TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
ACADEMY OF ARCHITECTURE AND URBAN STUDIES

WIND ANALYSIS AND DESIGN OF URBAN AREA FEATURES AND LAYOUT FOR IMPROVING WIND COMFORT AND LIVABILITY IN ÜLEMISTE CITY

TUULTE ANALÜÜS JA SELLE RAKENDAMINE LINNAPLANEERIMISES KASUTAJASÕBRALIKU AVALIKU RUUMI LOOMISEKS ÜLEMISTE CITY'S

MASTER THESIS

Student: Jelena Kazak

Student code: 165215EAUI

Supervisor: Francesco De Luca,
Jenni Vilhelmiina Partanen

Tallinn 2022

(*On the reverse side of title page*)

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

“.......” .... 20…..

Author: ....
/signature /

Thesis is in accordance with terms and requirements

“.......” .... 20…

Supervisor: …..........................
/signature/

Accepted for defence

“.......”....................20… .

Chairman of theses defence commission: ....
/name and signature/

Non-exclusive licence for reproduction and publication of a graduation thesis[1]

I, Jelena Kazak,

1. grant Tallinn University of Technology free licence (non-exclusive licence) for my thesis

WIND ANALYSIS AND DESIGN OF URBAN AREA FEATURES AND LAYOUT FOR IMPROVING WIND COMFORT AND LIVABILITY IN ÜLEMISTE CITY,

supervised by Francesco De Luca and Jenni Vilhelmiina Partanen,

1.1 to be reproduced for the purposes of preservation and electronic publication of the graduation thesis, incl. to be entered in the digital collection of the library of Tallinn University of Technology until expiry of the term of copyright;

1.2 to be published via the web of Tallinn University of Technology, incl. to be entered in the digital collection of the library of Tallinn University of Technology until expiry of the term of copyright.

2. I am aware that the author also retains the rights specified in clause 1 of the non-exclusive licence.

3. I confirm that granting the non-exclusive licence does not infringe other persons' intellectual property rights, the rights arising from the Personal Data Protection Act or rights arising from other legislation.

______________ (date)

[1] *The non-exclusive licence is not valid during the validity of access restriction indicated in the student's application for restriction on access to the graduation thesis that has been signed by the school's dean, except in case of the university's right to reproduce the thesis for preservation purposes only. If a graduation thesis is based on the joint creative activity of two or more persons and the co-author(s) has/have not granted, by the set deadline, the student defending his/her graduation thesis consent to reproduce and publish the graduation thesis in compliance with clauses 1.1 and 1.2 of the non-exclusive licence, the non-exclusive license shall not be valid for the period.*

Table of contents

List of Figures

List of tables

Preface

I would like to thank my supervisor, professor Francesco De Luca for guiding me at times when I got lost in the vast simulation data and for steering me in the right direction.

My design solution and understanding of urban space issues would not be the same without the support of my co-supervisor, professor Jenni Partanen.

My sincere thanks go to the landowners and developers of Ülemiste City for giving me the opportunity to propose vision for the development and to Katrin Sulg and Mati Fjodorov for the materials and suggestions.

I am very grateful to my coursemates, Anna Solts, Ervin Golvih, Daniella Ljahh and Marta Volchek for the support and feedback.

And last, but not least, I am grateful for the moral support from my parents, my sisters, Oksana, Anna and Alesja and my friends Diana and Ksenia.

Abstract

Wind comfort plays a central role in improving the safety, livability, and resilience of urban environments. The modification of wind patterns by buildings can cause physical discomfort to vulnerable populations and can pose a danger. In addition to the height and location of the buildings and urban features, their shape and size have a significant effect on wind acceleration or mitigation.

A study analyzed four pedestrian areas (Lõõtsa park, Viktor Palmi square, Heath Centre park and Sepise pedestrian street) in terms of wind comfort in Ülemiste city. As the area is located on a plateau at the edge of the city and is surrounded by irregularly distressed buildings, the wind mitigation is poor. Now Ülemiste City is mostly an office district, but it aims to create residential spaces and provide dwellers with a pleasant and green urban environment. People want to spend time outdoors, so an attractive, safe and pleasant urban environment is crucial in the case of Ülemiste City development.

The aim of the research is to analyze four chosen pedestrian areas in terms of wind comfort and define the most critical wind conditions for each. Depending on the most critical direction of each area, a more accurate analysis of each was done to determine uncomfortable parts of the areas. Consequently, urban feature layout and design solutions were developed through a multi-stage process which involved simulations in evaluating the actual conditions and improvement of pedestrian wind comfort in the areas.

The investigation combined parametric design and CFD simulations to test a variety of wind shelter types and sizes and urban planning to incorporate them into the layout of open spaces. A Lawson wind comfort criterion was used to evaluate wind discomfort in the actual situation and the possibility of improving comfort with the shelter.

The initial urban design solutions showed significant improvements in the area provided with wind comfort conditions, with increments from 40 % to 83 %. The methods and results are presented in detail in the paper. The novelty of the work lies in the scarcity of wind comfort analysis in urban environments in the region and in the lack of proposals for urban design solutions to improve pedestrian comfort.

Annotatsioon

Tuulemugavus mängib keskset rolli linnakeskkonna ohutuse, elamismugavuse ja vastupidavuse parandamisel. Tuulemustrite muutumine linna keskonnas võib elanikele tekitada ebamugavust ja isegi olla ohtlik. Lisaks kõrgusele ja asukohale ning linnaehituslikele eripäradele on hoonete kujul ja suurusel oluline mõju tuule kiirenemisele või leevendamisele.

Uuringus analüüsiti nelja jalakäijate ala (Lõõtsa park, Viktor Palmi plats, Tervisekeskuse park ja Sepise jalakäijate tänav) Ülemiste city tuulemugavuse seisukohalt. Kuna piirkond asub linna servas platool ja on ümbritsetud ebaregulaarselt asuvate hoonetega, on tuule leevendamine kehv. Praegu on Ülemiste City valdavalt büroopiirkond, kuid selle eesmärk on luua elamispindu ning pakkuda elanikele meeldivat ja rohelist linnakeskkonda. Inimesed tahavad aega veeta õues, seega on Ülemiste City arenduse puhul oluline atraktiivne, turvaline ja meeldiv linnakeskkond.

Uurimistöö eesmärk on analüüsida nelja valitud jalakäijate ala tuulemugavuse seisukohalt ja määratleda igaühe jaoks kõige kriitilisemad tuuletingimused. Sõltuvalt iga piirkonna kõige kriitilisemast suunast tehti igaühe täpsem analüüs, et määrata kindlaks piirkonna ebamugavad osad. Sellest tulenevalt mitmeetapilise protsessi kaudu töötati välja linnaobjektide paigutus- ja kujunduslahendused. Protsess hõlmas endas simulatsioone tegelike tingimuste hindamisel ja jalakäijate tuule mugavuse parandamisel piirkondades.

Uurimine ühendas endas parameetrilise disaini ja arvutusliku vedeliku dünaamika (CFD) simulatsioone, et testida erinevaid tuulevarjude tüüpe ja suurusi, et lisada need avaliku ruumi konteksti. Tuule ebamugavuse hindamiseks tegelikus olukorras ja varjualuste mugavuse parandamise võimaluste hindamiseks kasutati Lawson'i tuulemugavuse kriteeriumi.

Välja töödatud linnaehituslikud lahendused näitasid tuulemugavuse märkimisväärset paranemist, kasvades selle 40%-lt 83%-le. Meetodid ja tulemused on üksikasjalikult esitatud töös. Töö uudsus seisneb tuulemugavuse analüüsi nappuses linnakeskkonnas regioonis ning linnakujunduslike lahenduste ettepanekute puudumises jalakäijate mugavuse parandamiseks.

1. Introduction

Ground-level air flow patterns depend on the interaction between wind with buildings and structures. The increase of high-rise structures led to struggles, discomfort and could even be dangerous on the pedestrian level (Gandemer 1978). The field of wind studies developed from simple and straightforward models to complex studies involving different data like climate and aerodynamics of buildings and structures (Davenport 2002). As the accuracy and complexity of the possibilities for the evaluation of wind studies constantly develop, more attention is being paid to the research of the topic. Best practice guidelines were developed for the use of Computational Fluid Dynamics (CFD) for the evaluation of pedestrian wind comfort (Blocken and Stathopoulos 2013). Latest trends are showing that people are becoming more aware of the surrounding environment. As nowadays cities are designed mostly according to best practices in the organization mechanisms such as street patterns, building typologies, and block structures, not much attention has been paid to the urban comfort and resilience. It is necessary to implement the resilience concept at an early design and planning stage as well as find solutions for existing urban structures to become more focused on the users of the space and their comfort around it (Chokhachian et al., 2017).

1.1 Concept of urban comfort and resilience

Architects design buildings as a protection from different climate conditions – rain, snow, wind, cold, and heat. Climate has a big impact on the building itself – the way it looks and how complex and multi-layered it is. The majority of used materials, structures, and typologies depend on the local climate conditions. However, the climate in architecture is not taken into account only for indoor protection or a way of reducing consumed energy by the building. The climate becomes a part of the newly-built environment, and the way it behaves and changes in it is unpredictable (Krautheim et al., 2014). Often much less attention is paid to what surrounds the building rather than the structure itself. As stated in City and Wind by M. Krautheim et al.: "These days the climate is mainly seen as something we need to protect ourselves against." (2014b). This brings us to the topic of urban comfort and resilience of the surrounding environment. Each new structure, building district or even smaller-scale change like planting new trees or remaking the existing urban space can become a totally new experience for the users of the space. The experience can be good – light breeze between buildings during summer, the warmth of the sun on a square during winter. The experience can also bring uncomfortable or even unsafe feelings

– accelerated wind in building corridors, overheated areas because of the usage of wrong materials or building mass or orientation. In conclusion, the climate around the built environment has a big potential for research and for finding ways to analyze it and suggest solutions for the improvement not only on the building scale but also in the scale of pedestrian users of the outdoor environment created by modern architecture.

In the process of creating an architectural design project, the problem of mechanical wind effects on pedestrian comfort should always be considered. As the project has different stages, the wind comfort could also be analyzed in different ways. In the beginning phase, when the design is still conceptual, the assessment will be general and inaccurate, based on previous experience and tests. During the development of the design, the assessment also improves until a decision could be made – whether the significant problem of considering wind exists or not. At this stage project could be taken further to the simulation process for developing solutions (Lawson and Penwarden 1975).

The built environment has a big impact on the urban microclimate. Microclimate, in turn, is also affected by global climate change, which causes conflicts over the temperature, humidity, daylight, wind, and other microclimate elements. This could influence a lot the usage of urban space – how comfortable it is to spend time during different seasons and times of the day, how healthy is the surrounding environment air for humans and other living beings, how fluently is mobility organized, in which ways and for which activities the space could be used. This is the main reason why the analysis of outdoor thermal and wind comfort is becoming very important lately (Kastner and Dogan 2020b).

The usage of open urban space, in turn, influences city life from both the social and the economic aspects. To conclude, one benefits the other. A pleasant urban environment boosts the economy and social aspect of the city, which in turn benefits city development. There are many principles to create a pleasant urban environment in the city, such as high concentration and diversity of uses, human-scale proportions, various types of buildings and many others discussed below (Jone Johnson, 2020) (J. Jacobs, 1993). For the spaces to be even more attractive, memorable and used, it is crucial to pay attention to their microclimate. This brings the interest on the municipal and government level to study and analyze the existing built environment and find ways to make the surrounding microclimate more comfortable for city dwellers (Stathopoulos 2011).

1.2 Analyzed urban area

Ülemiste City is a business quarter near the airport of Tallinn and the lake Ülemiste. As the area is located on a plateau at the edge of the city, it is not protected from winds by any other building structures. Ülemiste City is a developing district of an old factory area called Dvigatel. In the present day, a lot of new high-rise buildings were built and are planned to be built there, which would be modifying, blocking, and accelerating the wind patterns causing struggles with pedestrian comfort around the area. The height of the buildings varies from around 3 meters for smaller structures and up to 45 meters for the new office blocks.

This study takes into account the current building layout and near-future developments. Four pedestrian areas were chosen for the analysis: 1) Lõõtsa park; 2) Viktor Palmi square; 3) Health Centre park; and 4) Sepise pedestrian street (Figure 1).

Figure 1. The four pedestrian areas used in a study, the actual and the new buildings (blue dots) of the Ülemiste City

Also, four new developments (marked with blue dots) were taken into account during the studies (Figure 1). The one in the Lõõtsa park area is Keevise tn 3, which got building permission in 2007. It is planned to be a 3-story building and 11.2 meters high. The second development located near Viktor Palmi square is Lõõtsa tn 1b office building. The project was done by Novarc architecture bureau; the architect was Ilmar Klammer. The project got building permission in 2020. The office building is 45 meters high and has 12 floors. The third development above the Health Center park area is the Sepapaja 10 building with mixed functions of office and residential. It is a development which also considers the historical part of the building and adds a new construction and value to it. The project was made by the Pluss architecture bureau and got building permission in 2020. The building is 44.9 meters high and has 12 floors. The fourth new development beside the Sepise pedestrian street considered in the study is located on Sepise 7, and the construction process of the building is almost finished. The project was made by the Pluss architecture bureau and got building permission in 2021. The building is 40.2 meters high and has 11 floors.

1.3 Research questions

The present study aims to analyze chosen pedestrian areas in the Ülemiste City district in terms of pedestrian wind comfort. The aim is to define the most problematic wind direction for each area, perform wind comfort analysis from simulations and define the most problematic space in each area. Based on this information, an urban feature layout proposal would be developed to improve pedestrian wind comfort in the areas.

The objective of the study is to answer the following research questions:

- How comfortable are the public areas in terms of pedestrian wind comfort?
- What is the most problematic wind direction for each area?
- Which are the design parameters of the wind shelters to provide wind comfort in the public areas?
- Which are the optimal layout configurations and architectural characteristics of the sheltering urban features to improve wind comfort and urban quality of public spaces?

To answer the research questions various studies were made. It was stated that the Ülemiste City district is not comfortable for pedestrians in terms of wind comfort, as the area is located on a plateau and open for the most incoming wind directions. Using the simulation tools selected areas were tested and the process and the result are presented in the current work. The structure of the research includes the analysis of Ülemiste city district areas and history and choosing the most used pedestrian urban areas. Areas were also chosen depending on the different urban situations, so the final outcome of the work could solve different possible wind problems in the area. The work includes analysis of overall urban space qualities and brings out qualities of the space which make it pleasant and willing to stay for the users. The qualities are consequently implemented in the design, combining comfortable wind shelter layout solutions with creating an attractive environment. Various simulations with different accuracy levels were made to analyze areas in terms of pedestrian wind comfort. The investigation integrated parametric design and CFD simulations through the plug-in Eddy in Grasshopper to test a number of wind shelter types and sizes. Different wind tunnels were used, cylindrical and rectangular, due to the different scales of buildings and shelters.

The paper presents an investigation of the potential of small scale elements for increasing wind comfort. Based on the results of the simulations, urban layout configurations were developed. To evaluate the current situation with the design proposal and select the best layout configuration and features new simulations were made. The novelty of the work lies in the scarcity of studies about the small scale potential of improving wind comfort and in the lack of wind mitigation studies in the region. As the analysis of pedestrian wind comfort and the possibility of creating wind mitigating elements was not analyzed in the Ülemiste City district before, the current work presents the analysis of the existing wind comfort situation considering a few new developments in the area. The study aims to consider existing problems, propose possible solutions which are easy to implement and raise interest and awareness in studying wind flow patterns in earlier stages of the urban design process. Shelter design, integration of pre-designed shelters and final layout solution, detailed simulation methods and evaluations are presented.

2. Background

2.1 Introduction to wind analysis

The beauty of the wind lies in the experiencing of the invisible. There is a difference between experiencing a light breeze during a warm summer day and distracting gust during stormy cold weather, still both cause people to experience emotions**.**

Differences in air barometric pressure cause wind. Changes in temperature affect these differences. When the air is warmed up, it rises up and creates an area of low air pressure. On the opposite, cold air is heavier and sinks, causing high air pressure on the earth's surface. As the earth is not heated evenly, there are plenty of areas with high air pressure and low air pressure. In general, air tends to move from the higher pressure areas to the adjacent areas with lower air pressure causing wind. The strength of the wind depends on the difference between the pressures, the bigger the difference is – the faster the air would be moving.

American architect Richard Buckminster Fuller once said "Don't fight the forces, use them!" (Krautheim et al., 2014b). In the human-built environment constructions masses, the height of the buildings and the urban layout cause different effects on the surrounding environment. Two major wind effects are the mechanical and the thermal effect. The mechanical effect of the wind represents the mechanical interaction between the wind and a person. The most serious effect wind can cause to a person is to blow him over and be a cause of injury. Mostly the wind can cause an unpleasant experience like blowing away a person's hat or an umbrella or just create uncomfortable conditions while spending time in the area. These criteria could be assessed by dividing comfort levels by a certain wind speed (Lawson & Penwarden, 1975).

Assessment of the thermal effect of the wind is more complex due to the interrelation of several climatic and environmental factors such as air temperature, humidity and radiant temperature, and physiological factors. A person could subjectively describe the thermal effect of the wind by his or her skin temperature. This, in turn, is controlled by a person's metabolism and current activity. Secondly, a person's clothing also impacts the experience (Lawson & Penwarden, 1975). The present work focuses on using mechanical effect as an assessment criteria.

2.2 Existing studies and literature review

Building aerodynamics has had a role in scientific literature since the 1960s due to the development and usage of better wind tunnel solutions that allowed researchers to precisely mimic the flow around structures. Numerous studies have been conducted mostly in the Wind Engineering community. Building aerodynamics is important in practically every sector of construction. With the proper tools and nowadays software indoor climate could be analyzed. For example, numerical modelling of the ventilating system and indoor microclimate of the building could be performed. Building aerodynamics is also used in calculating the force of the wind on the structure, rain and snow influence, convective heat losses, outdoor climate like microclimate around building structures and pedestrian wind comfort (Blocken & Carmeliet, 2004).

A great number of authors have stressed the necessity of a comfortable and safe wind environment around structures.

According to Lawson and Penwarden, two elderly ladies died in 1972 after being swept over by strong wind gusts near a high-rise structure (Lawson & Penwarden, 1975). Assessment criteria introduced by T.V. Lawson in his studies are also widely used nowadays (Lawson, 1978) and are considered as assessment criteria also in this study. Recognizing the significance of the outside wind climate, many city governments now mandate pedestrian wind environment assessments for significant building projects. Wind tunnel modelling was used in the bulk of previous investigations. CFD (Computational Fluid Dynamics) is a technology that has recently become accessible (Blocken & Carmeliet, 2004).

There is a difference drawn between wind's mechanical and thermal impacts. People are affected mechanically by the wind in a variety of ways, from feeling a gentle breeze on their skin to being blown over by a violent gale (Blocken & Carmeliet, 2004) (Blocken & Carmeliet, 2004).

As the field of the study was developing, many different assessment criteria were suggested, used and evaluated. Murakami et al. discovered that a steady wind of 5 m/s only causes little hair and clothing disruption and feeling of the wind on the skin, a steady wind of 10 m/s causes serious effects like hair being disturbed and fluttering garments, wind of 15 m/s causes very serious effect and starts to be dangerous, and a steady wind of 25–33 m/s blows individuals away (Murakami et al., 1980) (Blocken & Carmeliet, 2004). As Bottema stated in his studies, wind impacts are not often associated with wind discomfort. Pedestrian discomfort develops when wind effects become so intense and frequently occur that persons encountering such wind effects feel uncomfortable, grow annoyed and finally attempt to avoid them. An acceptable wind comfort criteria consist of a discomfort threshold and a possibility of exceeding it. A discomfort threshold is the lowest wind speed and turbulence level that causes discomfort (Bottema, 2000) (Blocken & Carmeliet, 2004).

Wind tunnel modelling was first used in the aviation sector before being used for builading aerodynamics. The wind tunnels utilized were particularly developed for aviation research, having a consistent wind speed and little turbulence over the tunnel portion. These aviation tunnels were used to make the earliest attempts to mimic building aerodynamics (Blocken & Carmeliet, 2004). Wind loading (pressure distributions) and the dynamic impacts of wind on buildings and structures were the focus of the early investigations in building aerodynamics and boundary layer wind tunnels in particular. Airflow around buildings and pedestrian wind environments were first given major consideration in the 1960s when architects and engineers were increasingly faced with the unsatisfactory wind condition around their constructions (Blocken & Carmeliet, 2004).

There are two types of methodologies for analyzing pedestrian wind conditions in wind tunnels: the point method and the area method. Quantitative data at certain points in the flow field is provided by the point method. The area method has the benefit of providing a comprehensive representation of pedestrian level wind flow over the whole area of interest. To create this type of visualization using point techniques, a very dense grid of measuring points and a lot of data processing would be required (Blocken & Carmeliet, 2004). Wind tunnel investigations can be replaced by numerical modelling using CFD (Computational Fluid Dynamics). The simulation process requires less time and is less expensive than wind tunnel modelling because it provides detailed wind flow at every point included in the analyzed area. The main disadvantage is that model validation is required before this tool can be used with confidence. Another disadvantage could be that the process still takes a long computational time for simulations, especially when high accuracy is needed (Blocken & Carmeliet, 2004).

Nowadays, many software tools exist that can analyze relevant environmental processes in an urban setting. There are different tools and methods to analyze indoor and outdoor comfort. Methodologies that are specialized in the examination of urban outdoor environments are ENVI-met, SOLWEIG, RayMan, and CitySim, which have some examples of microclimate solutions. Neither of these tools yet allows full-year simulations with suitable computation durations to use in architectural design solutions (Kastner & Dogan, 2021). Any simulation considering the whole year on a small scale microclimate level would become very time-consuming. There is a need for a novel, rapid approach for predicting microclimate at an acceptable size and with reasonable simulation times that can be included in design and planning software (Kastner & Dogan, 2021). As a solution to his problem, the Eddy 3D plug-in for Grasshopper uses a decoupled simulation technique in which just the most important factors for each climate are simulated. Physical processes that could be temporarily separated and do not need to be simulated at once are separated and calculated one by one. For example, this is the case for wind and solar radiation. For the wind simulations OpenFOAM software is used. Decoupled simulation approach allows running the engine with great precision and spatial resolution while saving substantial time and allowing for a year-long simulation (Kastner & Dogan, 2021). In the present study Eddy 3D is used for the simulation process.

2.3 Similar studies

Wind study on a pedestrian level is currently a developing area of study. Studying wind mitigation when the building design process is finished could create difficulties and be expensive and ineffective. A growing number of studies take wind into account from the start of the planning process or even before. Even in this case implementing wind mitigation into the architectural design could be difficult (Blocken & Carmeliet, 2004). Here, two examples of studies which considered small scale wind mitigation solutions are presented.

A study was developed to analyze windbreak screen shelters during the early stage of the design process. Two types of geometry were analyzed – regular and membrane. The study evaluated three different simulation software, which could be used at an early stage to understand the wind patterns around windbreaks. The tested programs were Autodesk Vasari, ODS-Studio, and ANSYS CFX. Observation included pre-processing of software usage like how easily operable the software is, how it visualizes the wind and also evaluated the results after the process was finished. In conclusion, Autodesk Vasari is better at observing large-scale wind phenomena over the whole shelter. Furthermore, the intermediate CFD tool ODS-Studio, which uses OpenFOAM software, may be more efficiently employed in a detailed depiction of wind interaction with design aspects. Finally, for the final verification of results, a more advanced CFD tool like ANSYS CFX may be added to the early design stage process (Moya Castro, 2015).

The second study analyzing wind in a small residential building district in Moscow used the fluid dynamics software package FLUENT. The aim of the study was to analyze current pedestrian wind comfort in the area, create various layouts of the windscreens and analyze the impact and improvement of the area. As a result, the solution shows the best placement of the shelters with a significant impact on pedestrian wind comfort. The study's findings also reveal that slight changes to the renovation plan, such as the placement of tiny architectural forms (windscreens), have a substantial impact on the comfort of the building area and are frequently the only option. Overall compliance with pedestrian wind comfort improvement has a big impact on people's living conditions (Poddaeva & Churin, 2021).

2.4 Urban wind patterns

City planning, the layout of the building forms, size and height of buildings, in particular, have an influence on the urban wind flow patterns. (Krautheim et al., 2014a, p. 71) Ground-level flow patterns are the outcome of a complicated response between the wind and the building masses. The position, size and height of the structures create different flows and pressure zones around buildings. In general, the larger an obstacle appears in relation to the wind scale, the bigger its influence on the velocities and directions of the flow (Gandemer, 1978).

As a result, the appearance of flows is caused by the mutual location of the high pressure and low-pressure zones (high pressure to low pressure). The wind causes overpressure distribution on the windward face of a large obstacle as a function of height, dependent on the vertical gradient of average speed. Furthermore, a flow descends along the windward face and forms a vortical roll when it meets the ground; strips of air are forced to pass around the obstacle, and low-pressure zones appear in the wake region (leeward side of the building), starting at the separation lines along sharp edges and essentially related to the speed at the top of the building. Due to arcades, under buildings, or around corners, the juxtaposition of air volumes at differing pressures causes very rapid local flows that are connected with violent eddies. Finally, the juxtaposition of structural elements can create wind deflectors that route air through restricted tunnels where flow is locally accelerated (Gandemer, 1978).

The main and the most problematic wind flow zones at the pedestrian level are the standing vortex and the sideway sweeps, which occur when the vortex stretches out and the flow separation occurs. The standing vortex is created when the flow is deviated on the windward facade to the lower pressure zones upward, sidewards and downwards. Downward air flows reach the ground and cause the standing vortex to occur when it meets the initial flow (Blocken & Carmeliet, 2004). Due to this, it is recommended to avoid entrances near the corners of the high-rise buildings. Besides the high wind speeds, sideway sweeps near corners also cause sudden wind direction changes. As the sideway flow is fixed by the facade direction, it meets the initial airflow, which has a different wind direction. Pedestrian paths and bicycle roads are also not recommended to be placed near high-rise building corners. If it is decided to create a recreational area around a high-rise structure, it is not recommended to place it in close proximity to the structure. If placed near a high rise building, a public recreational area should be designed with the air flows in mind. It is strongly recommended to study the air flows and create wind mitigating elements in the urban space around the building (Figure 2).

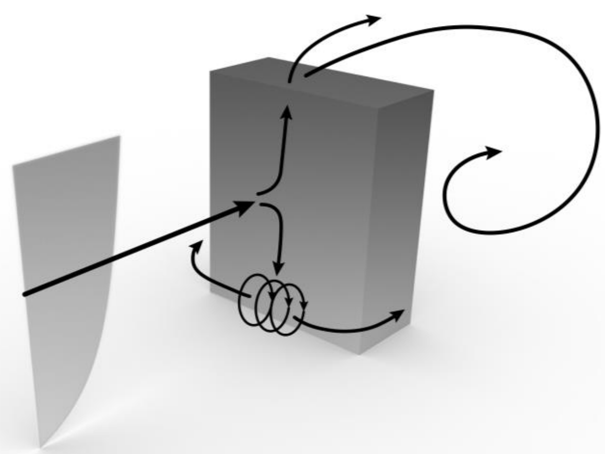


Figure 2. A schematic representation of wind flow around a single wide high-rise rectangular building

2.5 Ülemiste City

2.5.1 Location

Ülemiste City is a developing smart city district located in Tallinn, Estonia. It is situated in the south part of the Lasnamäe region near the Ülemiste lake, the airport, Ülemiste mall and the future location of the Rail Baltic station. Considering the city centre of Tallinn, Ülemiste City district is located toward a south-east part of the town. Ülemiste lake is toward the south-west and the sea is toward the north. The district is surrounded by Suur-Sõjamäe, Sepise, Keevise and Sepapaja streets.

2.5.2 History

Nowadays the modern quarter is sited at the location of the former factory called "Dvigatel", which means "Engine" translated from Russian. The company Dvigatel was founded in 1897 by Nicholas II, who was the last Emperor of Russia. The site was chosen carefully – on the one side there was a Tallinn – Tartu highway, on the second side a Tallinn – Saint-Petersburg railway. The existence of the slate mine was also considered an advantage because of the supply of the building material. With the help of 8000 workers, the factory was built in an incredible time – only nine months (Ojalo, 2020). In the surroundings, 220 buildings were built in a year. Dvigatel occupied 116 hectares, which were surrounded by almost 4 kilometers long and 3 meters high stone wall. With all the extra plots, the area reached 131 hectares (Dvigatel, 2021). In this way, Tallinn gained the largest railway plant in Estonia. The factory finally opened its doors in 1899 and started exporting thousands of railway carriages to the different sites of the Russian Empire (*Ülemiste City*, n.d.). In the early years, the factory produced different types of railway carriages. Afterwards, some orders like iron bridges, switches and crossings, trolleys, junctions and all kinds of metal spare parts were also produced. At the beginning of the 20th century, Dvigatel factory production was influenced by the economic crisis in Russia and World War I. After the Estonian War of Independence (1918 – 1920) economic relations between Russia and Estonia were interrupted and the number of employees at the factory was decreased by almost 90 percent. Factory maintained producing the materials for only a small Estonian market, which led to the most difficult times in its history. In the 1930s, Dvigatel production volumes began to increase. Different types of passenger and transport aircraft were made (Lausing, 2004). In the same years, the area near the factory develops into an airport with very heavy traffic at that time (*Ülemiste City*, n.d.). The full capacity of production could not be developed due to the interruptions of World War II. After the war, it was decided to rebuild the damaged plant and from there on the production varies from nuclear power equipment to milk drying equipment (Lausing, 2004). During the Soviet time in the 1950s, thousands of workers were brought to continue working at the factory, which caused the development of the plant's surrounding area. Many schools, kindergartens, residential areas, hospitals and cultural buildings were developed. When the Cold War started in 1947, the Dvigatel factory started to manufacture experimental technologies and equipment for the Soviet army and the space industry. The city dwellers of Tallinn did not know anything about the development which was taking place behind the high walls and concrete structures of the factory (*Ülemiste City*, n.d.). After the collapse of The Soviet Union and the re-independence of the Republic of Estonia, the Dvigatel factory was privatized and divided into subsidiaries. The focus of the production turned more and more toward the European market (Lausing, 2004). Dvigatel became an industrial park where activities continued in the form of industry, commercial activities and also the leasing of land to other companies. Soon there were already 180 companies, institutions and organizations operating in the area and 1 500 people were working there. The connection of the industrial park previously separated from the city also became an important topic for Lasnamäe district and Tallinn to discuss and develop (Sekavin, 2018). After a few years, the company was privatized by Mainor AS. In 2005 Mainor's leader and visionary Ülo Pärnits had an idea to develop the abandoned district into a smart business campus to promote the Estonian economy and society. Thus Ülemiste City started to grow (*Ülemiste City*, n.d.). Developers divided the area into two major blocks. One was an innovative business district. The second one – is a high-tech production quarter. Many innovational media, IT, telecommunication and technology companies were welcome to join the district life. The plan was to create an incubation centre, office hotel and support system. In the year 2008, Ülemiste City park was opened, which also supported the idea of involving the Lasnamäe region and Tallinn back in the area, which was restricted the years before (Sekavin, 2018). In 2010 Technopolis Plc joined the smart city development. These two leading companies started to elaborate strategies for the district to grow and evolve. Ülemiste city became a member of the network of business districts in the Nordic countries and the Baltic States. Ülemiste City has been rapidly developing. On the site of a former factory thousands of people have offices and working spaces. Additionally, in 2018 began the construction of the first homes (*Ülemiste City*, n.d.). The aim of Ülemiste City is to upgrade all 36 hectares into a smart city with a convenient, modern and largest knowledge-based economic environment in the Baltics. The owner companies Mainor AS and Technopolis Plc are open to innovations and bright ideas to make the Ülemiste City experience for its habitants unique and pleasant (*Mainor Ülemiste*, n.d.). In the future plans, the strategy sees Ülemiste become a fully functioning independent city and a gate to Estonia, where the airport, Rail Baltic terminal and Tallinn-Helsinki tunnel meet. By the year 2025, the aim is to provide 20 000 people with a living, work and study places. There would be 400 companies and 10 000 workplaces (Sekavin, 2018).

2.6 Wind discomfort in Ülemiste City

Ülemiste City is located in the south-east part of Tallinn. The district lies on the outskirts of the city. The district is located on a plateau. The ground height of the area varies from 40 to 47 meters above sea level (*X-GIS 2.0 [Maainfo]*, n.d.). To the south from Ülemiste City Tallinn airport is located. On the south-west and west part of the district there is Ülemiste lake. The area to the south of Ülemiste City is also located lower, at 37 to 40 meters above the sea level (*X-GIS 2.0 [Maainfo]*, n.d.). According to the weather data used in the studies, the most frequent wind in Tallinn is from the south, and one of the strongest directions for the wind is west (*Climate.Onebuilding.Org*, n.d.) (*EST_HA_Tallinn*, n.d.) (Figure 3).

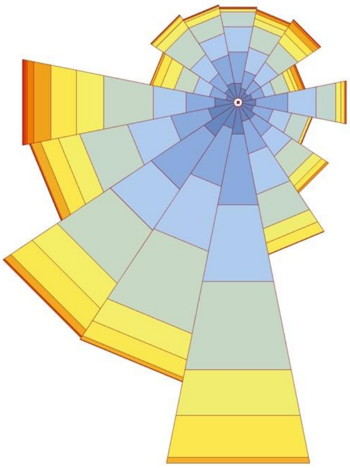


Figure 3. Wind rose from weather data used in studies

As mentioned above, there are some irregularly distressed buildings located to the south or south-west from Ülemiste City, so wind mitigation is poor. As the district is developing, new high-rise buildings are being built, and the problem of wind discomfort on a pedestrian level appears. High-rise buildings require special solutions and methods to create safe, pleasant and attractive surroundings around the building, as they tend to create vortexes and accelerate the wind on a ground-level around themselves (Blocken & Carmeliet, 2004). The layout of buildings creates even more complex wind patterns in the area (Figure 4).

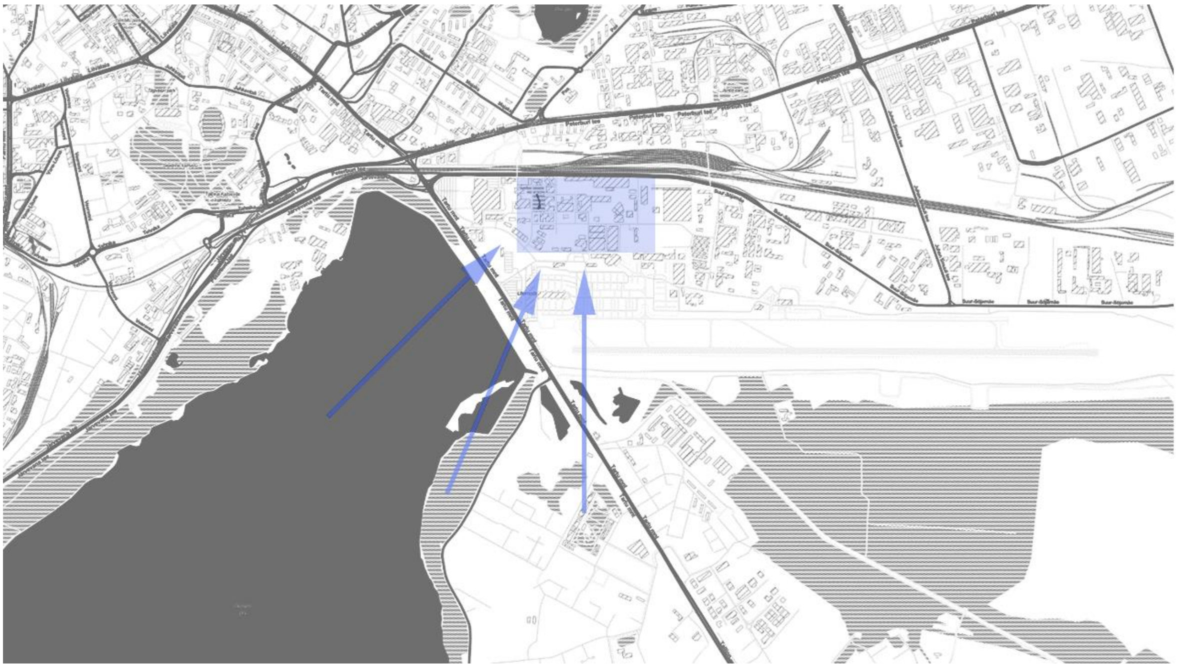


Figure 4. Situation plan of Ülemiste City district

2.7 Urban comfort of the public space

Perception of the city is formed significantly on the basis of the quality of surrounding public spaces. Whether the experiencer is a common dweller familiar with the surroundings or a tourist who gets involved in the city life and culture for the first time, the impression of the city is mainly based on the urban space (Pacheco, 2017). A lot of great public spaces are known worldwide and define the city by being good attractions and landmarks. They create an opportunity for people to socialize, often include many additional functions like sport, skateboarding, meeting for an outside lunch or a picnic, pleasant spaces for sitting and reading or just enjoying the view and good weather or could even be decent places for creating an improvised outdoor event. As the cities are constantly developing and becoming denser great public spaces provide people with a sense of freedom and an opportunity to escape from domestic confinement (Lutyens, 2020).

Streets in the city serve more functions than just being routes for traffic and places for technical equipment like sewers and electric cables. The communication and ability to get to the destination as well as the opportunity to conveniently access the public or private property and transport commodities and goods is undeniably the major purpose of the streets. But still, other roles such as safety, a comfortable urban environment and possibilities for communication should also receive attention and development to create pleasant urban surroundings for pedestrians (A. B. Jacobs, 1993a).

The comfort and safety of dwellers depend on the shape, form and organization of the streets. As the streets bring users an outdoor experience, their size and position are also important in terms of daylight and shading they would bring (A. B. Jacobs, 1993a).

In the urban environment not only solar radiation plays an important role in pedestrian comfort, but as the city grows and forms, the wind is also becoming an issue. Different positions of the streets and building configurations could create different situations in terms of pedestrian wind comfort. Building masses could accelerate the wind, cause vortical rolls or induce rapid local flows (Gandemer, 1978). As one of the aspects of comfortable urban space, wind comfort should also be analyzed.

The streets of the city are always living and being in a constant movement. They are a place to see and a place to be seen in. Moving past strangers, meeting your friends, seeing different scenarios and experiencing different emotions which are not always pleasant, but they still require to take a pause and think for some time about the life of other residents you meet. Whether it is a lovely couple, a mother with a child, a businessman or a homeless person, streets unite and create possibilities for interaction between people.

Besides communication functions, streets also serve informational and business purposes and create places to spend time in. Street facades could be interactive and used for exhibiting goods or services (A. B. Jacobs, 1993a).

They could also be extended and provide a possibility for a café or a restaurant to create a terrace for people to spend time in and enjoy a cup of coffee or a meal outside.

Streets also provide a possibility to display advertisements and catch the interest of people walking by. Streets could be analyzed in terms of physical elements filling the street, visual qualities of the surroundings, the behaviour of the dwellers and their activity preferences. All the studies contribute to improving the quality, accessibility, functionality and livability of the streets and common public areas. However, the qualities of the space are experienced by the inhabitants in an empirical manner. This leads to diverse opinions based on the difference in experience, background and cultural context of the viewer. There are still some common aspects that could be obtained and applied, which are common to human perception. The problem is that the most discussed characteristics of the space appear to be abstract and are hardly adaptable to real-life scenarios (Meetiyagoda & Munasinghe, 2009).

City streets shape the form, structure and comfort of an urban environment. The street is one of the main public places where social interactions take place. According to Allan B. Jacobs, great streets are the ones that have magic in them (1993). However, it is hard to define what is responsible for this magic without taking a further look at some of the great streets as an example. The grandness of a certain street could be defined through the relation between human activities and the physical environment. The way people interact with the surrounding space is the key aspect to defining physical characteristics that can be designed to improve the quality of the space. People often visit certain places and enjoy them more than others because of their physical characteristics or because of the activity and tranquillity they find there (A. B. Jacobs, 1993b).

One of the most certain and important criteria for creating a great street or any public space is that it should provide opportunities for the creation of a community. This means that the space should be accessible, easy to orient in and open for everyone. In terms of physical characteristics, a large street is a convenient and safe place (A. B. Jacobs, 1993b). It provides enough possibilities to combine different types of transport, have separate routes for pedestrians and bicycles, and create active facades, so, for example, cafes could create a pleasant terrace space. Still, a large street should be separated into more human-scaled divisions, otherwise on a large street with heavy traffic humans would feel vulnerable and left out. Only if a large street is functional for pedestrians and creates smaller-scale areas, which consider and create a possibility for communication and spending time, then it should be called a great street.

The second aspect of the so-called magic of the great streets is the functionality they offer. The more functional the street or a square is, the better it is. All streets have their own environment depending on which functions are performed. As cities develop, the environment around streets changes, so the streets change too (A. B. Jacobs, 1993b).

Furthermore, streets evolve. They are continually tinkered with. Every shift provides an opportunity for growth. If we can develop and design streets to be magnificent, rewarding places for community-building and appealing public spaces for all people, we will have successfully planned about one-third of the city and had a huge impact on the rest. As a result, studying the physical, designable, and buildable aspects of the best streets—the great streets—is critical in our pursuit of good and meaningful urban spaces (A. B. Jacobs, 1993b).

2.7.1 Examples of great streets

There are some of the examples of great streets presented in "Great Streets" by Allan. B. Jacobs (1993). Roslyn Place street is a small street located in the Shadyside neighbourhood in Pittsburgh, Pennsylvania. It was built in 1914, and the street is about 75 meters long and 20 meters wide. The street is wooden-paved, which already makes it stand out as something that creates a unique experience. The dimensions of the street and structures with similar appearances create a safe, cosy and welcoming feeling as people walk there. A friendly neighbourhood creates a feeling that you want to move there and live there. As discussed above, a large street could create a feeling of safety and convenience, but if we look closely at Roslyn Place, the street itself is not large, though it means that pedestrians do not have to worry about high speeding cars and are provided with a sense of seclusion and intimacy. As the first floors and gardens are open to the public, this creates an inviting environment and a possibility to contemplate those in public (A. B. Jacobs, 1993b).

In Estonia Julius Kuperjanovi street in Tartu could be named as such an example. The street is about 570 m long and about 20 m wide. Part of the street (approximately 300 m long) where cars move is stone-paved, which prevents cars from exceeding the speed limit, so the traffic is not disturbing to the pedestrians. On one side of the street, there is a park, and on other side of the street there are two to three-storey houses. Most of the houses are from the end of the 19. century with a unique architectural appearance. The street ends with the Tartu train station building from 1876 (*7013 Tartu Raudteejaama Hoone*, n.d.).

The overall surrounding architecture, the stone-paved road, trees that separate car road from pedestrians, green park and some small-business shops and cafes on the ground floor create a pleasant experience and cosy environment when spending time on the street.

Two great examples of the streets from medieval times could be Via dei Giubbonari in Rome and Stroget street in Copenhagen. Both streets are pedestrian with active facades towards the street with many shops and cafes, being a good experience for users and a great destination for visiting tourists. They are both old elongated medieval streets, which usually wind at least a little, are relatively narrow and have a certain halo of mystery. The facades of the buildings on both streets are rich in detail. Both streets are open to everyone, which creates a possibility for all people to come together. There is no curb separating cars from pedestrians (A. B. Jacobs, 1993b).

There are also great examples of similar streets in Tallinn Old Town, such as Viru street on Suur- and Väike-Kaarja streets. Similarly to the examples from before, streets have active facades and are pleasant to walk in. There is a curb separating cars from pedestrians, but as the car traffic in the Old Town is very limited, people often walk on the car part and it is mostly considered pedestrian with some exceptions.

One opposite example is Via del Corso street in the historical centre of Rome. The street was conceived as a memorable and special public street, although the proportions of the street are not the best possible. The height of the surrounding buildings can become oppressive. The noise and traffic in combination with narrow sidewalks also contribute to the lack of comfort (A. B. Jacobs, 1993b).

Analogue experience for pedestrians in Estonia could be Luise street in Tallinn city centre. Pedestrian parts of the street are narrow and the traffic through the street is dense at almost any time of the day. The surrounding buildings are lower compared to the ones on Via del Corso, yet still could seem oppressive for the pedestrians.

To conclude, the street should have something special in itself, and not because of certain historical buildings, a square, or an isolated event taking place on the street. These could only add value, but the street should be inviting and safe by itself. The dimensions of the streets and the possibility for interaction with active facades are very important.

2.8 Public space

Public spaces, which bring life to the urban voids, are inextricably linked to the creation of what the city is called and have an impact on the connections that are developed inside it. They create an identity of the city. Neighbourhood community bonds are shaped by public spaces. They are meeting spaces that can engage with political mobilization, actions, and crime prevention. They are places where people may interact and exchange ideas about how to improve the quality of the surroundings. Cafes, small shops, and bars, while not called "public areas," have similar effects. Public spaces also provide physical and mental health benefits: people feel better in a safe environment and in more active and attractive public spaces (Pacheco, 2017).

The way common areas are built, controlled, and used is reflected in a place's culture, structure, and social hierarchy. The more diverse and active urban environments are, the more egalitarian, prosperous, and democratic society develops, as Ben Rogers shows out (Brown et al., 2017). This claim is founded on the definition of public space, which is open for everyone, democratic and with a free access location (Pacheco, 2017).

A great public space represents diversity and inspires users to live together in harmony while also providing the necessary circumstances for permanence and inviting people to be out on the streets. People are drawn to locations because of their energy. The ability to appreciate urban areas in a variety of ways ensures this vibrancy (Pacheco, 2017).

Project for Public Spaces is a non-profit organization dedicated to assisting individuals in creating and maintaining public spaces. The aim of the organization is to observe, experience, collaborate and create places for everyone and by everybody. To create a beautiful outdoor experience, bound people and make them lose track of time in urban space (*Home — Project for Public Spaces*, n.d.).

Project for Public Spaces points out ten criteria for a good public space, in other way, areas just become routes for passing by and do not create a will in people to stay. With more urban vitality, the presence of quality and accessible public places will boost the feeling of security and functionality of these spaces (Pacheco, 2017).

In a two-way street people would spend time, if they would feel safe, same works otherwise – the more people start using the street, the safer the environment gets.

Below are ten principles to consider while designing a high-quality public area. The aspects are interconnected — active facades and human-scale structures, for example, are intimately linked to local economic development. It is the combination of these factors that will ensure that people have access to open, egalitarian, and safe venues.

1. **Variety of uses:** The more functional area is, the more attractive, nice and safe it seems for people. When there are residential, office, and commercial uses mixed together, when the space is surrounded by restaurants, cafes and bars, small shops and services, people have more reasons to go there and are likely to stay. External activities contribute to the safety of places – crime level is reduced when there are

more people on the streets. However, it is important to create a diversity of uses which covers all hours of the day. If the venues are inviting and bustling only during the day, they will be dangerous at night. Planning public areas in a way that promotes human coexistence and constancy is also a form of security investment (Pacheco, 2017) (Brown et al., 2017).

2. **Active facades:** A big contribution to the attractiveness of public space is the relation between the street, sidewalk and ground level of the surrounding buildings. People use streets that are visually more fascinating more frequently. Furthermore, this relationship has an impact on people's perceptions of the city and how they use it (Pacheco, 2017) (Brown et al., 2017).
3. **Social dimension and urban vibrancy:** Public space has an impact on the social dimension because it serves as a gathering place for people. Spacious wide streets with access for everyone, cosy parks and squares, comfortable sidewalks, availability of bike routes and functional urban furniture encourage people to connect with the environment, make better use of space, and boost urban life. It is critical to include the outskirts in addition to high-density metropolitan regions, ensuring appropriate public spaces for the population that is not from the city centre (Pacheco, 2017) (Brown et al., 2017).
4. **Human scale:** Dense and very high scale surroundings can have a negative impact on people's health. People enjoy walking through lively and active environments rather than empty and inactive ones. Pedestrians also try to pass those quickly. People's impressions of public areas are improved by human-scale structures because they believe they were considered during the planning process (Pacheco, 2017) (Brown et al., 2017).
5. **Lighting:** Efficient lightning, which considers human-scale, makes it easier to use public spaces at night improves safety and provides obligatory conditions for moving when there is no natural light (Pacheco, 2017) (Brown et al., 2017).
6. **Stimulating local economy**: Walking and cycling are encouraged by the safe and pleasant environment, allowing for simple access to local commerce and stimulating it.
7. **Local identity:** Large businesses help the local economy in general, but they do not pay attention to the surrounding neighbourhood. Local enterprises otherwise create a character for the place, contribute to its personality and identity and have a long-term impact on the community (Pacheco, 2017) (Brown et al., 2017).

8. **Complete streets:** This idea refers to the streets that are built to enable the safe movement of all users, including pedestrians, cyclists, car drivers and public transport users. A complete street should include things like well-maintained sidewalks, bicycle infrastructure, street furniture, and signage for all users (Pacheco, 2017) (Brown et al., 2017).
9. **Green spaces:** Greeneries in the city environment have a great impact not only on the air quality but also influence the area's microclimate in a good way. Green parks and urban spaces tend to attract people and create a pleasant outdoor environment to spend time in, as well as overall reduce stress levels and improve city well-being. Furthermore, trees, plants, and flowerbeds are important for urban drainage and biodiversity (Pacheco, 2017) (Brown et al., 2017).
10. **Social participation:** As every neighbourhood has its own unique appearance and identity, it is mandatory to involve its inhabitants in the planning process. The more community contributes to the surrounding space, the more people feel like a part of the space which was not created for them but rather by them, the more valuable space gets, and the more natural usage is created. Space will not be used or maintained if it does not represent the needs and preferences of the local community. The building of safer, more equal public spaces requires social engagement (Pacheco, 2017) (Brown et al., 2017).

2.9 Studied areas

Four areas in Ülemiste City are chosen different in proportions, surroundings and experience of the space. There are two parks, a pedestrian street and a square (Figure 5).

Lõõtsa park is the biggest park in the surrounding. In the middle, there is a small pond, and in the northern part of the park, there are plenty of trees. Such an area is good for a change to the built office district around. In terms of good urban space, the park creates a pleasant impression and invites pedestrians. Surrounding buildings have an active facade toward the park – there are some cafes and small shops near. A lot of activities for Ülemiste City users are held in the park, which encourages people to socialize and also spend time outdoors. There are also a lot of small-scale elements in the park, like benches, small tables and other outdoor furniture. A lot of people go there for lunch during the warmer season.

Health Centre park, on the other hand, is a lot smaller yet still brings green space and vegetation inside the urban surrounding. In the park, there is a terrace space, a small pavilion for outdoor office space and some hammocks to rest in. In this way park also provides possibilities for people to spend time and socialize. The disadvantage of the smaller park is the big parking space near it, which can be noisy and distracting.

Viktor Palmi square is a quite new development. There is a bus stop near, and some benches and trees in the area. As the area is open from the east side (there is a plan to build a building there in the near future, but currently, there is a huge parking space), it is hard to experience a feeling of a square in the space. In such a big open space with a lack of functions to stay or a lack of a pleasant and more divided and intimate place to spend time, people are not using it that much. There is a possibility that new building development would improve the situation.

Sepise pedestrian street is a good example of a pedestrian street. It has active facades with cafes and restaurants with terraces, plenty of urban furniture and some vegetation. As the two buildings on the western side of the street are high-rise buildings (one currently under construction), the street lacks microclimate comfort and a pleasant urban environment for pedestrians. Buildings create a wind corridor and accelerate the wind within the area.

Figure 5. Photos of the areas: Lõõtsa park (up left), Vuktor Palmi square (up right), Heath Centre Park (down left), Sepise pedestrian street (down right)

3. Aim of the study

The study aims to attract attention to pedestrian wind comfort in urban areas in Estonia. Ülemiste City district was chosen as the study area for the evaluation of pedestrian wind comfort. Due to the location of the district and the fast development and building process of new high-rise buildings, Ülemiste City struggles with the problem of pedestrian wind comfort. As the area is located on a plateau at the edge of the city and is surrounded by irregularly distressed buildings, the wind mitigation is poor. Now Ülemiste City is mostly an office district, but it aims to create residential spaces and provide dwellers with a pleasant and green urban environment. People want to spend time outdoors, so an attractive, safe and pleasant urban environment is crucial in the case of Ülemiste City development.

As Aristotle said, "We can't change the wind, but we can adjust the sails." (Krautheim et al., 2014b). The study deals with an already developed environment considering some of the future building development. The aim of the research is to analyze four chosen pedestrian areas in terms of wind comfort and define the most critical wind conditions for each. Depending on the most critical direction of each area, a more accurate analysis of each was done to determine uncomfortable parts of the areas. Consequently, urban feature layout and design solutions were developed through a multi-stage process which involved simulations in evaluating the actual conditions and improvement of pedestrian wind comfort in the areas.

4. Methods

In this study, a methodology consisting of several steps was developed to investigate pedestrian wind comfort in Ülemiste City. The method includes several simulation processes with different aims and accuracy levels. The information from initial simulations was used to develop design solutions, which then were involved in a second simulation process to evaluate the improvement of pedestrian wind comfort.

4.1 Parametric design workflow

For the current work, the building three-dimensional models used for the simulation was realized in Rhinoceros (*Rhinoceros 3D*, n.d.). The simulation process and parametric modelling were realized in Grasshopper (*Grasshopper*, n.d.). The EnergyPlus Weather File (EPW), which contains weather data measured in Tallinn, Estonia (*EST_HA_Tallinn*, n.d.) was used for the wind simulations using the grasshopper plug-in Eddy3D (*Eddy3D*, n.d.) (Figure 6). The file was obtained from the repository, which was specifically created to contain climate data files and support the building simulation process (*Climate.Onebuilding.Org*, n.d.). The data contained in the weather file is measured at the airport of Tallinn, close to the Ülemiste City district. Eddy 3D uses OpenFOAM software Blue-CFD for the simulations (*Eddy3D*, n.d.). The data relative to the wind used from the weather file was the annual hourly wind speed and direction. Simulations were done using best practice guidelines for the CFD simulation of flows in the urban environment (Franke & Baklanov, 2007).

*Figure 6. Software used for the studies (*Rhinoceros 3D*, n.d.), (*Grasshopper*, n.d.), (*Eddy3D*, n.d.)*

Eddy 3D plug-in for evaluating wind comfort comprises several components, which allow to create different types of wind tunnels and set the necessary CFD parameters.

First, a cylindrical wind tunnel and simulation domain, which analyzed 16 wind directions, or a rectangular wind tunnel, which analyzes wind specifically from one direction, were created, and then simulation parameters were defined.

A fixed wind velocity of 5 m/s at the wind tunnel inlet at 10 m height was used. Terrain roughness component Z_0, which defines what type of area is surrounding the modelled environment. There are several types of effective terrain roughness according to the Davenport classification. Terrain roughness z_0 = 0.0002 represents a flat plain or open water or lake for more than 3 km of the surrounding. Terrain roughness Z_0 = 0.5 represents an intensively cultivated landscape with several rather big obstacle groups, like farms of parts of the forest. Terrain roughness Z_0 = 1 represents an urban landscape with similar objects located at uniform distances, like a town. Also, this terrain roughness could be used to identify forest areas (Aguilar et al., 2003). The current study uses terrain roughness Z_0=1. The simulation also requires building geometry component.

After the geometry and boundary conditions are defined, the simulation domain requires the size of the tunnel and the accuracy of the simulation grid to be defined. In the case of a circular wind tunnel, the height of the tunnel was 10xheight(max), which means that the height of the tallest building multiplied by ten defines the height of the tunnel. In the case of a rectangular wind tunnel, the height of the highest building involved in the simulation is multiplied by 5, so 5xheight(max) (Kastner & Dogan, 2020). The size of the circular wind tunnel was defined by the modelled building geometry. This means that from the most outer modelled building to the external boundary of the cylindrical tunnel mesh, the distance was 15xheight(max). In the case of a rectangular wind tunnel, on the windward side, from which wind enters and on both sides, the distance from the outer modelled building to the edge of the rectangular wind tunnel was 5xheight(max). The leeward side distance was 15xheight(max) (Kastner & Dogan, 2020). For each simulation 2000 iterations were used for the simulation process. The probing of the simulated wind velocities was done at the height of 1.5 meters to evaluate pedestrian wind comfort. A circular wind tunnel had a grid in size of 3 x 3 meters, and a rectangular wind tunnel had a grid in size of 0.6 x 0.6 meters to perform wind simulations using urban features where more accuracy is needed to the smaller size comparing buildings.

4.2 Wind analysis

A parametric design workflow was developed to analyze pedestrian wind comfort in different urban layout situations through Computational Fluid Dynamics (CFD) and the Tallinn statistical wind velocities and directions obtained from weather data. For the study the Eddy plug-in (*Eddy3D*, n.d.) for Rhinoceros/Grasshopper (*Rhinoceros 3D*, n.d.) (*Grasshopper*, n.d.) was used (Dogan, n.d.).

The wind analysis was performed in three steps. In the first step, CFD wind simulations were performed for a large area encompassing the three pedestrian areas and their surrounding buildings, using a cylindrical wind tunnel (Kastner and Dogan 2020a) considering 16 different directions. In the second step, the simulated wind patterns and velocities as modified by the buildings were used to determine the most critical wind direction for each area. Most of the buildings in the area are offices, so the time frame for pedestrian outdoor wind comfort was considered was from 8 a.m. to 6 p.m. In the third step a rectangular single direction wind tunnel was used from the most critical wind direction of each area with a smaller mesh size to obtain more accurate wind simulation results to study each area separately and more precisely. The same wind tunnel was then used for the simulations including the urban features used as wind shelters.

4.3 Wind comfort assessment

4.3.1 Lawson LDDC & evaluation

To evaluate pedestrian wind comfort, the Lawson assessment criteria was used. More specifically, the version developed for the London Development Dock Corporation (LDDC) of the Lawson wind comfort criteria was used. This is the de-facto industry standard wind comfort assessment criteria in the UK and other countries. It defines a wind speed which is comfortable for a certain activity considering and maximum exceedance of 5 % of the time (Lawson, 1978). The wind comfort of the area is assessed at 1,5 m above the ground to determine the wind comfort of the pedestrians. According to the activity pedestrian is involved in, there are different comfort levels he could experience. The Lawson comfort criteria provides certain thresholds for the wind speed for a certain activity. The wind speed in each threshold can be exceeded only for 5% of the time throughout the year to not take into account infrequent wind events (Jenkins, 2021) (Lawson & Penwarden, 1975). Following, the activity and according to wind speed threshold used for the studies are presented (Table 1).

Table 1. Lawson LDDC wind comfort criteria

Wind speed	**Occurancy**	**Activity**
< 4 m/s	< 5%	Sitting
≥ 4 m/s	< 5%	Standing
≥ 6 m/s	< 5%	Walking
≥ 8 m/s	< 5%	Business walking
≥ 10 m/s	> 5%	Uncomfortable for every activity

4.4 Design of the test shelters

The aim of the study is to investigate possible shelter solutions to design comfortable pedestrian areas for the users of Ülemiste City. To accomplish these different shelter forms were developed to be analyzed individually and then modified according to the needs of the urban spaces. Three different wind shelter types were developed: Comfort Island, Permanent shelter, Half-shelter, Operable shelter and Textile wall adjustable shelter.

Each shelter was tested using CFD wind simulation through a rectangular wind tunnel, without any surrounding structure, with different wind velocities to evaluate the area of comfort it allowed depending on the size and height of the shelters. It was decided to create three sizes of each shelter type to evaluate the size of the created comfort area depending on the wind conditions and the size of the shelter.

'Comfort Island' is the biggest type characterized by a moon shape and is inspired by the traditional protection of vines from constant wind in Lanzarote, where the landscape is used to protect plants from the wind (Krautheim et al., 2014a). The concept of the structure was to implement the shelter in the surrounding public areas. The created slope could be covered with vegetation and even smaller trees or bushes, which would add even more protection in terms of the wind. The area protected from the wind space in front of the shelter has a round shape. The structure could be covered with wooden material to create a cosy feeling while being inside. The structure is spacious enough to allow creating different functions and allowing different activities. For example, outdoor office space could be created, a playground for children could be placed there or an outdoor gym. It is also possible to place this type of shelter in built environments like squares or urban parks. This way it could create a separated, more intimate space to spend time in and also bring greenery into the surrounding. The shelter was designed parametrically, allowing to create a more sharp or more rounded structure and change the height, width and length of the shelter. It was designed with the thought of Lõõtsa park in Ülemiste City, as it is the biggest green area which could fit this type of shelter. Also, the landscape in the park is designed in a way that it already creates some small hills in the area. As already mentioned, the size of the shelter varies to evaluate the comfort area created by the type. The smallest tested version is 15 meters wide and 12 meters long, and the height of the structure is 3 meters. The middle shelter size is 18.3 meters wide and 15 meters long, and 4 meters high. The biggest tested shelter is 21.5 meters wide, 18 meters long and 5 meters high (Figure 7).

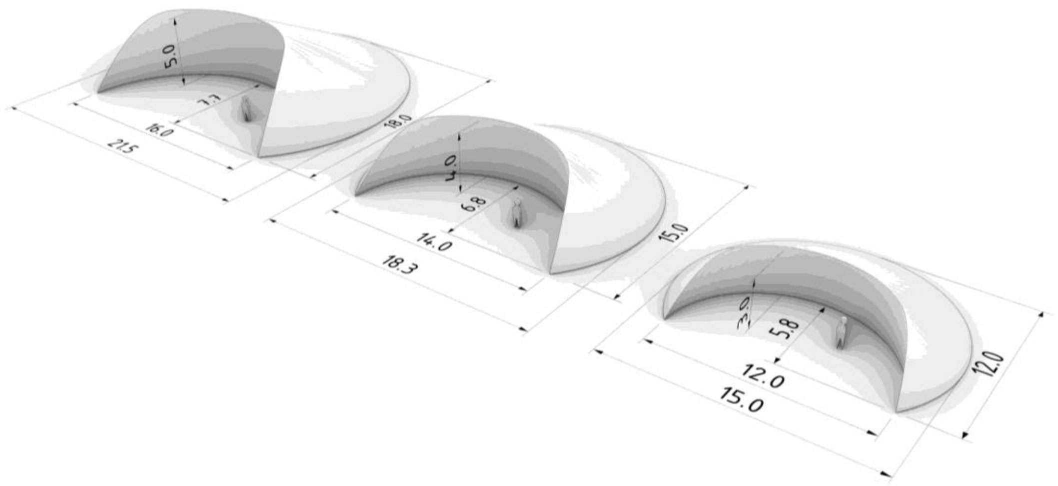


Figure 7.Comfort Island shelter sizes

'Permanent shelter' was modelled to create a half-closed space with a roof structure above to protect also from direct sun during summer and rain. The design was inspired by the industrial past of the Ülemiste City district when it was used by the Dvigatel plant, the largest railway plant in Estonia (*Ülemiste City History*, n.d.). The structure was designed from bent metal beams, which represent the rails. Between the metal beams a glass or a textile structure could be placed to create protection from the wind yet allow to see through the structure. The shelter was created with the possibility to use it for providing comfortable space for pedestrians while waiting for a bus at the bus stop or for the protection of restaurant terraces. The size of the shelter also provides a possibility for creating different functions inside. For example, a small pavilion with seating spaces could also be used as an outdoor office. The smallest tested version, which could be used as a bus stop pavilion, for example, is 6 meters wide, 4.2 meters long and 3 meters high. The middle version is 8 by 5.7 meters, and the height is 4 meters. The biggest size involved in the simulation is 10 by 7 meters and 5 meters high (Figure 8).

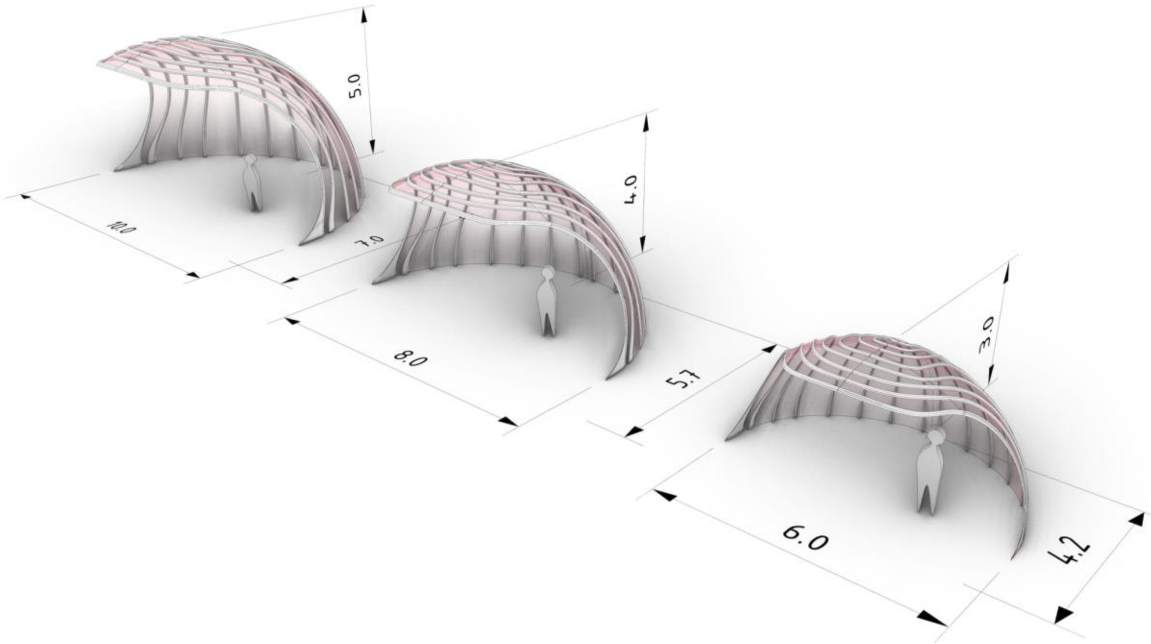


Figure 8. Permanent shelter sizes

'Half-shelter' is similar to the permanent shelter type. One of the problems that the mechanical effect of the wind could create is the opening of the door. Especially entrances in narrow corridors surrounded by high-rise structures are affected because of the acceleration of the wind. In the case of Ülemiste City, one of the areas – Sepise pedestrian street – has a similar problem. With this in mind, half shelter type was created. The construction is the same as in the permanent shelter – metal beams with glass or textile, the difference is that only half of the structure is used. The structure is built against the wall in front of the entrance, providing wind shelter for those who enter and leave the building. Similarly to the other shelter types, three different sizes of the shelter were tested. The difference was that this time simulation included building structure against what the shelter was built. The smallest version of the shelter is 3 meters wide, 4.5 meters long and 3.1

meters high. The middle structure is 4 by 5.9 meters and 4.2 meters high. The biggest tested size of the shelter was 4.8 meters wide, 7.1 meters long, and 5 meters high (Figure 9).

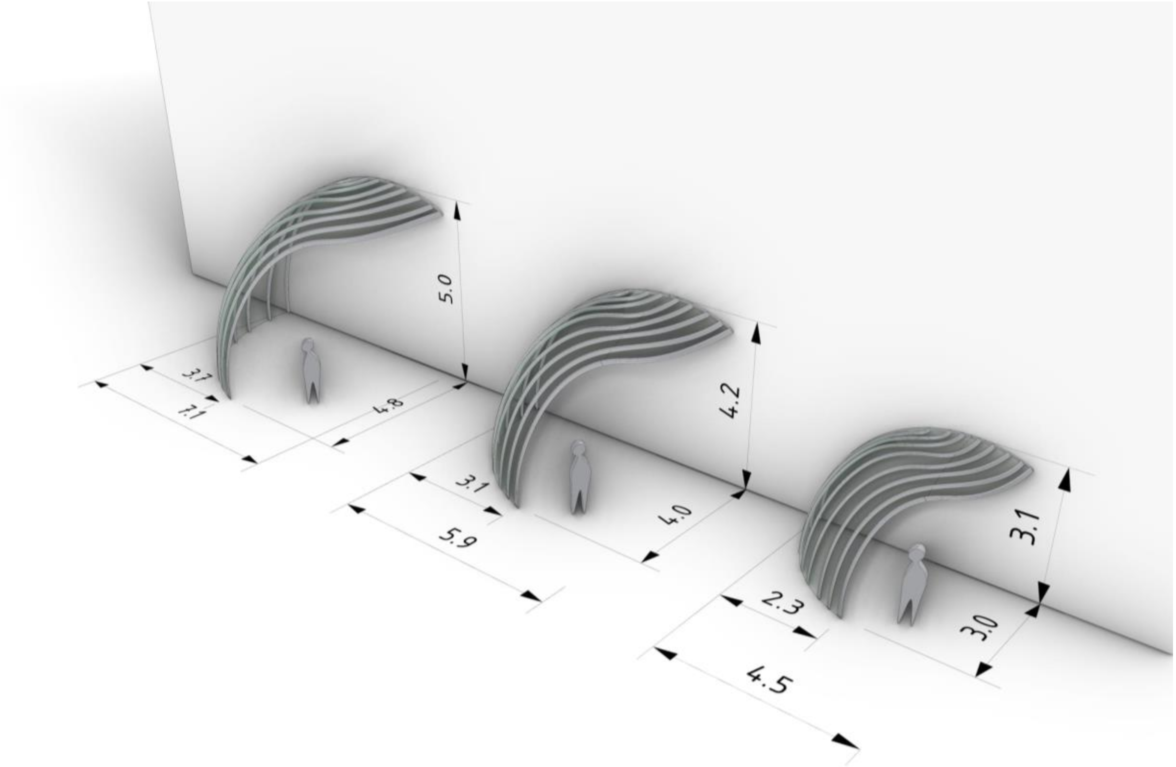


Figure 9. Half-shelter sizes

'Operable shelter' is another curved shelter type designed as a test shelter. It is a segment of a sphere which can be folded together or unfolded when protection from the wind is needed. It was designed for the Sepise pedestrian street case, which is not wide, and with the placement of permanent shelter structures, the view and possible paths would be blocked. In the case of operable shelters, when the cafes or restaurants do not require these, they could be closed and provide view and passage. The smallest version of the shelter is 6.1 meters wide, 3 meters long and 3 meters high. The middle structure is 8.1 by 4 meters and 4 meters high. The biggest tested size of the operable shelter was 10.1 meters wide, 5 meters long, and 5 meters high (Figure 10).

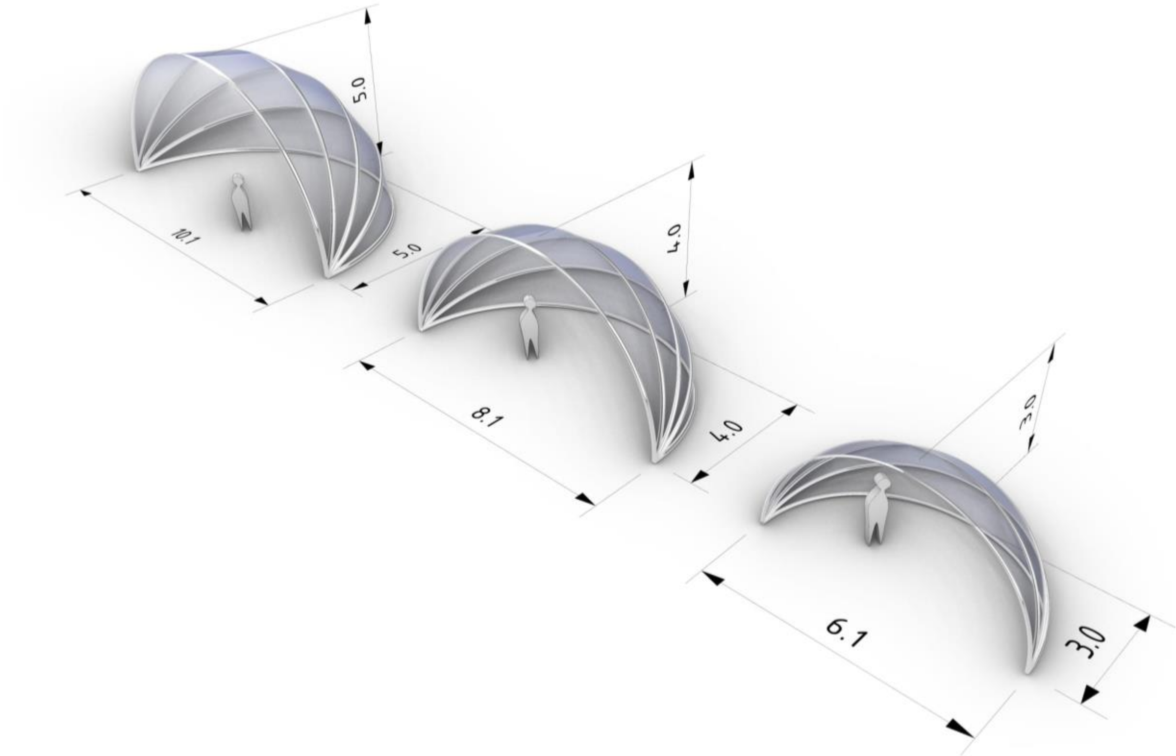


Figure 10. Operable shelter sizes

'Textile wall' was the smallest of the types used and was developed to create a shelter operable by the people who use the place. It consisted of two inclined posts between which a textile could be pulled out and rolled back through a spring system. This type could be installed near benches and other standing or seating points, so people could pull out the textile as a curtain if wind protection is needed and use the area. The sizes of the shelters were kept as small as possible to guarantee the usage of those. Also, to create a better wind flow over the structure, the shelters were designed with an incline of 20 degrees. The smallest version of the shelter is 3.4 meters wide and 2.5 meters high. The middle structure is 3.9 and 3 meters high. The biggest tested size of the shelter was 4.4 meters wide and 3.5 meters high (Figure 11).

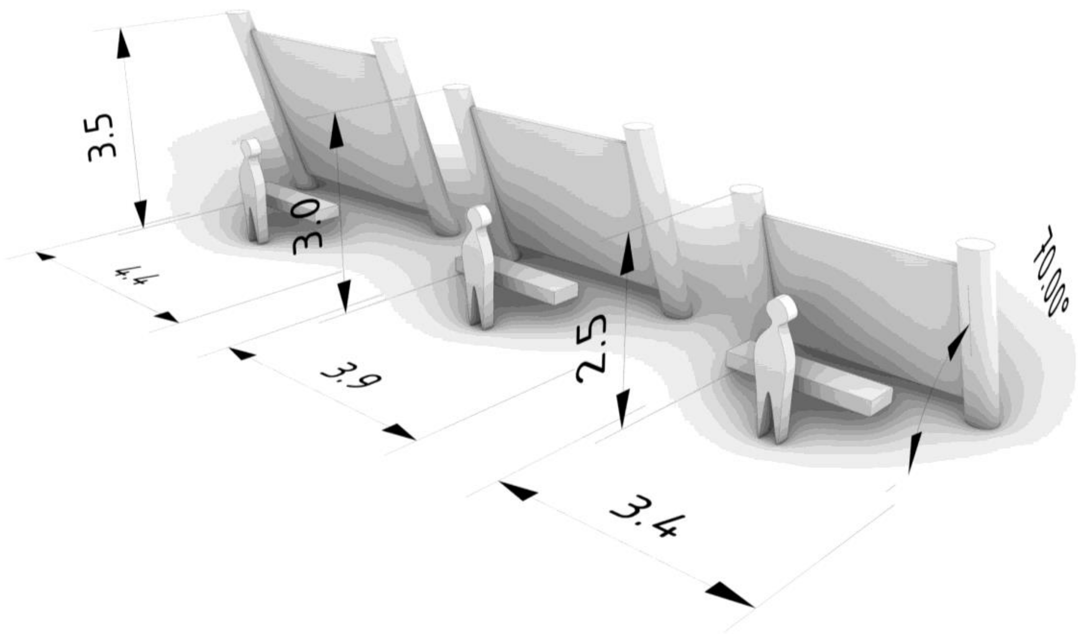


Figure 11. Textile wall sizes

4.5 Wind simulations

As described in the Wind analysis section, the current study included various simulation steps. Here is a more detailed description of each simulation step and its required parameters.

4.5.1 Circular wind tunnel

For the first step described in the Wind analysis section, a cylindrical wind tunnel with a height 450 m (10 times the height of the tallest building) and an outer radius of 3000 m, which is 675 m from the outer modelled building to the border of the cylindrical mesh (15 times the height of the tallest building, respectively) was used following best norms for wind tunnel sizing (Franke et al. 2007). The inner rectangle of the cylindrical wind tunnel includes all four areas of interest and is 350 x 350 m in size (Figure 12). The accuracy of the cells inside the inner rectangle was approximately 3 m. Simulations were performed from 16 wind directions (from 0° every 22.5°). Among the 16 wind directions, the most critical for each analyzed area is selected to be sued for the analysis of wind protection of the shelters in the urban environments .

The most critical direction was defined through different steps in the parametric workflow. First, the annual simulated wind velocities per hour per every probing point were taken from the performed simulation. Thus, 8760 velocity values per point were obtained. From these results only daytime hours from 8 a.m. to 6 p.m. were included (time when urban space is mostly used by pedestrians). Then the wind velocities which occurred for at least 5% of the time were sorted and the associated wind directions were recorded. The same wind velocities were sorted from largest to smallest and the wind directions were associated with those accordingly. From this information, the most frequent wind directions were chosen.

A fixed wind velocity of 5 m/s (at 10 m height) at the wind tunnel inlet and the logarithmic wind profile was used for the 16 CFD simulations. The terrain roughness used is $Z_0=1$, that is that of urban areas uniformly populated by large obstacles (buildings) of similar size and open spaces of the same order of magnitude as the buildings. Simulated wind velocities are probed on a grid of 3 m x 3 m at 1.5 m height from the ground (De Luca, 2019). Each area has a different grid extension. Lõõtsa park covers an area of 11818 m^2 and had a grid of 1323 cells. Viktor Palmi square covers an area of 3213 m^2 and had a grid of 357 cells. Health Centre park covers an area of 3744 m^2 and had a grid of 416 cells. Sepise street covers an area of 4900 m^2 and had a grid of 602 cells (Table 2). The simulated wind patterns and velocities for each area were used to calculate the wind factors. These were then used to remap wind velocities from the annual Tallinn weather data (*Climate.Onebuilding.Org*, n.d.).

Table 2. Parameters of circular wind tunnel for each area

	Area (m^2)	**Number of cells**
Lõõtsa Park	11 818 m^2	1323
Viktor Palmi square	3 213 m^2	357
Health Centre park	3 744 m^2	416
Sepise pedestrian street	4 900 m^2	602

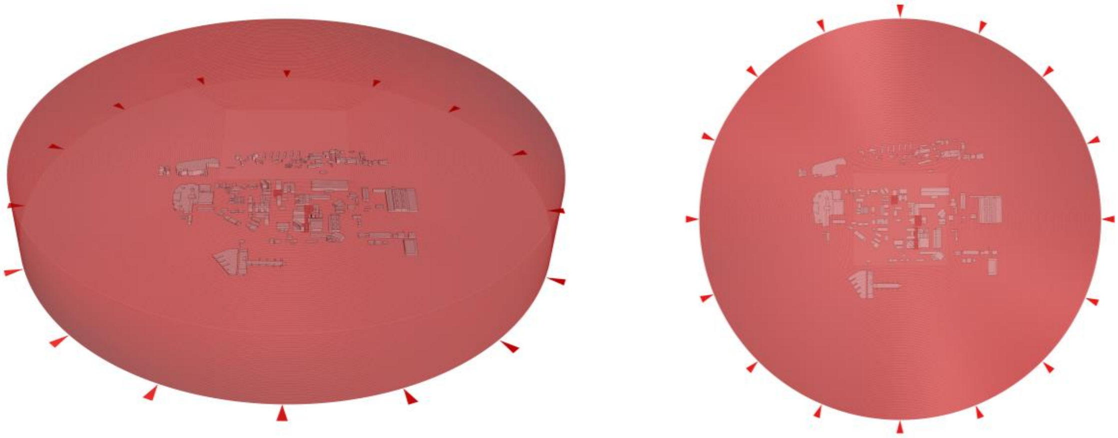


Figure 12. Circular wind tunnel

4.5.2 Rectangular wind tunnel

After having defined the most critical direction for each pedestrian area, it was used for wind simulations performed with a rectangular wind tunnel with a smaller grid size for the area of interest in the wind tunnel, 0.6 m x 0.6 m to obtain a more accurate results. The same level of accuracy was then used to simulate wind patterns when the shelter was in place in the urban environments. Though the surrounding buildings are of a large scale, this small grid size was used to take into account the small scale object like shelters after they were designed for each area and used in the simulations. After having evaluated the wind conditions in the actual urban areas and after with the shelters and their designed layout, the pedestrian wind comfort difference was significant.

The rectangular wind tunnel considered only one wind direction (Figure 13). As for the cylindrical wind tunnel simulations, the wind velocity of 5 m/s (10 m height), the logarithmic wind profile and the terrain roughness of Z_0=1 representing a homogeneous urban area were used. The width and the height of the rectangular wind tunnel were different for each area. The width was ten times the height of the tallest building (from the outer building included in the simulation to the border of the wind tunnel from both sides), and the height was 5 times the height of the tallest building. The wind tunnel for Lõõtsa park was 475 meters wide and 170 meters high. The wind tunnel for Viktor Palmi square was 1140 m wide and 240 m high. The wind tunnel for Health Centre park was 895 m wide and 225 m high. The wind tunnel for Sepise street was 745 m wide and 225 m high (Table 3).

Table 3. Parameters of rectangular wind tunnel

	Rectangular tunnel width (m)	**Rectangular tunnel height (m)**
Lõõtsa Park	475 m	170 m
Viktor Palmi square	1140 m	240 m
Health Centre park	895 m	225 m
Sepise pedestrian street	745 m	225 m

***Figure** 13. Rectangular wind tunnel for Lõõtsa park, red building are considered into simulation*

4.5.3 Test shelter simulating

For simulating the three types of designed shelters without any surroundings, a smaller rectangular wind tunnel was used. Each version(size) of the shelter type was tested with three different wind speed conditions 8 m/s, 10 m/s and 12 m/s. In the first step of the study, smaller wind velocities were used as well, though in this paper results relative to most critical conditions are presented. The aim was to get a certain comfort level around the tested shelter (comfortable for walking - yellow, business walking – orange, and uncomfortable for all activities - red), so it was possible to obtain the size of the area that would be protected by each shelter type and size and would guarantee the maximum level of comfort (seating activity), to use in the design of the open areas under investigation. In the wind tunnel, the analyzed area around the shelter was a 50 m x 50 m square with a 0.5 m x 0.5 m grid cell size.

5. Case study

Based on the results of pedestrian wind comfort of each area in the actual conditions and compared to the results of the size of the protected area by each type and size of shelters, urban solutions were developed for each area. To improve the urban space quality and livability not just in terms of pedestrian wind comfort but also considering the optimal layout configurations for a high architectural quality of the space, the shelters were modified according to each area-specific characteristics, surrounding buildings and functions.

5.1 Area-specific shelter layout design

Test shelters were designed as independent objects, but during the study, it became clear that each area needed a more thoughtful and unique approach. At this point, it was decided not to just place the shelters in the area, as they would create an out of place object feeling, but to develop the design further and create a unique urban layout considering also architectural values besides the urban comfort.

As the wind comfort analysis showed that the Lõõtsa park area is mostly comfortable for pedestrians, it was decided to leave it out of the design process. Also, the Lõõtsa park area already has a well-working layout and design.

It was decided to create a walkway for the pedestrians through all three areas and create a special urban experience in each. In this way, origami-like structures in the Viktor Palmi square would provide people with a more intimate space on the square and could be implemented with different functions. In the space created by the shelters, different functions could be implemented, like sitting, outdoor library, bus stop place, outdoor gym or any other. Also, inclined surfaces would be planted with greenery, which would mitigate the wind even more and create a cosy and healthy urban environment for Ülemiste City users.

Moving forward, one would reach Health Center park. As the results showed that the majority of the park is comfortable for pedestrians conditions, it was decided to include in the study the area in front of the new building development, which was regarded as more problematic due to building morphologies. In that location, a structure was created to provide terraces comfortable and safe from the wind. The park was also redesigned, as there was no need for the parking space there, as Ülemiste City is aiming to be car-free. The park got a little maze-like concept, so people can wander around and maybe feel the park as a bigger space than it currently is. Also, the aim was to still keep it walkable yet find a way to create more personal spaces for people to stay in. In the middle of the park, a place for the outdoor office possibility or just a place for gatherings was also created.

Sepise street had major wind problems at the beginning of the corridor on the south, so origami-like wind shelters were also placed there to mitigate the wind. In a way, they also make the entrance to the street more narrow, so when a person reaches the street, it seems wide and pleasant. Pavilions were placed on the street to create a possibility for restaurant terraces and outdoor office places (Figure 14).

Figure 14. Shelter layout design proposal

6. Results

Results of the study are presented for the pedestrian wind comfort of each area considering the most critical wind direction. The current situation is compared with the proposed design solution using sheltering urban features and layouts derived from the tested shelters morphing their shape while maintaining the sizes. The comparison was performed by assessing the percentage of an area which guaranteed the different levels of pedestrian comfort in the actual situation and through the proposed urban design. The scope was to maximize the areas in seating comfort condition, the one which is comfortable for all the other types of activities according to the Lawson LDDC pedestrian comfort criteria used.

6.1 Actual situation

As already discussed in Wind simulations, cylindrical wind tunnel CFD simulation presented results from 16 wind directions. Wind factors calculated from the simulation combined with velocities from the annual Tallinn weather data file allowed to define critical wind direction for each area. The time frame included in the simulation was from 8 a.m. to 6 p.m. The analysis periods used were calculated on the basis of the occurrence of the wind from the most critical directions during the entire year. Lõõtsa park area, Viktor Palmi square and Sepise pedestrian street's most critical wind direction is from the south (180°) (Figures 15, 16 and 18). Health Centre area most critical wind direction is south-southwest (202,5°) (Figure 17). Wind velocity ranges for each area are as follow: Lõõtsa park from 0.01 m/s to 3.17 m/s; Viktor Palmi square from 0.03 m/s to 5.18 m/s; Health Centre park 0.04 m/s to 6.24 m/s; Sepise pedestrian street from 0.3 m/s to 5.81 m/s (Table 4).

Table 4. Results from annual wind simulation from 16 directions

	Most critical wind direction	**Wind velocity range**
Lõõtsa Park	south (180°)	from 0.01 m/s to 3.17 m/s
Viktor Palmi square	south (180°)	from 0.03 m/s to 5.18 m/s
Health Centre park	south-southwest (202,5°)	from 0.04 m/s to 6.24 m/s
Sepise pedestrian street	south (180°)	from 0.3 m/s to 5.81 m/s

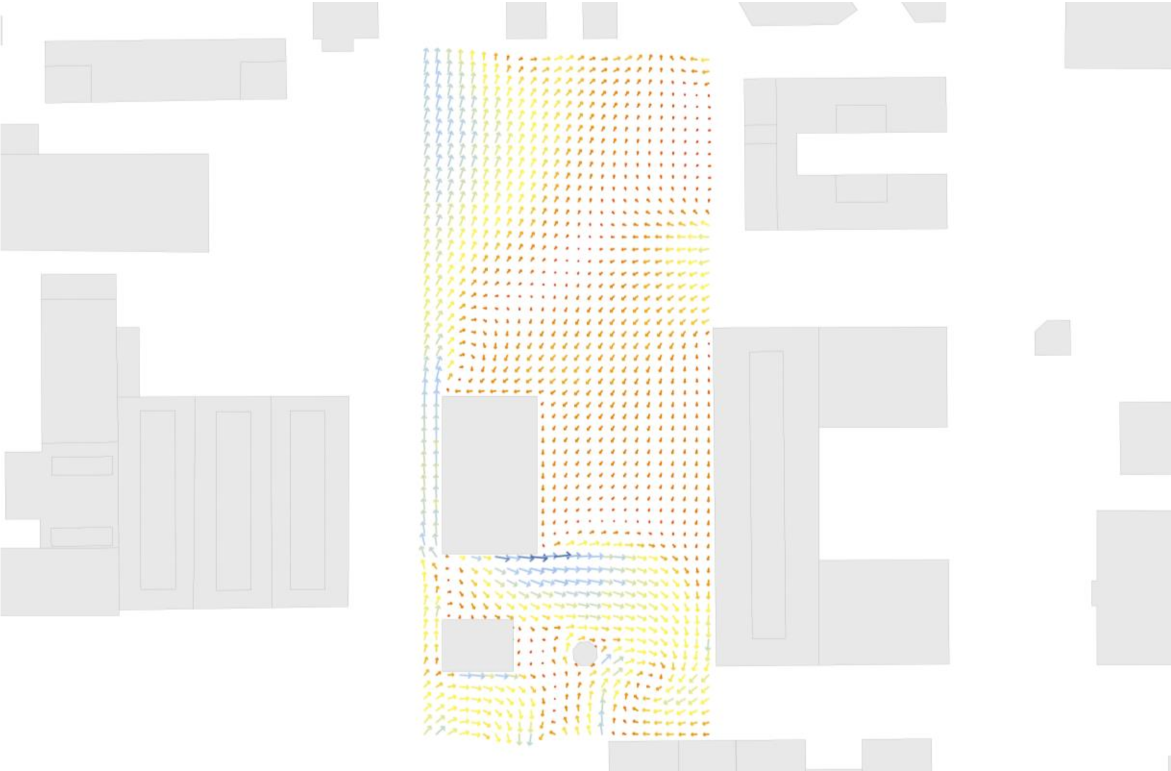


Figure 15. Wind flow and velocity plot in Lõõtsa park 180°

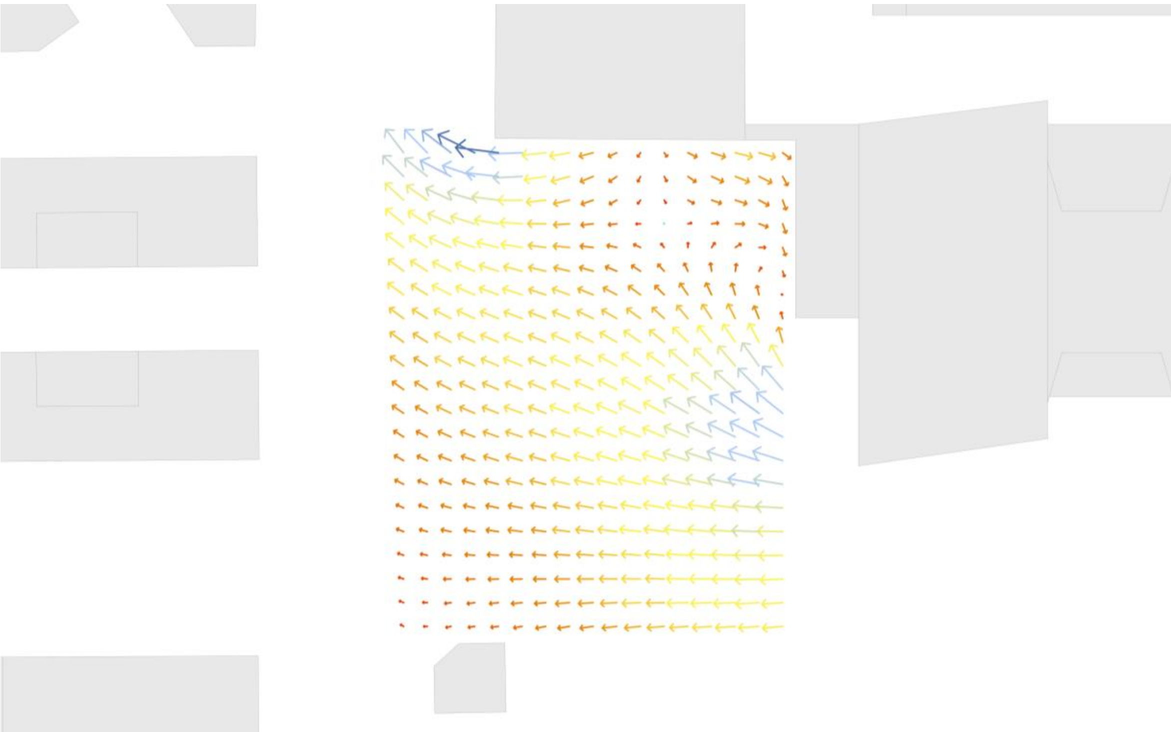


Figure 16.Wind flow and velocity plot in Viktor Palmi square 180°

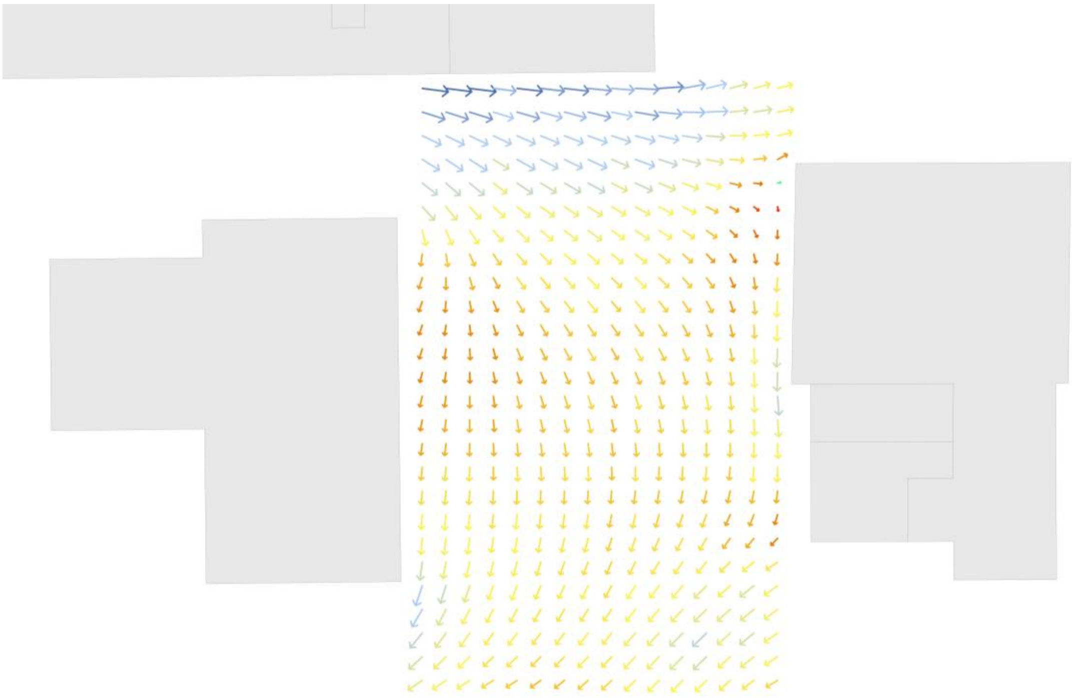


Figure 17.Wind flow and velocity plot in Health Centre park 202.5°

Figure 18.Wind flow and velocity plot in Sepise pedestrian street 180°

The following more accurate simulations performed with a rectangular wind tunnel from the most critical direction for each area separately showed the current situation according to the Lawson LDDC assessment criteria. Areas comfortable for sitting and standing were considered as comfortable. However, if sitting areas were designed in the areas comfortable for standing according to wind analysis, the latter was considered to be redesigned. Areas comfortable for walking, business walking and uncomfortable for every activity were considered as uncomfortable. The aim was to design shelters according to the architectural and functional needs of each space and reduce the percentage of areas suitable for standing and walking by making these comfortable for sitting. The scope was to improve the livability of the places, to enjoy time and social life and to use them for every activity. The results showed that the most comfortable area in terms of wind was Lõõtsa park – it has 98.6% of the area comfortable for every activity and the other 1,4% comfortable for walking (Figure 19). At this point, it was decided to leave Lõõtsa park out of the design process, as the area is comfortable in terms of wind comfort. The area also has already a well-developed design, and also there are a lot of trees, which also improve wind mitigation. The second most comfortable area is the Health Centre area – it has 72,5% comfortable for sitting (Figure 21). The results of the actual situation analysis showed that Viktor Palmi square is the most uncomfortable area, with only 39,5 % comfortable for every activity (Figure 20). Sepise street has a comfortable area of 54.9% (Figure 22). Walking comfort level is the most critical level of discomfort appearing in the results, so it was decided to increase the sitting comfort area in each case as much as possible.

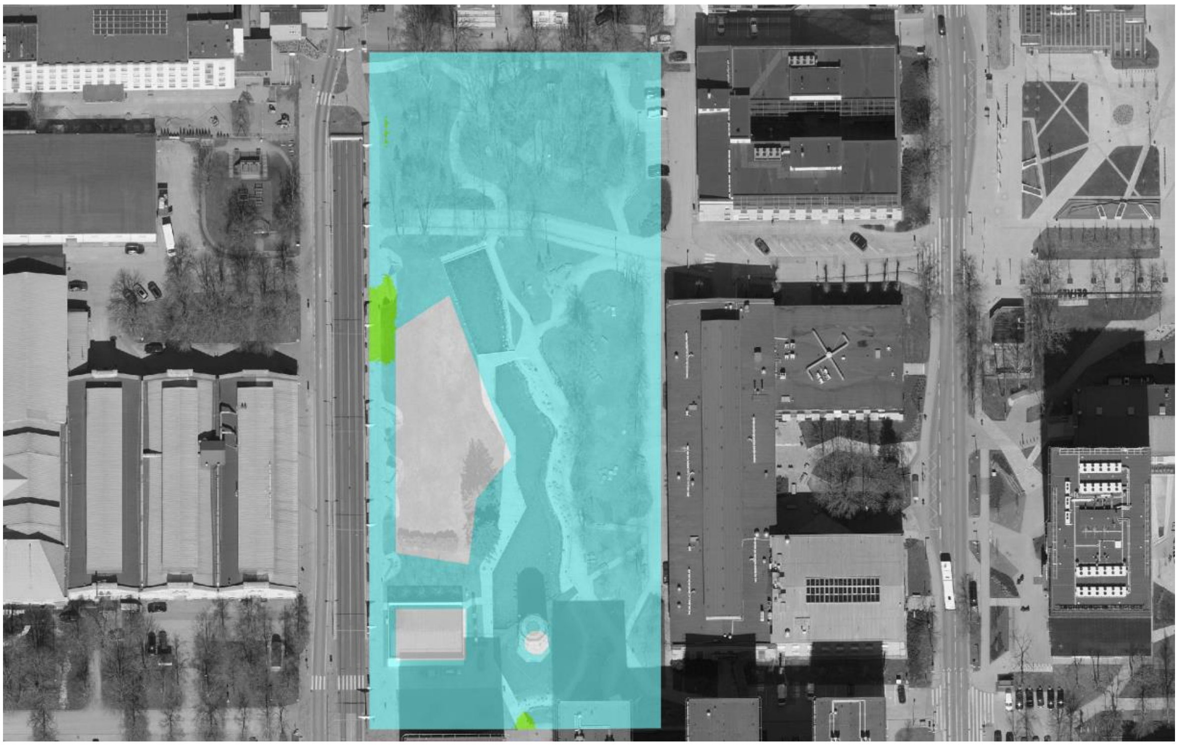


Figure 19. Wind comfort map for current situation in Lõõtsa park. Sitting (blue) 98,63 %; Standing (green) 1,37 %.

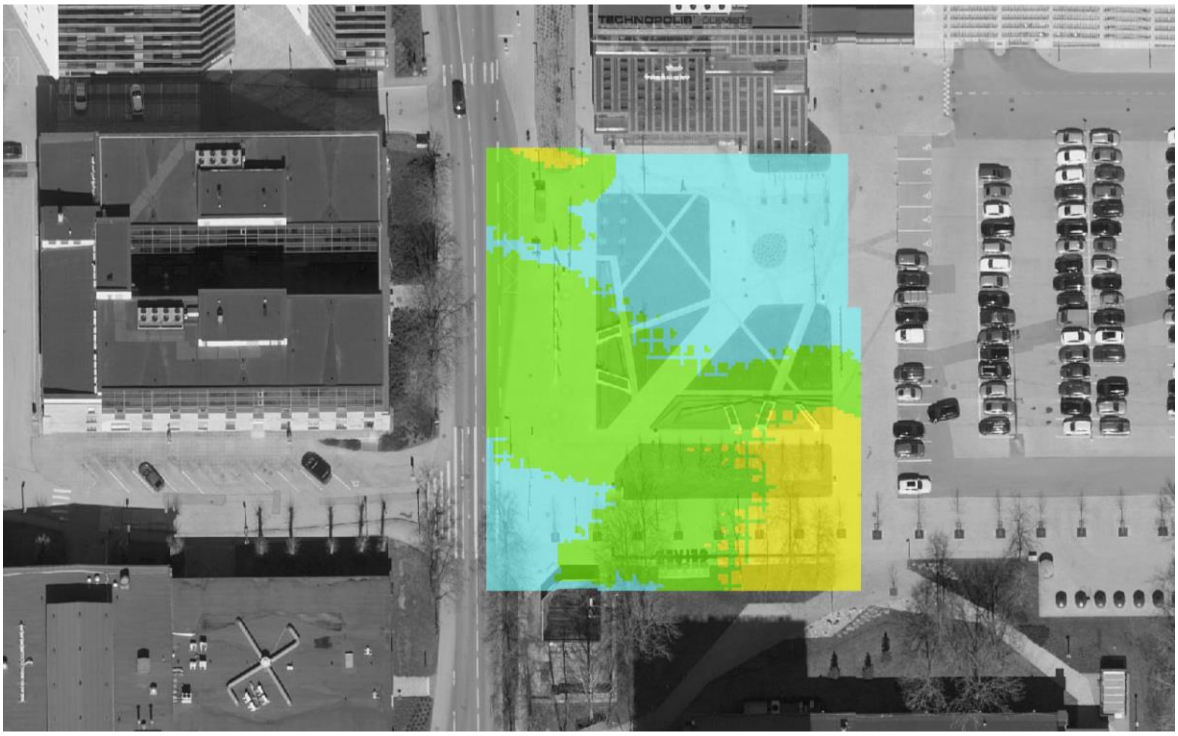


Figure 20. Wind comfort map for current situation in Viktor Palmi square. Sitting (blue) 39,50%; Standing (green) 47,45 %; Walking (yellow) 13,05 %.

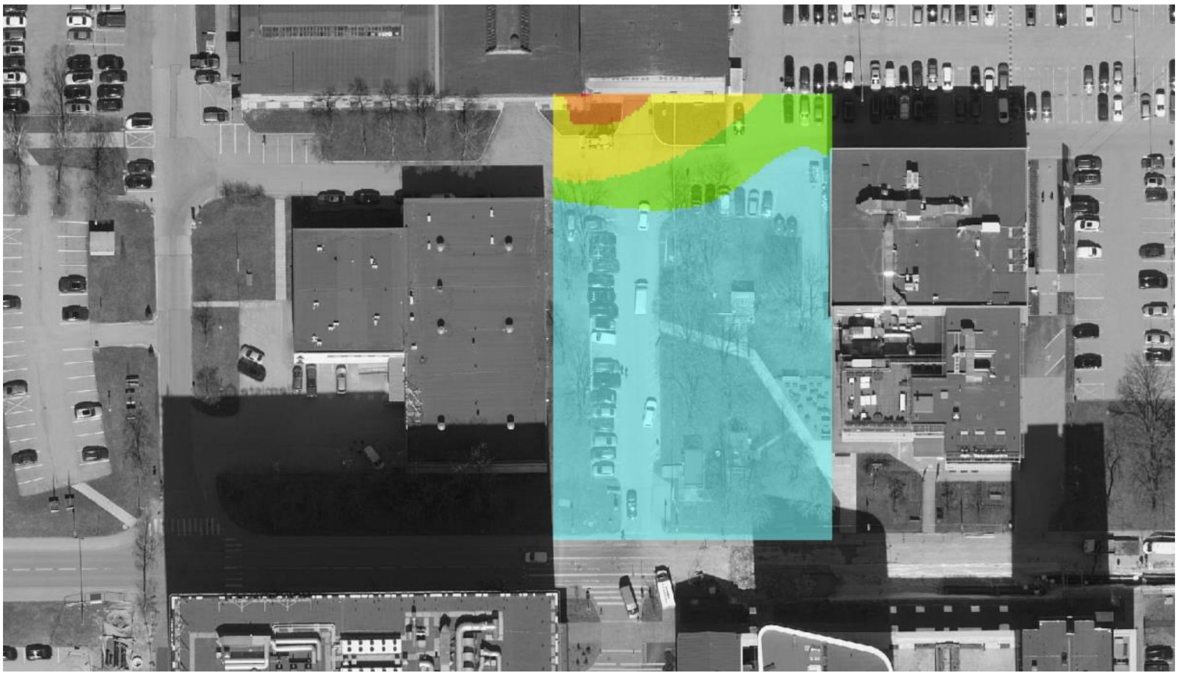


Figure 21. Wind comfort map for current situation in Health Centre park. Sitting (blue) 78,51%; Standing (green) 10,92 %; Walking (yellow) 8,86 %; Business walking (orange) 1,68%.

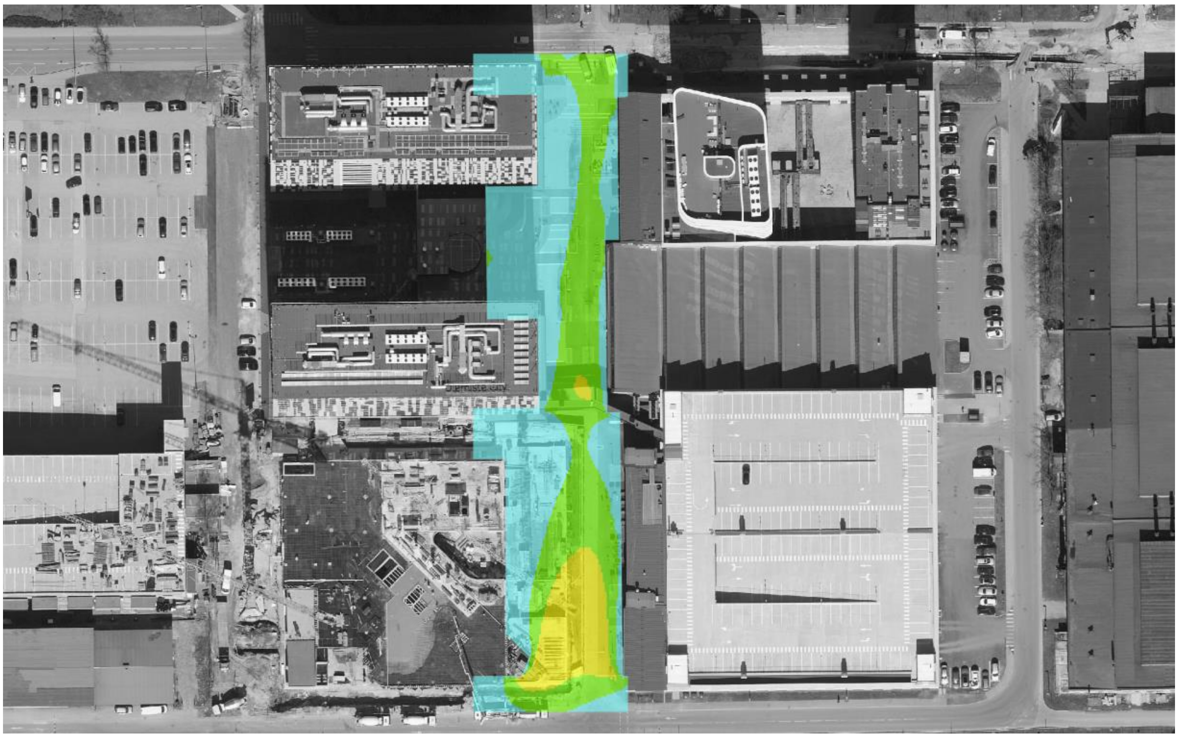


Figure 22. Wind comfort map for current situation in Sepise street. Sitting (blue) 54,86%; Standing (green) 33,87 %; Walking (yellow) 11,27 %.

6.2 Single wind shelters

As described in the section Wind simulations, each shelter type and size was tested separately in three different comfort conditions (Figure 23).

The biggest shelter type, 'Comfort Island', provides wind comfort for all activities for areas from 78.3 m^2 to 270 m^2, i.e., from 3.1 % to 10.8 % of the tested area, respectively, using the shelter size from the smallest to the largest. The smaller version of ‘Permanent shelter’ allowes a 22.3 m^2 area comfortable for every activity and the biggest version creates a 92.3 m^2 area in the same conditions. The smallest version of the operable shelter creates a comfort area of 26.8 m^2, and the biggest version creates an area of 155,5 m^2 suitable for every activity in the comfort conditions suitable for walking. The smallest' Textile wall' creates a comfort area of 10.3 m^2, and the largest allowes an area in comfortable conditions for all the activities of 40.3 m^2, which is a good indicator to state that even very small scale interventions in the urban space could cause a lot more comfort for the users. All the other results are presented in Figures 24-27 and in the Appendix.

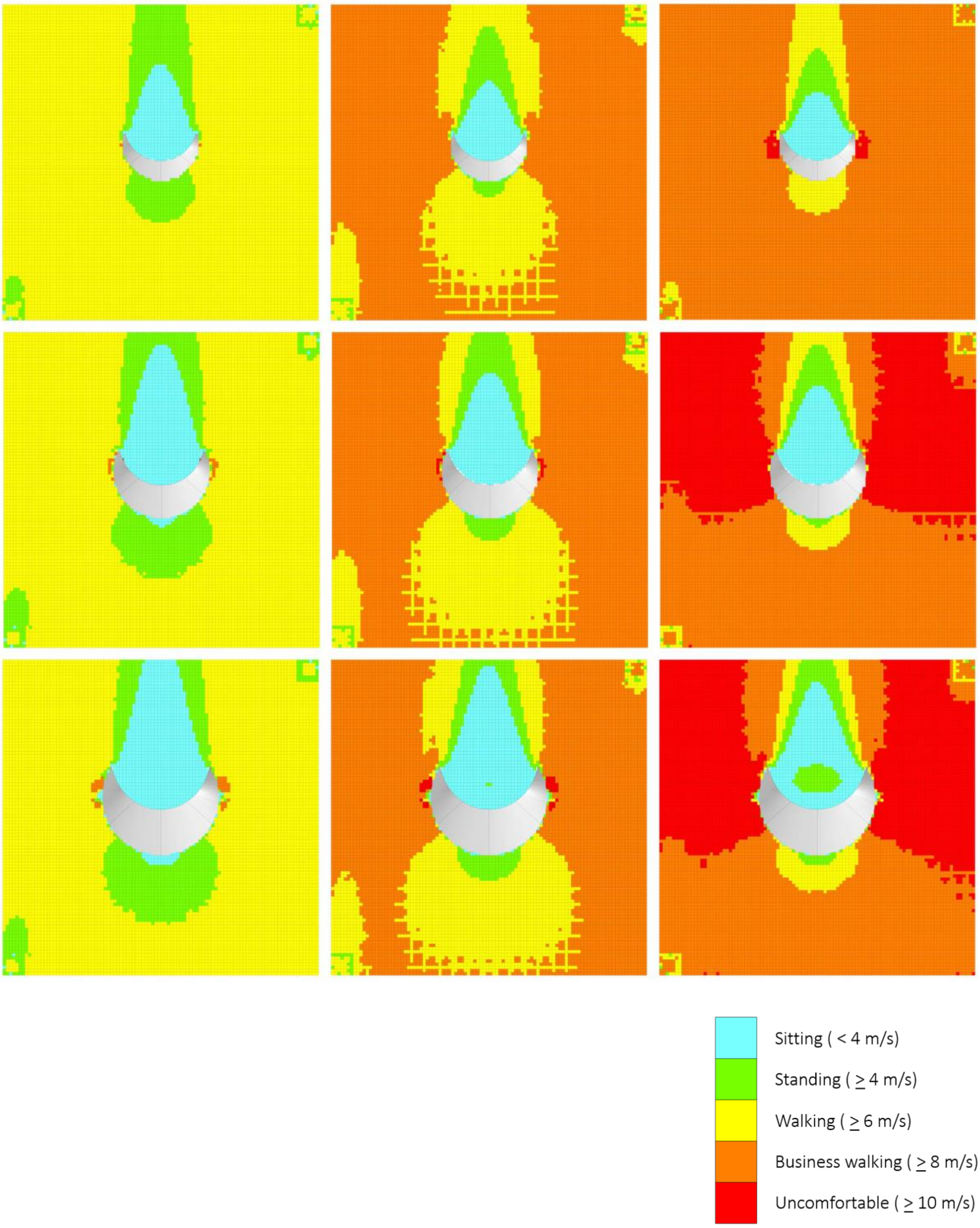


Figure 23. Comfort Island shelter simulation results

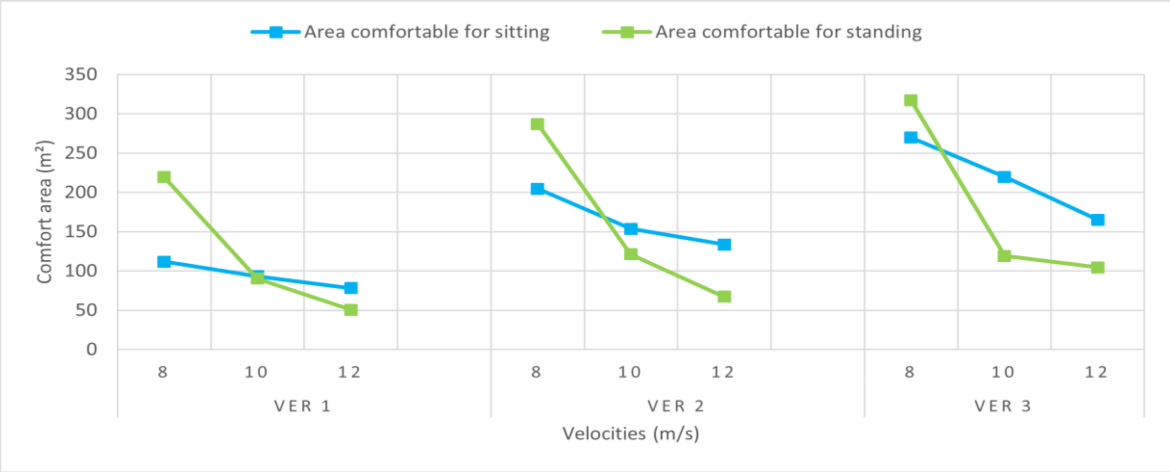


Figure 24. Comfort area size improved by Comfort Island shelter in different comfort conditions

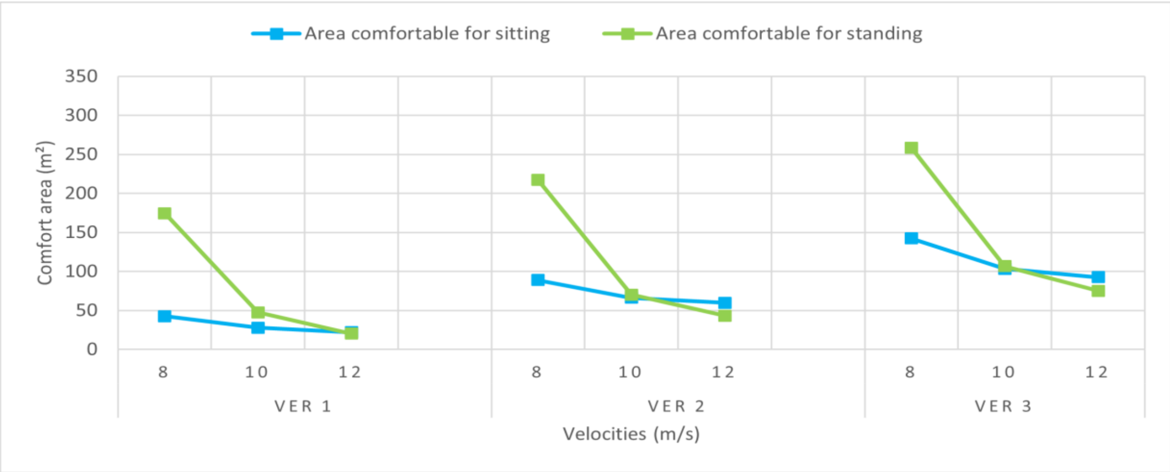


Figure 25.Comfort area size improved by Permanent shelter in different comfort conditions

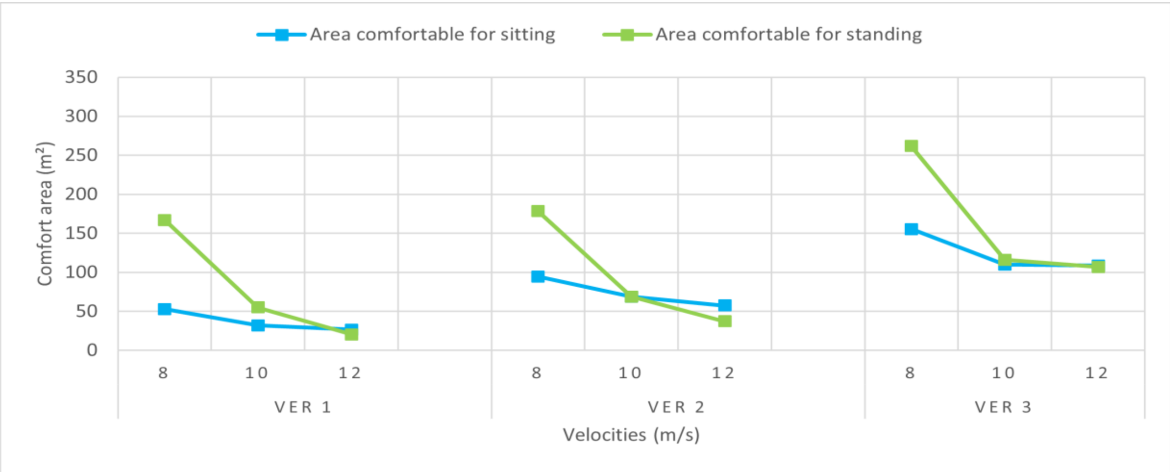


Figure 26.Comfort area size improved by Operable shelter in different comfort conditions

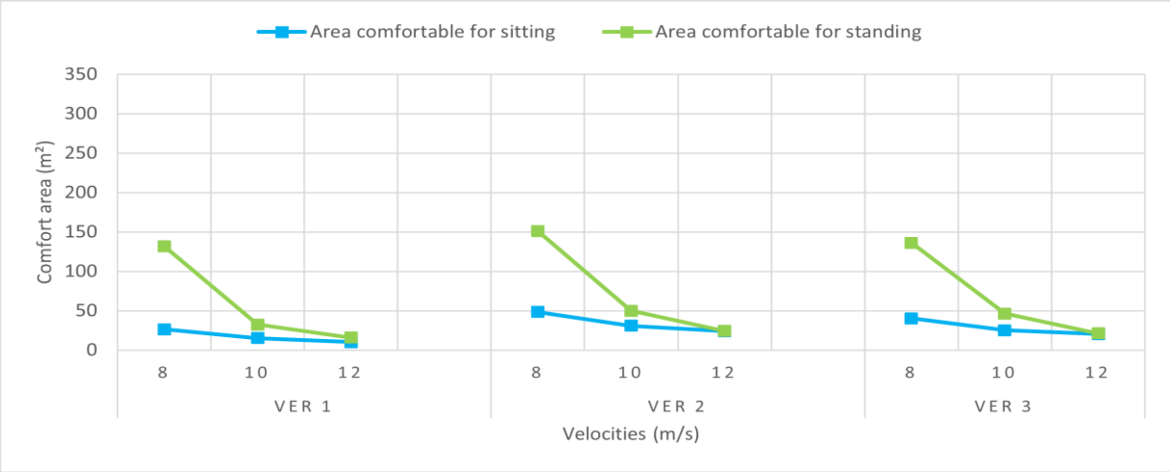


Figure 27.Comfort area size improved by Textile Wall shelter in different comfort conditions

6.3 Improved comfort areas

In the case of Viktor Palmi square, results show sitting was located in an area comfortable for standing and walking. It was decided to create a structure similar to 'Comfort island' with a more polygonal and segmented shape, resembling an origami. This allowed to leave the existing passages and create interesting urban experiences. Results show that the new design of the square using shelters increases area comfortable for sitting from 39.5% to 82.6%. Area comfortable for standing reduces from 47.5% to 14.6%. Area comfortable for walking reduces from 13.0% to 2.9%. (Figures 28 – 30).

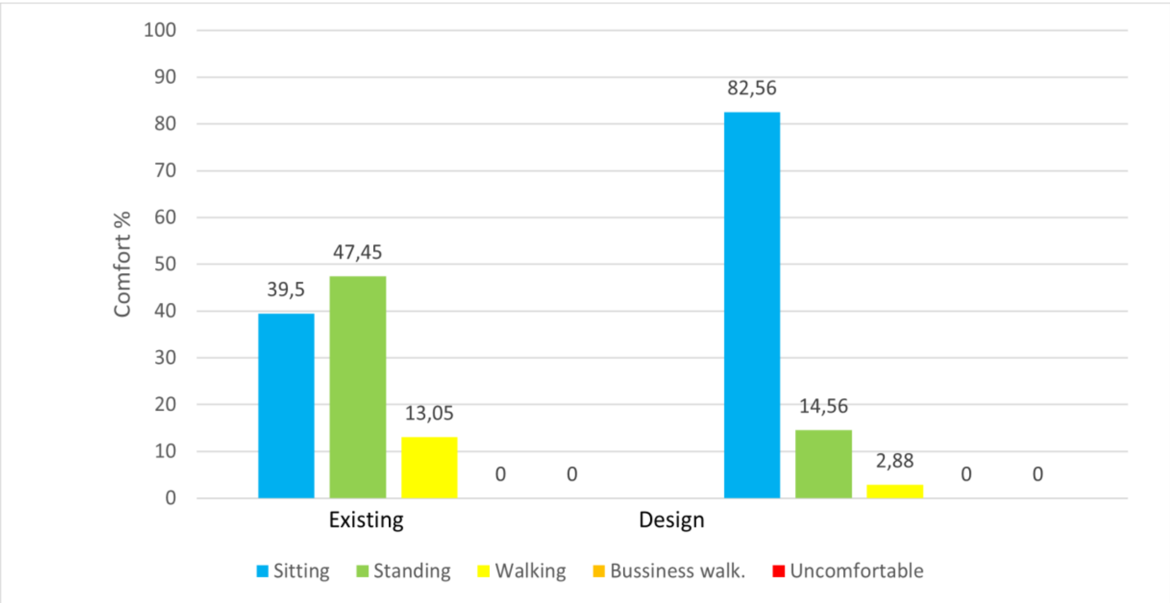


Figure 28. Comparison between comfort percent of existing area and designed shelter version for Viktor Palmi square

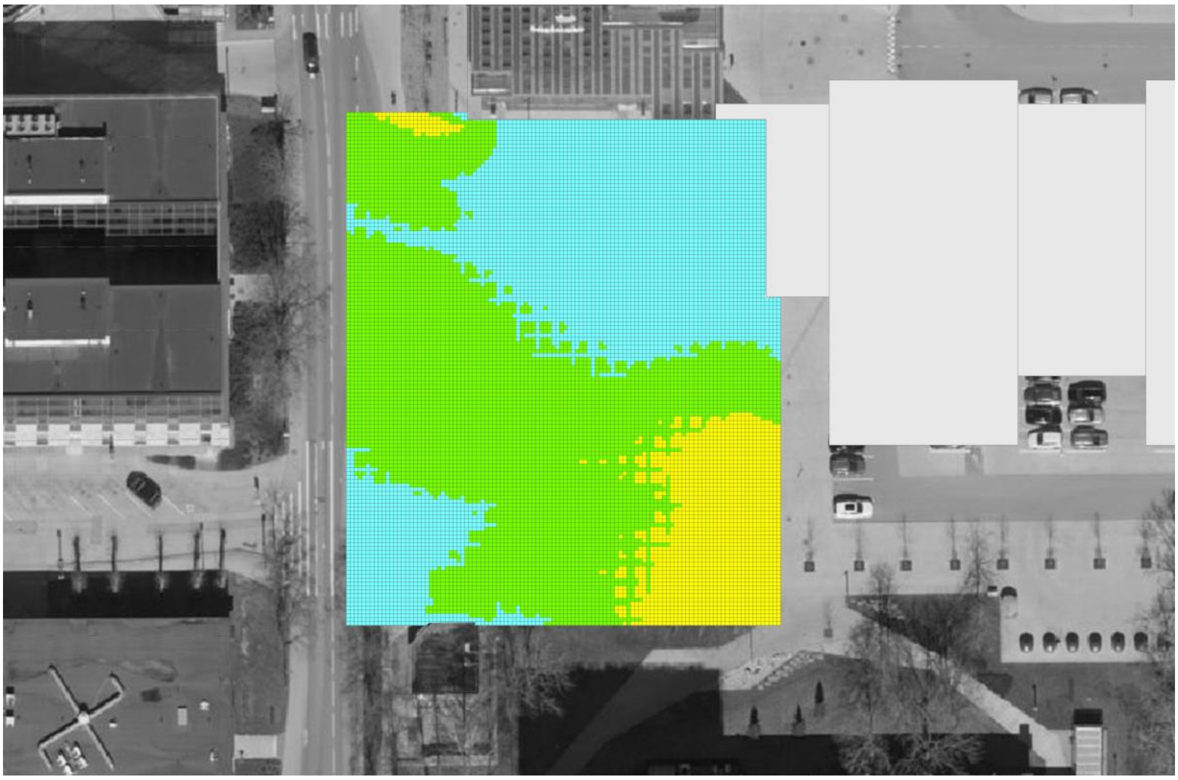


Figure 29. Wind comfort map for existing layout in Viktor Palmi square

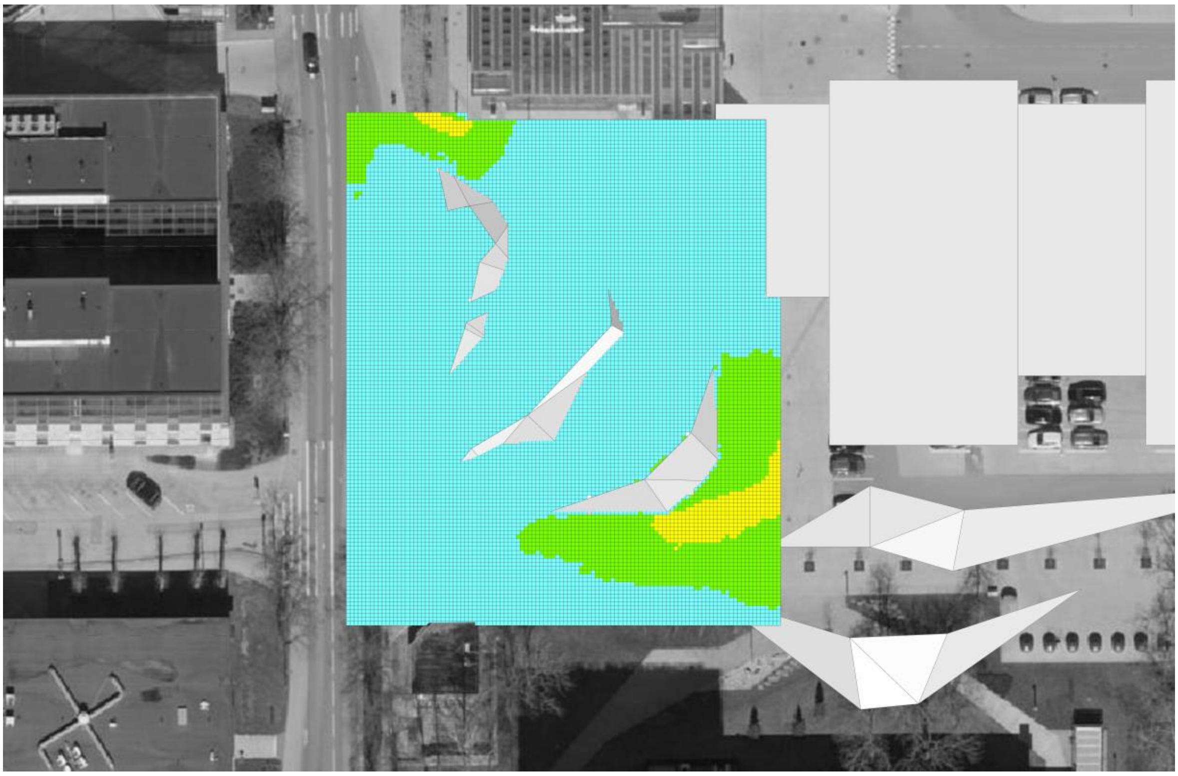


Figure 30. Wind comfort map for designed layout in Viktor Palmi square

In the first phase of the study, the wind analysis in the Health Centre area was performed only for the small park. As the results showed that the park is most comfortable, it was decided to extend the analysis area to the upper left corner and also consider space in front of the new high rise building planned to be built there. Since the new building will have outdoor terraces, it was decided to improve the wind comfort of these. Results of the simulations with the shelters show that the area comfortable for sitting increases from 72.5% to 77.1%. Area comfortable for standing is reduced from 19.9% to 17.7%. Area comfortable for walking reduces from 7.6% to 4.8%. (Figures 31 – 33).

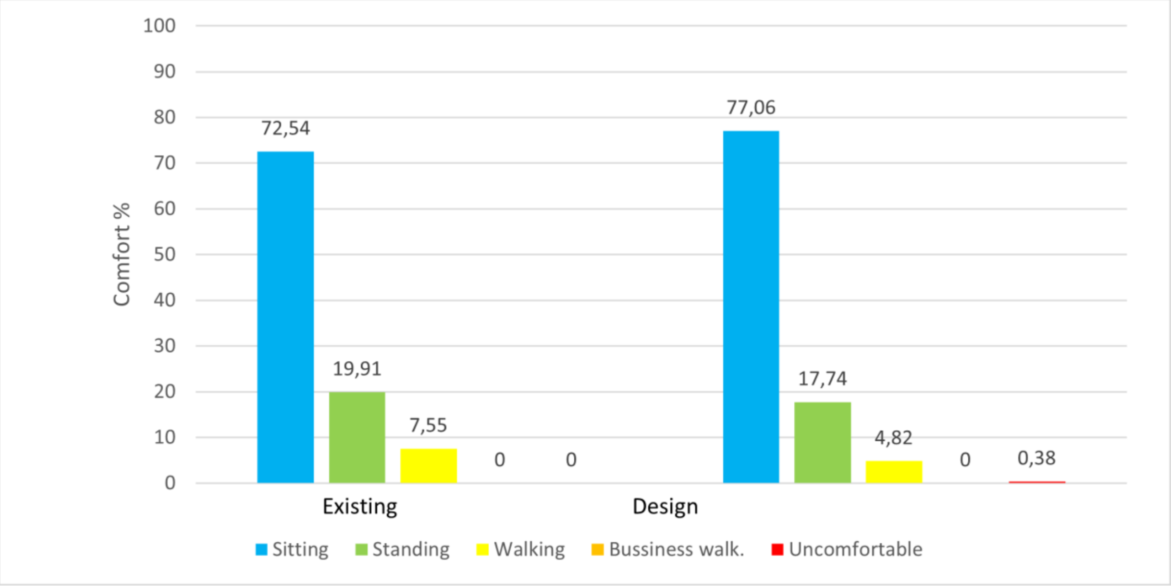


Figure 31. Comparison between comfort percent of existing area and designed shelter version for Health Centre area

Figure 32.Wind comfort map for existing layout in Health Centre area

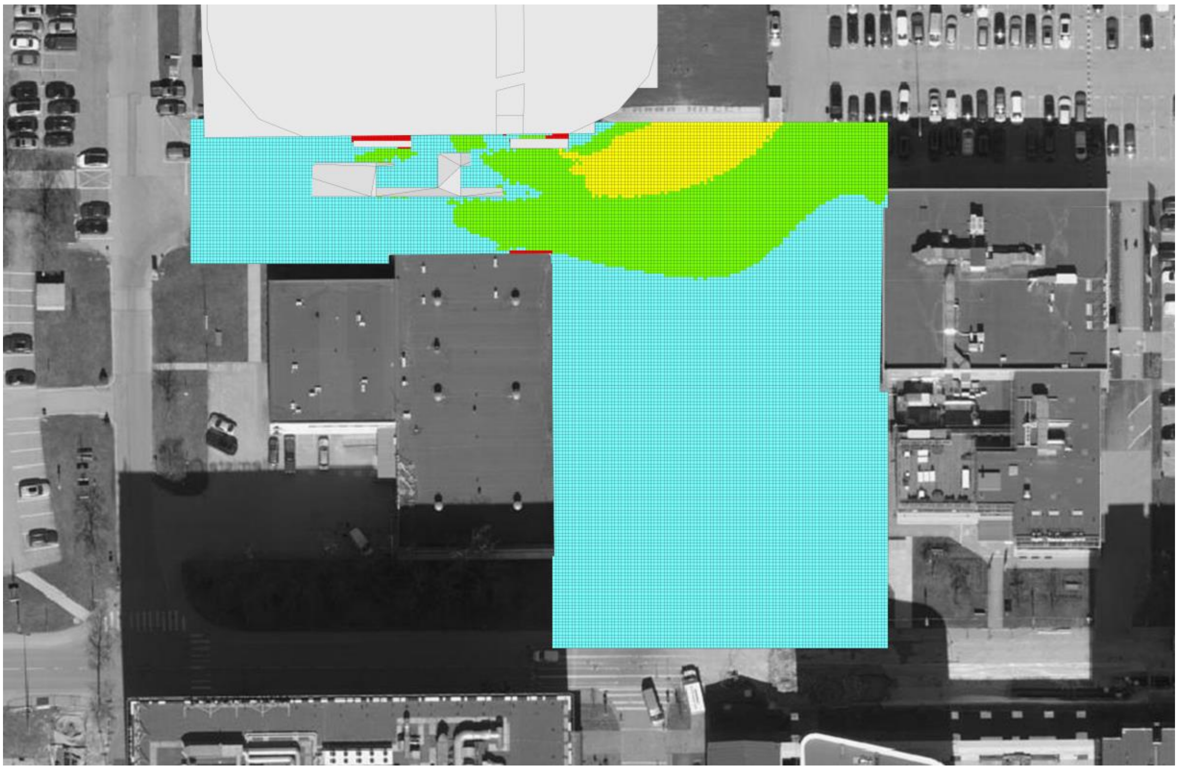


Figure 33. Wind comfort map for designed layout in Health Centre area

Sepise pedestrian street showed a high percent of discomfort at the beginning of the corridor from the south, where wind enters the area and is accelerated by the high rise buildings around. Sepise street is pedestrian and it has various terraces and benches where people tend to spend time. The aim was to create a possible windbreak at the beginning of the corridor and protect existing seating. Results show that the new design using shelters increases the area comfortable for sitting by 20%. Area comfortable for standing is reduced from 33.9% to 22.4%. Area comfortable for walking is reduced from 11.3% to 2.6% (Figures 32 – 34).

The results show designs of the shelter layout for the areas. For this study, various design solutions were made, of which the most suitable for the urban context were selected and developed for the final design proposal.

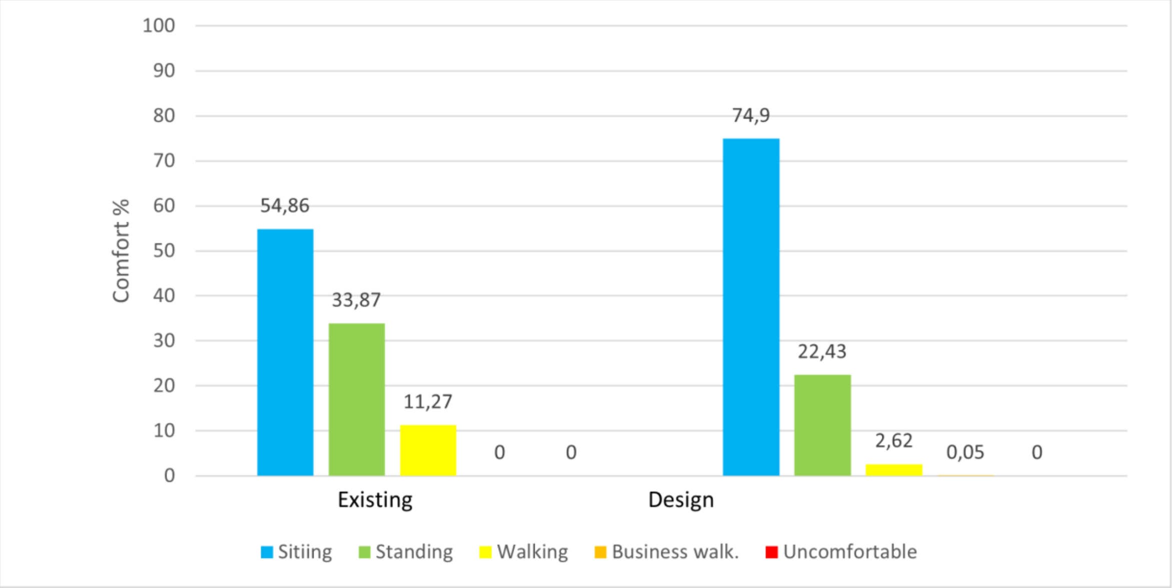


Figure 34.Comparison between comfort percent of existing area and designed shelter version for Sepise street

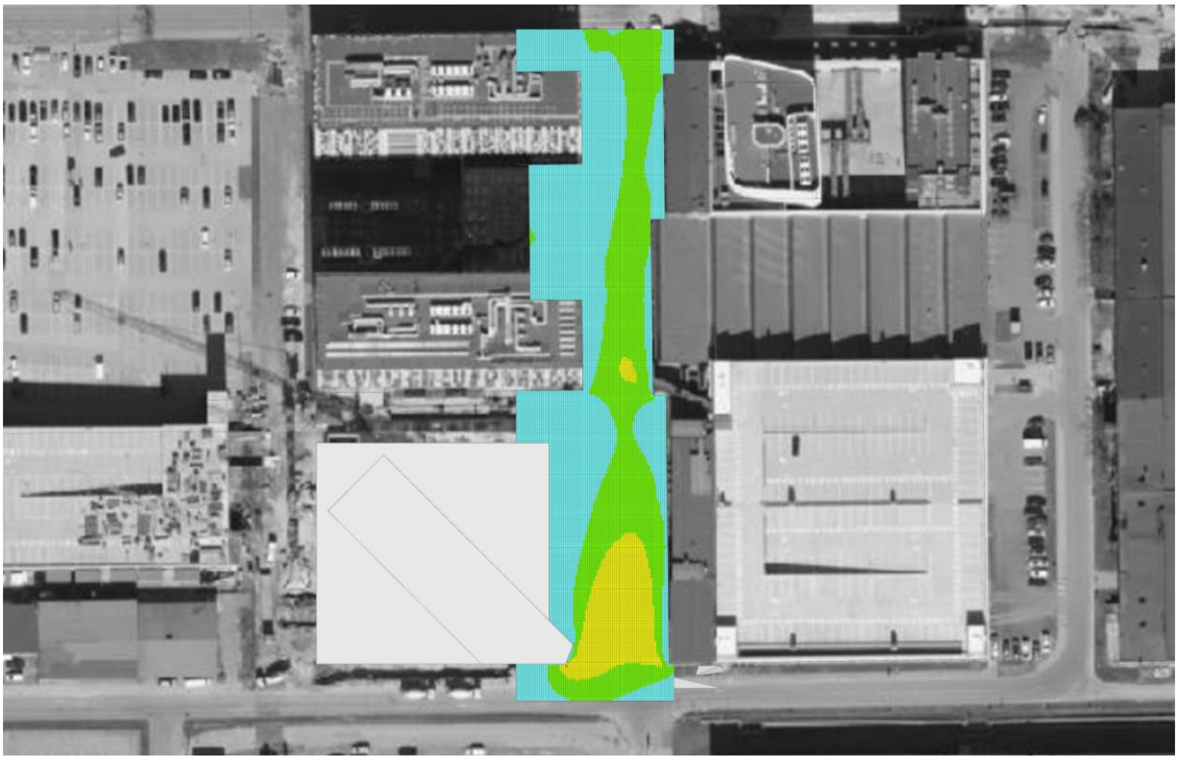


Figure 35. Wind comfort map for existing layout in Sepise street

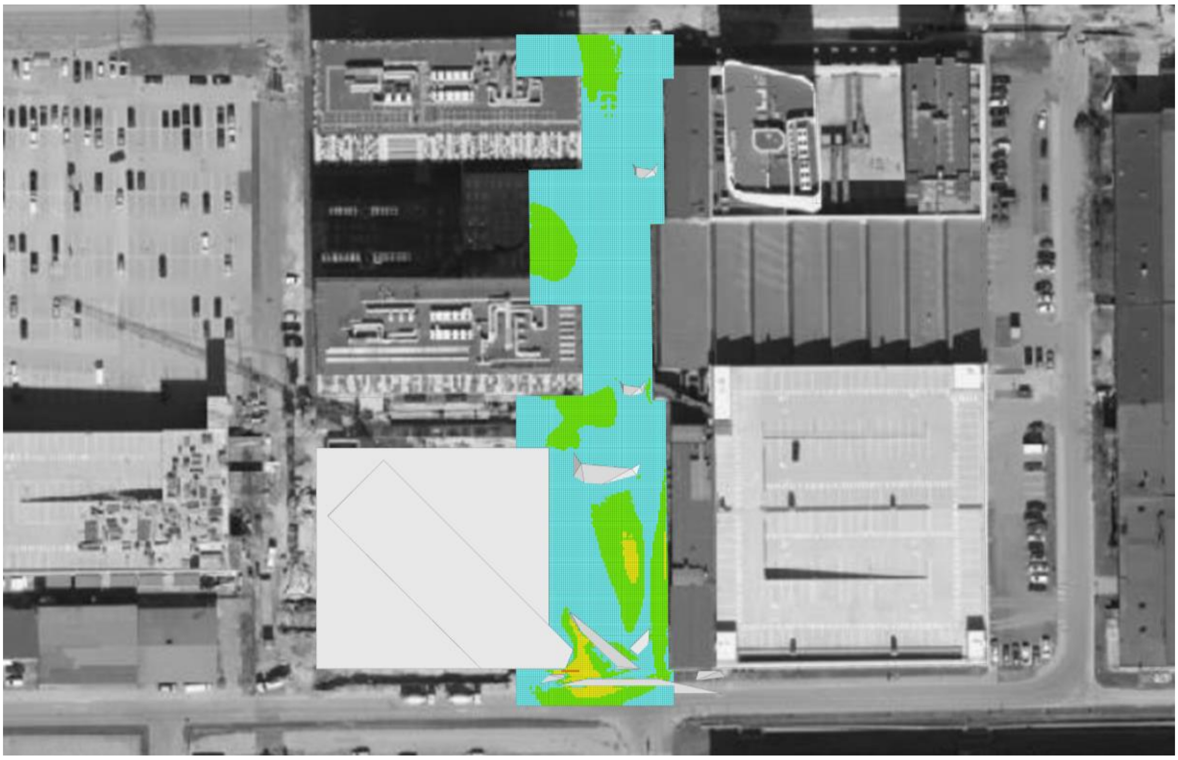


Figure 36. Wind comfort map for designed layout in Sepise street

7. Discussion

The interesting part of the design lies in transforming initial test shelters into final layout solutions for the areas. Comfort Island was transformed into an origami-like structure on the Viktor Palmi square and entrance to the Sepise street. The aim was to allow pedestrians to use the same paths as right now yet still mitigate the wind and create more divided and personal space for different functions. The structure, similar to the shards, also reminds of the history of the area, when the Dvigatel factory was there producing the railways. Also, the curved shapes of the initial test shelters resemble natural shapes reminding nature, while segmented and polygonal resample more industrial shapes and the past of the area.

To analyze the design proposal from the urban quality point of view, it should be stated that design solutions improve the surrounding urban space in the Ülemiste City district. Now the space is sharded, separated, and in some cases, lacks a unique identity. Connecting urban spaces together through the similarities in the design while still creating a unique experience for each area separately creates a complete design for the area when users would not feel left out. New spaces and functions of the areas would attract attention and provide possibilities for people to spend more time outdoors and socialize. These would also create possibilities for the local businesses to blend in, for example, as an outdoor library or gym. The human-scaled approach also brings more quality to the space not only in terms of pedestrian wind comfort but also in a better feeling surrounded by high-rise structures. To conclude, it is important to analyze the area as a whole and unite and create new changes and a unique identity for each place (Figure 37 – 43).

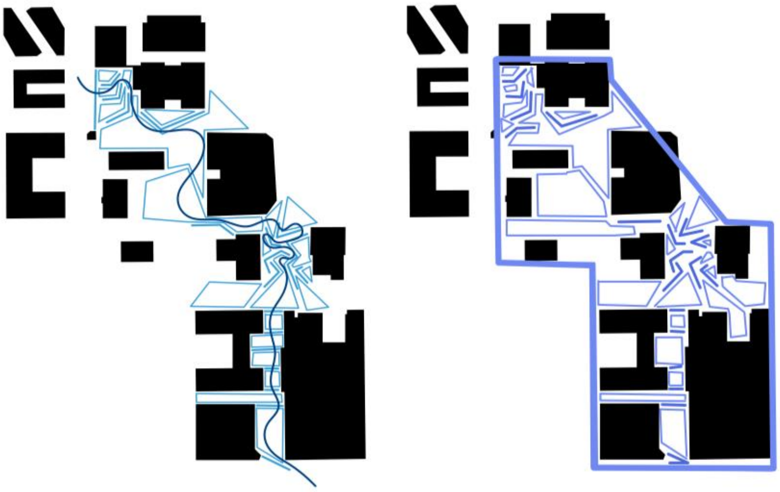


Figure 37. Concept for creating design proposal in Ülemiste City

Figure 38. Design proposal on Viktor Palmi square

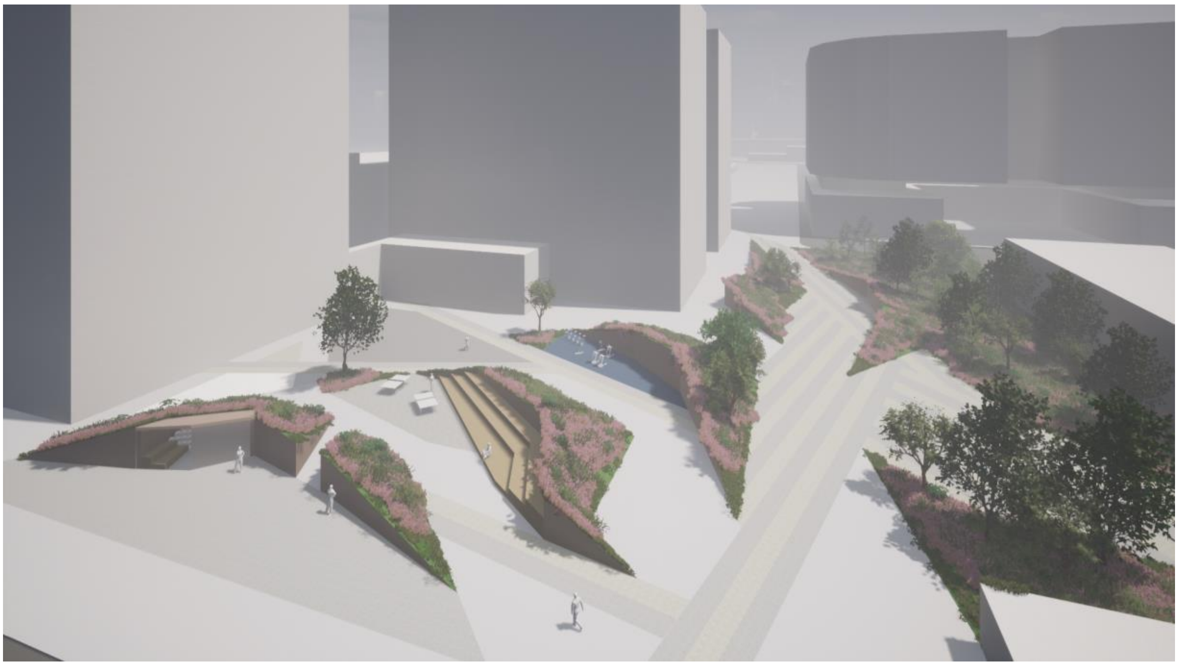


Figure 39. Design proposal on Viktor Palmi square

Figure 40. Design proposal on Viktor Palmi square

Figure 41. Design proposal on Health Centre park

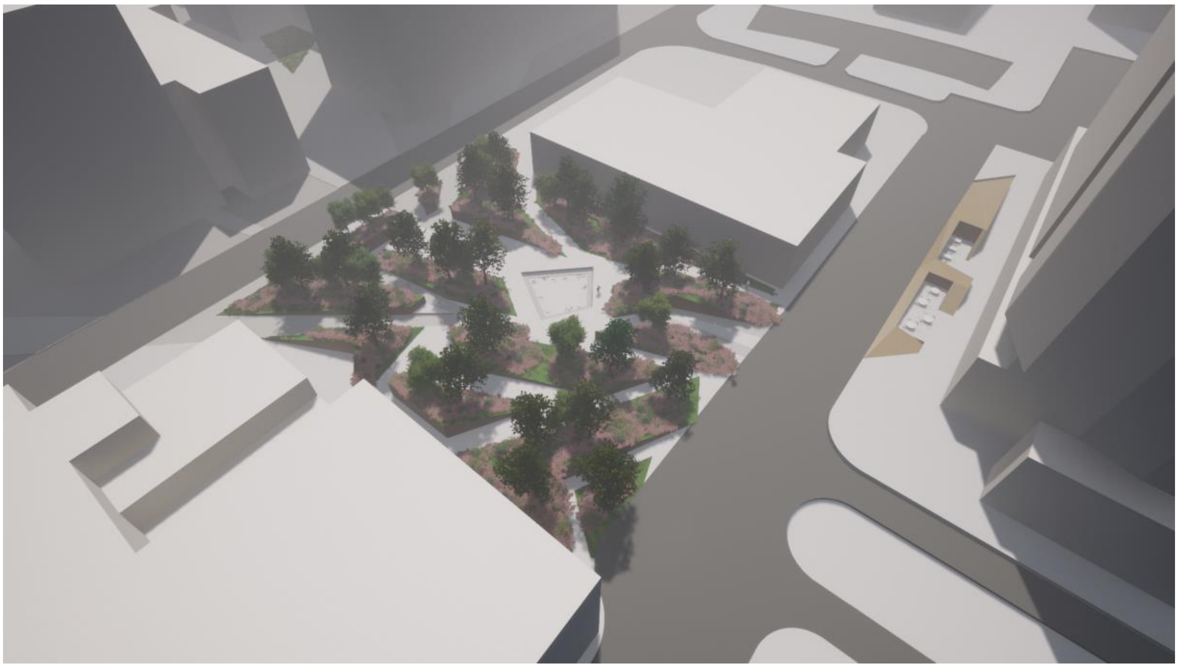


Figure 42. Design proposal on Health Centre park

Figure 43.Design proposal on Sepise street

8. Conclusion

The presented study analyzed pedestrian wind comfort in three public areas in the Ülemiste City district in Tallinn, Estonia, through CFD wind simulations to propose urban layout design solutions for improving urban space livability.

The first aim of the work was to determine actual wind comfort conditions in the areas. According to the study, the most problematic wind direction for three out of four areas is south, which is the most frequent wind direction in Tallinn. Consequently, five different shelter types and three different sizes of each were designed and tested through wind simulations to determine the extension of the areas with wind comfort conditions provided by each shelter type and size. The study showed that even the smallest wind shelter type created sufficient difference in the area's pedestrian wind comfort. Finally, on the basis of this knowledge, every area was designed differently in terms of wind protection needs and architectural values and functionality.

The initial urban design solutions showed significant improvements in the area provided with wind comfort conditions, with increments from 40 % to 83 %. The novelty of the work lies in the scarcity of wind comfort analysis in urban environments in the region and in the lack of proposals for urban design solutions to improve pedestrian comfort. Future work of the research could investigate other areas in the city of Tallinn using an additional type of wind shelters to produce results actionable by the city urban development department. The work could also help to raise awareness of the need for implementation of the simulation process already at the design stage of the building development or at least acknowledgement of the wind discomfort for pedestrians especially around high-rise buildings.

List of references

7013 Tartu raudteejaama hoone. (n.d.). 7013 Tartu Raudteejaama Hoone Vaksali 6, 1876.-1878. a • Mälestiste Otsing • Mälestised. Retrieved 13 May 2022, from https://register.muinas.ee/public.php?menuID=monument&action=view&id=7013

Aguilar, E., Auer, I., Brunet, M., Peterson, T. C., & Wieringa, J. (2003). Guidelines on climate metadata and homogenization. *WMO-TD No. 1186*, *1186*.

Blocken, B., & Carmeliet, J. (2004). Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples. *Journal of Thermal Envelope and Building Science, 280402*, 1097–1963. https://doi.org/10.1177/1097196304044396

Blocken, B., & Stathopoulos, T. (2013). CFD simulation of pedestrian-level wind conditions around buildings: Past achievements and prospects. *Journal of Wind Engineering and Industrial Aerodynamics*, *121*, 138–145. https://doi.org/10.1016/j.jweia.2013.08.008

Bottema, M. (2000). A method for optimisation of wind discomfort criteria. *Building and Environment*, *35*(1), 1–18. https://doi.org/10.1016/S0360-1323(98)00065-1

Brown, R., Hanna, K., & Holdsworth, R. (2017). *Making good – shaping places for people*. Centre for London. https://www.centreforlondon.org/wp-content/uploads/2017/02/CFLJ5081_collection_essay_placemaking_0217_WEB.pdf

Chokhachian, A., Santucci, D., & Auer, T. (2017). A Human-Centered Approach to Enhance Urban Resilience, Implications and Application to Improve Outdoor Comfort in Dense Urban Spaces. *Buildings*, *7*. https://doi.org/10.3390/buildings7040113

Climate.onebuilding.org. (n.d.). Retrieved 19 May 2022, from https://climate.onebuilding.org/default.html

Davenport, A. G. (2002). Past, present and future of wind engineering. *Journal of Wind Engineering and Industrial Aerodynamics*, *90*(12), 1371–1380. https://doi.org/10.1016/S0167-6105(02)00383-5

De Luca, F. (2019). *Sun and Wind. Integrated Environmental Performance Analysis for Building and Pedestrian Comfort*.

Dogan, P. K., Timur. (n.d.). *Eddy3D*. Eddy3D. Retrieved 31 March 2022, from https://www.eddy3d.com

Dvigatel. (2021, April 18). et.info-about.info. https://amp.et.info-about.info/141984/1/dvigatel.html

Eddy3D. (n.d.). Eddy3D. Retrieved 18 May 2022, from https://www.eddy3d.com

EST_HA_Tallinn. (n.d.). Retrieved 18 May 2022, from https://energy-models.com/content/ESTHATallinnAP260380TMYx2003-2017zip

Franke, J., & Baklanov, A. (2007). *Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment: COST Action 732 Quality Assurance and Improvement of Microscale Meteorological Models*.

Gandemer, J. (1978). *Discomfort due to wind near buildings: Aerodynamic concepts*. University of Michigan Library.

Grasshopper. (n.d.). Retrieved 18 May 2022, from https://www.grasshopper3d.com/

Home—Project for Public Spaces. (n.d.). Retrieved 10 May 2022, from https://www.pps.org/

Jacobs, A. B. (1993a, September 1). Great Streets. *ACCESS Magazine, 1(3)*. https://escholarship.org/content/qt3t62h1fv/qt3t62h1fv.pdf?t=mdhhtu&v=lg

Jacobs, A. B. (1993b). *Great Streets*. MIT Press.

Jacobs, J. (1993). *The death and life of great American cities*. Vintage Books.

Jenkins, M. (2021, April 14). Wind Comfort Criteria: Lawson, Davenport, and NEN 8100. *SimScale*. https://www.simscale.com/blog/2019/12/wind-comfort-criteria/

Jone Johnson, L. (2020). Jane Jacobs: New Urbanist Who Transformed City Planning. *ThoughtCo*. https://www.thoughtco.com/jane-jacobs-biography-4154171

Kastner, P., & Dogan, T. (n.d.). *Predicting Space Usage by Multi-Objective Assessment of Outdoor Thermal Comfort around a University Campus*. 7.

Kastner, P., & Dogan, T. (2020). A cylindrical meshing methodology for annual urban computational fluid dynamics simulations. *Journal of Building Performance Simulation, 13*(1), 59–68. https://doi.org/10.1080/19401493.2019.1692906

Kastner, P., & Dogan, T. (2021). Eddy3D: A toolkit for decoupled outdoor thermal comfort simulations in urban areas. *Building and Environment*, 108639. https://doi.org/10.1016/j.buildenv.2021.108639

Krautheim, M., Pasel, R., Pfeiffer, S., & Schultz-Granberg, J. (Eds.). (2014a). *City and wind: Climate as an architectural instrument*. DOM publishers.

Krautheim, M., Pasel, R., Pfeiffer, S., & Schultz-Granberg, J. (Eds.). (2014b). *City and wind: Climate as an architectural instrument*. DOM publishers.

Lausing, T. (2004). *DVIGATEL sai 105-aastaseks*. 4.

Lawson, T. V. (1978). The widn content of the built environment. *Journal of Wind Engineering and Industrial Aerodynamics, 3*(2), 93–105. https://doi.org/10.1016/0167-6105(78)90002-8

Lawson, T. V., & Penwarden, A. D. (1975). *Wind Effects on Buildings and Structures* (pp. 567–622). Cambridge University Press.

Lutyens, D. (2020, March 6). *Five stunning outdoor spaces for all*. https://www.bbc.com/culture/article/20200602-five-stunning-outdoor-spaces-for-all

Mainor Ülemiste. (n.d.). Mainor Ülemiste. Retrieved 15 May 2021, from https://www.mainorulemiste.ee/en

Meetiyagoda, L., & Munasinghe, J. (2009). Towards Great Streets: An Empirical Approach to Study a Streetscape. *Bhumi, The Planning Journal*, *1*.

Moya Castro, R. (2015). *EMPIRICAL EVALUATION OF THREE WIND ANALYSIS TOOLS FOR CONCEPT DESIGN OF AN URBAN WIND SHELTER*.

Murakami, S., Uehara, K., & Deguchi, K. (1980). WIND EFFECTS ON PEDESTRIANS: NEW CRITERIA BASED ON OUTDOOR OBSERVATION OF OVER 2000 PERSONS. In J. E. Cermak (Ed.), *Wind Engineering* (pp. 277–288). Pergamon. https://doi.org/10.1016/B978-1-4832-8367-8.50032-2

Ojalo, H. (2020, May 8). DVIGATELI AMEERIKA MÄED: Vagunitehasest mööblitootjaks ning lõpuks kosmose- ja tuumaettevõteks | Ajalugu. *Õhtuleht*. https://ajalugu.ohtuleht.ee/1001096/dvigateli-ameerika-maed-vagunitehasest-mooblitootjaks-ning-lopuks-kosmose-ja-tuumaettevoteks

Pacheco, P. (2017, June 9). Public Spaces: 10 Principles for Connecting People and the Streets. *TheCityFix*. https://thecityfix.com/blog/public-spaces-10-principles-for-connecting-people-and-the-streets-priscila-pacheco/

Poddaeva, O., & Churin, P. (2021). Improving the comfort of pedestrian and recreational areas of the stylobate part of the residential complex. *Energy Reports*, *7*, 395–402. https://doi.org/10.1016/j.egyr.2021.07.111

Rhinoceros 3D. (n.d.). Www.Rhino3d.Com. Retrieved 18 May 2022, from https://www.rhino3d.com/

Sekavin, L. (2018). *Kohtade identiteet endistel tööstusaladel Volta kvartali ja Ülemiste City näitel*. https://dspace.emu.ee//handle/10492/4229

Stathopoulos, T. (2011). *Introduction to Environmental Aerodynamics*. 28.

The Effects of Wind on People in the Vicinity of Buildings—Wind Effects on Buildings and Structures.pdf. (n.d.).

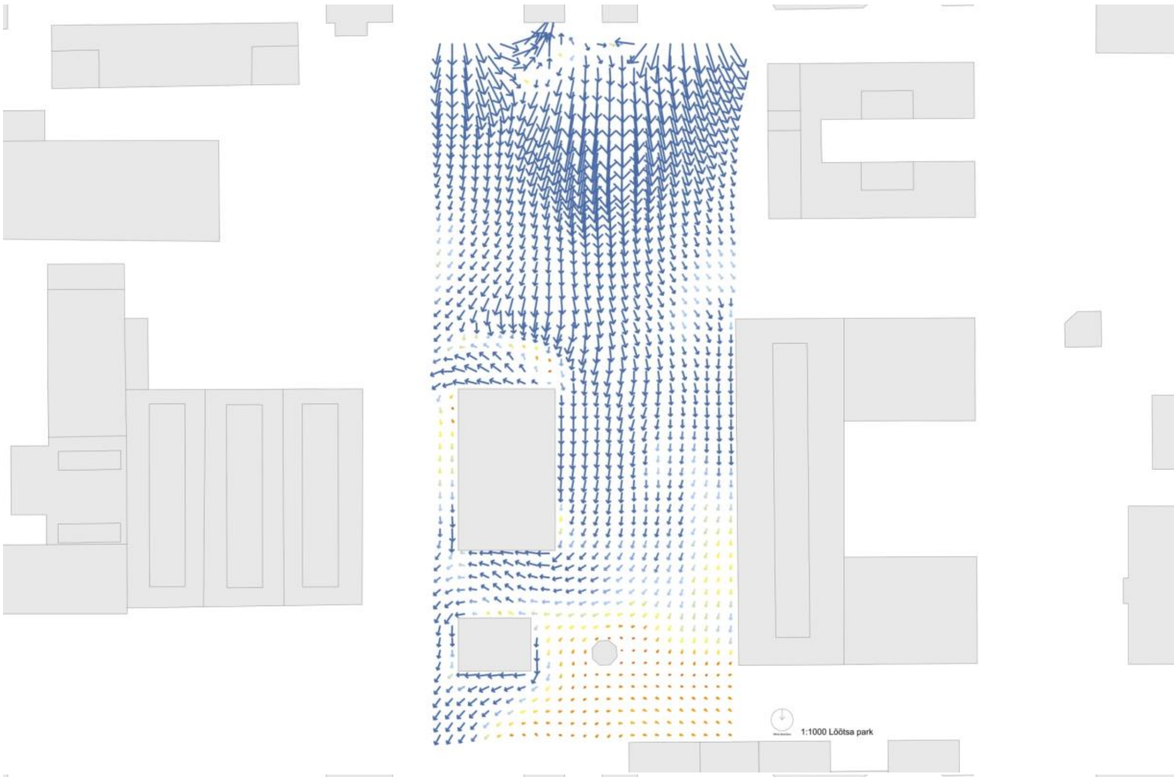
Ülemiste City. (n.d.). Retrieved 14 May 2021, from https://www.ulemistecity.ee/

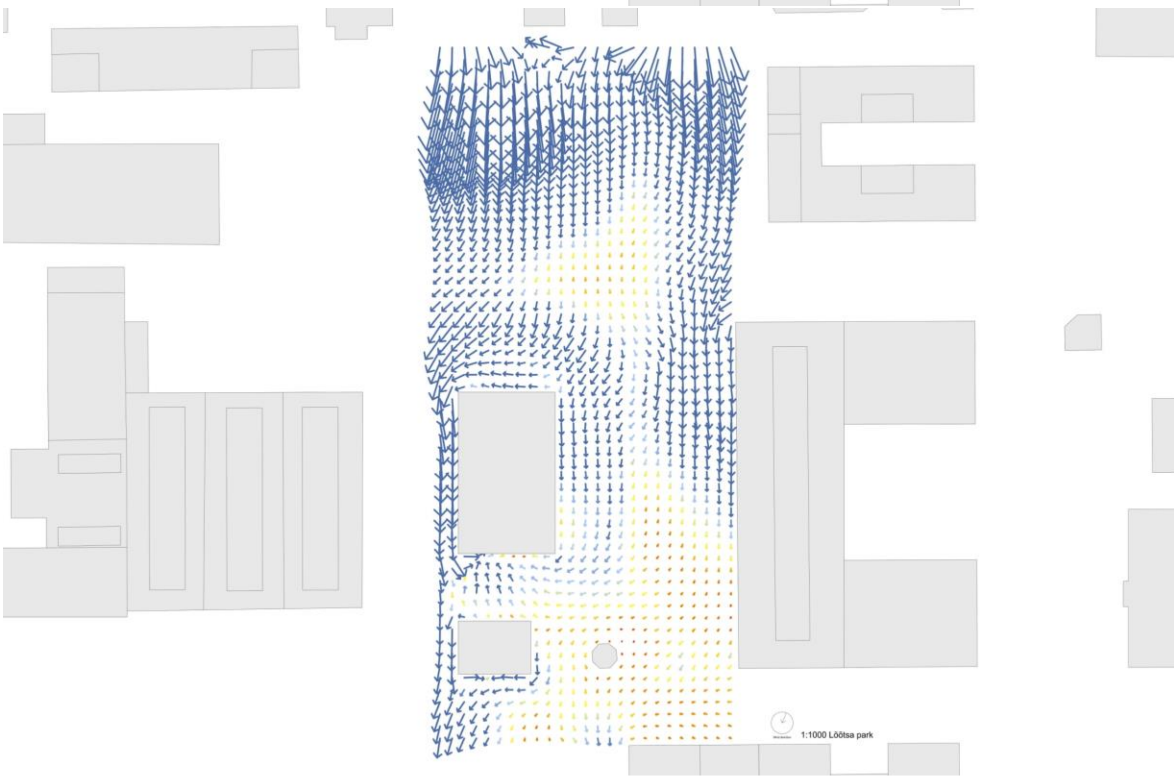
Ülemiste City History. (n.d.). Ülemiste City. Retrieved 1 April 2022, from https://www.ulemistecity.ee/en/about/

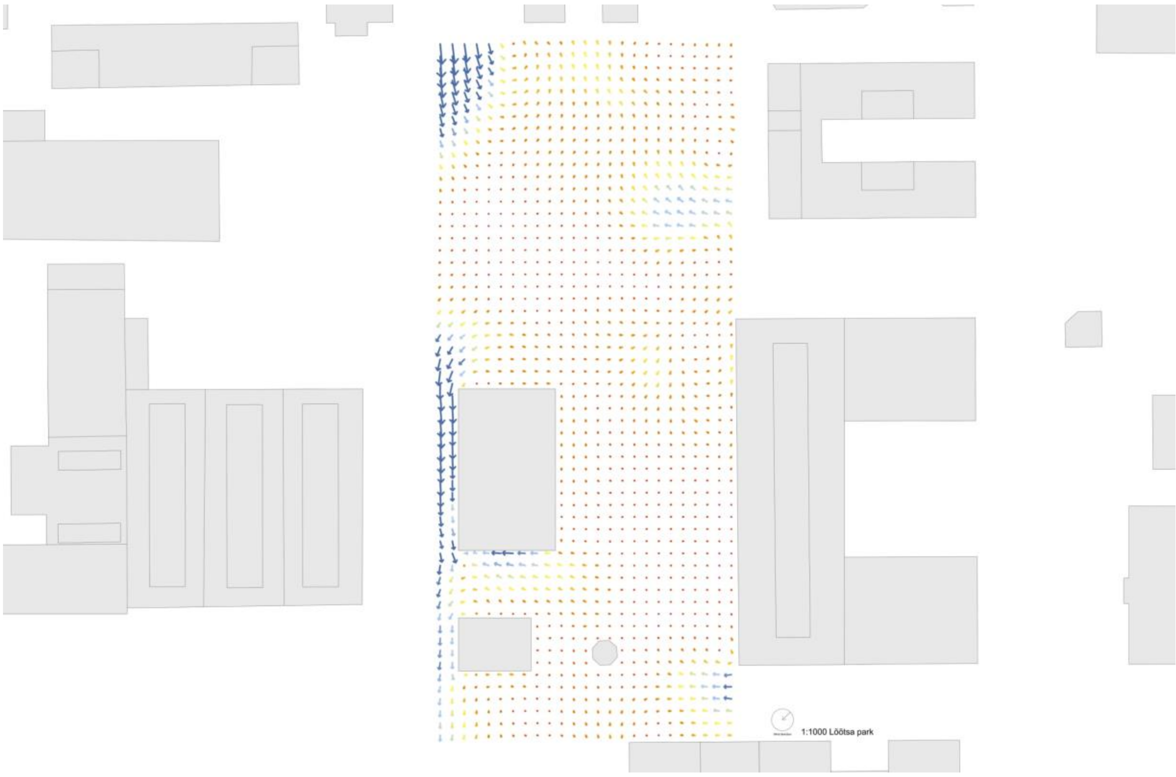
X-GIS 2.0 [maainfo]. (n.d.). Retrieved 19 May 2022, from https://xgis.maaamet.ee/xgis2/page/app/maainfo

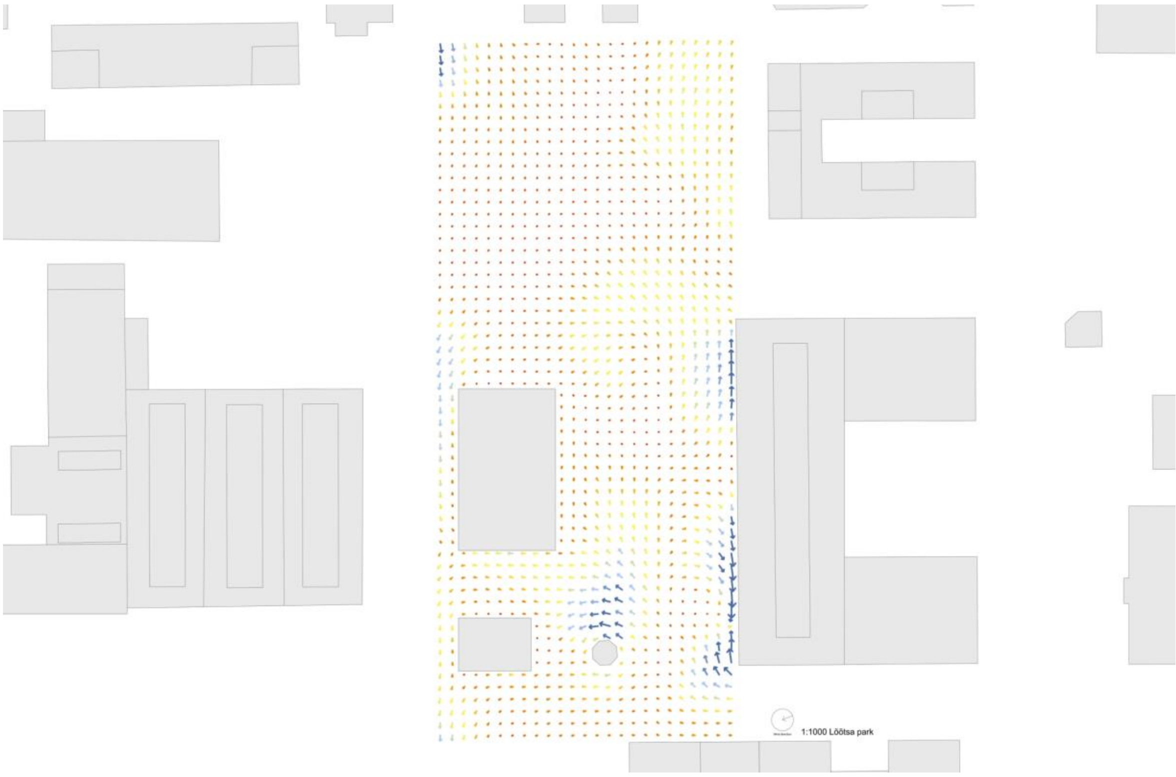
Appendices

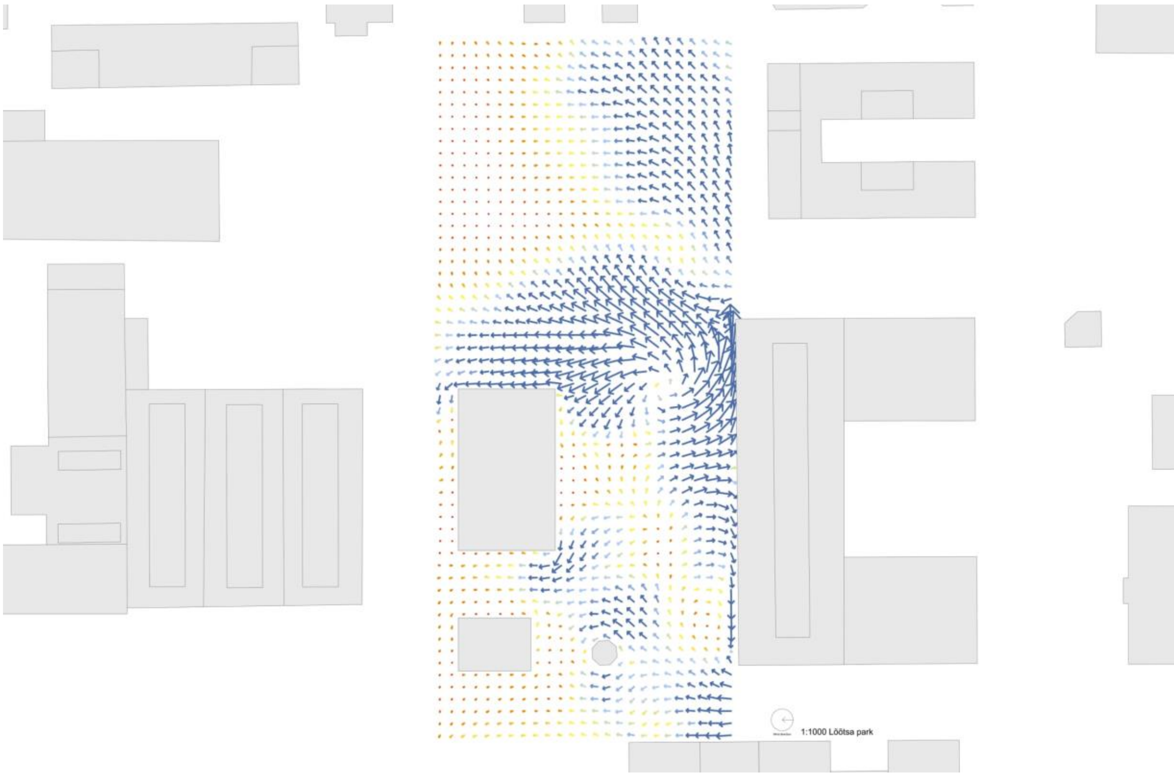
Appendix 1. Wind flow and velocity plot in Lõõtsa park for the 16 directions

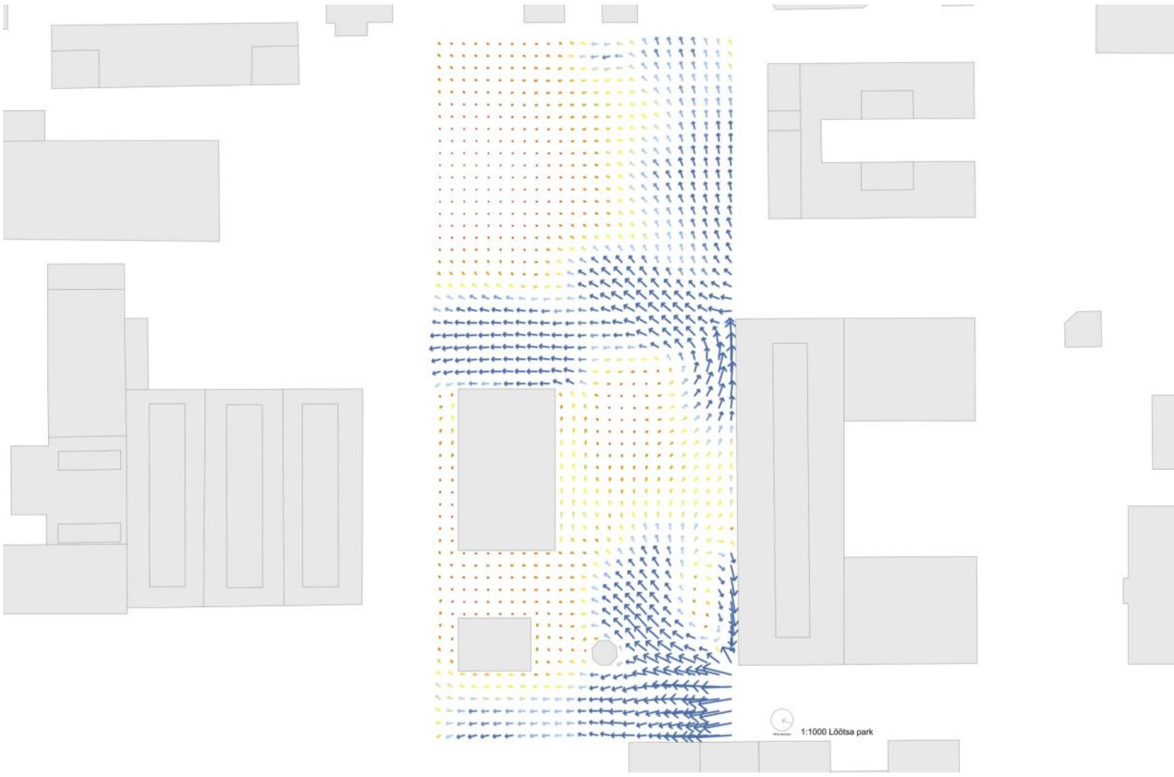


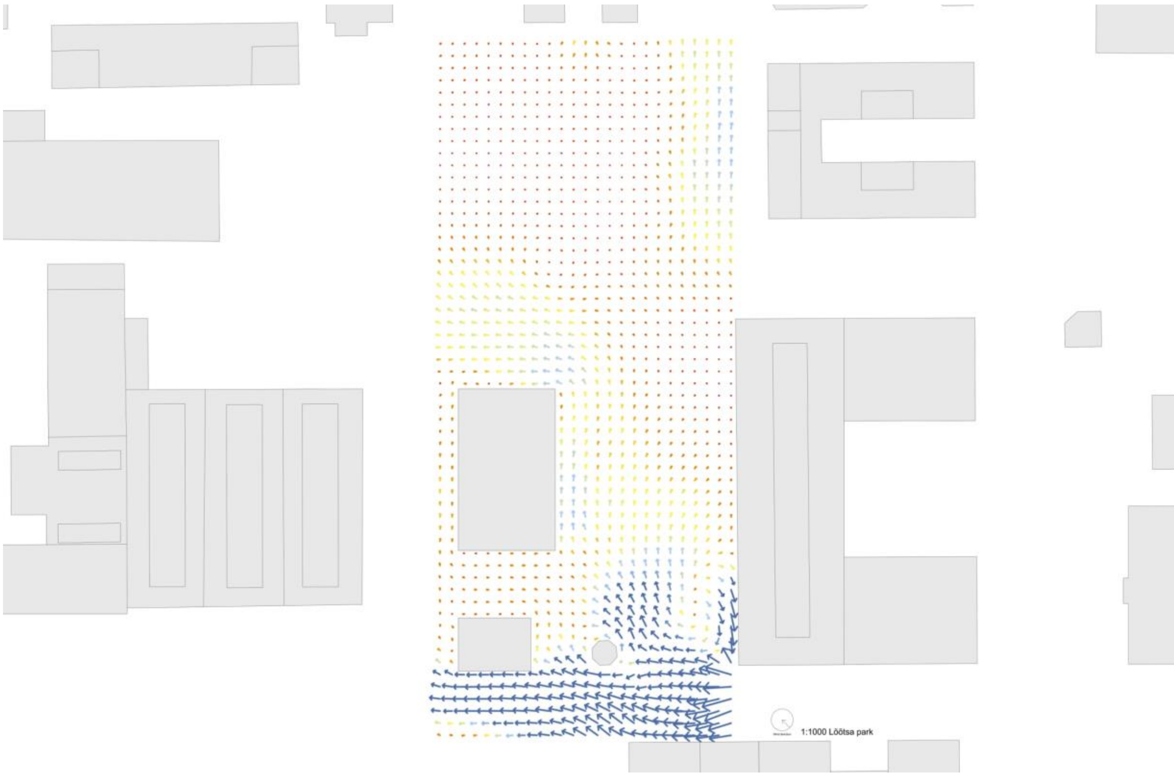



1:1000 Löötsa park

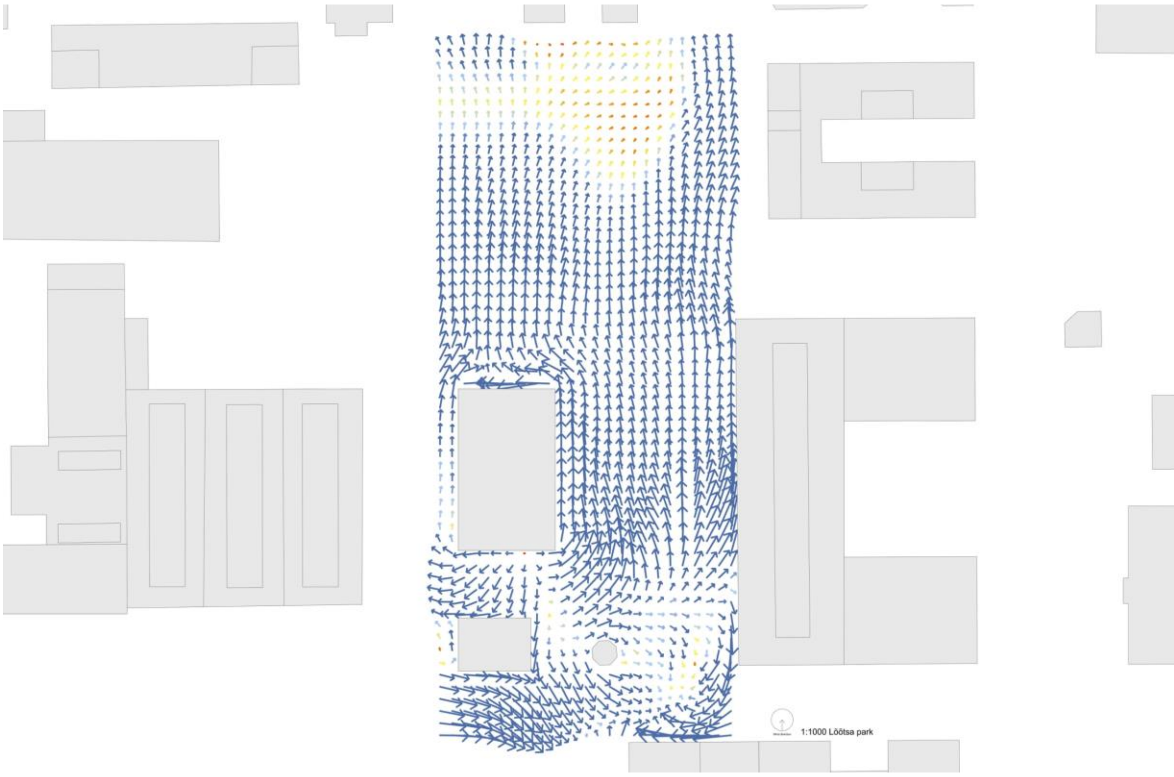

1:1000 Löötsa park

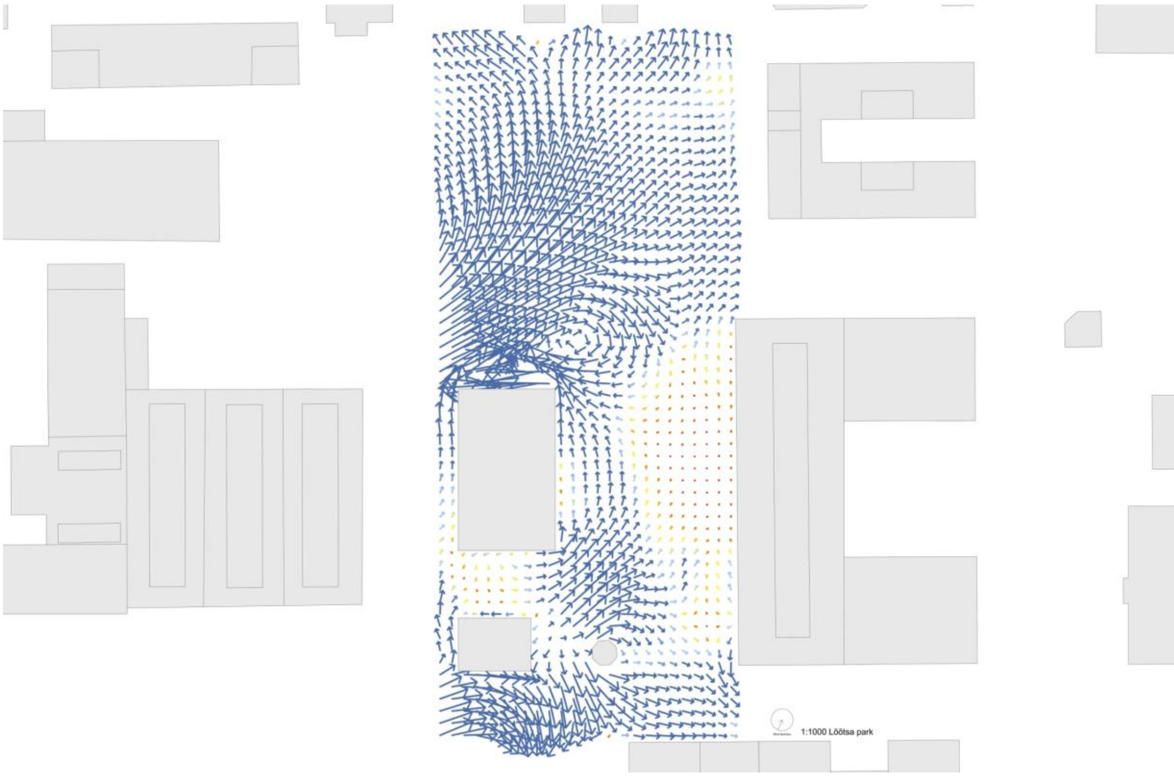

1:1000 Lõõtsa park


1:1000 Lõõtsa park

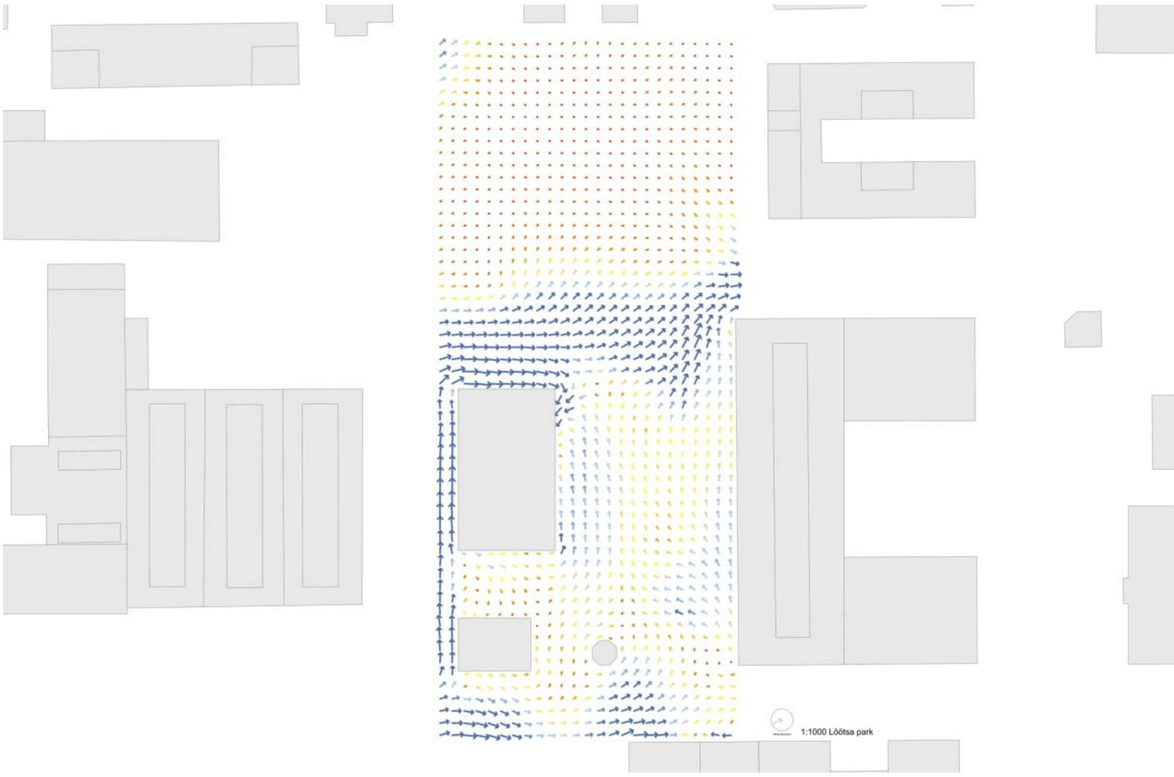

1:1000 Lõõtsa park

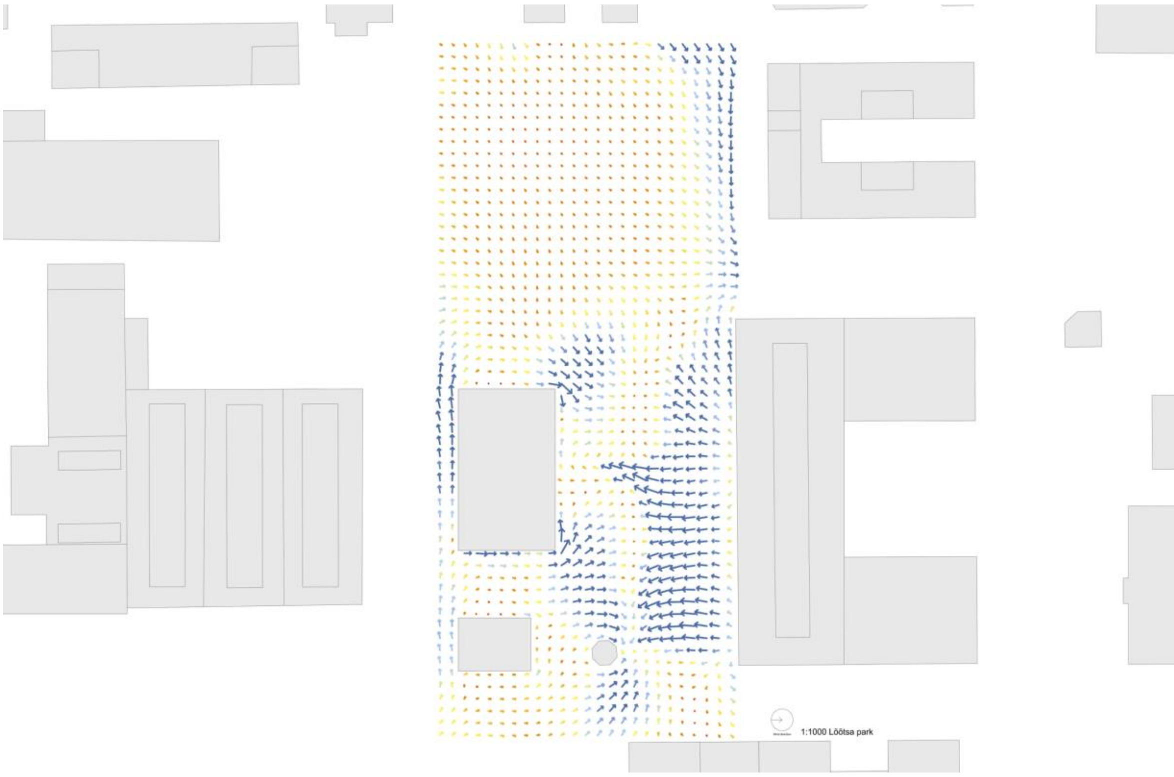

1:1000 Lõõtsa park

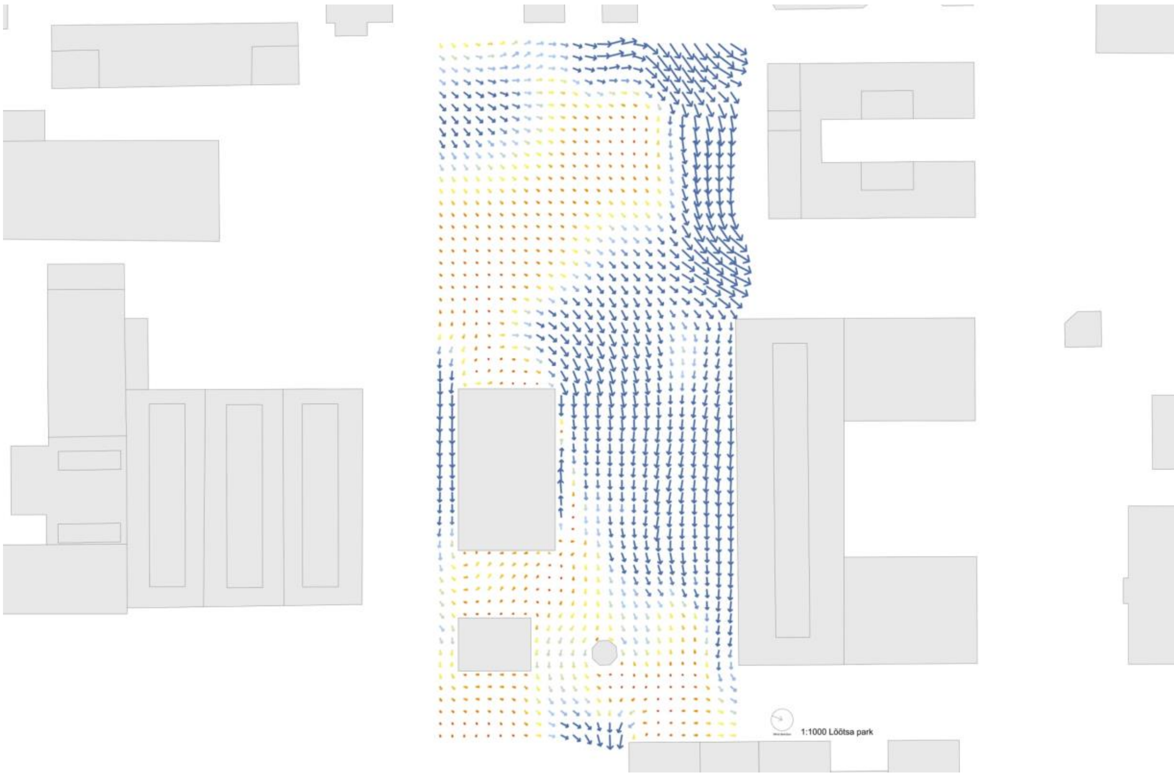

1:1000 Lõõtsa park

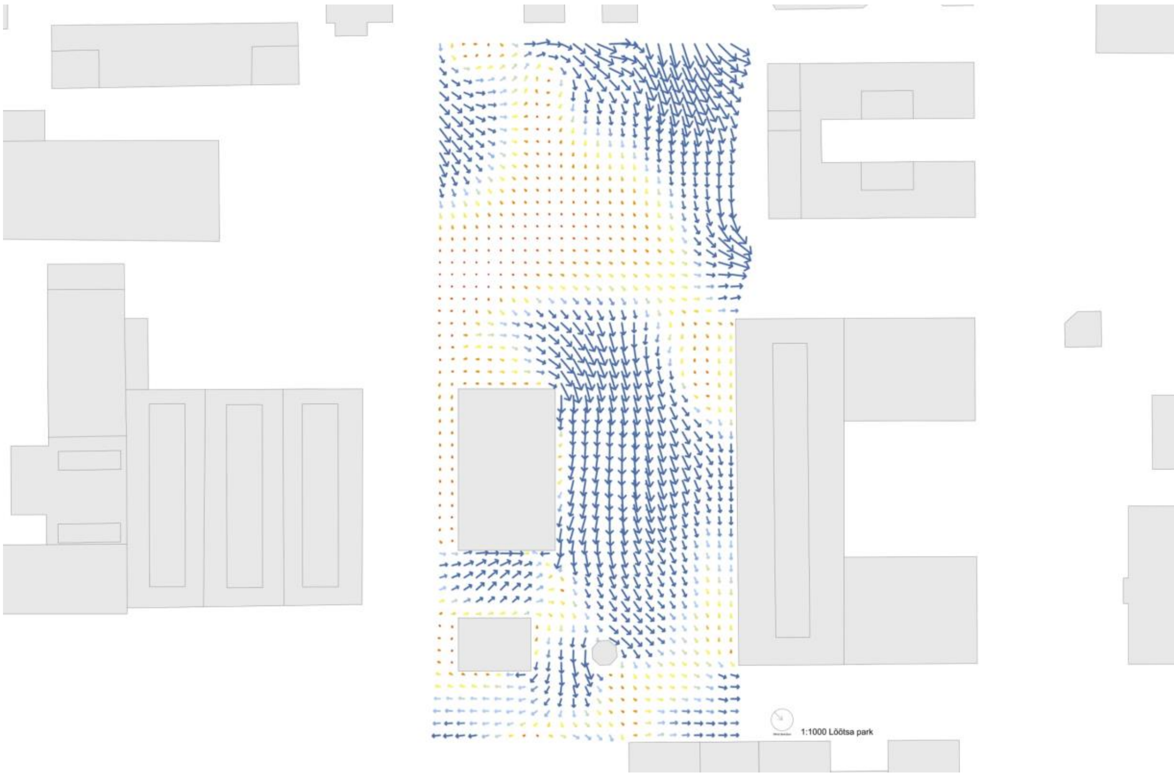

1:1000 Lõõtsa park

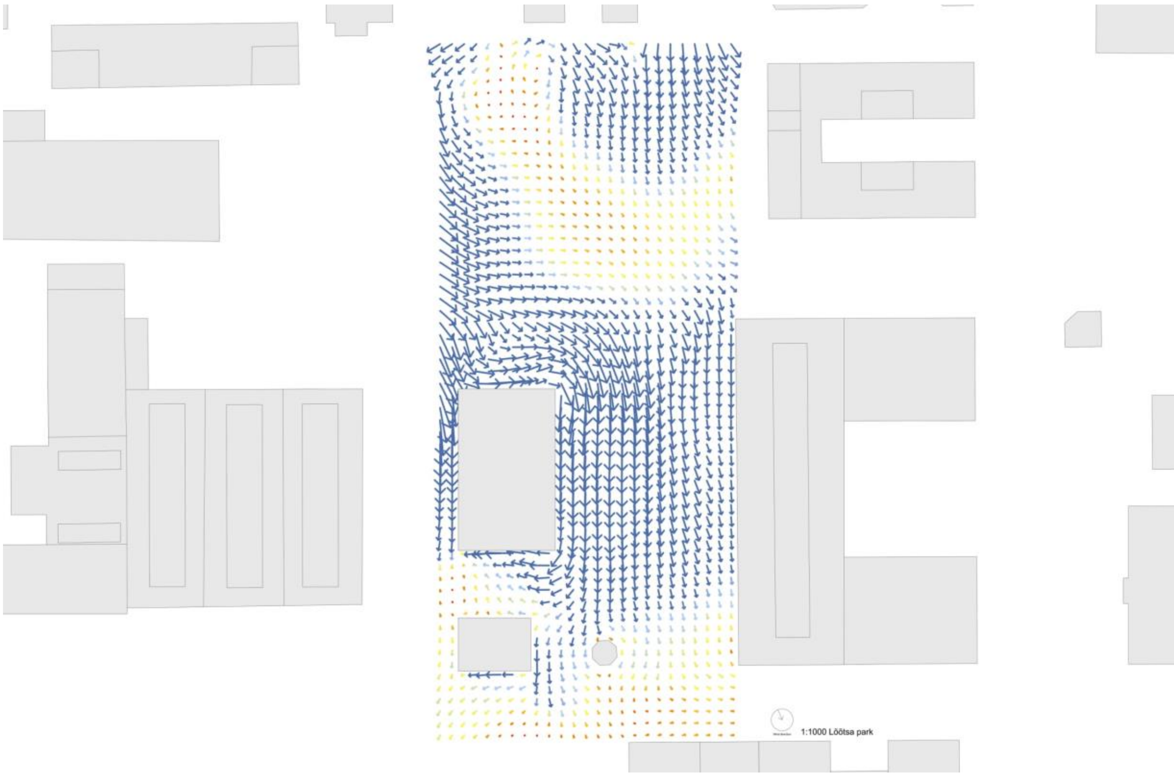

1:1000 Lõõtsa park


1:1000 Lõõtsa park

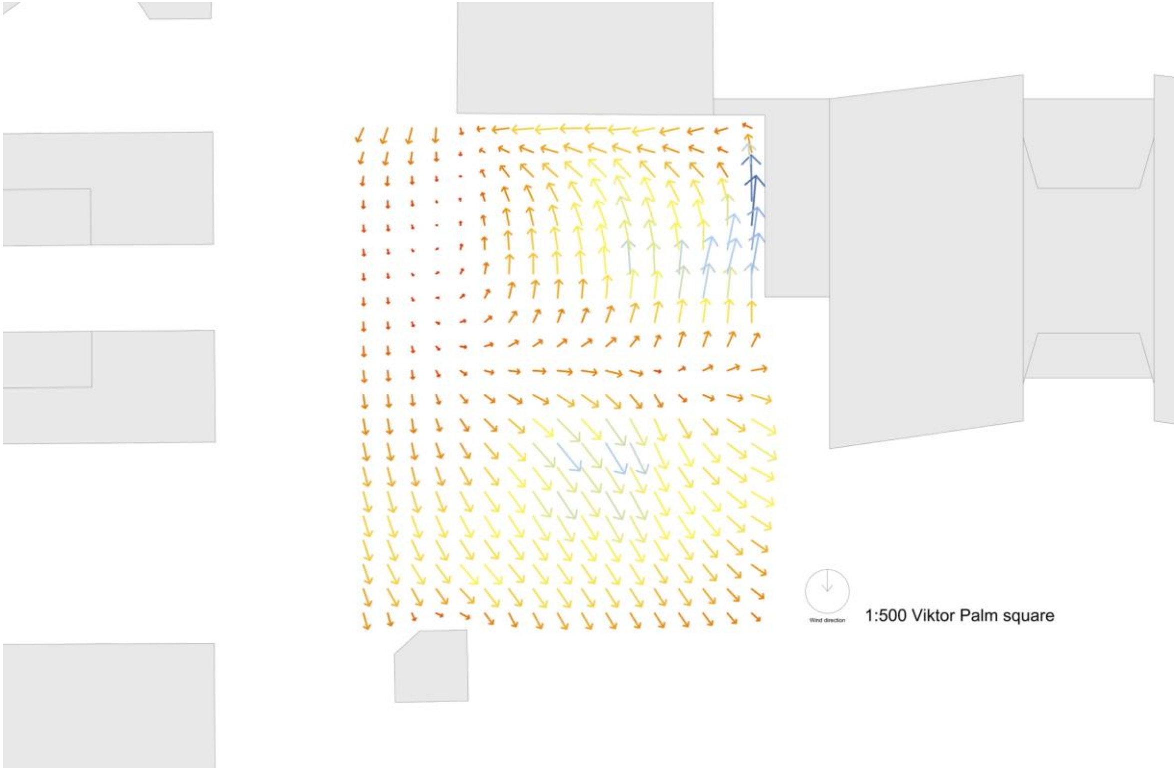

1:1000 Lõõtsa park

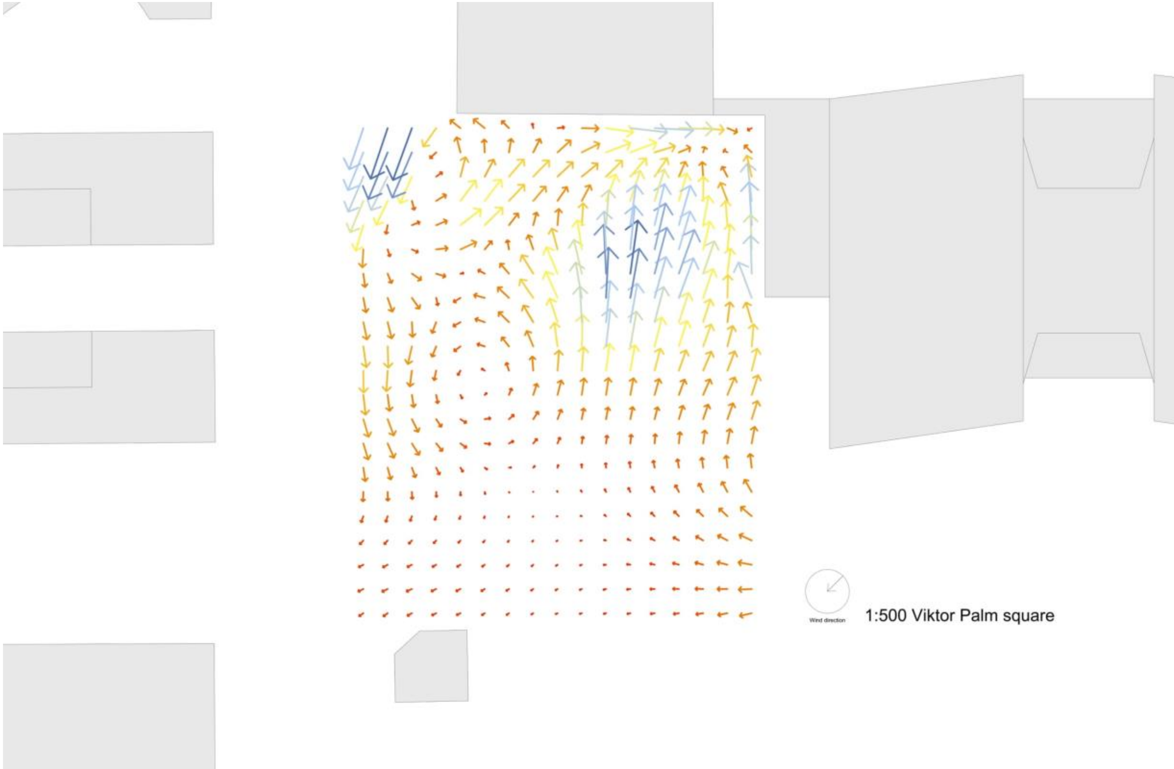

1:1000 Lõõtsa park


1:1000 Löötsa park

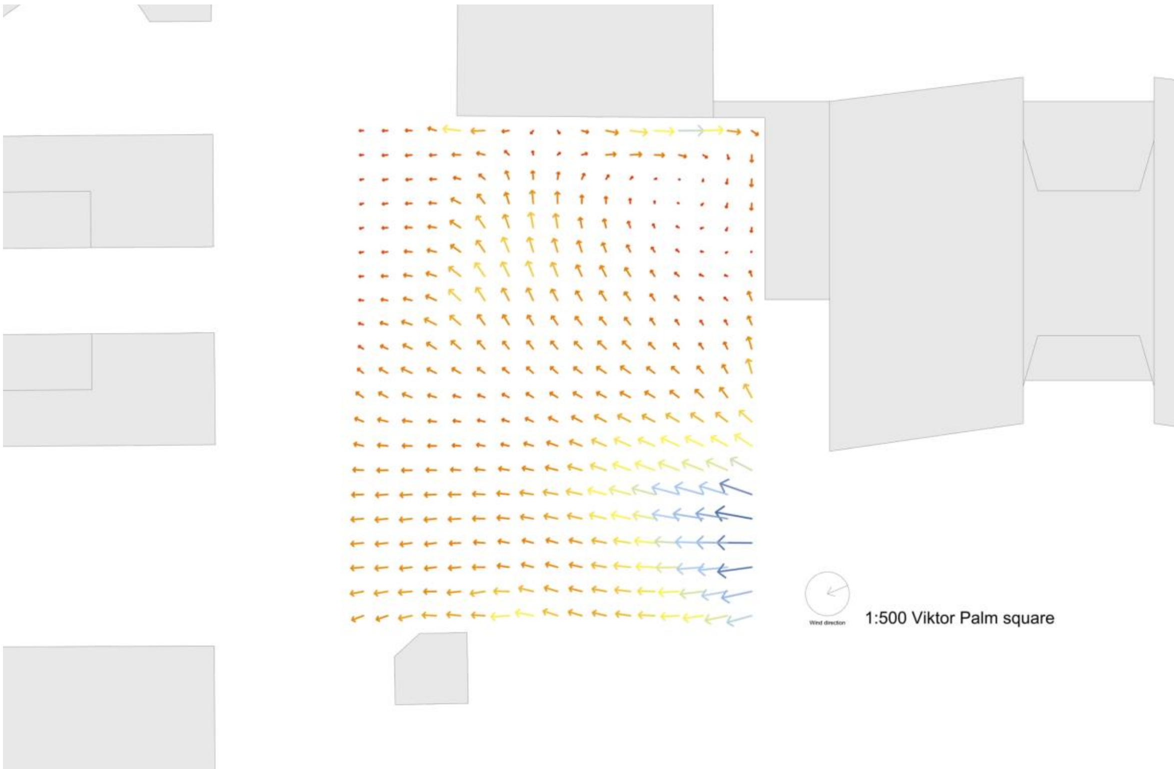

1:1000 Löötsa park

Appendix 2. Wind flow and velocity plot in Viktor Palmi square for all the 16 simulated directions

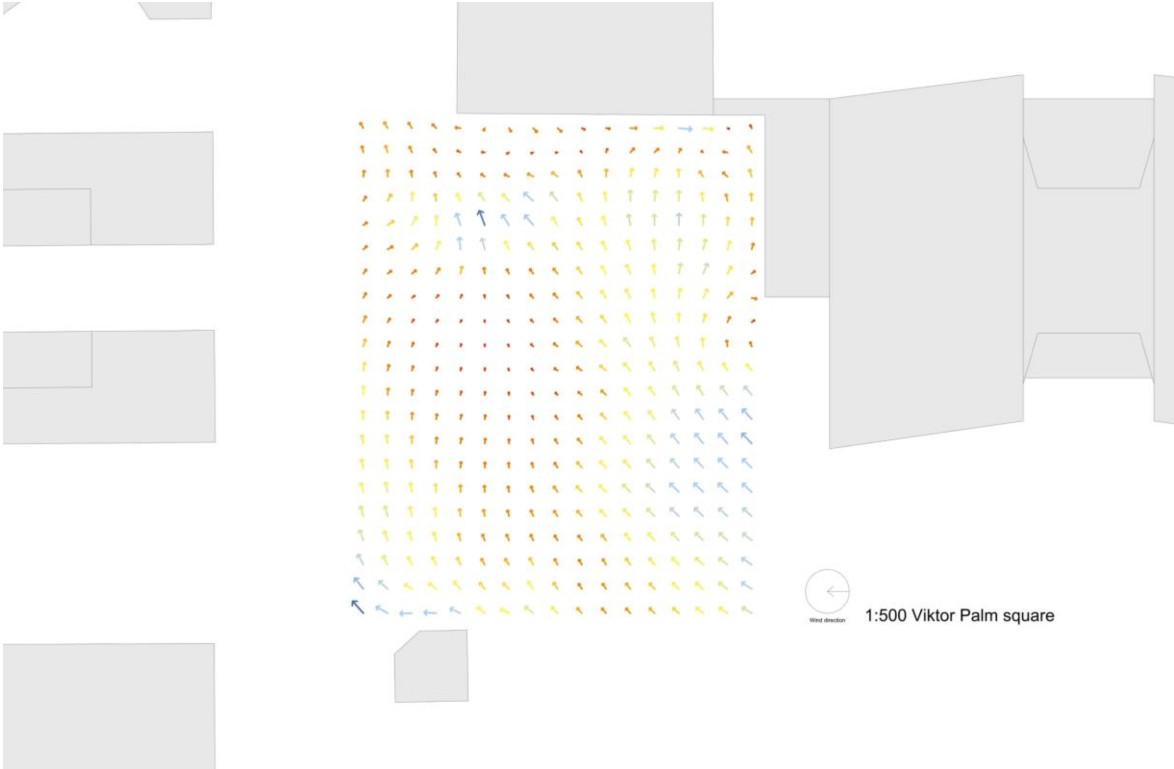




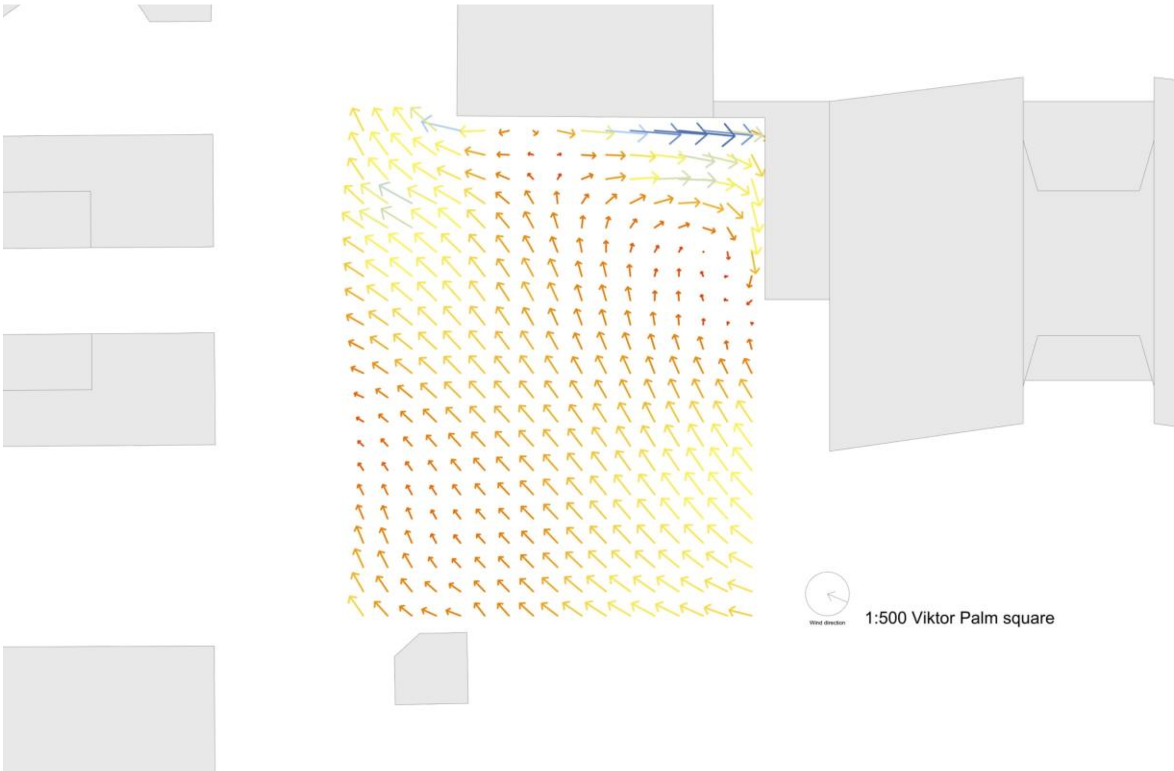
1:500 Viktor Palm square



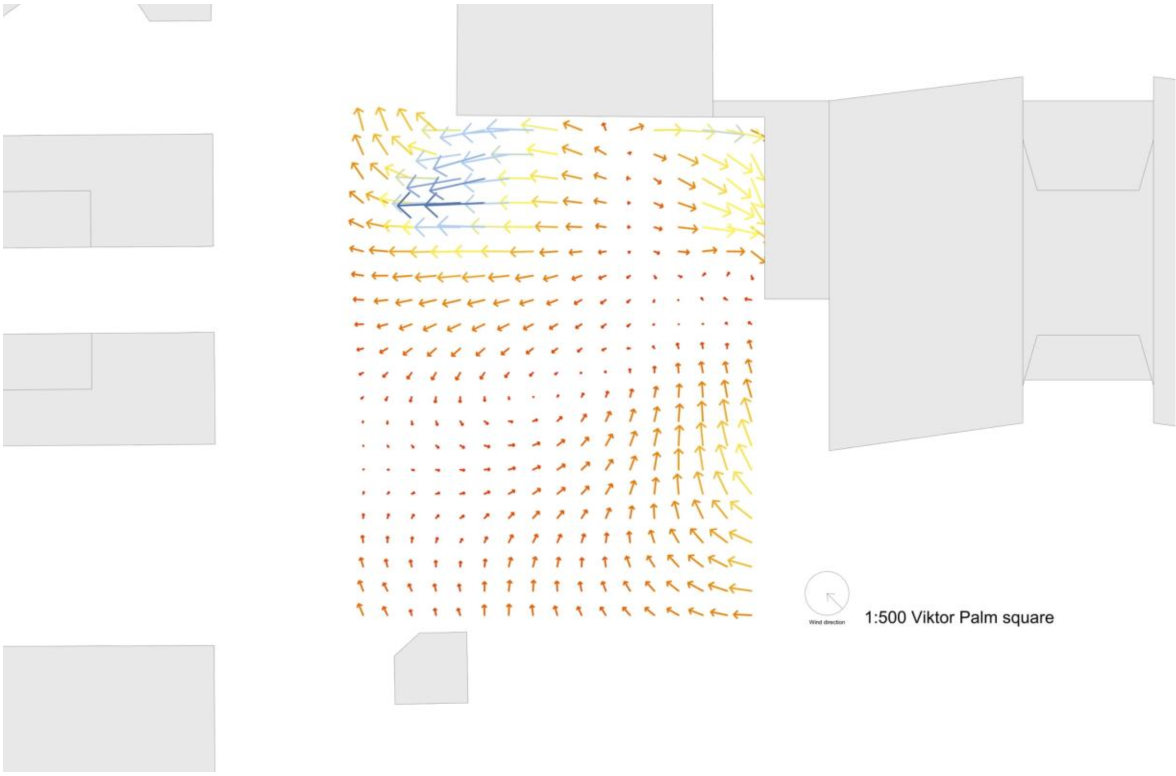
1:500 Viktor Palm square



1:500 Viktor Palm square

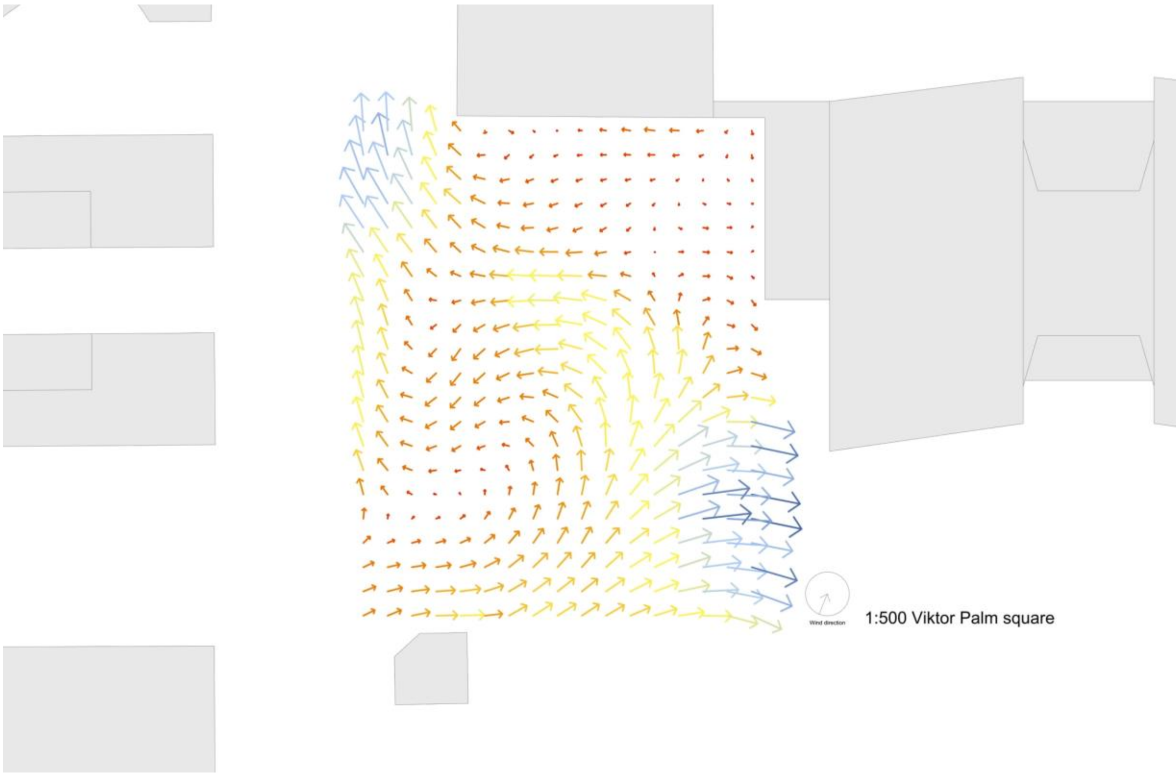


1:500 Viktor Palm square

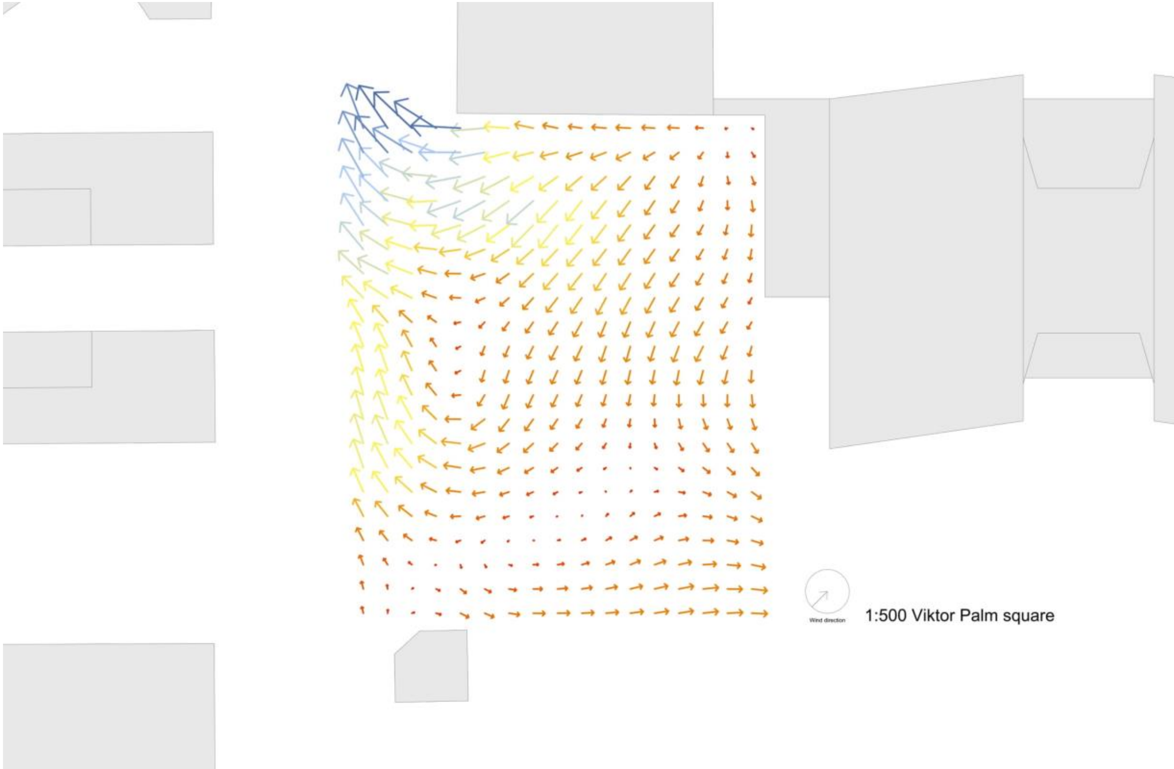

Wind direction
1:500 Viktor Palm square


Wind direction
1:500 Viktor Palm square

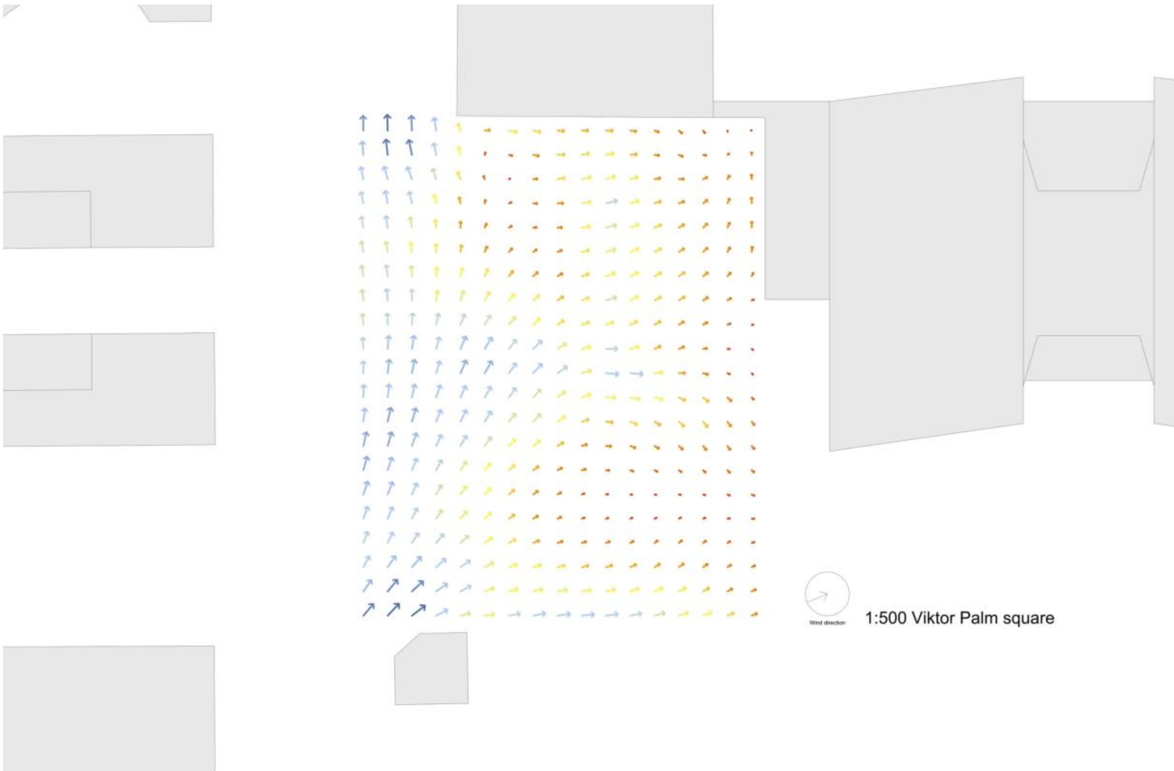
1:500 Viktor Palm square



1:500 Viktor Palm square



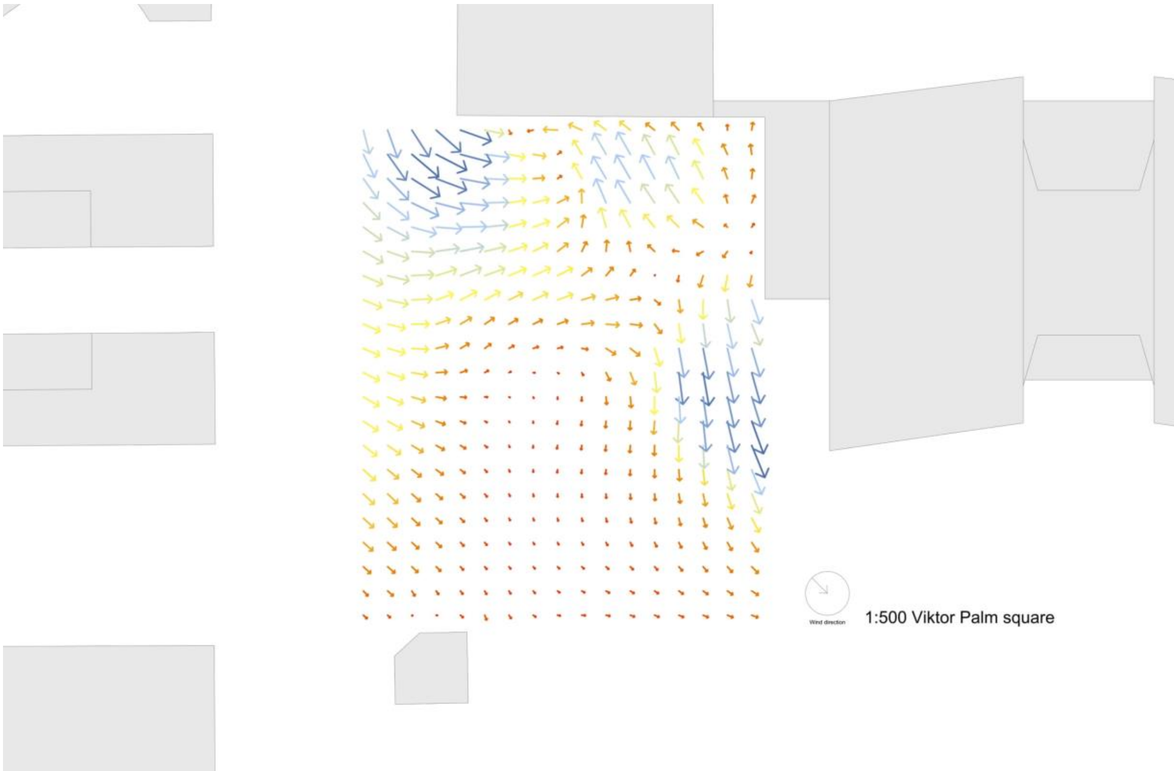
1:500 Viktor Palm square



1:500 Viktor Palm square

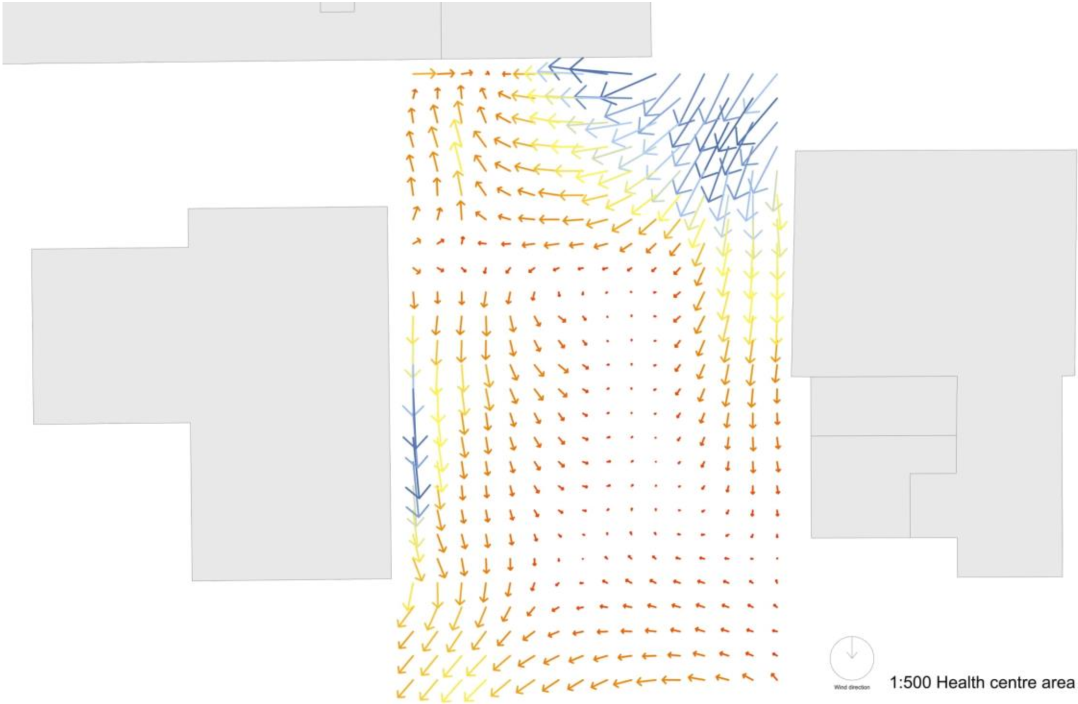
1:500 Viktor Palm square

1:500 Viktor Palm square


Wind direction
1:500 Viktor Palm square


Wind direction
1:500 Viktor Palm square

Appendix 3. Wind flow and velocity plot in Health Centre park for all the 16 simulated directions

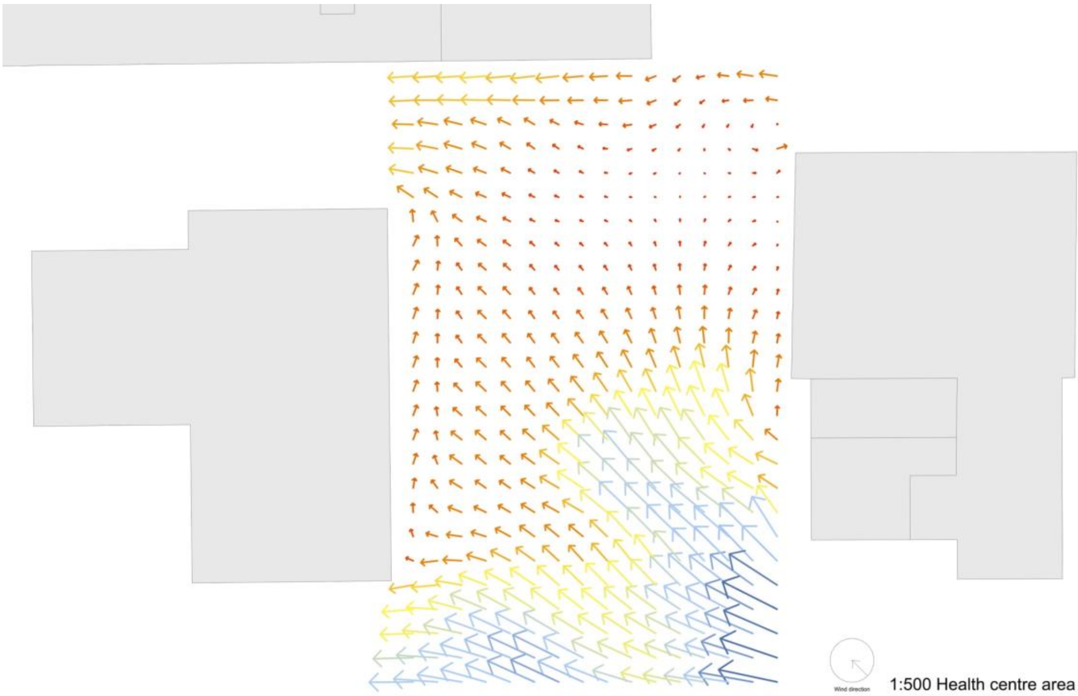


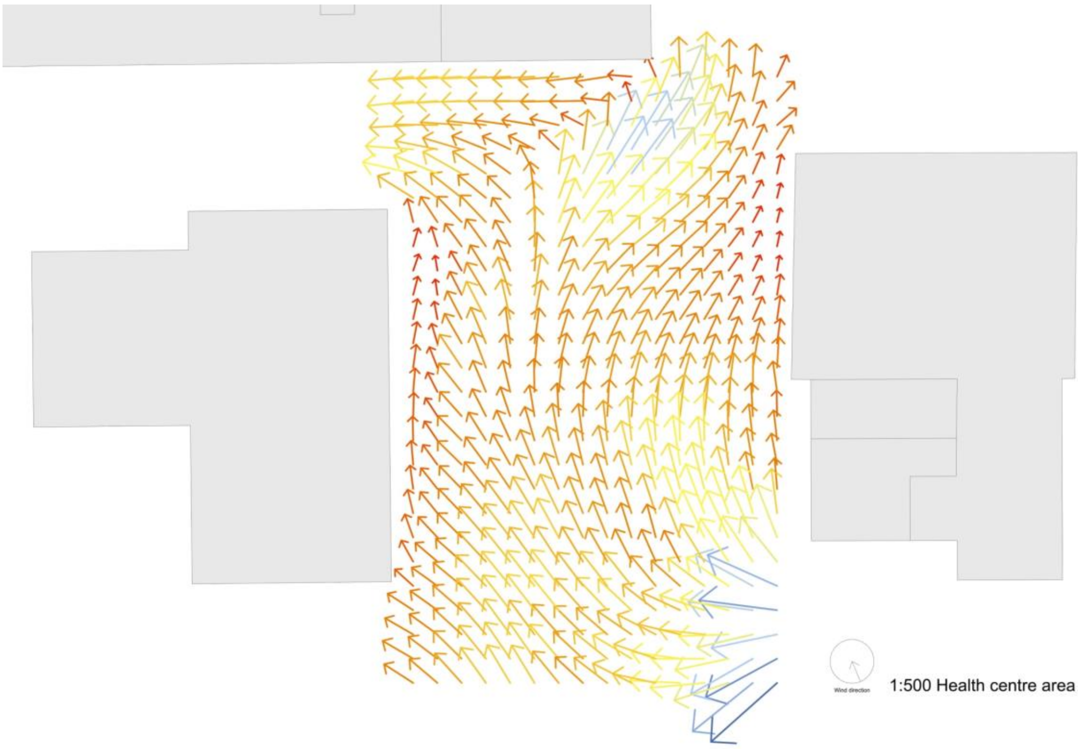

Wind direction
1:500 Health centre area

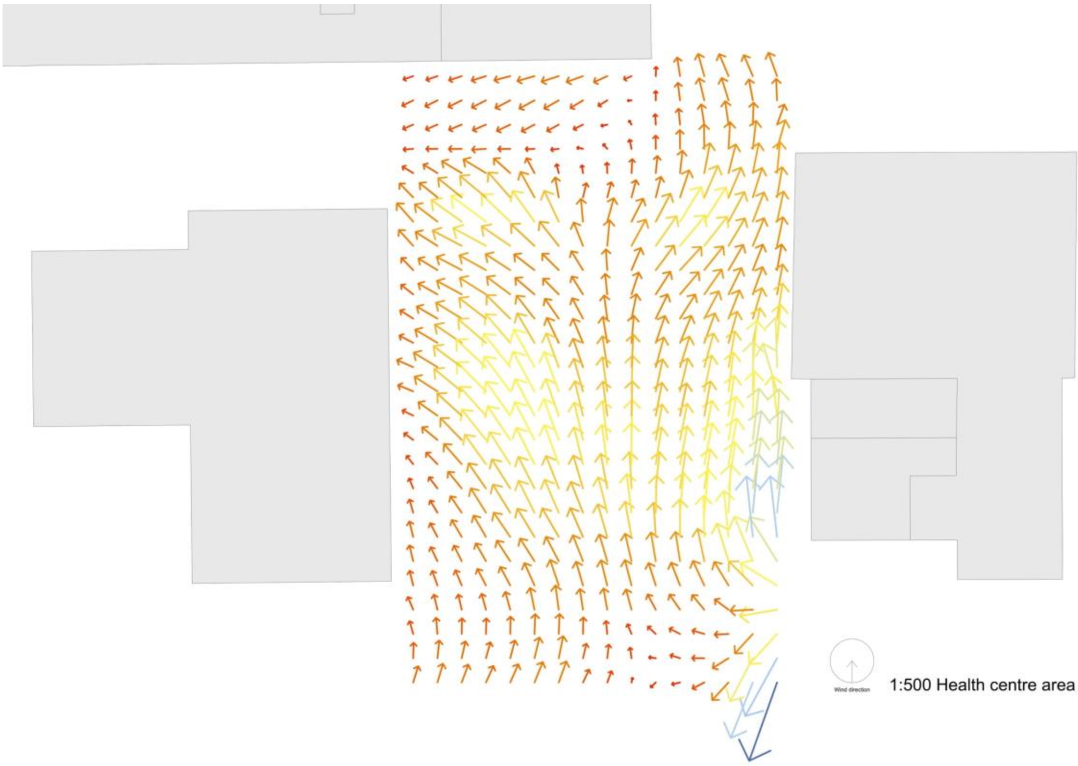

Wind direction
1:500 Health centre area

1:500 Health centre area

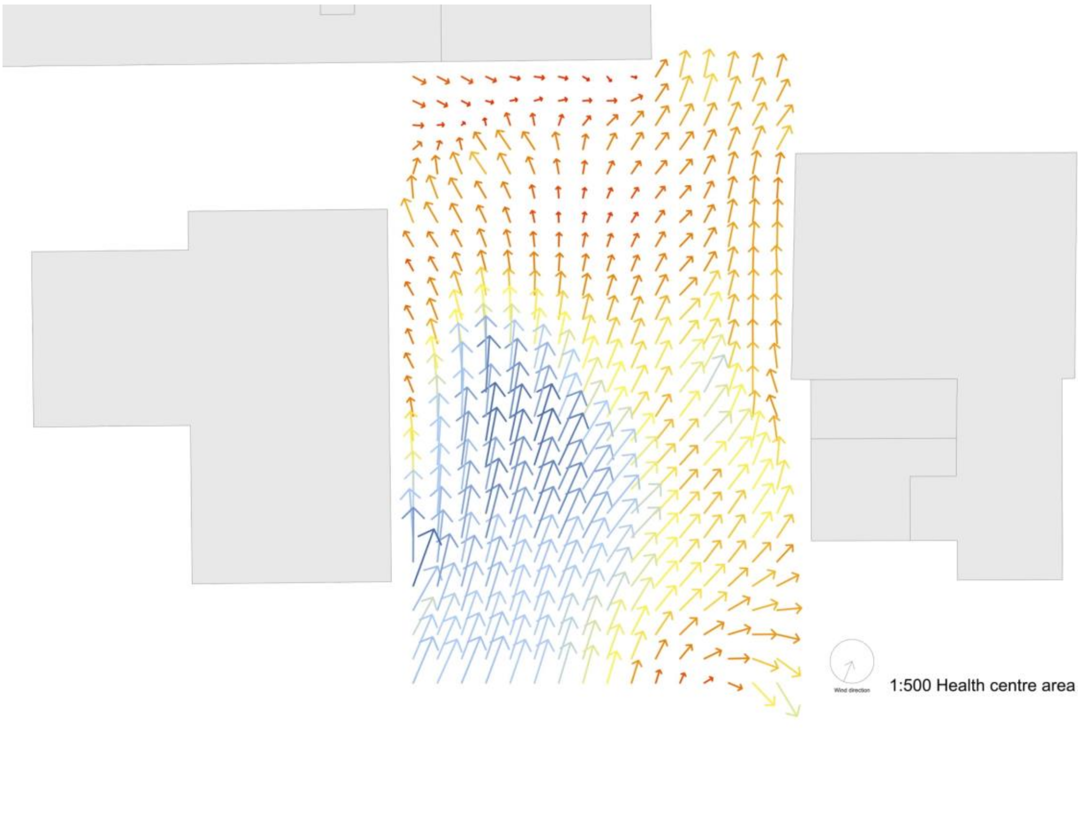
1:500 Health centre area


Wind direction
1:500 Health centre area

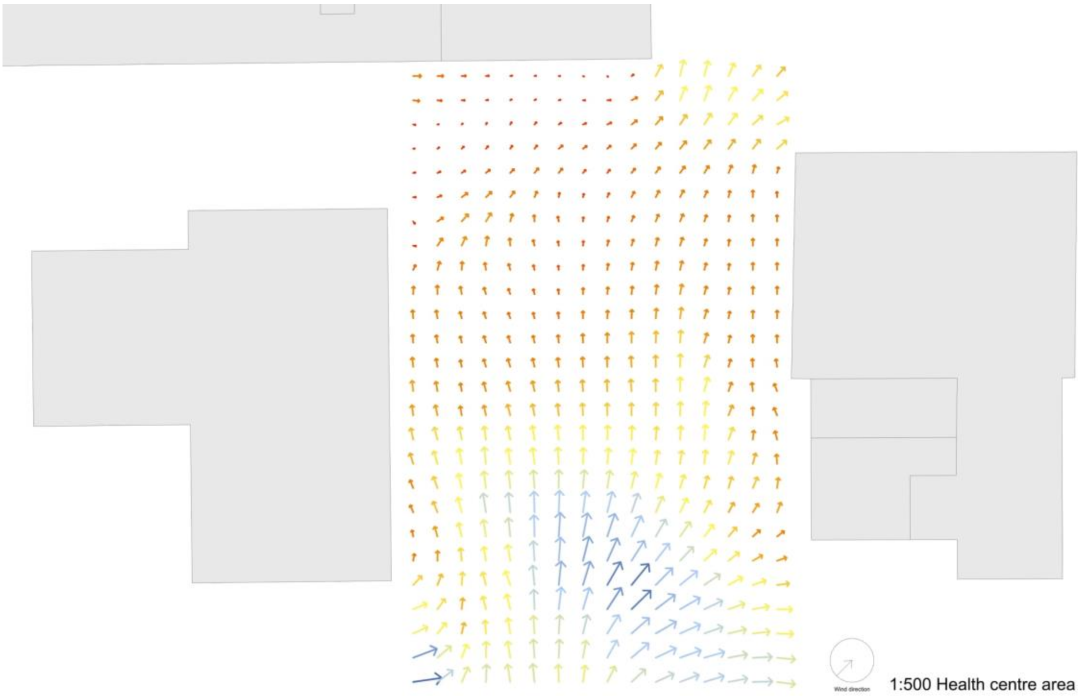

Wind direction
1:500 Health centre area

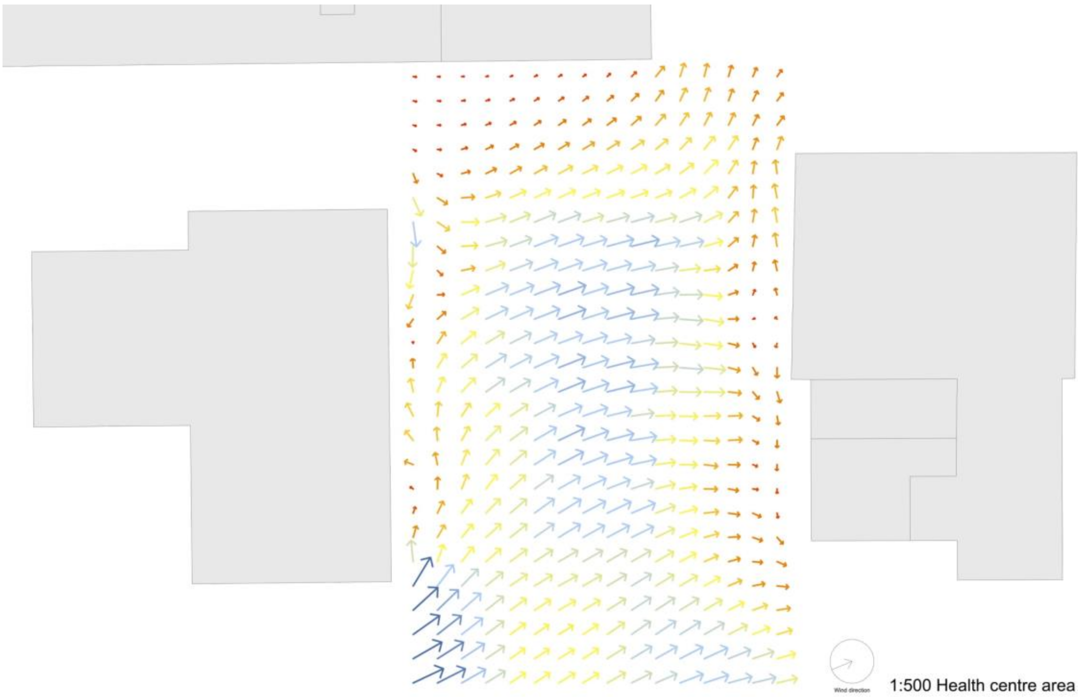


1:500 Health centre area

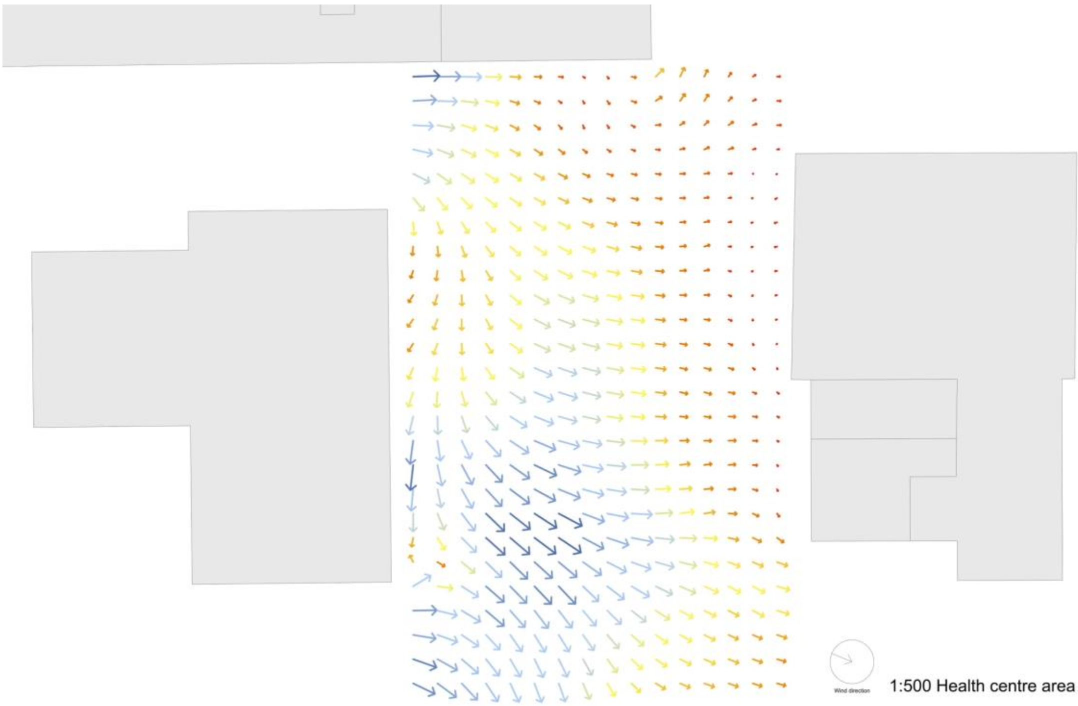


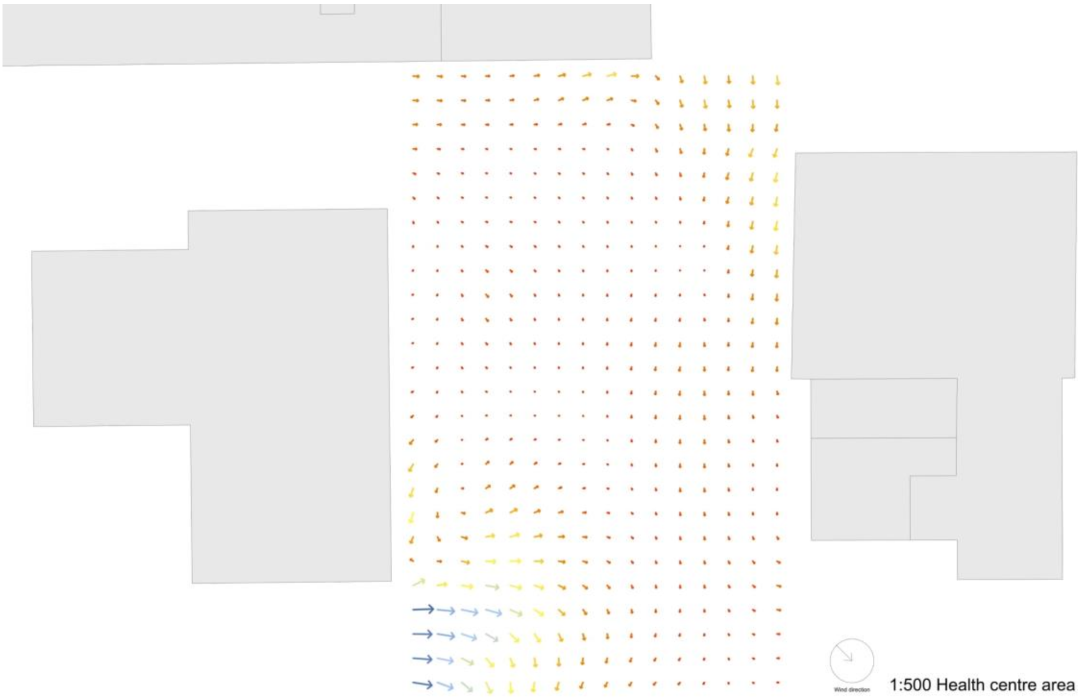
1:500 Health centre area

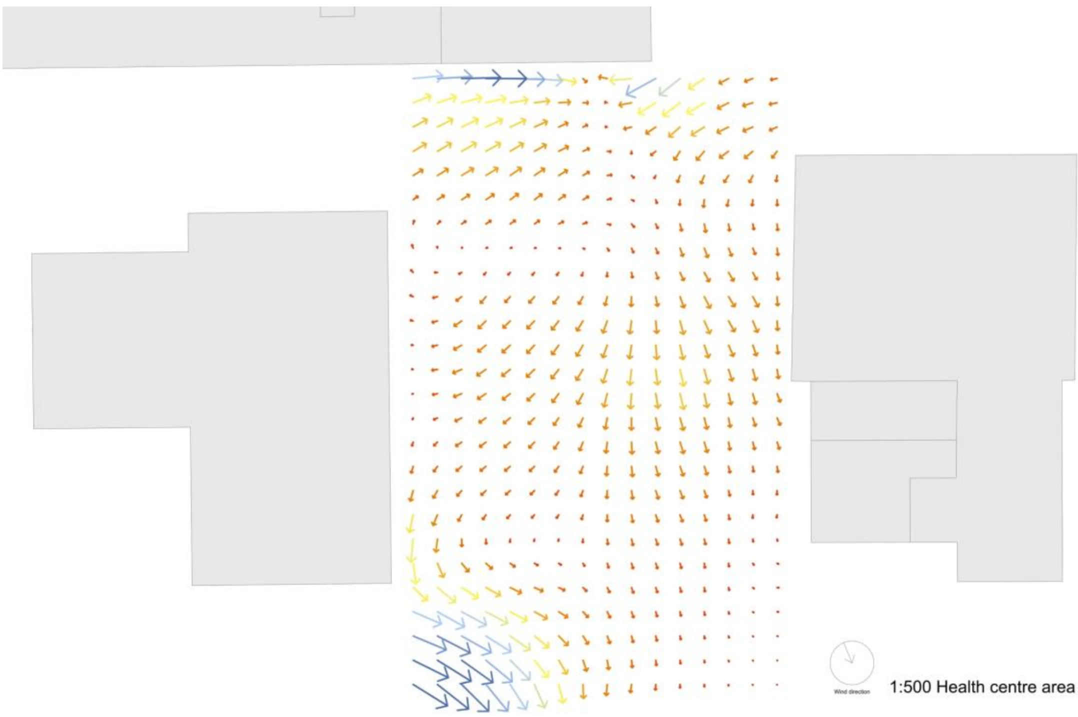

Wind direction
1:500 Health centre area


Wind direction
1:500 Health centre area


Wind direction
1:500 Health centre area

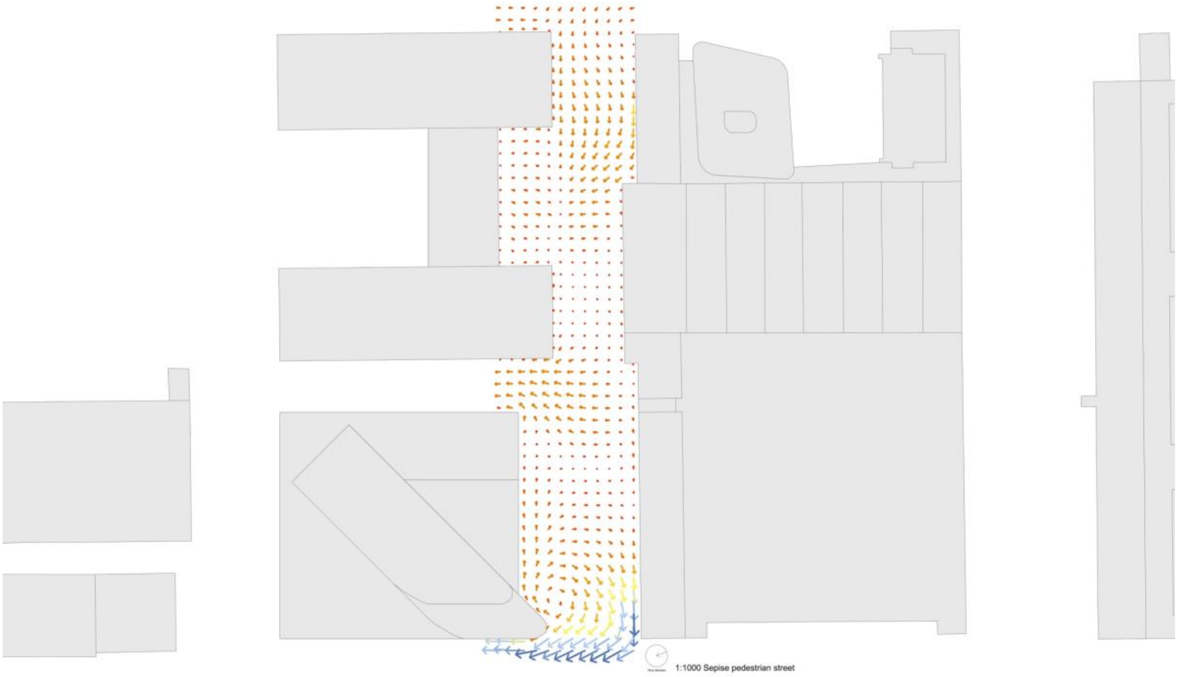

Wind direction
1:500 Health centre area

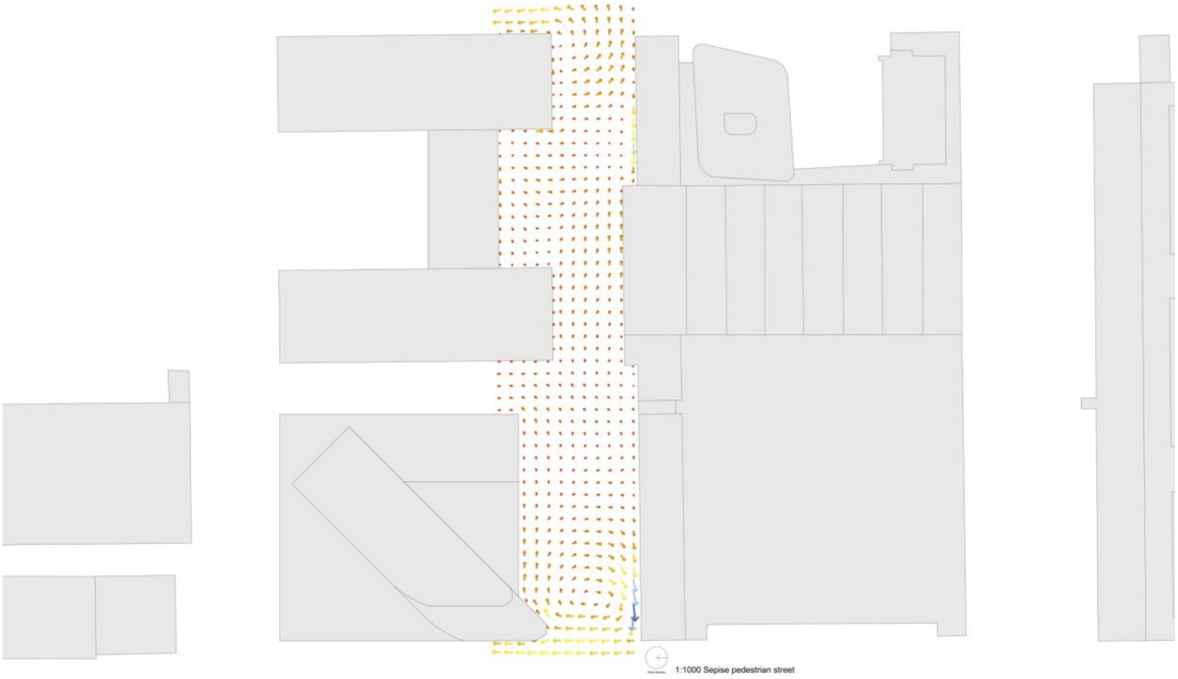

Wind direction
1:500 Health centre area


Wind direction
1:500 Health centre area

Appendix 4. Wind flow and velocity plot in Sepise street for all the 16 directions


1:1000 Sepise pedestrian street

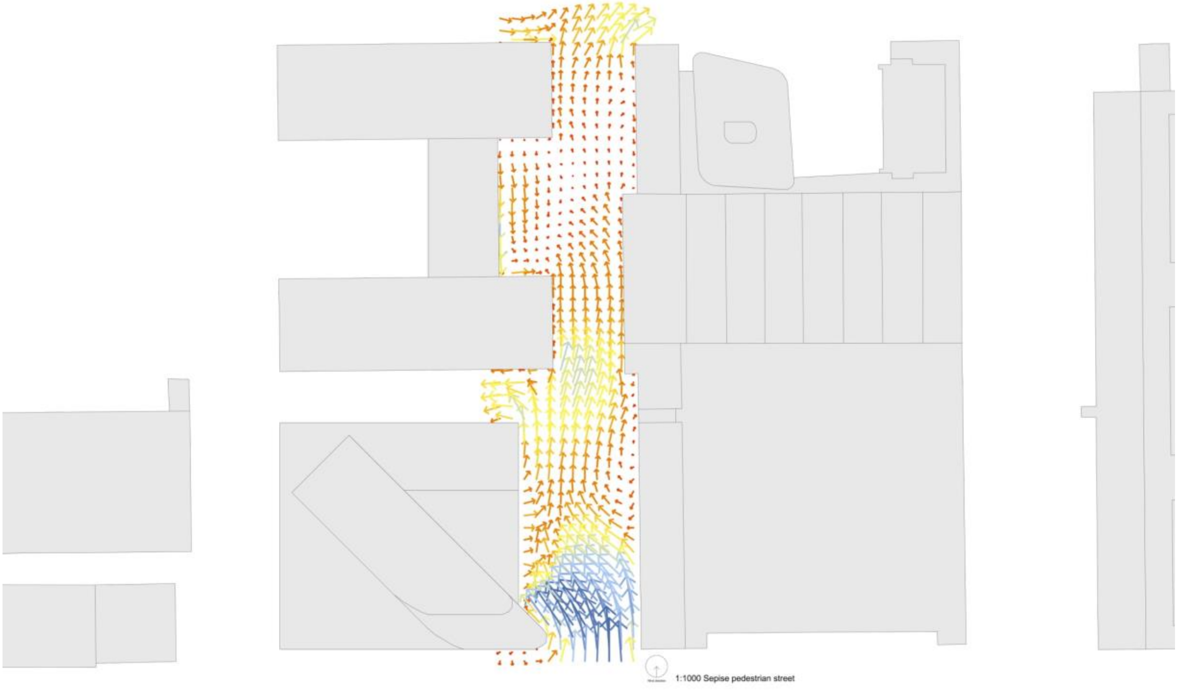

1:1000 Sepise pedestrian street


1:1000 Sepise pedestrian street

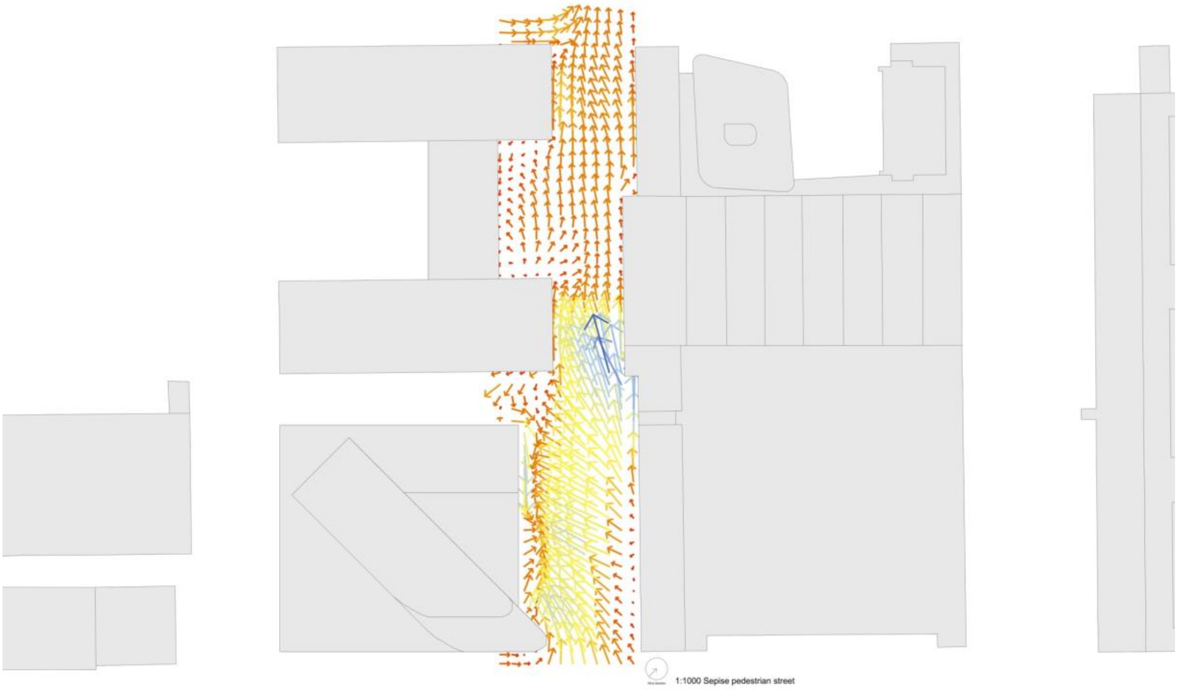

1:1000 Sepise pedestrian street

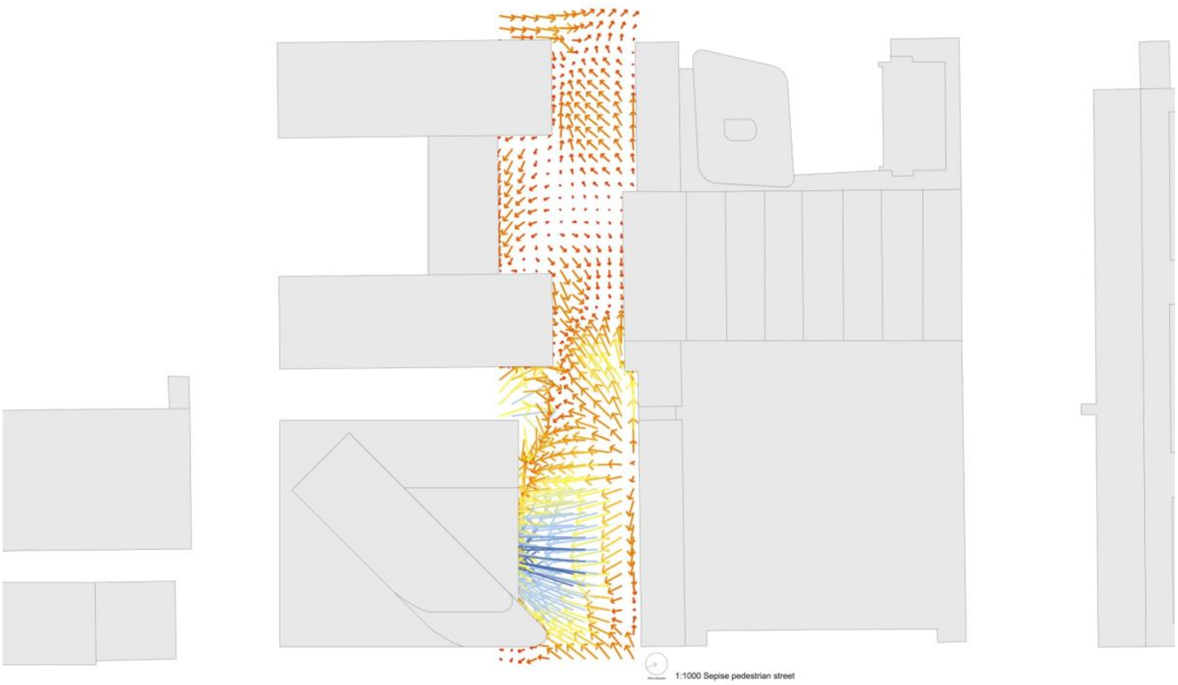

1:1000 Sepise pedestrian street


1:1000 Sepise pedestrian street


1:1000 Sepise pedestrian street


1:1000 Sepise pedestrian street


1:1000 Sepise pedestrian street


1:1000 Sepise pedestrian street

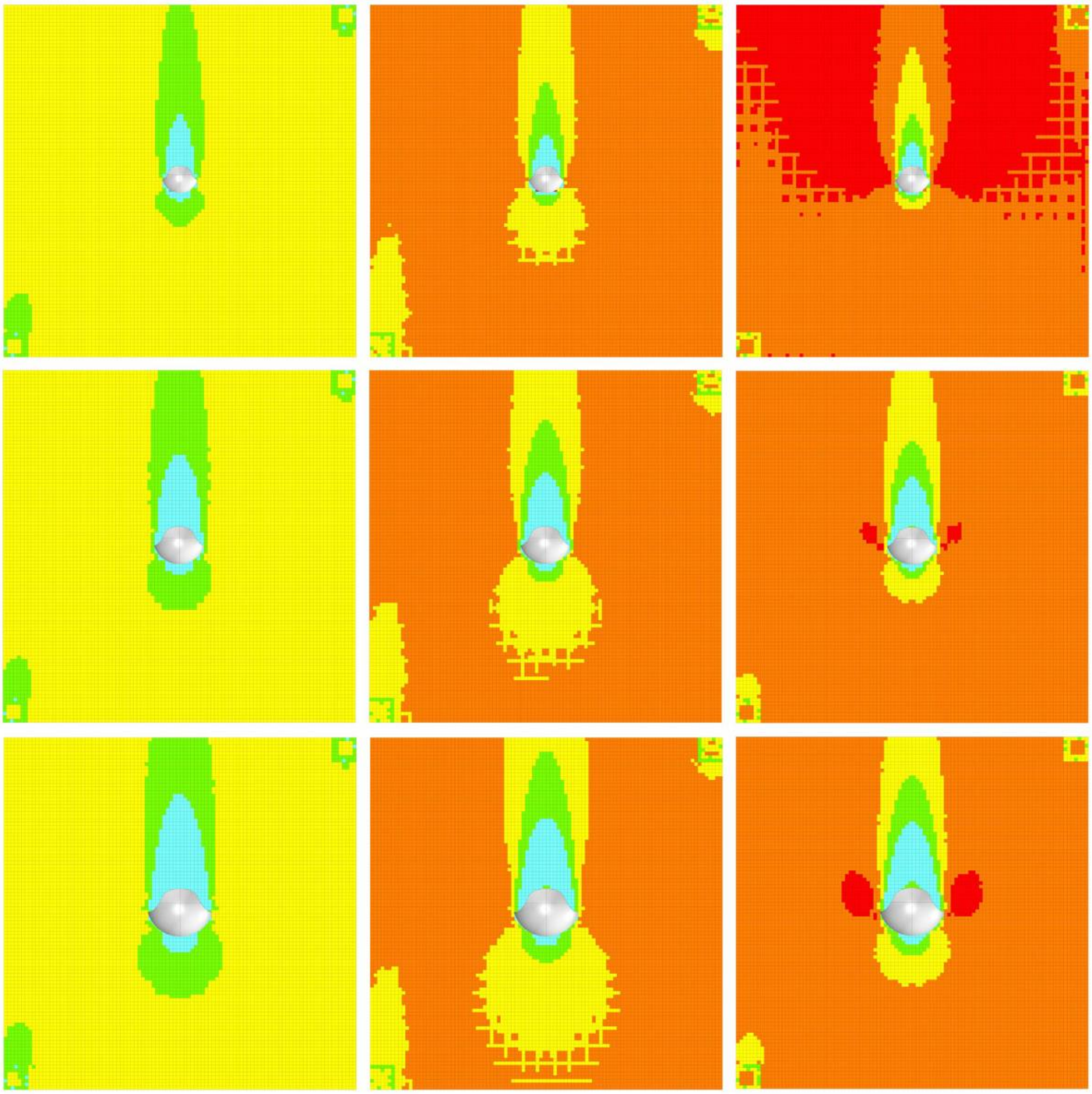
1:1000 Sepise pedestrian street

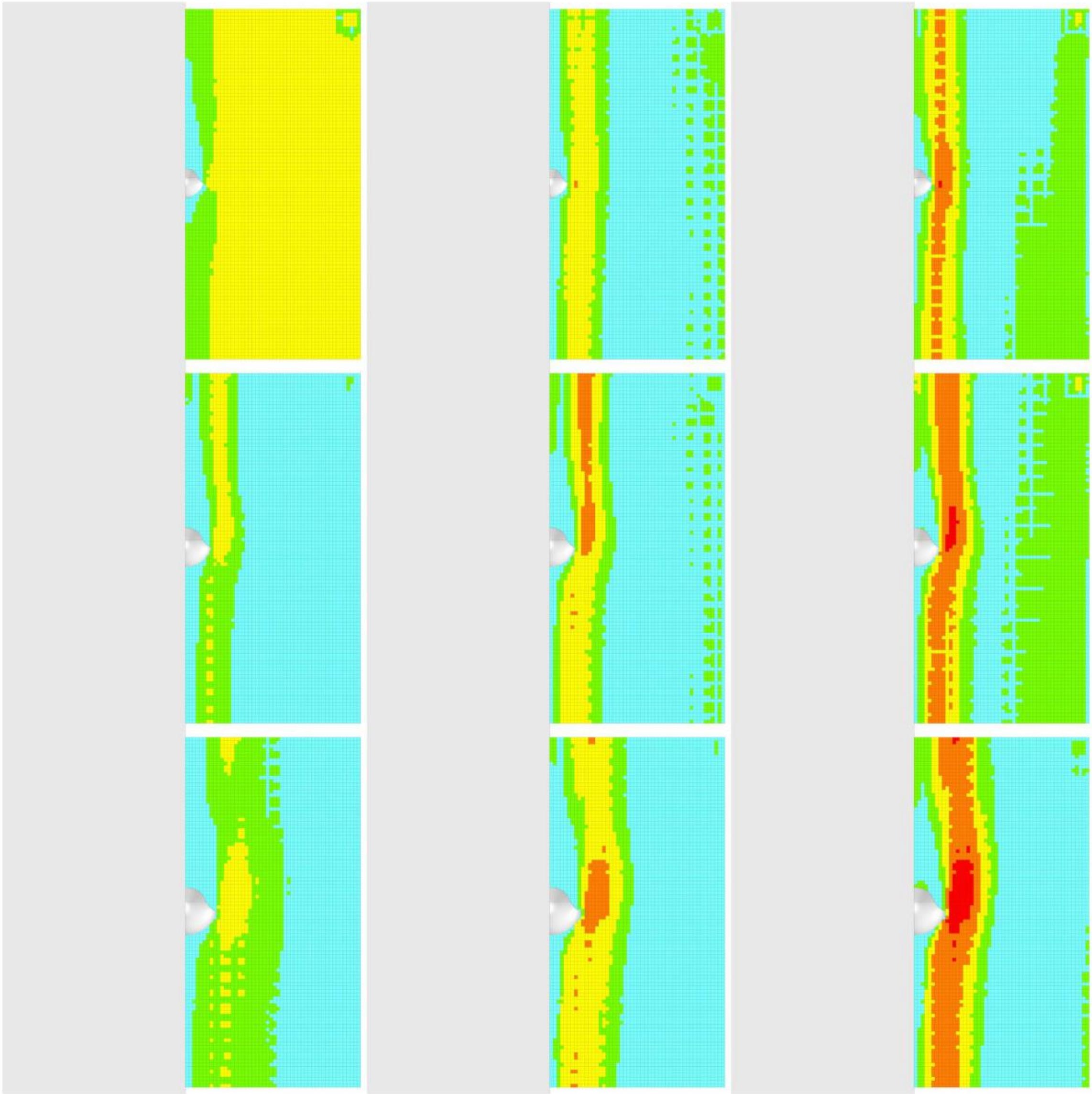
1:1000 Sepise pedestrian street

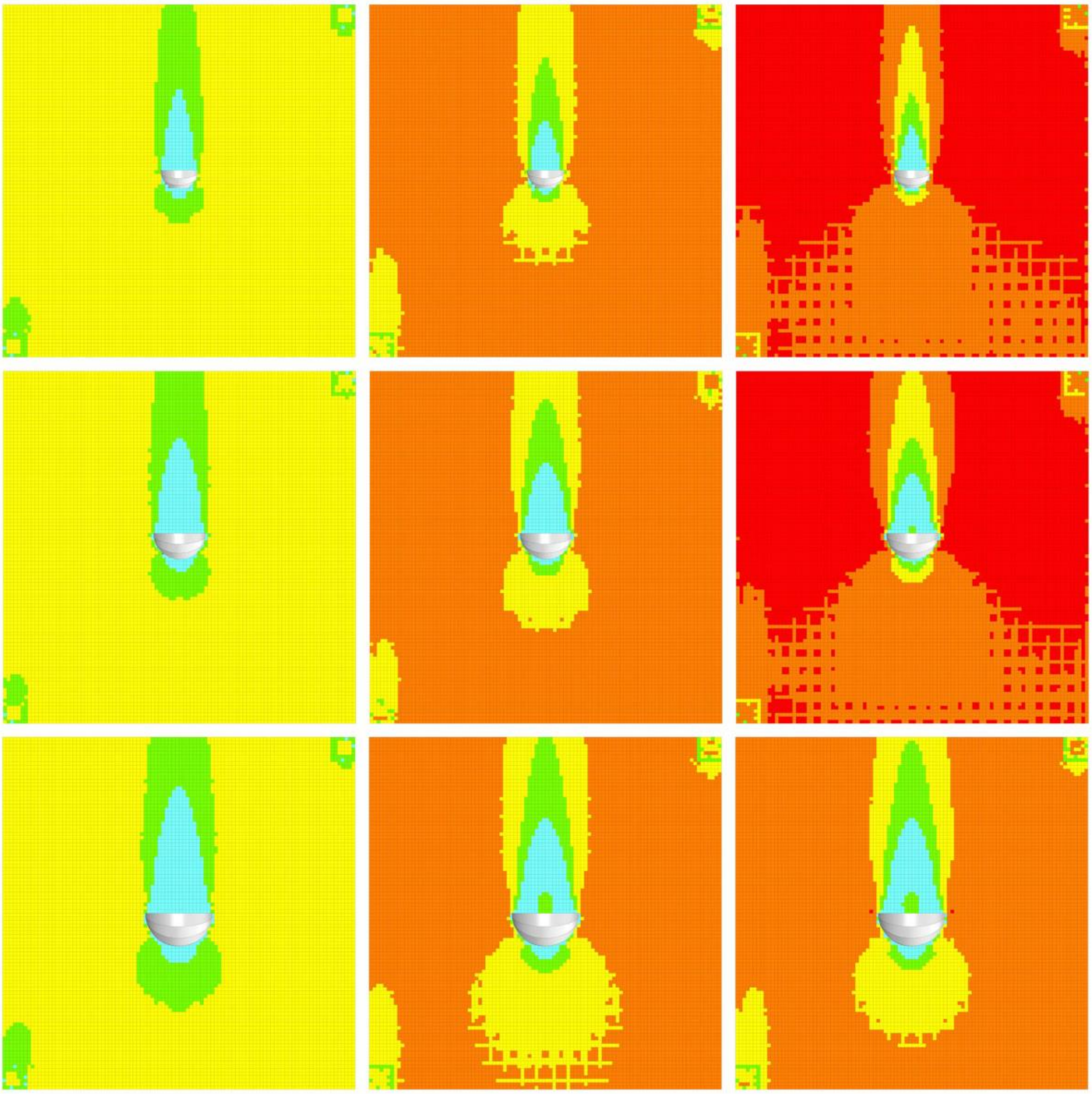

1:1000 Sepise pedestrian street

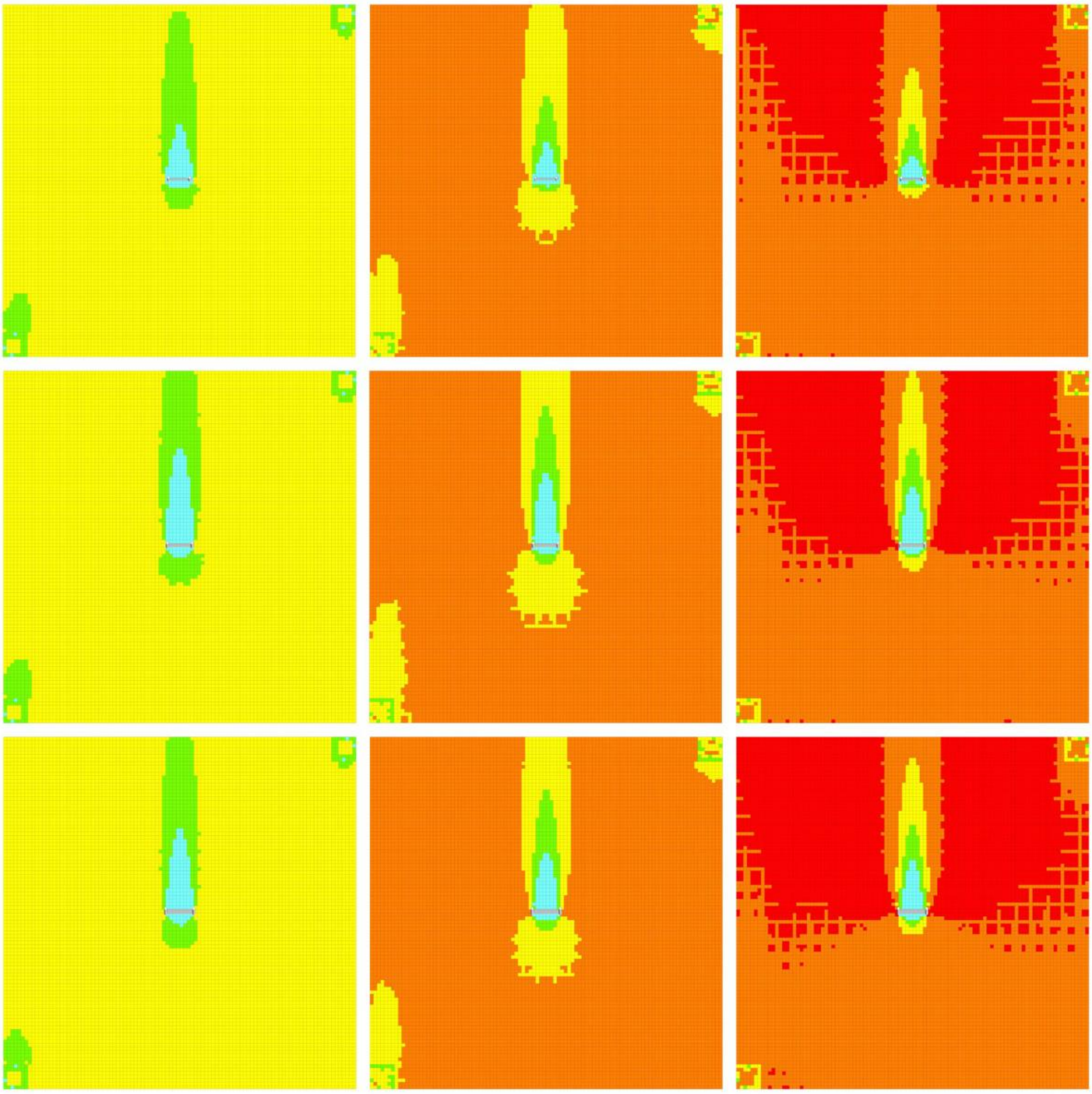

1:1000 Sepise pedestrian street

Appendix 5. Test-shelters simulation results in different comfort conditions: Permanent shelter, Half shelter, Operable shelter, Textile wall.









Appendix 6. Visualization of test shelters

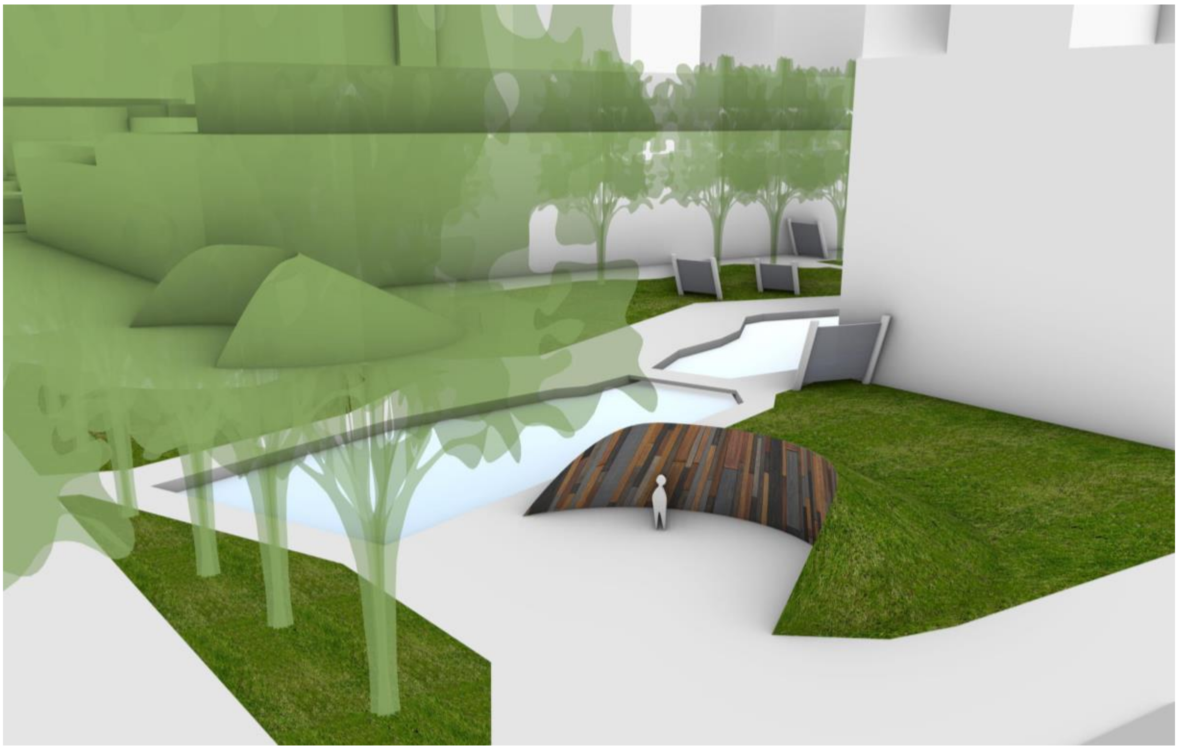


Figure 44. Comfort Island shelter

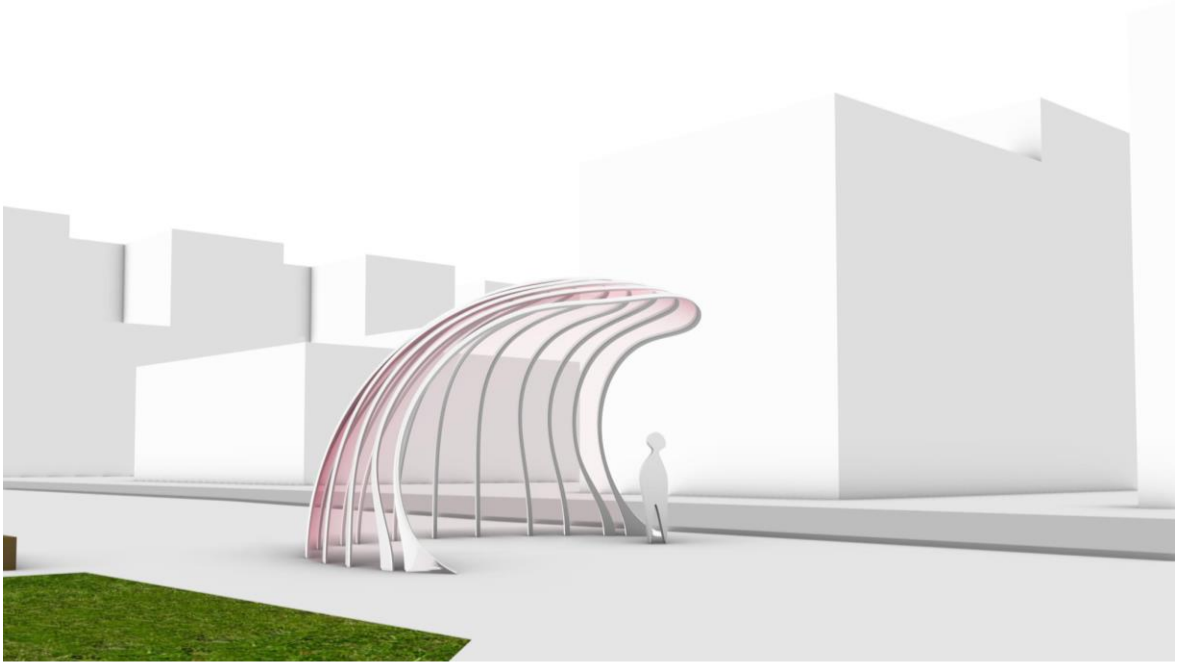


Figure 45. Permanent shelter

Figure 46. Half-shelter

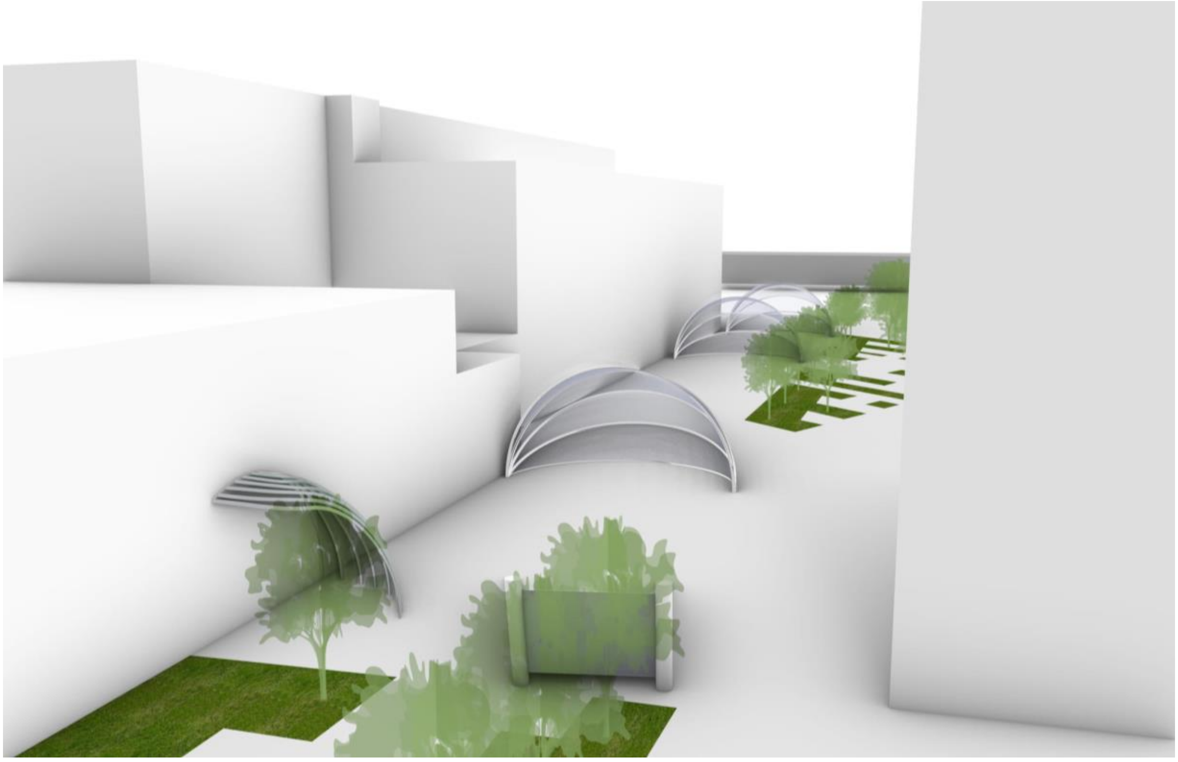


Figure 47. Operable shelter

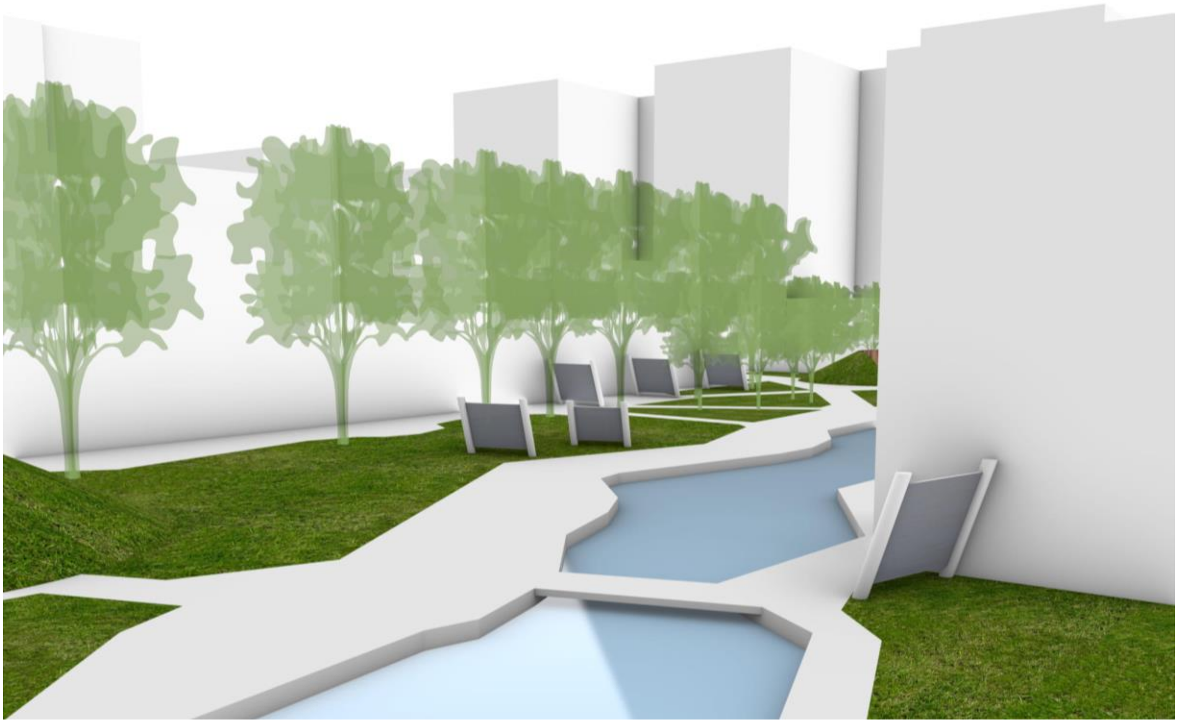


Figure 48. Textile wall

Appendix 7. eCAADe 2022 conference paper submitted on the basis of current work

Wind Comfort Analysis and Design of Small Scale Elements for Improving Urban Space Livability

A case study in Tallinn, Estonia

Jelena Kazak[1], Francesco De Luca[1], Jenni Partanen [1]
[1]Tallinn University of Technology
[1]{ jekaza|francesco.deluca|jenni.partanen}@taltech.ee

Pedestrian wind comfort plays a central role to improve safety, livability and resilience of urban environments. Wind patterns modified by buildings can create physical discomfort and can be dangerous for the vulnerable population. The location and height of the buildings and urban features, how close they are placed to each other, their shape and the size have a significant impact on the wind acceleration or mitigation. The paper presents an investigation about the potential of small scale elements of increasing wind comfort in three pedestrian areas in the Ülemiste district in Tallinn, Estonia, which presents strong urban wind discomfort. The investigation integrated parametric design and CFD simulations to test a number of wind shelter types and sizes, and urban design to integrate them in the layout of open areas. The Lawson wind comfort criteria was used to assess wind discomfort in the actual situation and the potential of the shelter to improve comfort. Initial results show an improvement of area in state of comfort from 40 % to 83 %. Detailed methods and results are presented.

Keywords: *Wind comfort, Urban comfort, Wind simulations, Mitigation strategies, Shelter design evaluation.*

INTRODUCTION

Ground level flow patterns depend on the interaction between wind and the surrounding building structure. With the increase of a high rise structures a small number of research was investigating wind phenomena in the urban areas. This led to struggles, discomfort and could be even dangerous on the pedestrian level (Gandemer 1978). The field of wind studies developed from simple and straightforward models to complex studies involving different data like climate and aerodynamics of buildings and structures. (Davenport 2002) As the accuracy and complexity of the possibilities for the evaluation of wind studies constantly develops, more attention is being paid to the research of the topic. Best practice guidelines were developed for the use of Computational Fluid Dynamics (CFD) for evaluation of the pedestrian wind comfort. (Blocken and Stathopoulos 2013) Latest trends are showing that people are becoming more aware of the surrounding environment. As nowadays cities were designed mostly according to best practices in the organization mechanisms such as street patterns, building typologies and block structures, not much attention was paid to the urban comfort and resilience. It is necessary to implement resilience concept at an early design and planning stage as well as find solutions for existing urban structures to become more focused on the users of the space and their comfort around it. (Chokhachian et al. 2017)

Concept of urban comfort and resilience

Architects design buildings as a protection from different climate conditions – rain, snow, wind and heat. Climate has a big impact on the building itself – the way in looks, how complex and multi-layered it is. Majority of used materials, structures, typologies depend on the local climate conditions. Although climate in architecture is not defined only as an indoor protection or a way of reducing consumed energy by the building. Climate becomes a part of the new built environment and the way it behaves and changes in it is unpredictable. (Krautheim et al. 2014) Often much less attention is paid to what surrounds the building rather that the structure itself. As stated in City and Wind by M. Krautheim et al.: „These days climate is mainly seen as something we need to protect ourselves against." This brings us to the topic of urban comfort and resilience of the surrounding environment. Each new structure, building district or even smaller scale changes like planting new trees or remaking the existing urban space can become a totally new experience for the users of the space. The experience can be good – light breeze between buildings, warmth of the sun on a summer terrace. The experience can also bring uncomfortable or even unsafe feeling – accelerated wind in building corridors, overheated areas because of the usage of wrong materials or building mass or orientation. In conclusion, climate around built environment has a big potential for researches and for finding ways to analyse it and suggest solutions for the improvement not only on building scale, but also in the scale of pedestrian users of the outdoor environment created by modern architecture.

In the process of creating an architectural design project the problem of mechanical wind effects on pedestrian urban comfort should always be considered. As the project has different stages the wind comfort could also be analyzed in different ways. In the beginning phase when the design is still raw, the assessment will be general and inaccurate, based on previous experience and tests. During the development of the design the assessment also improves until decision could be made – whenever significant problem considering wind exists or not. At this stage project could be taken further to the simulation process and developing solutions. (Lawson and Penwarden 1975)

Built environment has a big impact on the urban microclimate around itself. Microclimate in turn is also affected by the global climate change, which causes conflicts over the temperature, daylight, wind and other microclimate elements. This could influence a lot the usage of an urban space – how comfortable it is for spending time during different seasons and time of the day, how healthy is the surrounding environment for humans and other living beings, how fluently is mobility organized, in which ways and for which activities the space could be used. This is the main reason why the analysis of outdoor thermal and wind comfort is becoming very important lately. (Kastner and Dogan 2020b)

The usage of an open urban space in turn influences city life from both the social and the economic aspects. This brings the interest on the municipal and government level to study and analyze existing built environment and find ways to make surrounding microclimate more comfortable for city dwellers. (Stathopoulos 2011)

METHODOLOGY

Urban area

Ülemiste City is a business quarter near the airport of Tallinn and the lake Ülemiste. As the area is located on a plateau at the edge of the city it is not protected from winds by any other building structures. Ülemiste City is a developing district of an old factory area called Dvigatel. In the present days a lot of new high-rise buildings were built there, which accelerate the wind patterns causing struggles with pedestrian comfort around the area. Height of the buildings varies from around 8 meters for smaller structures and up to 45 meters for the new offices. This study takes into account current building layout and near future developments. Authors chose three pedestrian areas for analysis: 1) Viktor Palmi square; 2) Health Centre park; and 3) Sepise pedestrian street (Figure 1).

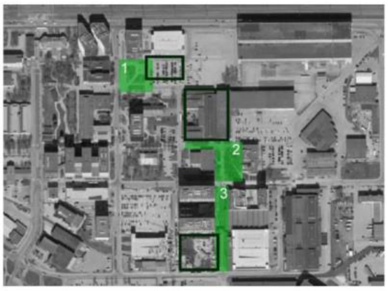


Figure 1
The three pedestrian areas used in the study, the actual and the new buildings (black) of the Ülemiste quarter.

Wind analysis

Authors developed a parametric design workflow to analyze pedestrian wind comfort in different urban layout situations through Computational Fluid Dynamics (CFD) and the Tallinn statistical wind velocities and directions obtained from weather data. For the study we used the Eddy plug-in for Grasshopper. (Dogan, n.d.)

The wind analysis was performed in three steps. In the first step CFD wind simulations were performed for a large area encompassing the three pedestrian areas and their surrounding buildings, using a cylindrical wind tunnel (Kastner and Dogan 2020a) considering 16 different directions. In the second step, the simulated wind patterns and velocities as modified by the buildings were used to determine the most critical wind direction for each area. Most of the buildings in the area are offices, so the time frame for pedestrian outdoor wind comfort we considered was from 8 a.m. to 6 p.m. In the third step we used a single wind tunnel from the most critical wind direction of each area with smaller mesh size to obtain more accurate wind simulation results to study each area separately and more precisely. The same wind tunnel was then used for the simulations including the wind shelters.

Wind comfort assessment

To evaluate pedestrian wind comfort, the Lawson LDDC assessment criteria was used. It defines a wind speed which is comfortable for a certain activity considering and maximum exceedance of 5 % of the time.(Lawson, 1978)

- Sitting (< 4 m/s)
- Standing (≥ 4 m/s)
- Walking (≥ 6 m/s)
- Business walking (≥ 8 m/s)
- Uncomfortable (≥ 10 m/s)

Design of the test shelters

The aim of the study was to investigate possible shelter solutions to design comfortable pedestrian areas for the users of Ülemiste City. To accomplish this authors developed different shelter forms to be analysed individually and then modified according to the needs of the urban spaces. Three different wind shelter types were developed: Comfort Island, Permanent shelter and Textile wall adjustable shelter (Figure 2).

'Comfort Island' is the biggest type characterized by a moon shape and is inspired by traditional protection of vines from constant wind in Lanzarote, where landscape is used to protect plants from the wind (Krautheim et al., 2014).

'Permanent shelter' was modelled to create a half closed space with a roof structure above to protect also from direct sun and rain . The design was inspired by the industrial past of the Ülemiste City district, when it was used by the Dvigatel plant the largest railway plant in Estonia. ("Ülemiste City History," n.d.)

'Textile wall' was the smallest of the types used and was developed to create a shelter operable by the people use the place. It consisted of two inclined posts between which a textile could be pulled out and wind back through a spring system. This type could be installed near benches and other seating, so people could pull out the textile as a curtain if wind protection would be needed and enjoy the area.

Authors tested each shelter using CFD wind simulation through a rectangular wind tunnel with different wind velocities to evaluate the area of comfort it allowed depending on the size and height of the shelters.

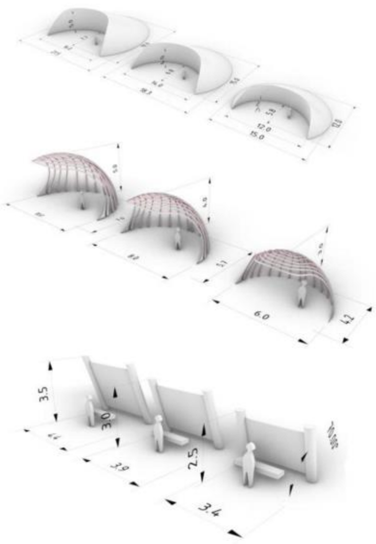


Figure 2
The three pedestrian areas used in the study, the actual and the new buildings (black) of the Ülemiste quarter.

Figure 3
Cylindrical wind tunnel used for the annual wind simulations.

Simulation and software parameters

For the first step described in the Wind analysis section, a cylindrical wind tunnel with the height 450 m (10 times the height of the tallest building) and outer radius of 3000 m, which is 675 m from outer modelled building to the border of the cylindrical mesh (15 times the height of the tallest building, respectively) were used following best norms for wind tunnel sizing (Franke et al. 2007). The inner rectangle of the cylindrical wind tunnel included all three areas of interest and is 350 x 350 m in size. The accuracy of the cells inside the inner rectangle was approximately 3 m. Simulations were performed from 16 wind directions (from 0° every 22.5°). Among the 16 wind directions, the most critical for each area analysis including the shelters in the urban environments (Figure 3).

A fixed wind velocity of 5 m/s (10 m height) at the wind tunnel inlet and the logarithmic wind profile were used for the 16 CFD simulations. The terrain roughness used that of the urban areas Z_0=1. Simulated wind velocities are probed on a grid 3 m x 3 m at 1.5 m height from the ground. (De Luca, 2019). Each area has different grid extension. Viktor Palmi square covers area of 3213 m^2 and had a grid of 357 cells. Health Centre park covers area of 3744 m^2 and had a grid of 416 cells. Sepise street covers area of 4900 m^2 and had a grid of 602 cells. The simulated wind patterns and velocities for each area were used to calculate the wind factors. These were then used to remap wind velocities from the annual Tallinn weather data.

After having defined the most critical direction for each pedestrian area, authors performed new wind simulations with a smaller grid size of the area of interest in the wind tunnel, 0.6 m x 0.6 m to obtain more accurate results. The same level of accuracy was then used to simulate wind patterns when the shelter were out in place in the urban environments. Though the surrounding buildings are of a large scale, this small grid size was used to take into account the small scale object like shelters after they were designed for each area and used in the simulations. After having evaluated the wind conditions in the actual urban areas and after with the shelters and their designed layout, the pedestrian wind comfort difference was noticeable.

The rectangular wind tunnel we used considered only one wind direction. As for the cylindrical wind tunnel simulations, the wind velocity of 5 m/s (10 m height), the logarithmic wind profile and the terrain roughness of $Z_0=1$ representing an urban area were used. The width and the height of the rectangular wind tunnel was different for each area. Width was 10 times the height of the tallest building (from the outer building included into the simulation to the border of wind tunnel from both sides) and height was 5 times the height of the tallest building. Wind tunnel for Viktor Palmi square was 1140 m wide and 240 m high. Wind tunnel for Health Centre park was 895 m wide and 225 m high. Wind tunnel for Sepise street was 745 m wide and 225 m high.

For simulating the three types of designed shelters without any surrounding we used a smaller rectangular wind tunnel. Authors tested each version(size) of the shelter type with three different wind speed conditions 8 m/s, 10 m/s and 12 m/s. In the first step of the study, smaller wind velocities were used as well, though in this paper results relative to most critical conditions are presented. The aim was to get a certain comfort level around the tested shelter (comfortable for walking - yellow, business walking – orange, and uncomfortable for all activities - red), so it was possible to obtain the size of the area that would be protected by each shelter type and size to use in the design of the open areas under investigation. The analyzed area around shelter was a 50 m x 50 m square with a 0.5 m x 0.5 m grid cell size.

Area specific shelter layout design

Based on the results of pedestrian wind comfort of each area in the actual conditions and compared to the results of the size of the protected area by each type and size of shelters, authors developed urban solutions for each area. To improve the urban space quality and livability not just in terms of pedestrian wind comfort but also considering the optimal layout configurations for a high architectural quality of the space, we modified the shelters according to each area specific characteristics, surrounding buildings and functions.

RESULTS

Results of the study are presented for the pedestrian wind comfort of each area considering the most critical wind direction. Current situation is compared with the proposed design solution using sheltering urban elements derived from the tested shelters morphing their shape while maintain the sizes. The comparison was performed assessing the percentage of area which guaranteed the different level of pedestrian comfort in the actual situation and through the proposed urban design.

Actual situation

As already discussed in simulations and software parameters, cylindrical wind tunnel CFD simulation presented results from 16 wind directions. Wind factors calculated from the simulation combined with velocities from annual

Tallinn weather data file allowed to define critical wind direction for each area. Time frame included in the simulation was from 8 a.m. to 6 p.m. Viktor Palmi square and Sepise pedestrian street most critical wind direction is from south (180°). Health Centre area mot critical wind direction was south-southwest (202,5°). Wind velocity ranges for each area was as follow: Viktor Palmi square from 0.03 m/s to 5.18 m/s; Health Centre park 0.04 m/s to 6.24 m/s; Sepise pedestrian street from 0.3 m/s to 5.81 m/s (Figure 4).

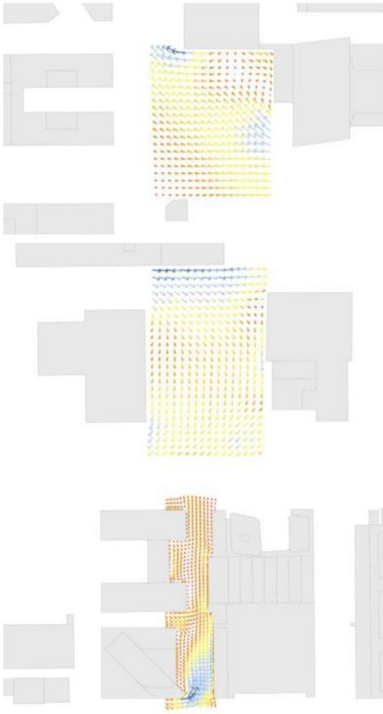


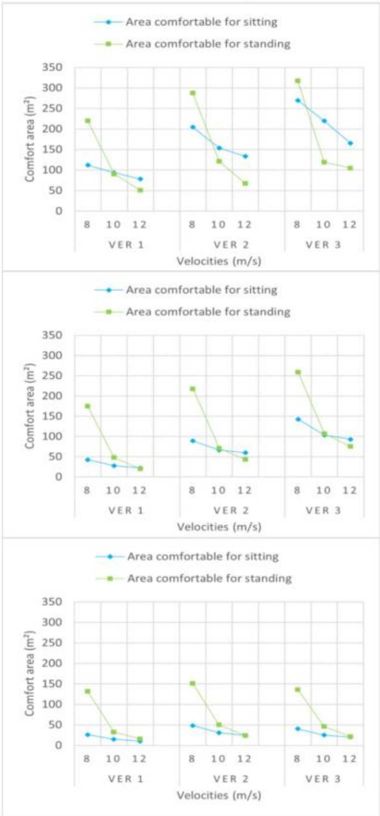
Figure 4
Plots of the wind flows and velocities. Viktor Palmi square 180°, Sepise street 180°, Health Centre area 202,5°.

The following more accurate simulations performed with rectangular wind tunnel from the most critical direction for each area separately showed the current situation according to the Lawson LDDC assessment criteria. Areas comfortable for sitting and standing were considered as comfortable. Although, if sitting areas were designed in the areas comfortable for standing, they were considered to be redesigned. Areas comfortable for walking, business walking and uncomfortable for every activity were considered as uncomfortable. The aim was to design shelters according to the architectural and functional needs of each space and reduce percentage of areas suitable for standing and walking by making these comfortable for sitting. The scope was to improve the livability of the places, to enjoy time and social life and to use them for every activity. The results showed that the most comfortable area in terms of wind was Health Centre area – it had 72,5% comfortable for sitting. The results of the actual situation analysis showed that Viktor Palmi square was the most uncomfortable area with only 39,5 % comfortable for every activity. Sepise street had comfortable area of 54.9%. Walking comfort level was the most critical level of discomfort appearing in the results, so it was decided to increase sitting comfort area in each case as much as possible.

Single wind shelters

As described in the section Simulations and software parameters, each shelter type and size was tested separately in three different comfort conditions (Figure 6).

The biggest shelter type 'Comfort Island' provided wind comfort for all activities for areas from 78.3 m^2 to 270 m^2, i.e., for from 3.1 % to 10.8 % of the tested area, respectively, using the shelter size from the smallest to the largest. The smallest version of 'Permanent shelter' allowed a 22.3 m^2 area comfortable for every activity and the biggest version created a 92.3 m^2 area in the same conditions. The smallest 'Textile wall' created acomfort area of 10.3 m² and the largest alloweda n area in comfort conditions for all the activities of 40.3 m², which is a good indicator to state that even very small scale interventions in the urban space could cause a lot more comfort for the users. All the other results are presented in Figure 5.



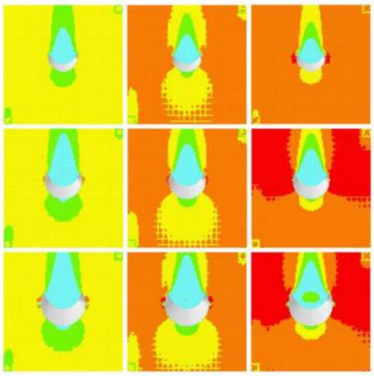


Figure 6
Comfort Island shelter simulation results

Figure 5
Comfort area size improved by different shelter versions and sizes in different comfort conditions. Comfort Island, Permanent Shelter, Textile wall

Improved comfort areas

In case of Viktor Palmi square results showed sitting was located in the area comfortable for standing and walking. We decided to create structure similar to 'Comfort island' with a more geometrical shape, resembling an origami. This allowed to leave the existing passages and create interesting urban experience. Results showed that the new design of the square using shelters increased area comfortable for sitting from 39.5% to 82.6%. Area comfortavle for standing redused from 47.5% to 14.6%. Area comfortable for walking redused from 13.0% to 2.9%. (Figure 7 and 9).

In the first phase of the study, the wind analysis in the Health Centre area were performed only for the small park. As the results showed that the park is mostly comfortable, we decided to extend the analysis area to the upper left corner and consider also space in front of new high rise building planned to be built there. Since the new building will have outdoor terraces, we decided to improve wind comfort of these. Results of the simulations with the shelters showed that the area comfortable for sitting increased from 72.5% to 77.1%. Area comfortable for standing reduced from 19.9% to 17.7%. Area comfortable for walking reduced from 7.6% to 4.8%. (Figure 8 and 10).

Sepise pedestrian street showed high percent of discomfort in the beginning of the corridor where wind enters the area and is accelerated by the high rise buildings around. Sepise street is pedestrian and it has various terraces and benches, where people tend to spend time. The aim was to create possible wind break in the beginning of the corridor and protect existing seating. Initial results showed that the new design using shelters increased area comfortable for sitting by 20%. Area comfortable for standing reduced from 33.9% to 22.4%. Area comfortable for walking reduced from 11.3% to 2.6% (Figure 11 and 12).

The results show initial designs of the shelter layout for the areas. For this study various design solutions were made and best are presented.

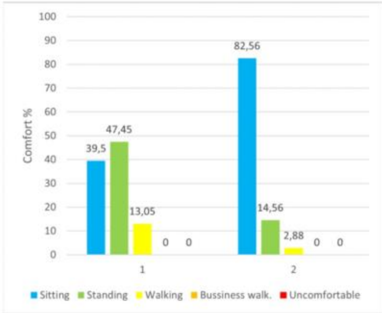


Figure 9
Comparison between comfort percent of existing area and designed shelter version for Viktor Palmi square.

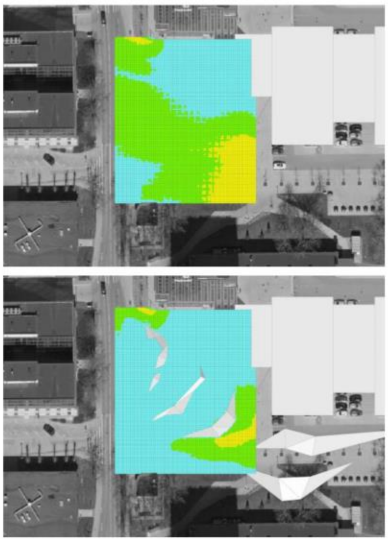


Figure 7
Wind comfort maps for existing layout and designed shelters version in Viktor Palmi square.

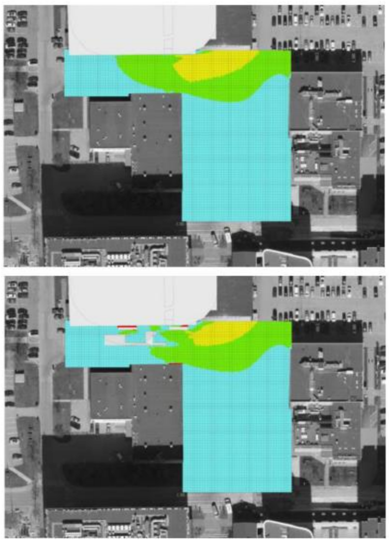
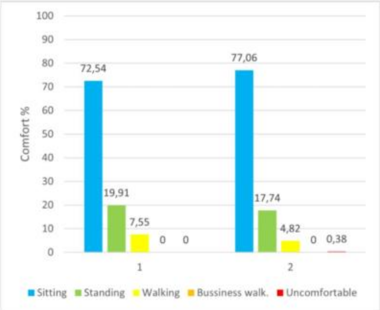


Figure 8
Wind comfort maps for existing layout and designed shelters version in Health Centre area.



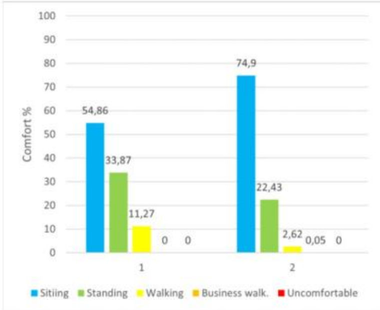
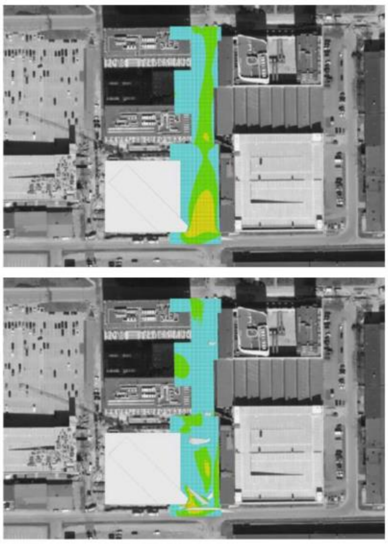


Figure 10 Comparison between comfort percent of existing area and designed shelter version for Health Centre area.



CONCLUSION

The presented study analyzed pedestrian wind comfort in three public areas in Ülemiste City district in Tallinn, Estonia through CFD wind simulations to propose small scale element urban design solutions for improving urban space livability.

The first aim of the work was to determine actual wind comfort conditions in the areas. Consequently, three different shelter types and sizes were designed and tested through wind simulations to determine extension of the areas with wind comfort conditions provided by each shelter type and size. The study showed that even the smallest wind shelter type created sufficient difference to the area pedestrian wind comfort. Finally, on the basis of this knowledge every area was designed differently in terms of wind protection needs and architectural and functionality.

The initial urban design solutions showed significant improvements of the area provided with wind comfort conditions, with increments from 40 % to 83 %. The novelty of the work lies in the scarcity of wind comfort analysis in urban environments in the region and in the lack of proposals of urban design solutions to improve pedestrian comfort. Future work of the research will investigate other areas in the city of Tallinn

Figure 11 Wind comfort maps for existing layout and designed shelters version in Sepise street.

Figure 12 Comparison between comfort percent of existing area and designed shelter version for Sepise street.

using additional type of wind shelters to produce results actionable by the city urban development department.

REFERENCES

Blocken, B. and Stathopoulos, T. (2013). 'CFD simulation of pedestrian-level wind conditions around buildings: Past achievements and prospects. ', *Wind Engineering and Industrial Aerodynamics* 121, pp. 138–145.

Chokhachian, A., Santucci, D., Auer, T. (2017). 'A Human-Centered Approach to Enhance Urban Resilience, Implications and Application to Improve Outdoor Comfort in Dense Urban Spaces', *Buildings (2017)*, *7*(4), 113.

Davenport, A.G., (2002). 'Past, present and future of wind engineering. ' *Journal of Wind Engineering and Industrial Aerodynamics* 90, 1371–1380.

De Luca, F., (2019). 'Sun and Wind. Integrated Environmental Performance Analysis for Building and Pedestrian Comfort. ' in *Proceeding of the 5th SimAUD Conference*, 07-09 April 2019.

Dogan, P.K., Timur, n.d. *Eddy 3D* [Software]. Available at: https://www.eddy3d.com (Accessed: 31 March 2022)

Franke, J., Hellsten, A., Schlünzen, H. and Carissimo, B. (2007). 'Best Practice Guideline for the CFD Simulation ofFlows in the Urban Environment. ' *COST Office*, Brussels, Belgium.

Gandemer, J. (1978). 'Discomfort due to wind near buildings: aerodynamic concepts.' University of Michigan Library Publishers.

Kastner, P., Dogan, T. (2020a). 'A cylindrical meshing methodology for annual urban computational fluid dynamics simulations.' *Journal of Building Performance Simulation* 13, 59–68.

K Kastner, P., Dogan, T. (2020b). 'Predicting Space Usage by Multi-Objective Assessment of Outdoor Thermal Comfort around a University Campus' *in Proceedings of Simaud 2020*, Vienna, Austria, 25-27 May 2020, pp. 85-91.

Krautheim, M., Pasel, R., Pfeiffer, S., Schultz-Granberg, J. (2014). 'City and wind: climate as an architectural instrument, Basics.' DOM publishers, Berlin.

Lawson, T.V. and Penwarden, A.D. (1975) 'The Effects of Wind on People in the Vicinity of Buildings' *in Proceedings of the International Conference on Wind Effects on Buildings and Structures*, Heatrow, UK, pp. 605-622.

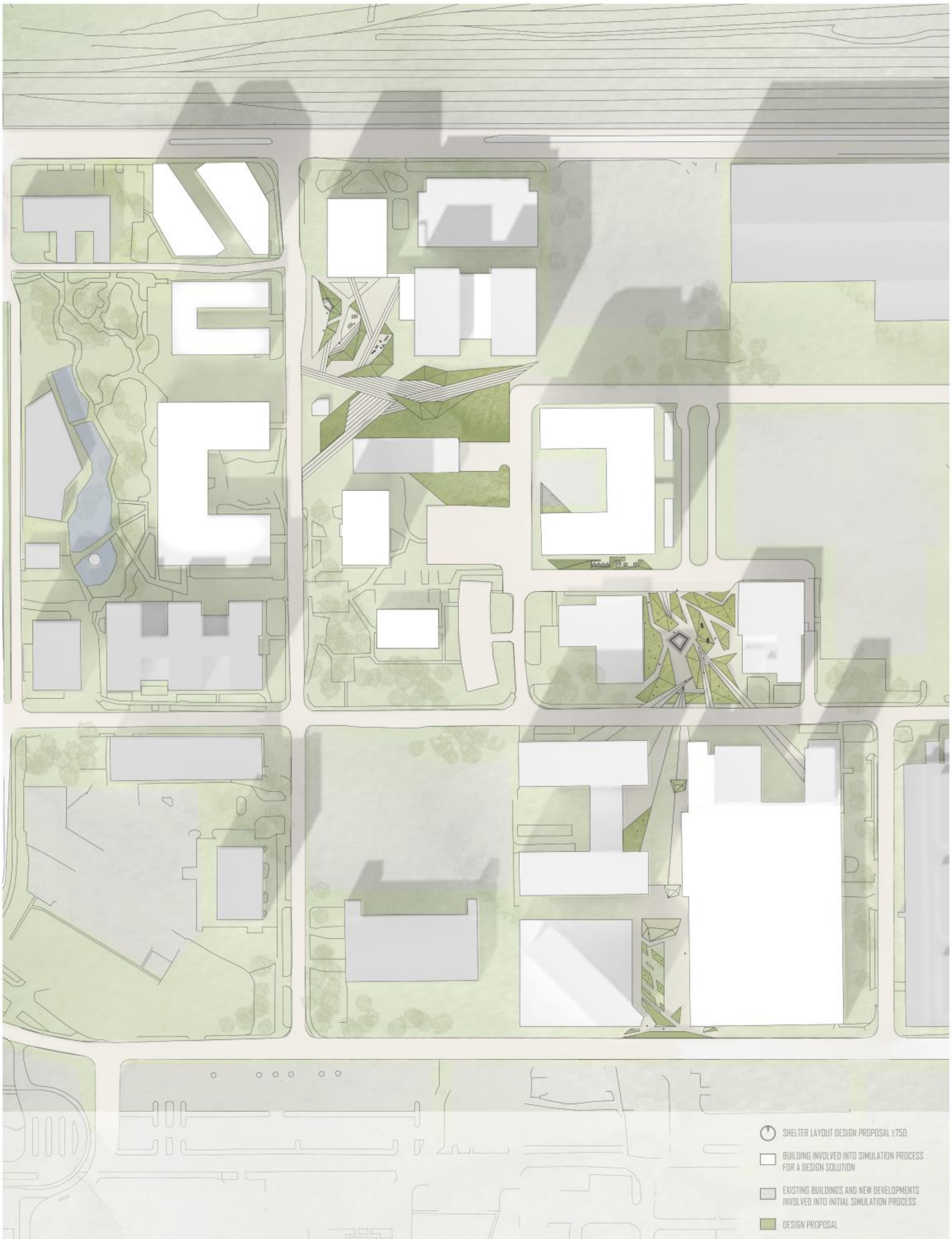
Lawson, T.V. (1978). 'The wind content of the built environment. ' *Journal of Wind Engineering and Industrial Aerodynamics* 3, 93–105.

Stathopoulos, T. (2011). 'Introduction to Environmental Aerodynamics' *Part of the* ***CISM Courses and Lectures*** *book series* (CISM,volume 531), 28.

Eaton K.J. (eds.) (1975). 'The Effects of Wind on People in the Vicinity of Buildings - Wind Effects on Buildings and Structures. '

Ülemiste City History n.d. [Online]. Available at: https://www.ulemistecity.ee/en/about/ (Accessed: 1 April 2022).

Appendix 8. Posters



WIND ANALYSIS AND DESIGN OF URBAN AREA FEATURES AND LAYOUT FOR IMPROVING WIND COMFORT AND LIVABILITY IN ÜLEMISTE CITY
TALLINN UNIVERSITY OF TECHNOLOGY 2022
RESEARCH MASTER THESIS

STUDENT : JELENA KAZAK

SUPERVISORS : FRANCESCO DE LUCA, JENNI PARTANEN

1 / 4

BACKGROUND

WIND AND ARCHITECTURE

The beauty of the wind lies in the experiencing of the invisible.
Differences in air barometric pressure cause wind. Changes in temperature affect these differences. When the air is warmed up, it rises up and creates an area of low air pressure. On the opposite, cold air is heavier and sinks, causing high air pressure on the earth's surface. As the earth is not heated evenly, there are plenty of areas with high air pressure and low air pressure. In general, air tends to move from the higher pressure areas to the adjacent areas with lower air pressure causing wind. The strength of the wind depends on the difference between the pressures, the bigger the difference is – the faster the air would be moving.
Ground-level air flow patterns depend on the interaction between wind with buildings and structures. The increase of high-rise structures led to struggles, discomfort and could even be dangerous on the pedestrian level. The field of wind studies developed from simple and straightforward models to complex studies involving different data like climate and aerodynamics of buildings and structures. As the accuracy and complexity of the possibilities for the evaluation of wind studies constantly develop, more attention is being paid to the research of the topic. Best practice guidelines were developed for the use of Computational Fluid Dynamics (CFD) for the evaluation of pedestrian wind comfort. Latest trends are showing that people are becoming more aware of the surrounding environment. As nowadays cities are designed mostly according to best practices in the organization mechanisms such as street patterns, building typologies, and block structures, not much attention has been paid to the urban comfort and resilience. It is necessary to implement the resilience concept at an early design and planning stage as well as find solutions for existing urban structures to become more focused on the users of the space and their comfort around it.

WIND DISCOMFORT IN ÜLEMISTE CITY

Ülemiste City is located in the south-east part of Tallinn. The district lies on the outskirts of the city. The district is located on a plateau. The ground height of the area varies from 40 to 47 meters above sea level. To the south from Ülemiste City Tallinn airport is located. On the south-west and west part of the district there is Ülemiste lake. The area to the south of Ülemiste City is also located lower, at 37 to 40 meters above the sea level. According to the weather data used in the studies, the most frequent wind in Tallinn is from the south, and one of the strongest directions for the wind is west.
As mentioned above, there are some irregularly distressed buildings located to the south or south-west from Ülemiste City, so wind mitigation is poor. As the district is developing, new high-rise buildings are being built, and the problem of wind discomfort on a pedestrian level appears. High-rise buildings require special solutions and methods to create safe, pleasant and attractive surroundings around the building, as they tend to create vortexes and accelerate the wind on a ground-level around themselves. The layout of buildings creates even more complex wind patterns in the area.

ANALYZED URBAN AREAS

Ülemiste City is a business quarter near the airport of Tallinn and the lake Ülemiste. As the area is located on a plateau at the edge of the city, it is not protected from winds by any other building structures. Ülemiste City is a developing district of an old factory area called Dvigatel. In the present day, a lot of new high-rise buildings were built and are planned to be built there, which would be modifying, blocking, and accelerating the wind patterns causing struggles with pedestrian comfort around the area. The height of the buildings varies from around 3 meters for smaller structures and up to 45 meters for the new office blocks.
This study takes into account the current building layout and near-future developments. Four pedestrian areas were chosen for the analysis: Lõõtsa park; Viktor Palmi square; Health Centre park; and Sepise pedestrian street.
Also, four new developments (marked with blue dots) were taken into account during the studies.

LÕÕTSA PARK (1)

Lõõtsa park is the biggest park in the surrounding. In the middle, there is a small pond, and in the northern part of the park, there are plenty of trees. Such an area is good for a change to the built office district around. In terms of good urban space, the park creates a pleasant impression and invites pedestrians. Surrounding buildings have an active facade toward the park – there are some cafes and small shops near. A lot of activities for Ülemiste City users are held in the park, which encourages people to socialize and also spend time outdoors. There are also a lot of small-scale elements in the park, like benches, small tables and other outdoor furniture. A lot of people go there for lunch during the warmer season.

VIKTOR PALMI SQUARE (2)

Viktor Palmi square is a quite new development. There is a bus stop near, and some benches and trees in the area. As the area is open from the east side (there is a plan to build a building there in the near future, but currently, there is a huge parking space), it is hard to experience a feeling of a square in the space. In such a big open space with a lack of functions to stay or a lack of a pleasant and more divided and intimate place to spend time, people are not using it that much. There is a possibility that new building development would improve the situation.

HEALTH CENTRE PARK (3)

Health Centre park, on the other hand, is a lot smaller yet still brings green space and vegetation inside the urban surrounding. In the park, there is a terrace space, a small pavilion for outdoor office space and some hammocks to rest in. In this way park also provides possibilities for people to spend time and socialize. The disadvantage of the smaller park is the big parking space near it, which can be noisy and distracting.

SEPISE PEDESTRIAN STREET (4)

Sepise pedestrian street is a good example of a pedestrian street. It has active facades with cafes and restaurants with terraces, plenty of urban furniture and some vegetation. As the two buildings on the western side of the street are high-rise buildings (one currently under construction), the street lacks microclimate comfort and a pleasant urban environment for pedestrians. Buildings create a wind corridor and accelerate the wind within the area.

1

2

3

4

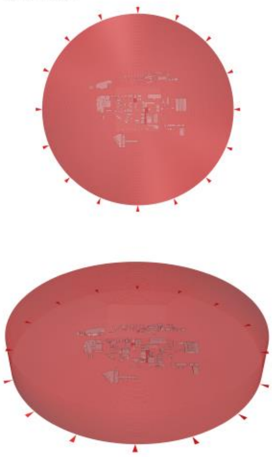
SOFTWARE

Rhinoceros

grasshopper

Eddy

CIRCULAR WIND TUNNEL



RECTANGULAR WIND TUNNEL

SIMULATION PROCESS

SOFTWARE

For the current work, the building three-dimensional models used for the simulation was realized in Rhinoceros. The simulation process and parametric modelling were realized in Grasshopper. The EnergyPlus Weather File (EPW), which contains weather data measured in Tallinn, Estonia was used for the wind simulations using the grasshopper plug-in Eddy3D. The file was obtained from the repository, which was specifically created to contain climate data files and support the building simulation process. The data contained in the weather file is measured at the airport of Tallinn, close to the Ülemiste City district. Eddy 3D uses OpenFOAM software Blue-CFD for the simulations. The data relative to the wind used from the weather file was the annual hourly wind speed and direction. Simulations were done using best practice guidelines for the CFD simulation of flows in the urban environment.

PARAMETRIC DESIGN WORKFLOW

The wind analysis was performed in three steps. In the first step, CFD wind simulations were performed for a large area encompassing the three pedestrian areas and their surrounding buildings, using a cylindrical wind tunnel considering 16 different directions. In the second step, the simulated wind patterns and velocities as modified by the buildings were used to determine the most critical wind direction for each area. Most of the buildings in the area are offices, so the time frame for pedestrian outdoor wind comfort was considered was from 8 a.m. to 6 p.m. In the third step a rectangular single direction wind tunnel was used from the most critical wind direction of each area with a smaller mesh size to obtain more accurate wind simulation results to study each area separately and more precisely. The same wind tunnel was then used for the simulations including the urban features used as wind shelters.

SIMULATION PARAMETERS

A fixed wind velocity of 5 m/s at the wind tunnel inlet at 10 m height was used. Terrain roughness component Z0, which defines what type of area is surrounding the modelled environment was Z0 = 1. It represents an urban landscape with similar objects located at uniform distances, like a town. For each simulation 2000 iterations were used for the simulation process. The probing of the simulated wind velocities was done at the height of 1.5 meters to evaluate pedestrian wind comfort.
In the case of a circular wind tunnel the distance from the most outer modelled building to the external boundary of the cylindrical tunnel mesh 15xheight(max), which is the height of the tallest building multiplied by 15. The height of the tunnel was 10xheight(max). Circular wind tunnel had a probing grid in size of 3 x 3 meters.
In the case of a rectangular wind tunnel the height of the tunnel was 5xheight(max). The windward side, from which wind enters and on both sides, the distance from the outer modelled building to the edge of the rectangular wind tunnel was 5xheight(max). Rectangular wind tunnel had a grid in size of 0.6 x 0.6 meters.

2 / 4

SIMULATION PARAMETERS AND RESULTS

LAWSON WIND COMFORT ASSESSMENT

To evaluate pedestrian wind comfort, the Lawson assessment criteria was used. More specifically, the version developed for the London Development Dock Corporation (LDDC) of the Lawson wind comfort criteria was used. This is the de-facto industry standard wind comfort assessment criteria in the UK and other countries. It defines a wind speed which is comfortable for a certain activity considering and maximum exceedance of 5 % of the time. The wind comfort of the area is assessed at 1,5 m above the ground to determine the wind comfort of the pedestrians. According to the activity pedestrian is involved in, there are different comfort levels he could experience. The Lawson comfort criteria provides certain thresholds for the wind speed for a certain activity. The wind speed in each threshold can be exceeded only for 5% of the time throughout the year to not take into account infrequent wind events.

TEST SHELTERS

The aim of the study is to investigate possible shelter solutions to design comfortable pedestrian areas for the users of Ülemiste City. To accomplish these different shelter forms were developed to be analyzed individually and then modified according to the needs of the urban spaces. Three different wind shelter types were developed: Comfort Island, Permanent shelter, Half-shelter, Operable shelter and Textile wall adjustable shelter.
Each shelter was tested using CFD wind simulation through a rectangular wind tunnel, without any surrounding structure, with different wind velocities to evaluate the area of comfort it allowed depending on the size and height of the shelters. It was decided to create three sizes of each shelter type to evaluate the size of the created comfort area depending on the wind conditions and the size of the shelter.

COMFORT ISLAND

'Comfort Island' is the biggest type characterized by a moon shape and is inspired by the traditional protection of vines from constant wind in Lanzarote, where the landscape is used to protect plants from the wind (Krautheim et al., 2014a). The concept of the structure was to implement the shelter in the surrounding public areas. The created slope could be covered with vegetation and even smaller trees or bushes, which would add even more protection in terms of the wind. The area protected from the wind space in front of the shelter has a round shape. The structure could be covered with wooden material to create a cosy feeling while being inside. The structure is spacious enough to allow creating different functions and allowing different activities. For example, outdoor office space could be created, a playground for children could be placed there or an outdoor gym. It is also possible to place this type of shelter in built environments like squares or urban parks. This way it could create a separated, more intimate space to spend time in and also bring greenery into the surrounding. The shelter was designed parametrically, allowing to create a more sharp or more rounded structure and change the height, width and length of the shelter. It was designed with the thought of Lõõtsa park in Ülemiste City, as it is the biggest green area which could fit this type of shelter. Also, the landscape in the park is designed in a way that it already creates some small hills in the area.

PERMANENT SHELTER

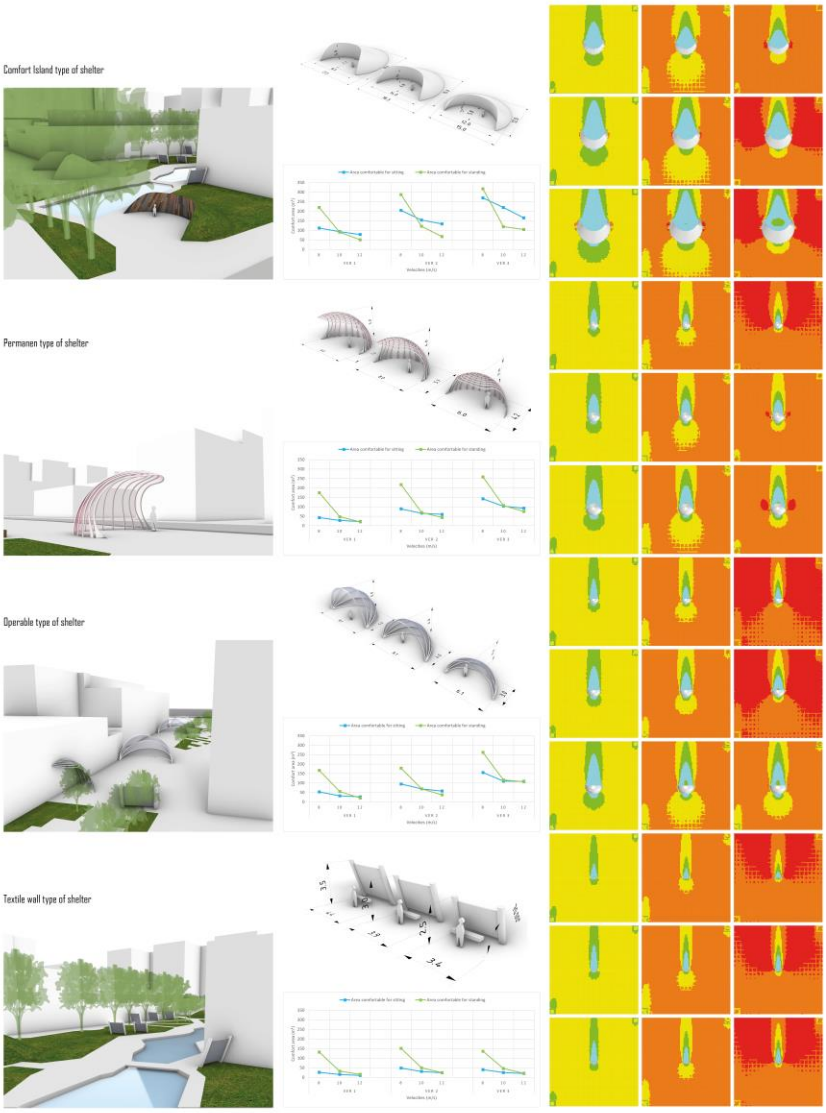
'Permanent shelter' was modelled to create a half-closed space with a roof structure above to protect also from direct sun during summer and rain. The design was inspired by the industrial past of the Ülemiste City district when it was used by the Dvigatel plant, the largest railway plant in Estonia (Ülemiste City History, n.d.). The structure was designed from bent metal beams, which represent the rails. Between the metal beams a glass or a textile structure could be placed to create protection from the wind yet allow to see through the structure. The shelter was created with the possibility to use it for providing comfortable space for pedestrians while waiting for a bus at the bus stop or for the protection of restaurant terraces. The size of the shelter also provides a possibility for creating different functions inside. For example, a small pavilion with seating spaces could also be used as an outdoor office.

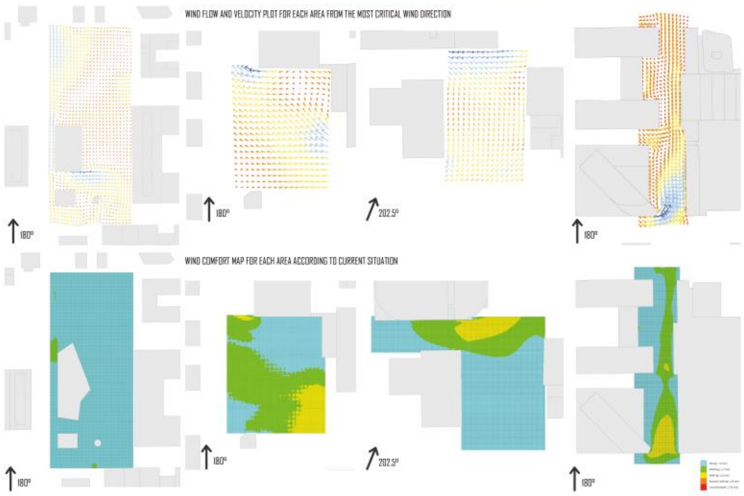
OPERABLE SHELTER

'Operable shelter' is another curved shelter type designed as a test shelter. It is a segment of a sphere which can be folded together or unfolded when protection from the wind is needed. It was designed for the Sepise pedestrian street case, which is not wide, and with the placement of permanent shelter structures, the view and possible paths would be blocked. In the case of operable shelters, when the cafes or restaurants do not require these, they could be closed and provide view and passage.

TEXTILE WALL

'Textile wall' was the smallest of the types used and was developed to create a shelter operable by the people who use the place. It consisted of two inclined posts between which a textile could be pulled out and rolled back through a spring system. This type could be installed near benches and other standing or seating points, so people could pull out the textile as a curtain if wind protection is needed and use the area. The sizes of the shelters were kept as small as possible to guarantee the usage of those. Also, to create a better wind flow over the structure, the shelters were designed with an incline of 20 degrees.





THE MOST CRITICAL WIND DIRECTION FOR EACH AREA

CIRCULAR WIND TUNNEL PARAMETERS AND PROCESS

A cylindrical wind tunnel with a height 450 m and an outer radius of 3000 m, which is 675 m from the outer modelled building to the border of the cylindrical mesh was used following best norms for wind tunnel sizing. Wind factors calculated from the simulation combined with velocities from the annual Tallinn weather data file allowed to define critical wind direction among the 16 for each area.

CIRCULAR WIND TUNNEL RESULTS

The time frame included in the simulation was from 8 a.m. to 6 p.m. The analysis periods used were calculated on the basis of the occurrence of the wind from the most critical directions during the entire year. Lõõtsa park area, Viktor Palmi square and Sepise pedestrian street's most critical wind direction is from the south (180°). Health Centre area most critical wind direction is south-southwest (202,5°).

RECTANGULAR WIND TUNNEL

After having defined the most critical direction for each pedestrian area, it was used for wind simulations performed with a rectangular wind tunnel with a smaller grid size for the area of interest in the wind tunnel, 0.6 m x 0.6 m to obtain a more accurate results. The rectangular wind tunnel considered only one wind direction. The width and the height of the rectangular wind tunnel were different for each area. The wind tunnel for Lõõtsa park was 475 meters wide and 170 meters high. The wind tunnel for Viktor Palmi square was 1140 m wide and 240 m high. The wind tunnel for Health Centre park was 895 m wide and 225 m high. The wind tunnel for Sepise street was 745 m wide and 225 m high.

RECTANGULAR WIND TUNNEL RESULTS

The results showed that the most comfortable area in terms of wind was Lõõtsa park – it has 98.6% of the area comfortable for every activity and the other 1,4% comfortable for walking. At this point, it was decided to leave Lõõtsa park out of the design process, as the area is comfortable in terms of wind comfort. The area also has already a well-developed design, and also there are a lot of trees, which also improve wind mitigation.
The second most comfortable area is the Health Centre area – it has 72,5% comfortable for sitting.
The results of the actual situation analysis showed that Viktor Palmi square is the most uncomfortable area, with only 39,5 % comfortable for every activity.
Sepise street has a comfortable area of 54.9%.

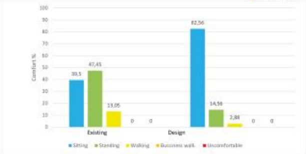
Walking comfort level is the most critical level of discomfort appearing in the results, so it was decided to increase the sitting comfort area in each case as much as possible.

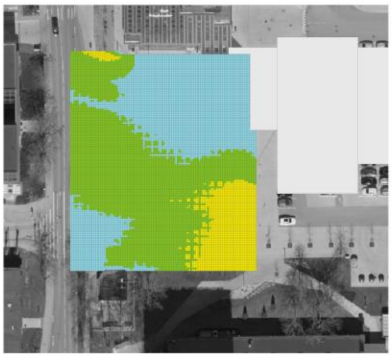
3 / 4

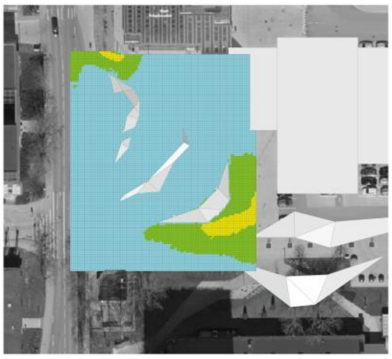
URBAN LAYOUT AND FEATURES

The interesting part of the design lies in transforming initial test shelters into final layout solutions for the areas. Comfort Island was transformed into an origami-like structure on the Viktor Palmi square and entrance to the Sepise street. The aim was to allow pedestrians to use the same paths as right now yet still mitigate the wind and create more divided and personal space for different functions. The structure, similar to the shards, also reminds of the history of the area, when the Dvigatel factory was there producing the railways. Also, the curved shapes of the initial test shelters resemble natural shapes reminding nature, while segmented and polygonal resample more industrial shapes and the past of the area.

VIKTOR PALMI SQUARE WIND COMFORT IMPROVEMENT
1:500

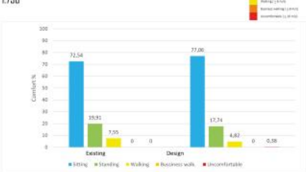


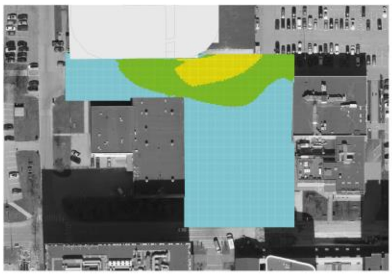


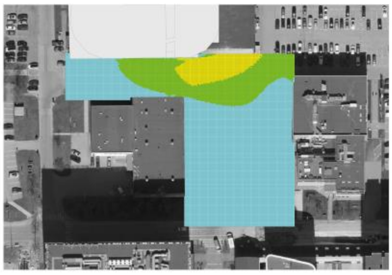


In the case of Viktor Palmi square, results show sitting was located in an area comfortable for standing and walking. Results show that the new design of the square using shelters increases area comfortable for sitting from 39.5% to 82.6%.
Since the new building will have outdoor terraces, it was decided to extend analysis area and improve the wind comfort of these. Results show that the area comfortincreases from 72.5% to 77.1%.

HEALTH CENTRE WIND COMFORT IMPROVEMENT
1:750

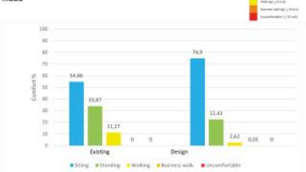


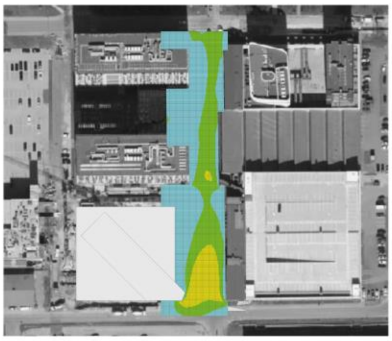


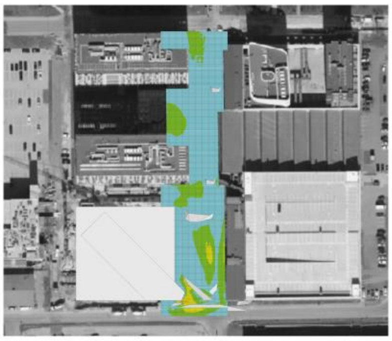


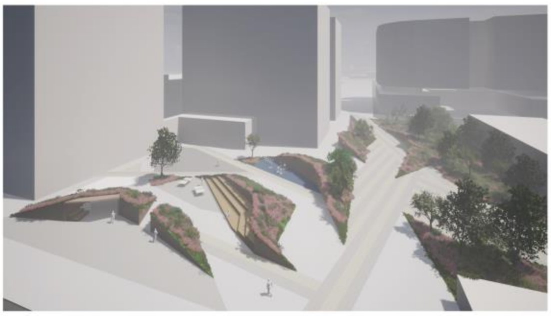
Sepise pedestrian street showed a high percent of discomfort at the beginning of the corridor from the south, where wind enters the area and is accelerated by the high rise buildings around. Sepise street is pedestrian and it has various terraces and benches where people tend to spend time. The aim was to create a possible windbreak at the beginning of the corridor and protect existing seating. Results show that the new design using shelters increases the area comfortable for sitting by 20%. Area comfortable for standing is reduced from 33.9% to 22.4%. Area comfortable for walking is reduced from 11.3% to 2.6%.

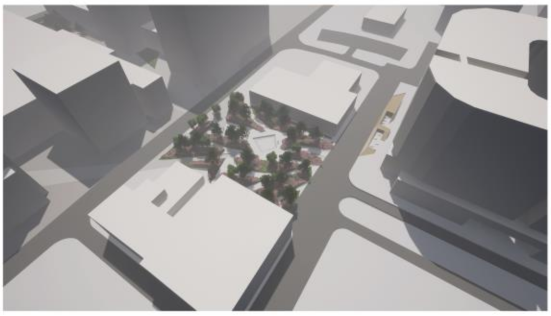
SEPISE PEDESTRIAN STREET WIND COMFORT IMPROVEMENT
1:1000











4 / 4