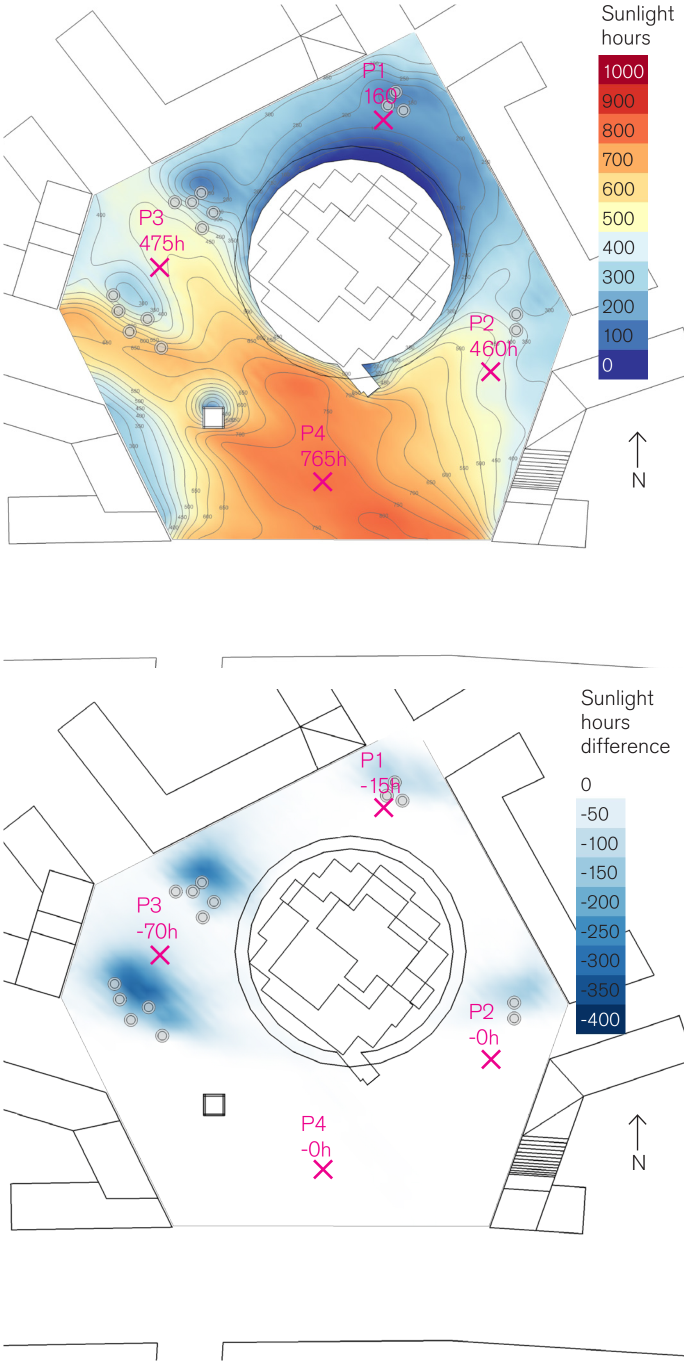


Figure 21: annual hours of direct sunlight using only clear skies for T1(above) and difference compared to T1 (below).

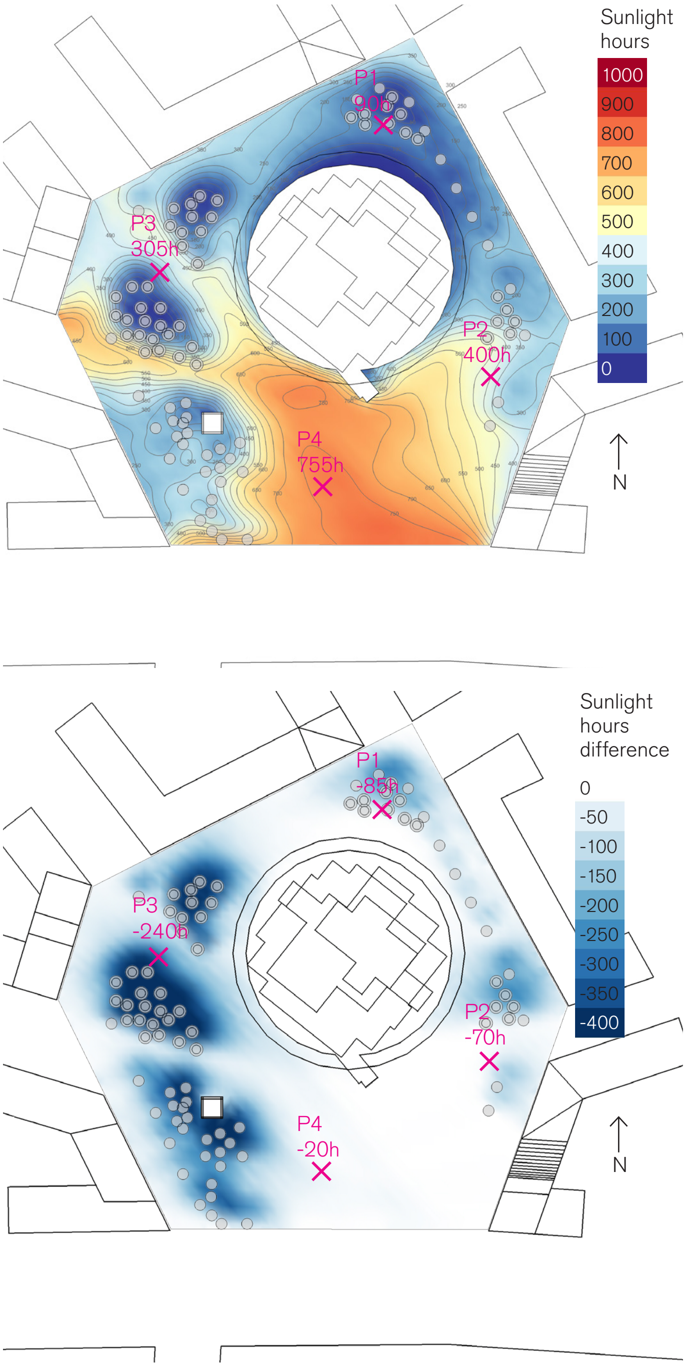


Figure 22: annual hours of direct sunlight using only clear skies for T1(above) and difference compared to T1 (below).

Table 6: Average UTCI (apparent temperature) for scenarios with different tree densities (12 am to 6 am excluded).

		Point 1			Point 2			Point 3			Point 4		
		T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
Winter	Avge. UTCI	-9,9°	-9,6°	-9,4°	-12,3°	-11,9°	-11,5°	-11,8	-10,1	-9,6	-9,5°	-9,5°	-10,1°
	Variation	-	+0,3°	+0,5°	-	+0,4°	+0,8°	-	+1,7°	+2,2°	-	0,0°	-0,6°
Spring	Avge. UTCI	5,9°	6,0°	6,3°	4,9°	5,6°	5,6°	4,9°	6,2°	6,5°	9,5°	6,6°	6,3°
	Variation	-	+0,2	+0,4	-	+0,6	+0,7	-	+1,3	+1,6	-	-2,9	-3,2
Summer	Avge. UTCI	10,8	10,9	11,0	10,0	10,4	10,6	10,3	10,9	11,1	13,6	11,1	10,8
	Variation	-	+0,1	+0,2	-	+0,4	+0,6	-	+0,6	+0,8	-	-2,5	-2,8
Autumn	Avge. UTCI	-5,2	-5,0	-4,9	-6,8	-6,5	-6,3	-6,5	-5,3	-5,0	-5,3	-4,9	-5,2
	Variation	-	+0,2	+0,3	-	+0,4	+0,6	-	+1,2	+1,5	-	+0 ,3	0,0

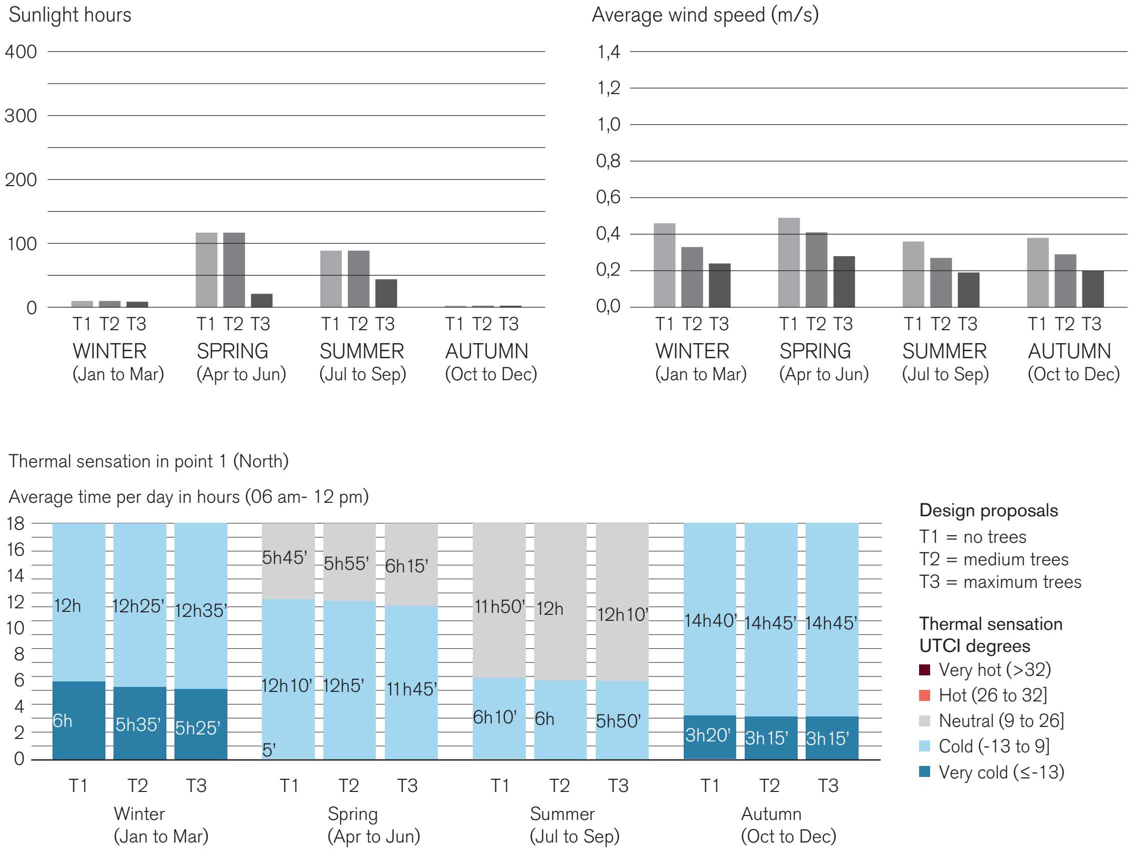


Figure 23: comparison of direct sunlight hours (top left) and average wind speed (top right) and thermal sensation (bottom) in point 1.

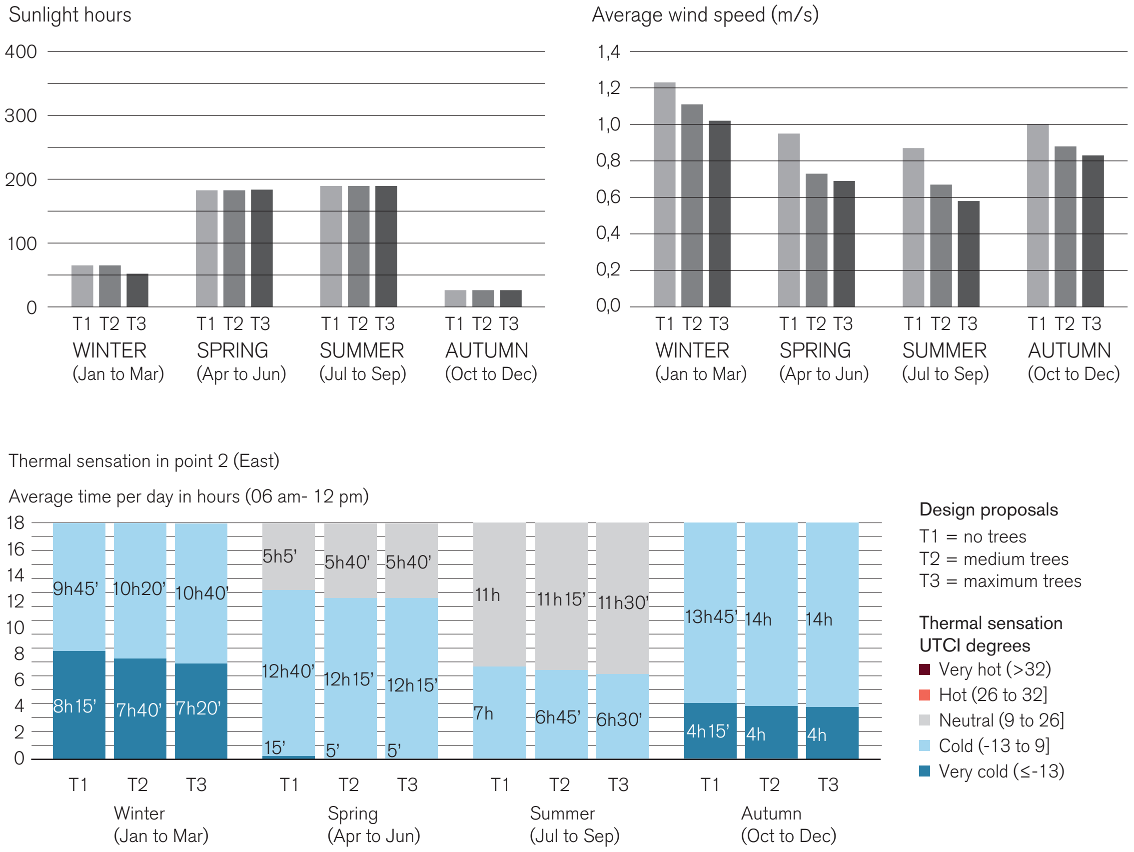
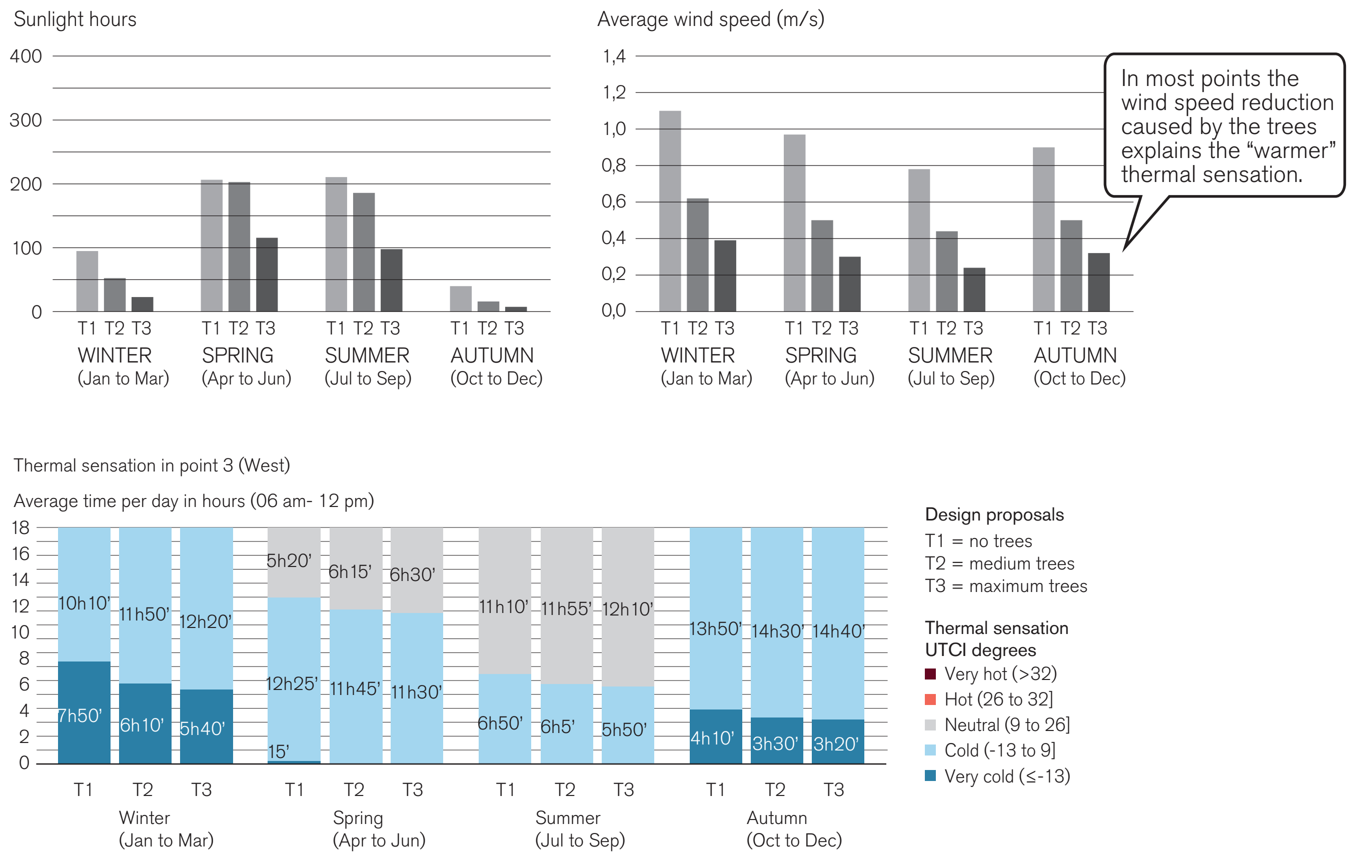
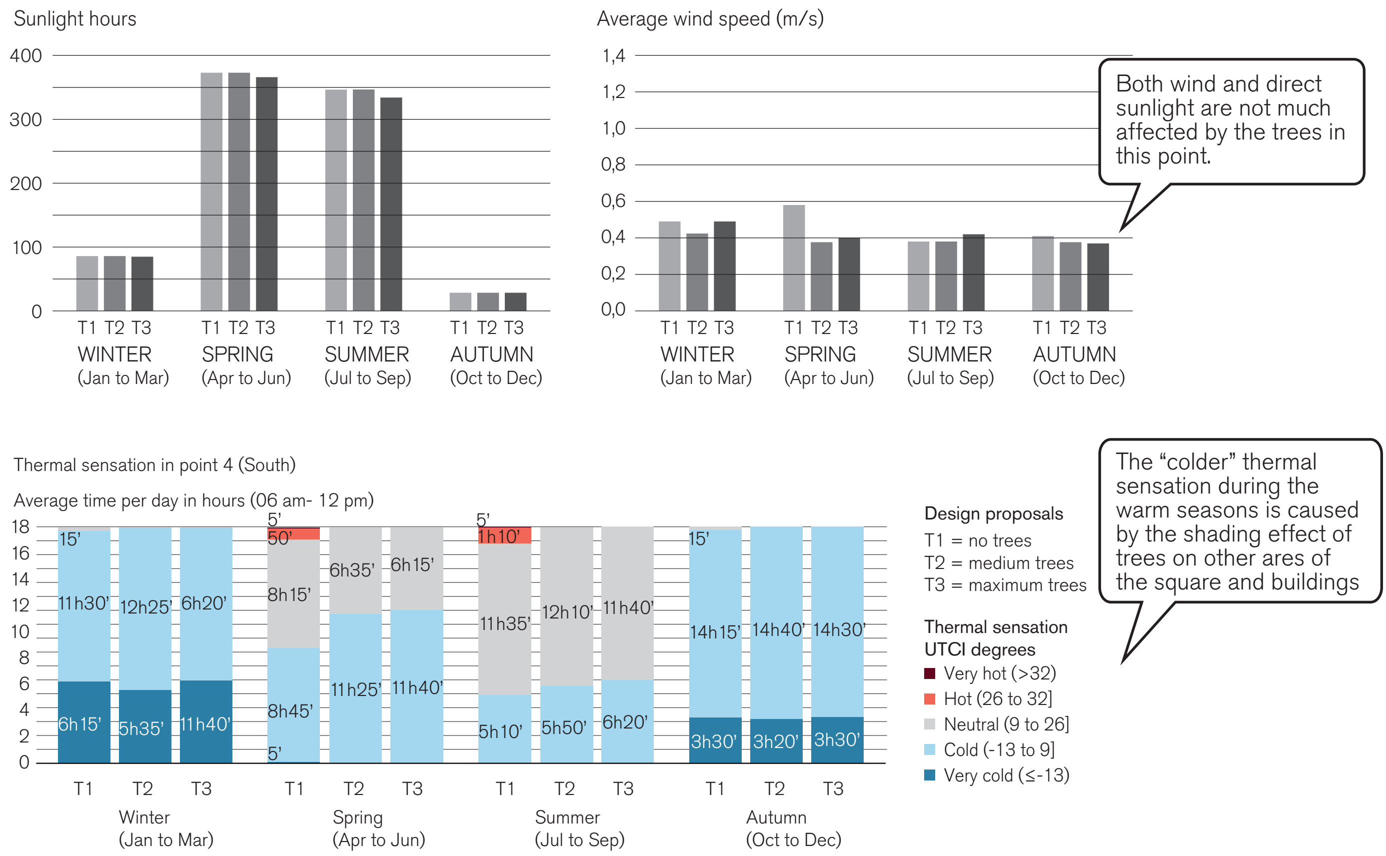


Figure 24: comparison of direct sunlight hours (top left) and average wind speed (top right) and thermal sensation (bottom) in point 2.



In most points the wind speed reduction caused by the trees explains the "warmer" thermal sensation.

Figure 25: comparison of direct sunlight hours (top left) and average wind speed (top right) and thermal sensation (bottom) in point 3.



Both wind and direct sunlight are not much affected by the trees in this point.

The "colder" thermal sensation during the warm seasons is caused by the shading effect of trees on other ares of the square and buildings

Figure 26: comparison of direct sunlight hours (top left) and average wind speed (top right) and thermal sensation (bottom) in point 4.

DESIGN RECOMMODATIONS

I. General design guidelines for the design of urban spaces in the Northern Scandinavian context

The North of Scandinavia has a subarctic climate with very cold winters and cool summers. Stress heat rarely happens. All efforts aiming to improve the thermal comfort in outdoor spaces should be focused on reducing cold stress. Different strategies can be used to accomplish that. A list of strategies ordered by effectiveness follows:

- A. Reduction of the average wind speed, effective all year round. This can be done by working with the disposition of the building volumes (avoiding the tunnel effect), by adding especial sheltering elements such as screens, pergolas or colonnades or by working with vegetal elements, especially evergreen trees that can offter protection during winter as well.

- B. Increase of the direct sunlight exposure. Effective for the summer and spring seasons.

- C. Avoid materials with a low solar radiation reflectance (dark colors). This measure effective only for areas with a high direct sunlight exposure. The use of light colors and grass or vegetation is recommended for such areas.

I. Specific design recommendations for the square

Silvia Coccolo, author of the first parametric study on floor surface material choice concludes the following:

"(...) Effectively, greening the outdoor environment has a positive effect in the thermal sensation of pedestrians, as well as on the microclimatic conditions of the site. A ground covering with granite has an important impact on the radiative environment, due to its high thermal conductivity. (...). Based on the analysis presented in this draft, the following recommendations, in order to improve the outdoor human comfort, are defined:

- Light ground covering could improve the thermal sensation during the daytime, improving the comfortable, slightly warm and warm hours for the southern part of the square. In order to maximize the comfortable thermal sensation, in this area is required to add shadowing devices, just during the warmer seasons, and a perfect bioclimatic example is the use of deciduous tree.

- Darker ground covering in the northern part of the square: this area is shadowed by neighbors building, and in order to increase the thermal sensation of pedestrian is important to increase the absorption of the ground covering. This area is recommended to be covered by vegetation (max. height 60cm), able to mitigate the microclimate improving the comfortable hours.
- Maximize the small vegetation or grass on the ground covering, which reduces the extreme cold or hot events, mitigating the microclimate.

- Provide pedestrian protections, for snow and rainfalls, as colonnades or galleries protected by glazing roofs (Givoni 1998).

In order to understand the livability of the square, following the architectural design, outdoor comfort analysis could be provided, by varying the pedestrian's metabolic activity (from relaxed to walking fast). The analysis could be defined on several locations, by analyzing the comfort as function of the time of the day. Obtained results could deal with a Comfort-Activity-Map of the square."

Figure 27: Summer view of the square

Reduction of the average wind speed, effective all year round. This can be done by working with vegetal elements, especially evergreen trees that can offer protection during winter as well.

Increase of the direct sunlight exposure. Effective for the summer and spring seasons.

The analysis could be defined on several locations, by analyzing the comfort as function of the time of the day. Obtained results could deal with a Comfort-Activity-Map of the square.

Avoid materials with a low solar radiation reflectance (dark colors). This measure effective only for areas with a high direct sunlight exposure. The use of light colors and grass or vegetation is recommended for such areas.

West area (PT3): idem East area.

North area (PT1): the material choice is irrelevant. The wind speed is already low in this area, it does not benefit so much from the sheltering effect of trees.

East area (PT2): Adding evergreen trees is recommended. This area has a medium direct sunlight access, that trees would reduce considerably. However, the area is relatively windy, so it would benefit to a large extent from the presence of evergreen trees that can shelter from wind all year round. If trees were included in this area, material choice has a limited impact. If trees were not included, avoid dark materials.

South area (PT4): this area has a high direct sunlight exposure and a low average wind speed. Trees are not recommmended in this area. The presence of trees (evergreen or deciduous) that would cast shadows around this area would undermine thermal comfort during the warmer months and it would not improve it significantly during the coldest months. It is highly recommended to avoid using black floor surface materials in this area that would increase the cold stress during the warmer seasons.

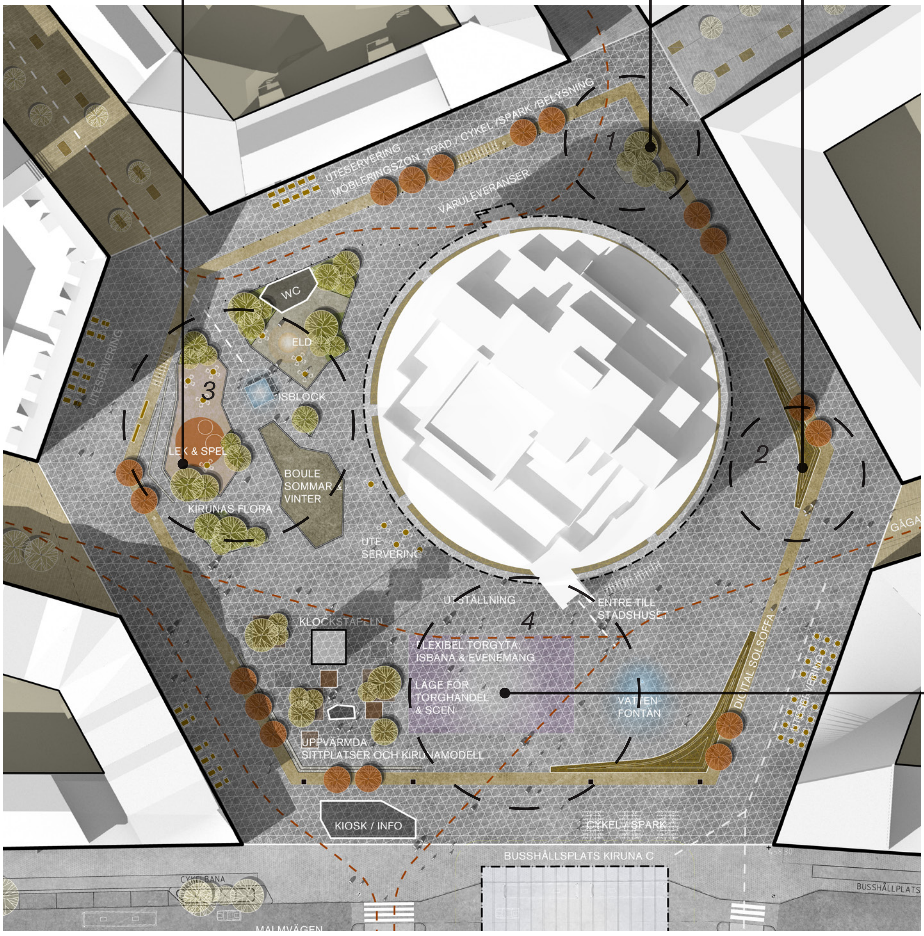


Figure 28: Plan of the square highlighting the focus areas

APPENDIX I:

PREASSESSMENT OF OUTDOOR THERMAL COMFORT METHODOLOGIES / TOOLS

A total of three different programs have been selected to carry out a comparative analysis, which will serve to evaluate which program is more suitable to inform in terms of thermal comfort the design of a public square in the new city of Kiruna. Other programs, such as IESVE, UMI or IDA ICE were investigated. However, they cannot perform outdoor thermal comfort analysis. The three alternative programs evaluated are: Envi_Met, CitySim Pro and a combination of Autodesk CFD and Ladybug/Honeybee. Table 7 shows a comparative analysis of the three alternatives.

ENVI_MET
http://www.envi-met.com/innovation#simulation_model Support: Michael Bruse (michael.bruse@envi-met.com)
Software specialized in addressing the impact of architecture and urban planning in the microclimate system. It can run detailed simulations for a few days in a row and takes in consideration all the parameters involved in thermal comfort.

CITYSIM PRO
http://www.kaemco.ch/download.php
Developed by: Solar Energy and Building Physics Laboratory of EPFL (Switzerland)
Support: Silvia Cocolo (silvia.coccolo@epfl.ch)
Graphical User Interface aiming at the simulation and optimisation of the sustainability of urban settlements. The outdoor thermal comfort tool is expected to be added soon (do not know exactly when) but its developer said that she would be willing to make it available for us already.

AUTODESK + GRASSHOPPER + LB/HB
http://www.autodesk.com/products/cfd/overview
http://www.grasshopper3d.com/group/ladybug
Support: Chris Mackey (LadYbUg/Honeybee, LB/HB) and Autodesk (Autodesk CFD)
Combination of two tools that we currently use at the DSD (Digital Sustainable Design) group: Ladybug/Honeybee (LB/HB) and Autodesk CFD. LB/HB can assess outdoor thermal comfort with the limitation of local wind. This can be solved by getting this input from the program Autodesk CFD. The methodology would be based in annual weather, and can be performed for the whole year or specific periods. Ladybug can be used both in Grasshopper and Dynamo. Honeybee can be used only in Grasshopper but the Dynamo version is under development at the moment when this was written. This method builds on a previous work called "A wind-sun exposure analysis method to predict pedestrian urban comfort at early design stage: Regnbågensallén at Luleå University Campus in Sweden" developed at White by Marie-Claude Dubois and Örn Erlendsson among others.

FUTURE DEVELOPMENT

Tool comparison/validation: Phase II.a (Floor material parametric study) was conducted by the PhD candidate at EPFL Silvia Coccolo by using a module under development of the program CitySim. However, such study could also be developed by any of the other two tools presented above. It would be useful to replicate the same study using these tools to validate the results.

ENVIMET: this tool was ruled out to be tested in this study due to its limitations regarding the lack of compatibility with modeling programs, the lack of flexibility and compatibility/interoperability and the fact that it was not adapted to cold climates. All of these have been solved during the development of this study: external models can now be imported, a new package for cold climates has been added and even some components have been created in Ladybug/Honeybee to connect with the program. Furthermore, ENVIMET seems to be succeeding in positioning itself as market leader for outdoor thermal comfort simulations. For all the above mentioned reasons, it is recommended to test the suitability of the program to conduct outdoor thermal simulations for urban planning and urban design projects.

Snow cover: the snow cover was not considered in this study, although it is present during a large part of the year in the Scandinavian context. It would be most relevant to include this parameter in future studies.

	Aspects to evaluate	ENVI_MET	CITYSIM PRO	INTERNALLY DEVELOPED TOOL (AUTODESK CFD + GH/LB+HB
USABILITY: to which dedree can the methodology be used to achieve the quantified objectives with efectiveness, efficiency and satisfaction?	1. Time-efficiency	↓ Low. Models have to be rebuilt in the program.	↑ Good	→ Medium
	2. Cost	↓ 2900€/year for a license including 2 hours of support. Maintenance included. 2000€ for a one day training for up to 5 people (travel expenses to Germany not included).	→ 2300€/year for a commercial license including training and support. Travel expenses to Switzerland for the training not included. Maintenance included.	↑ Low Development was estimated to take 14 hours more than the two previous alternatives. It would also need a validation (time?)
	3. Results display: are the results displayed in an intuitive, clear, understandable way?	↑ Yes	↑↑ Yes. Plus results can be exported and managed in Grasshopper.	↑↑ Yes. Good flexibility in the way we display and manage the results using Grasshopper.
	4. Adaptability: it can be applied to other projects of different size and nature.	↑ Yes	↑ Yes	↑ Yes
	5. Flexibility: Simulations can be run for specific periods of time (for example, weekdays afterwork) or for specific conditions (for example, when wind speed is larger than 5 m/s)	↓ No	→ Not directly, but the hourly results and the simulation points/mesh can be exported and managed in Grasshopper.	↑ Yes
	6. Vegetation: the methodology can include the effect of vegetation in terms of shading and wind obstruction and its seasonal changes.	↑ Yes. Evotranspiration included.	↑ Yes, the seasonal changes can even be considered running different scenarios and interpolating the results. Evotranspiration included.	↓ Seasonal changes can even be automatised parametrically. Evotranspiration not included. Challenging to include trees in CFD simulation.
	7. Compatibility: the methodology is compatible with the modelling software most commonly used at White.	↓ Not compatible. Models have to be rebuilt from stratch. They are developing a feature to allow DWG and DXF, but it is not finished.	↑ Good. Takes DXF and DWG.	↑↑ Very good (can be used with both Grasshopper and Dynamo)
SCIENTIFIC BASIS: to which degree is the methodology sound and reliable?	8. Metric used: it uses a validated metric to assess outdoor thermal comfort.	→ 1. PET: most widely used metric, validated for temperate climates, not so accurate for extreme climates, suitable for outdoor thermal comfort.	↑ 1. COMFA: suitable for all climates and scales. 2. ITS: developed to assess thermal stress, not suitable for cold climates.	↑ 1. UTCI: very widely used, similar to COMFA. Aplicable to all climates and scales from outdoor thermal comfort to macro scale. 2. SET: similar to PET
	9. Microclimate parameters: It considers all the parameters linked to microclimate, namely, local wind speed, solar irradiation and mean radiant temperature (temperature of surrounding objects, this is not really relevant in extremely cold climates).	↑ Yes	↑ Yes	→ Yes, but might be difficult to include trees in the wind simulation using Audodesk CFD. We have had problems in the past.
	10. Human parameters: It considers human parameters involved in thermal comfort, namely, metabolic rate and clothing level.	↑ Yes	↑ Yes	↑ Yes
	11. Relevance of the results: can they be used to withdraw conclusions on the microclimate? Ideally results should be based on annual hourly weather data.	→ Cannot perfort annual simulation. It is limited to up to a week in a row. However, it considers the effect of wind on the temperature of surrounding elements (relevant in cold climate?)	↑ Yes. It uses climate data. The results can be exported to Grasshopper.	↑ Yes
OTHERS:	12. Learning curve:	→ New tool, we do not have previous experience with it.	→ New tool, we do not have previous experience with it.	↑ No need to learn new tools, the methodology is a combination of tools that we already use.
	13. Possible continuation (APP project)	→ Possibly.	→ Possibly.	→ Possibly.
	14. Support:	↑ Good. They seem to be quick and good at giving support.	↑ Good.	↑ LB/HB: its developer (Chris Mackey) usually answers within 48h. Autodesk CFD: Autodesk support
	15. Others:	↑↑ They are open to negotiate to adapt the program to us if needed.	↑ The outdoor thermal comfort feature is still not added to the CitySim Pro program but the developer can make it available for us already.	→ Another challenge is to extract the data from Autodesk CFD. Worst case scenario it can be done graphically with Grasshopper.

Table 7: comparative study of alternative programs to assess outdoor thermal comfort.

APPENDIX II: DETAILED WIND RESULTS BY WIND DIRECTION

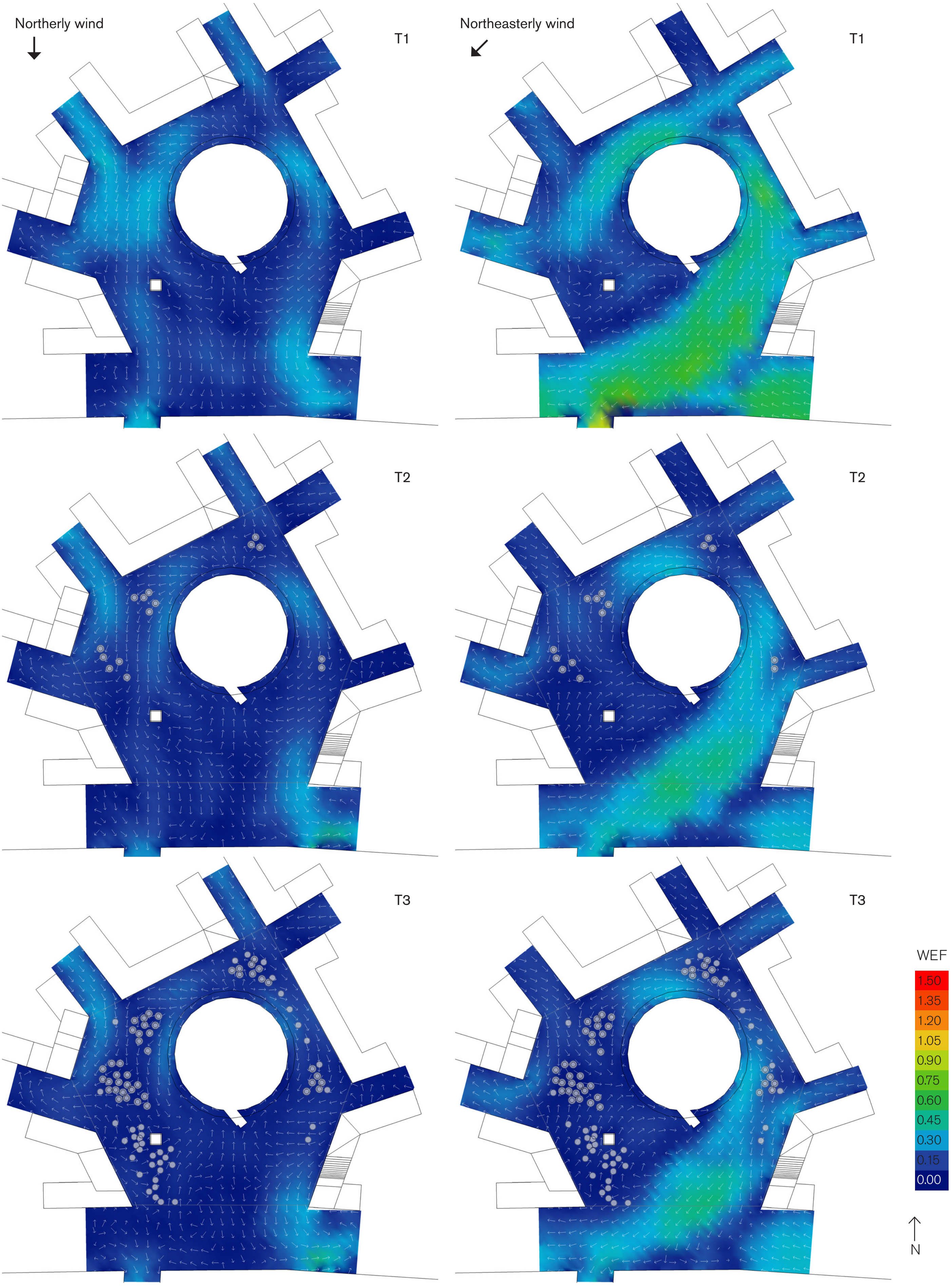


Figure 29: wind exposure factors (WEF) for each of the three tree distribution proposals for North wind (left) and Northeast wind (right).

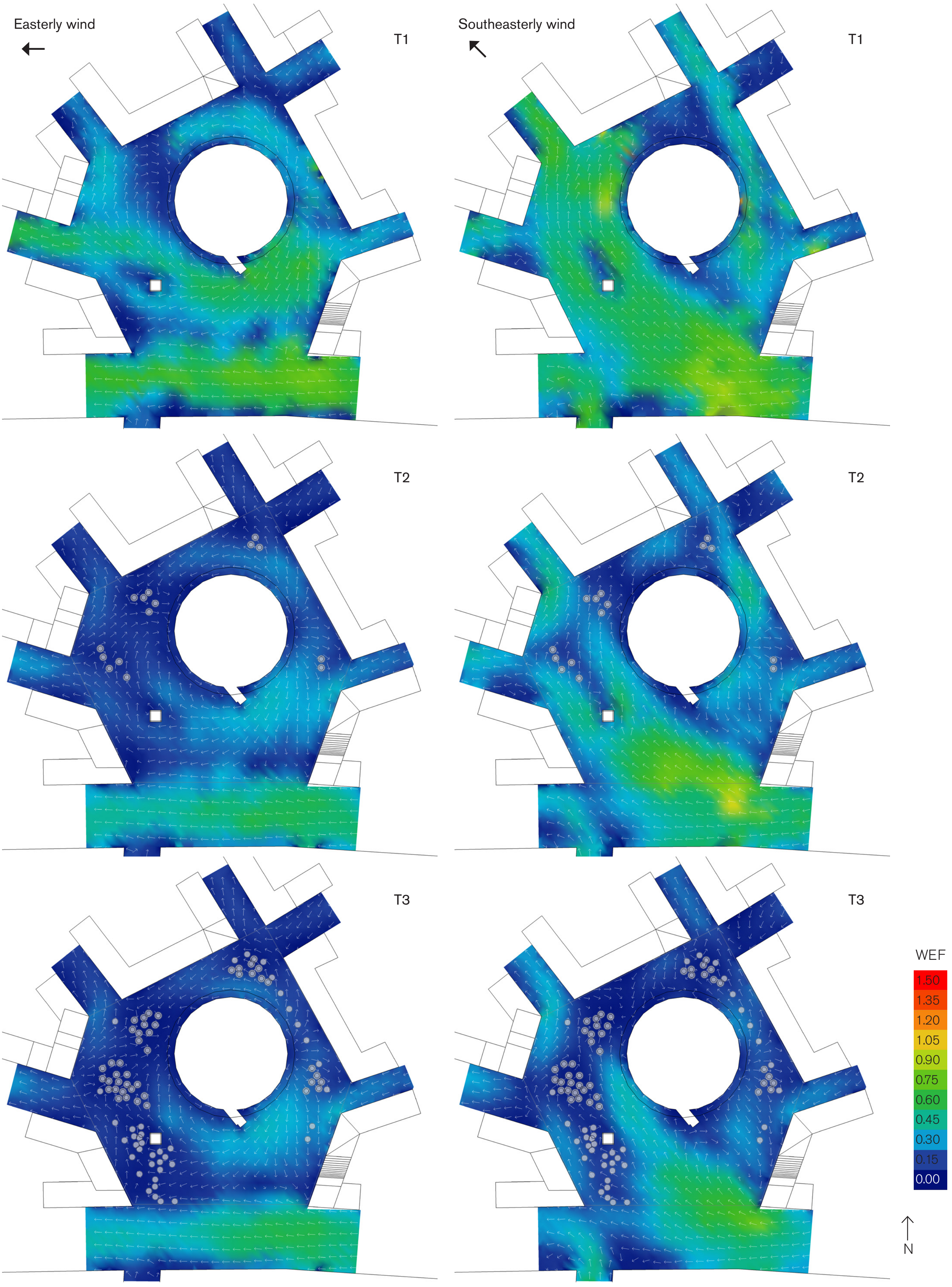


Figure 30: *wind exposure factors (WEF) for each of the three tree distribution proposals for East wind (left) and Southeast wind (right).*

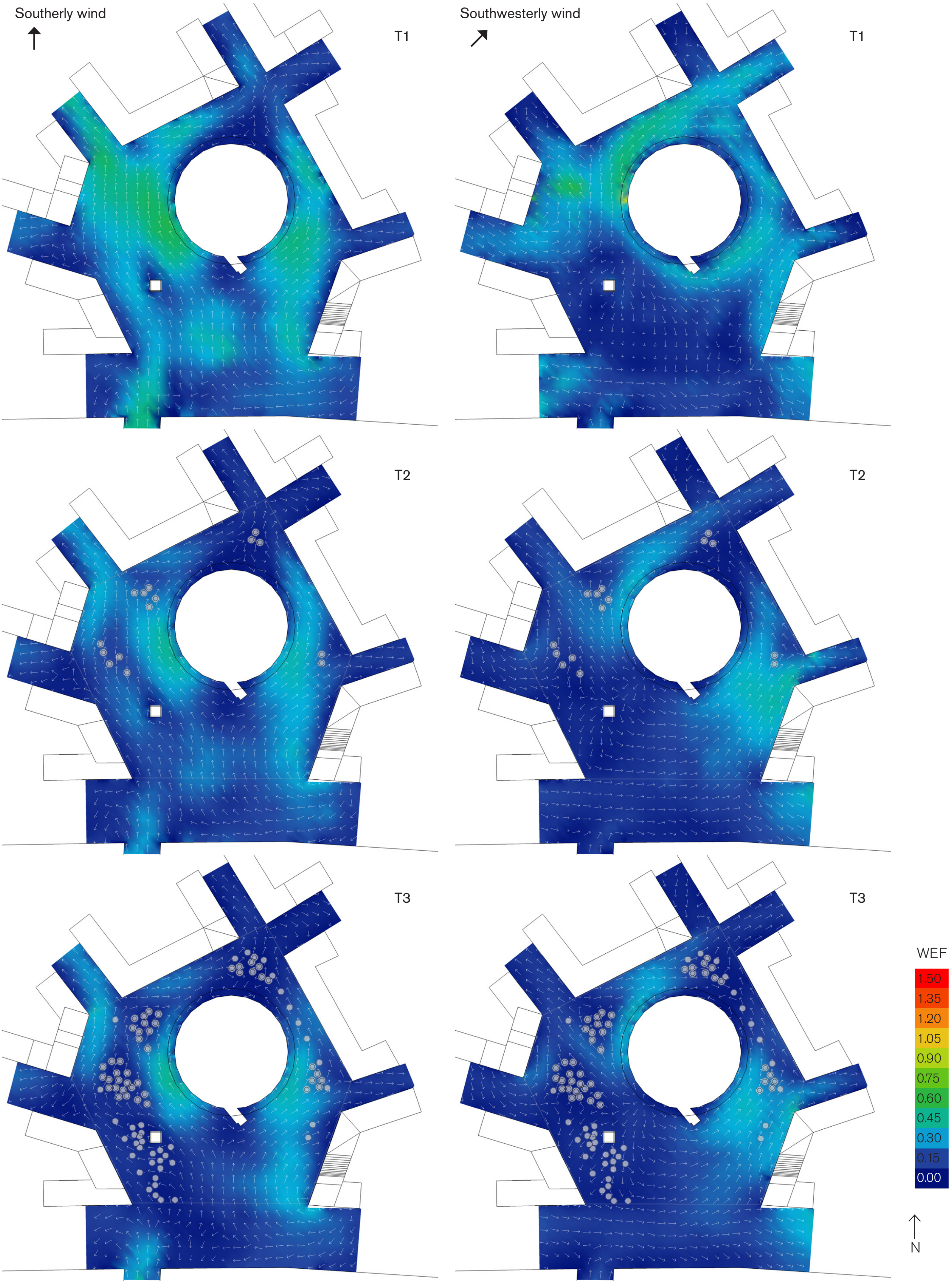


Figure 31: wind exposure factors (WEF) for each of the three tree distribution proposals for South wind (left) and Southwest wind (right).

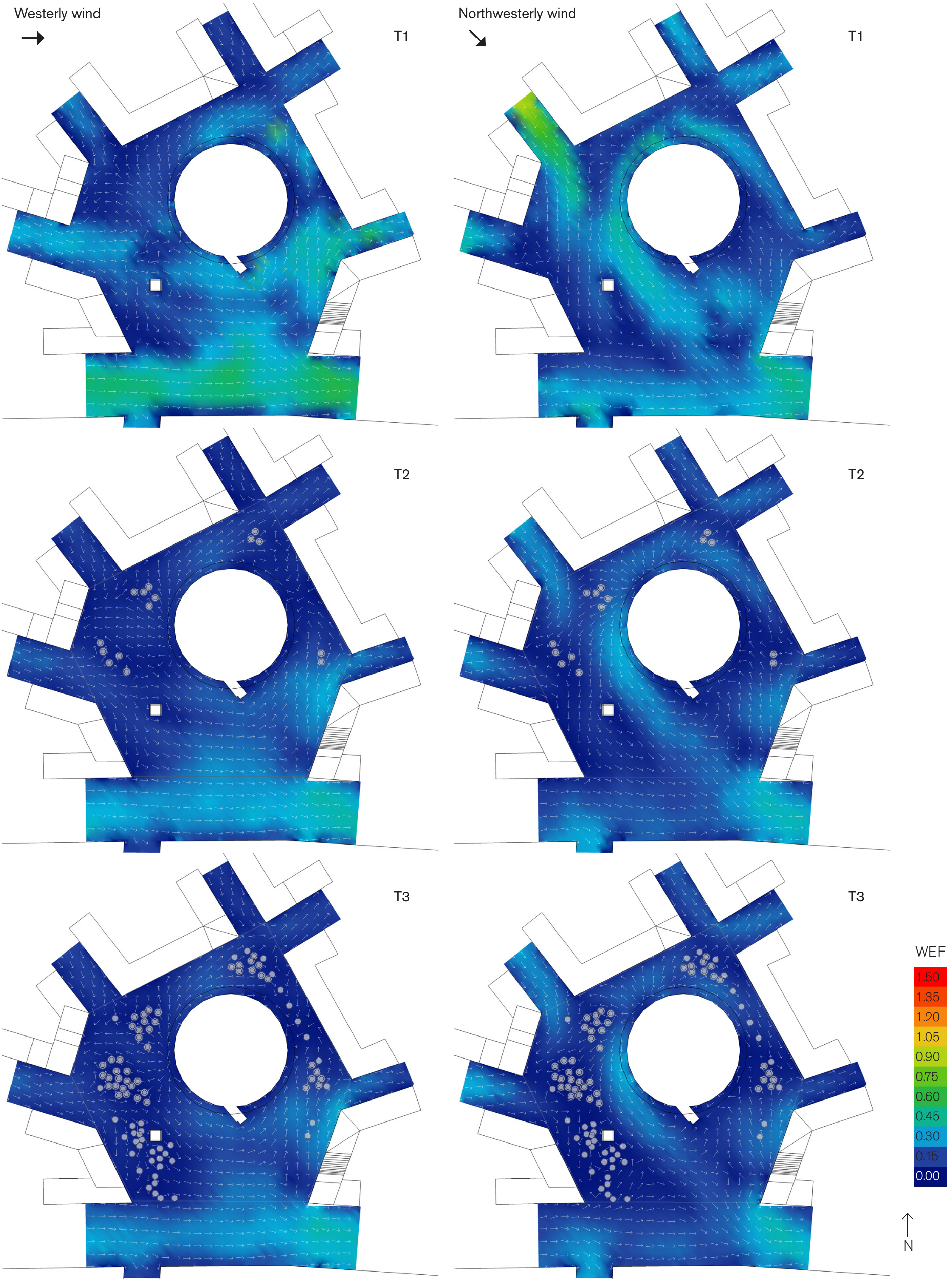


Figure 32: wind exposure factors (WEF) for each of the three tree distribution proposals for West wind (left) and Northwest wind (right).