Interactive Wind Simulation in Settlement Areas

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Abstract: We investigate the research problem of simulating interactive wind flows in settlement areas containing buildings of arbitrary shapes. To reach this goal we generate two-dimensional wind flow simulations based on geographic data from areas in Switzerland. In modern cities it is crucial to explore wind flows that might have effects on the fresh air circulation, urban heat islands, or transport and flow directions of polluted or contaminated air. In our work, we create a pipeline to define and implement the steps and techniques to generate a wind flow simulation with which we can monitor the flow around buildings while also allowing user interactions during and after the wind flow computation. To achieve our results we focus on data accessed from public geographic information systems (GIS) in Switzerland that are available in different geo-spatial granularities. The visualizations can combine several wind flow metrics like wind directions, wind intensities and velocities, as well as air pressure, either in separate visual depictions or as overlays in geographic maps. Finally, we discuss limitations and scalability issues and provide an outlook based on future directions.

1 INTRODUCTION

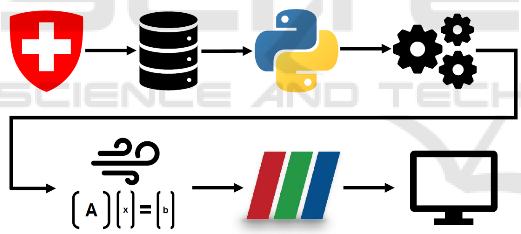

Figure 1: The steps in this research and how they build on each other. Data is accessed, processed, simulations are computed, visualized, and explored on users' demands.

Wind can have a crucial impact on natural and unnatural environments (Yan et al., 2022) including agricultural areas, forests, as well as buildings in settlement areas. In particular for the people living in such settlement areas (Meinel, 2008) the consequences can come in various forms. For example, wind flows are responsible for the air circulation, the reduction of the number and size of urban heat islands (Seebacher et al., 2019), as well as natural effects coming in the form of erosion or soil dehydration. Even contaminated or polluted air (Papalexiou and Moussiopoulos, 2006) or controlling the flow of fire and smoke (Forney et al., 2003) can be impacted by wind flows and their directions and intensities. Not only direction but even more the obstacles in the way in form of trees, mountains, or man-made buildings have an impact on how the aforementioned aspects have to be taken into account in certain geographic areas, in particular in wind simulation algorithms to compute reliable and realistic results.

In this paper, we describe a model for wind flow simulation taking into account buildings in settlement areas that have an influence on how the wind affects certain subregions or not. Such a simulation can be useful for experts or (political) decision makers in various application fields to monitor or predict heat islands, air pollution, or erosion and dehydration effects. Apart from generating static wind flow visualizations we integrate interactive simulations. This interactivity allows to modify several parameters like wind directions or building shapes to explore the impact of wind on certain user-defined situations. Moreover, the interactive visualizations can be a combination of overlaid views depicting streamlines for the wind direction as well as color coded contour lines for the geo-spatial pressure. Many more features are included in the visualization tool focusing on the task to identify wind effects in settlement areas.

We investigate the following **research question**:

- Which steps, techniques, and technologies are

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required to design, create, and run an interactive flow visualization for this kind of application based on GIS models (see Figure 1)?

To illustrate our approach we apply it to data from geographic information systems (GIS) focusing on Switzerland, allowing us to simulate wind in local regions of the country. The novelty of the approach is its interactivity to allow region selections and to generate a wind simulation on users' demands. As a proof-of-concept we simulate the data in the two-dimensional space, but we can also extend our work to three-dimensional data since the data is accessible in 3D. However, the 3D data is more coarse-grained at the moment compared to the 2D counterpart.

2 RELATED WORK

Our work is a composition of several subfields, in particular simulation, computer graphics, wind flow, and geographic information systems.

2.1 Simulations

We make use of numerical computations of wind flows (Kirkil and Lin, 2020; Yan et al., 2022) and focus on the simulation pipeline (Bader et al., 2011) that we adapt for our research purposes (see Figure 1) starting with the data acquisition and ending at the visual depictions of the computed simulations. Such a pipeline is important since it describes the stages from the data to the final output: Modeling, numerical treatment, implementation, visualization, and the embedding into a tool like in our case for example, in which we also integrate user interactions (Yi et al., 2007). Those can directly impact the visual depiction of the wind flow in the visual embedding. They also allow adaptations to involved parameters that impact the flow simulation like wind direction changes or modifications of the buildings in the scene, typically with the goal to detect patterns in the wind flows (Wang et al., 2022).

2.2 Computer Graphics Perspective

The modeling and technical processing of the coordinates is based on a grid that is used to maintain the pixel properties in the resulting image, also allowing to interactively draw lines, build and cut out shapes, or transform resolutions. On the grid we compute the simulation steps while we take into account each building and its outlines as obstacles for the flow and the flow directions. This is somewhat different to original work in flow visualization, for example based on surface particles (van Wijk, 1993) or taking into account virtual and augmented reality to create wind flow (Bryson and Levit, 1992). From a visualization perspective there are various options to depict the flow but we use a standard way of visualizing it given by streamlines (Schlemmer et al., 2007).

2.3 Flow Around Buildings

Modern city planning (Burch et al., 2020) has to take into account crucial aspects like heat (Seebacher et al., 2019) or air pollution (Papalexiou and Moussiopoulos, 2006), even special wind situations like tornados for example (Yang et al., 2010). Those are typically impacted by wind and wind flows around buildings (Li and Zhao, 2023; Zu and Lam, 2018), hence generating models that compute them and integrate the results into the city planning is of great importance. An efficient simulation model can reduce costs before they even occur (Paterson and Apelt, 1989). This means they can serve as pure monitoring tool but might even be used to predict (Mayo et al., 2018) situations to prevent human catastrophies or just reduce the costs during planning cities. Constructing aerodynamic buildings depends on many parameters as well as boundary conditions and mean a challenge for today's architects and the construction industry.

2.4 GIS-Related Concepts

Geographic information systems (GIS) are important to provide data of cities or city parts (Yin et al., 2014) for generating simulation models. Those can be provided in several resolutions and users should be able to extend them by adding extra buildings or parts of buildings that have a direct impact on the wind flow in the surrounding environment. The results of the simulations are datasets which are graphically depicted, for example using 3D vectorization (Ridzuan et al., 2023) or based on 3D city models (Deininger et al., 2020), but in most cases, interactions are not supported (Yi et al., 2007).

3 DATA

Before we can start simulating wind flows we need to access data from geographic information systems to integrate the buildings and their outlines into the model generation. We transformed the data to make it usable by our simulation tool.

3.1 Data Acquisition

The data source we base our work on is provided by the Ministerial Measurement of Switzerland which incorporates measurements from the whole country on different levels of geographic granularities. The data can be accessed by the federal office for ground topography and its Swisstopo's interface (Eidgenossenschaft, 2024). They also support 3D maps in addition to the more standard two-dimensional data measurements. The tool provides an easy way to access parts of the data and to enrich the current visual simulation by additional data, for example to interactively add surrounding buildings that were omitted in the first step of a simulation.

3.2 Data Processing and Further Steps

Once the original data is accessed it will be processed in several steps (see Figure 1). We use the programming language Python and several libraries to read and parse the data, preprocess it in a way to create a flag field, compute a wind flow simulation, and finally visualize the generated results while we also support user interactions. The data processing is important since on its basis we will compute the wind flow simulation, including additional parameters like wind directions as well as building extensions.

Due to the fact that we can access GIS data of the whole country of Switzerland (Eidgenossenschaft, 2024) we can simulate wind flows for any local region in the country, on different levels of geographic granularity which is one of the novelties in our work, i.e. interactions are possible that support the spatial navigation in the data as well as replacing buildings or changing wind directions on demand for example. The corresponding data parts are then processed to make these interactions a crucial component in our tool. Users of the tool decide which parameters to adapt and which visual variables are used to depict the simulation data (Wu et al., 2023).

4 FLOW SIMULATION

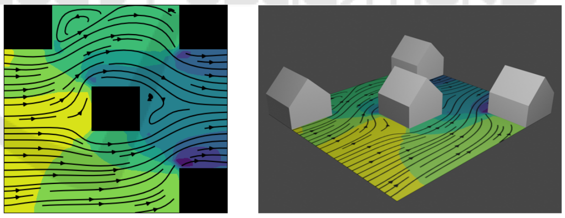
To compute wind flow we use block-structured Cartesian grids for the spatial discretization of geographic regions. The smaller the grid sizes are, the better we can capture geographic details, but the more expensive the computations will be due to growing numbers of grid cells. Hence, there exists some kind of trade-off between the accuracy of the results and the runtime performance given by the number of grid cells. In particular, for a real-time or live computation (important for interactive responsiveness of the tool) we should not exhibit too many grid cells since those would tremendously reduce the interactivity.

4.1 Algorithmic Concepts

We use an iterative computation approach for the transient wind flow simulation by numerically solving the Navier-Stokes equations (see Algorithm 1). We base our work on a relatively simple model that applies a finite differences method for spatial and temporal discretization of the derivatives. Applying Chorin's projection method (Chorin, 1967), we end up with a Poisson equation for the pressure computation which contributes as most complex part of the entire calculation. For each grid cell we compute the wind speed and the pressure by using a just-in-time (JIT) compiler based on the Python package called numba which compiles Python functions into machine code.

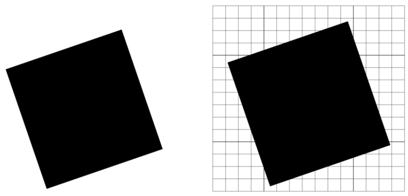
The integration of buildings or obstacles are incorporated by means of so called flag fields. A simple geometry is shown in Figure 2 used in a first test of the approach. It shows visualizations for the wind and pressure as a 2D scene (a) and a more 3D representation (b).

Algorithm 1 consists of five major subroutines for the initialization of the parameters, grids, and involved fields, the main simulation loop, the pressure calculation loop, the check for convergence, and the final plotting of the results.



(a) (b)

Figure 2: Wind flow and pressure: (a) A 2D scene with a few buildings. (b) The same scene augmented by a more 3D representation, a so-called quasi 3D visualization that adds 3D polygonal shapes on the buildings of the 2D representation to make it more understandable for the users.



(a) (b)

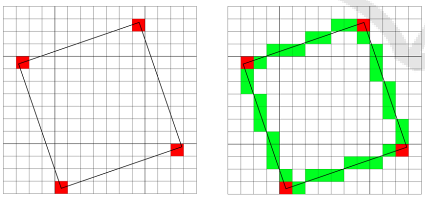
Figure 3: The 2D outline of a building (a) gets placed into a grid consisting of equally sized grid cells (b).

4.2 Integrating Outlines into a Grid

In a first step, we describe how an outline gets mapped to a grid which requires an exact matching from the building geometry to a corresponding grid of a certain resolution. Figure 3 illustrates a 2D model of a building depicted as black square (a) that is placed into a uniform grid of equally sized grid cells (b). It may be noted that the resolution of the grid cannot be infinitely high due to the fact that each grid cell will be treated as a separate variable in the physical computation, i.e. more of them would cause more complex computations resulting in a higher runtime performance. For this reason, we need an adequate resolution to allow live computations and hence, interactive responsiveness during the simulation process.

Each grid cell can only have one out of two states: Either it belongs to a building or not, requiring a pre-step before the simulation computation that checks each grid cell for this property. To get a quick solution to this problem we apply the Bresenham algorithm (Angel and Morrison, 1991) that is able to draw lines between the corners of the polygon modeling the building outlines. Negatively, we soon get effects that are well-known as pixel staircases in low resolution images (see Figure 4).

Finally, we obtain a geometry that is compatible with the simulation algorithm, i.e. we generate a so-called flag field that we take into account in the computation to judge whether a grid cell corresponds to a piece of a building or not (see Figure 5).

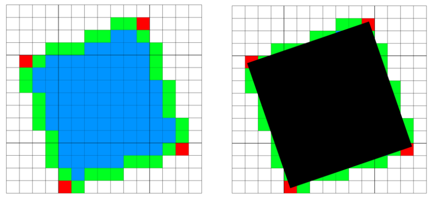


(a) (b)

Figure 4: Computing the corners (red squares) of the 2D outline (a) and identifying the grid cells that are hit by the corner-connecting lines (green squares) (b). This may result in some kind of staircase effect.

4.3 Invalid Geometry

The computation of the simulation is problematic at the walls and corners around an obstacle. We must apply boundary conditions to follow physical laws correctly. Otherwise, the wind might flow through walls or the pressure is incorrectly computed. Most of the computation methods have such problems with obstacle grid cells that have more than 2 free, direct neighbors or that have free neighbors above and below (which is a wall consisting of just one grid cell).



(a) (b)

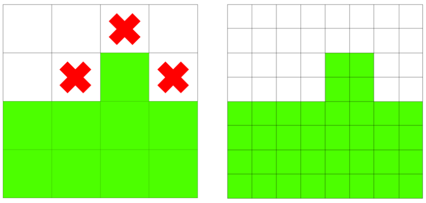
Figure 5: An identified outline of a building depicted as corners (red squares), outline connecting the corners (green squares), and the inside (blue squares) (a). Overplotting with the original 2D building shows the final result in the grid with the original shape (b).

Algorithm 1: The windy flow simulation algorithm.

```
Input: domain_size, grid_spacing, time_step_size, density,
kinematic_viscosity, inflow_velocity, n_iterations,
max_pressure_iterations
Output: velocity_fields, pressure_fields, plots

▷ Initialization
Initialize simulation parameters
Initialize grids
Initialize velocity, pressure, and flag fields
Mark obstacle locations in the flag field

▷ Main simulation loop
for i in range(n_iterations) do
    Calculate temporary velocity fields using central difference
    Apply boundary conditions to temporary velocity fields
    Prepare right hand side of the Poisson Pressure Equation

    ▷ Pressure calculation loop
    for j in range(max_pressure_iterations) do
        Update pressure field
        Apply boundary conditions to the pressure field

    ▷ Check for convergence
        Calculate residuals
        if residuals < threshold then
            break    ▷ Exit loop if convergence criterion is met
        end if
    end for
    Update velocity fields using the pressure gradient
    Apply boundary conditions to the updated velocity fields
    Update previous velocity fields with the current ones

    ▷ Plot current state every 10 iterations for visualization
    if i mod 10 == 0 then
        Plot current state
    end if
end for
Plot final state of the simulation
```

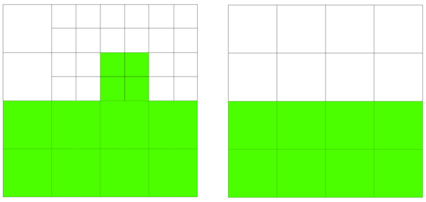

For this reason, we have to re-inspect all situations after the geometries have been computed to avoid such negative and error-prone cases. Actually, we have three options to avoid such cases:

- **Grid Refinement.** We refine the grid. If we split the involved grid cell into 2×2 grid cells we get rid of the problematic cell due to the fact that it does not have 3 free neighbor cells anymore. However, a new problem might be the increased number of cells that can cause a more complex



(a) (b)

Figure 6: Refining the grid due to the fact that there are free neighbors causing problems in the physical correctness: (a) One grid cell has 3 free neighbors. (b) Grid refinement avoids this situation.



(a) (b)

Figure 7: Two more options to get rid of the problematic situation: (a) Local adaptation of the grid. (b) Removal of the problematic grid cell.

and longer running computation (see Figure 6).

- **Adaptive Grid.** We adapt the grid by refining it only at locations in which invalid geometries exist. The benefit of this approach is that we do not need much more storage as in the general grid refinement, however as a drawback the storing process would get much more complex due to the fact that our data structures have to handle such special situations (see Figure 7 (a)).
- **Grid Cell Removal.** Just removing the problematic grid cell might be the simplest solution, however, the simulation will get less exact due to the missing geo-spatial information. In most cases such scenarios just occur for tiny pieces of houses or obstacles, hence this solution might be the best one, also because we have tested it in experiments (see Figure 7 (b)).

It may be noted that the grid is discretized, actually allowing to make it infinitesimally small but due to the fact that we have to solve equation systems whose complexity depends on the number of involved grid cells, we should avoid such a situation. This means the buildings have to be downscaled to make the simulation efficiently computable.

4.4 Algorithmic Performance

We tested our approach by applying it to a scenario containing 150×150 grid cells, in total 22,500 cells. The used hardware is a laptop with a CPU, a Microsoft Surface Laptop Studio processor Intel Core i7-11370H, 4 core, 3 GHz and 16 GB RAM.

The visualizations will be shown as animation which means they can be regarded as some kind of gif, overplotting each image in the sequence by the next one. The initialization lasts 2.4 to 3.5 seconds, but this is independent from the final performance. The concrete measurements for the running program and for 1,270 iterations and 127 visualizations are 2.7031 seconds for the initialization, 0.8409 seconds for the mean time between visualizations, 0.0022 seconds variance, 0.0468 seconds standard deviation, 1.0005 seconds maximum, and 0.7501 seconds minimum.

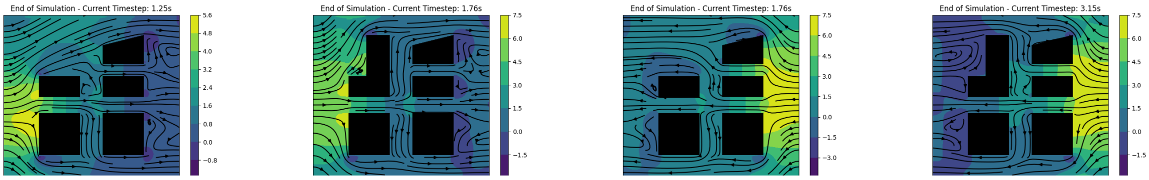
5 VISUALIZATION TOOL

To explore the results of the simulation algorithm we created a visualization tool that can depict the results in different visual encodings and views. Moreover, interactions are supported to let users adapt parameters or navigate in the visual results. Before implementing the tool we started with a design phase including visualization techniques and interactions as well as algorithmic concepts. All of them are integrated and laid out in a user interface.

We focus on the most prominent visualization techniques for this kind of data. The visualizations can be shown separately or as overlay on users' demands.

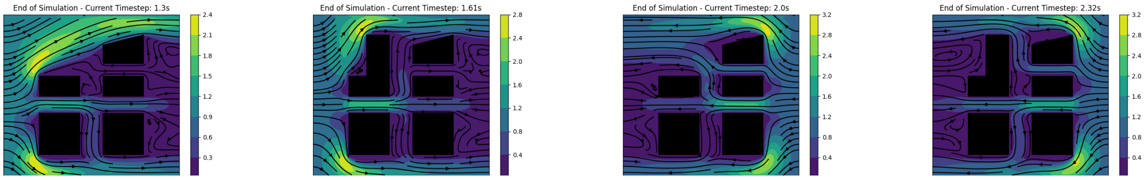
- **Wind Flow.** The wind flow will be displayed by streamlines, also showing the wind directions, densities, and speed by arrow heads, proximity, and frequency of arrow heads.
- **Pressure.** The pressure is visually depicted by a contour plot using color coding to show the pressure values in certain regions. We use a categorical color scale here instead of a continuous one.
- **Geography and Buildings.** A geographic map containing abstractions for the buildings provides an overview about the geo-spatial data.
- **3D Augmentation:** Quasi 3D depictions are useful to better illustrate the geographical scene with wind flows and pressures and look more natural and more aesthetically pleasing.

We integrate user interactions for modifying simulation parameters and for directly impacting the visual output (Yi et al., 2007).



(a) (b) (c) (d)

Figure 8: Visualizing the outcomes of the simulation for two scenarios: (a) shows streamlines for the wind direction overlaid on a contour map depicting the pressure with a color coding. (b) We modified one building (top left) to compare the impact on wind flows and pressure. (c) Same scenario as in (a) but this time the wind comes from East and not from West as in (a). In (d) we see again the modification of one building and its impact on the wind flow result.



(a) (b) (c) (d)

Figure 9: Visualizing the velocities of the wind flows for different wind directions as well as different building outlines: (a) Wind from West and standard buildings. (b) Wind from West and building extension. (c) Wind from East and standard buildings. (d) Wind from East and building extension.

6 APPLICATION EXAMPLE AND RESULTS

As some kind of stress test we applied our approach to GIS data from Zurich in Switzerland with 50,750 buildings.

6.1 Simple Scenarios

Figure 8 shows before-after scenes for the results of the simulation algorithm. The visualizations are composed of streamlines (for wind directions and intensities) and contour maps (for pressure values). Figures 8 (a) and (c) show the simulation result for different wind directions while the computation in Figures 8 (b) and (d) also show different wind directions but this time the scenario was modified by extending one building (top left) with an additional building. Figures 8 (a) and (b) show the wind coming from West while Figures 8 (c) and (d) show the simulation computation for wind coming from East.

For the variants without building extension in Figures 8 (a) and (c), we can see that the wind is moving more smoothly in the upper left corner without turbulent or eddy currents compared to Figures 8 (b) and (d), apart from the fact that in Figure 8 (a) the wind is moving in a diagonal (West-North) direction but in Figure 8 (c) this is not the case. For the scenario in Figure 8 (b) with the modified building we see that the wind from West is moving around the new building part while in Figure 8 (d) the wind from East creates turbulent and eddy currents and swirls in the upper left corner. For the pressure (the color coded contours) we can also see some differences between the scenarios. Comparing Figures 8 (a) and (b) for the wind from West we find stronger pressure regions in the corner of the modified building. For the situations in Figures 8 (c) and (d) with the wind coming from East we see that the pressure in the corner of the extended building got much lower which might be a hint for a quiet place in the garden to relax in cases the wind comes from the East direction. It may be noted that we are able to interactively modify those situations to explore the best shapes for new built houses, for example to create wind-free zones. Such a simulation might be of particular interest for architects who plan a new house based on the house owners' demands.

Figure 9 depicts the same building situation as in Figure 8 but in this case we focus on the wind speed instead of the wind pressure. The color of the contour plot indicates the strength of the wind in terms of wind speed. We can see that the wind speed is actually the highest around the corners of the building close to the direction from where the wind is coming. Also in a wind channel between two buildings we can see a higher wind speed than in the open environment which is due to physical laws related to wind speed and wind pressure.

Figure 10 shows another example with three buildings while one building is a bit smaller than the

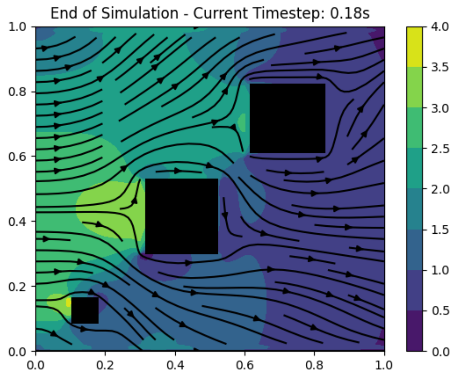
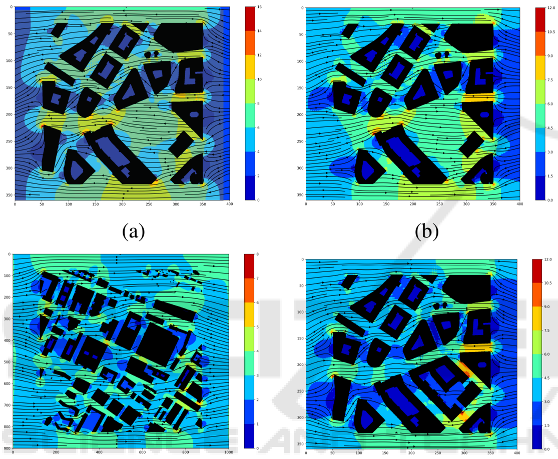


Figure 10: Three buildings while one is smaller than the two others. The wind is coming from West. We can clearly see the effect of the buildings on the wind.



(a) (b) (c) (d)

Figure 11: Buildings from Zurich and the impact of wind flows and the fact that buildings are removed: (a) A part from Zurich while the wind is coming from East. (b) One building is removed and the wind is coming from the West. (c) Industriequartier in Zurich. (d) Sihlporte in Zurich.

other two ones. The wind is coming from West and we can directly spot the largest pressure right before the buildings closer to the West. In general, the pressure is always largest at the side of the building facing the wind directly and lowest behind the building.

6.2 More Complex Scenarios

Figure 11 shows examples including more buildings than the scenes before. Also some real-world buildings from areas in Zurich are taken into consideration for this kind of wind simulation. Also different wind settings were applied resulting in different flows while buildings are removed to get an impression about the impact of new building environments.

In Figures 11 (a) and (b) we can easily detect that the wind direction has an impact on the wind flows around the buildings as well as the pressure. In (c) we detect that there are just some strong pressure regions while the center area of this environment seems to be a quiet place with not much wind and low pressure (blue color). In (d) it seems as if the wind is strongest when it is leaving the building environment (yellow and red colors to the right hand side).

6.3 Open Challenges and Perspectives

We are aware of the fact that there are also limitations of our approach, however we developed a solution to this problem at hand and will further develop more scalable and user-friendly versions of the tool. For example, more interaction techniques should be integrated in the future, also letting users modify more parameters to change algorithmic computations on-the-fly. There are also still some limitations with respect to scalability issues regarding visual, perceptual, and algorithmic issues. We are still experimenting with the tool and the algorithms that we use as well as the hardware could be enhanced in the future to get even faster and even more interactive results.

7 CONCLUSION AND FUTURE WORK

In this work, we investigated the research problem of computing wind flows in settlement areas with the goal to create a model to understand such wind situations, for example before a new building is planned, built, or just extended. We show the results of the simulations visually and let the users interactively change wind directions or add, remove, replace buildings as well as other obstacles while the simulation adapts immediately to the new situation. To illustrate the usefulness of our approach we applied it to GIS data from Switzerland and showed some visual results of the simulations under different conditions. For future work we plan to extend our work by using better hardware and more efficient algorithms and parallelization, in particular with a focus on interactive responsiveness. This means we might install the tool on some kind of large high-resolution display to let several experts explore the data in a collaborative manner (LHRD). We also plan to conduct an expert user study with city planners and architects, maybe also tracking eye movements (Burch, 2022) of the users with the goal to analyze their visual attention behavior.

REFERENCES

Angel, E. and Morrison, D. (1991). Speeding up bresenham's algorithm. *IEEE Computer Graphics and Applications*, 11(6):16–17.

Bader, M., Mehl, M., Rüde, U., and Wellein, G. (2011). Simulation software for supercomputers. *Journal of Computational Science*, 2(2):93–94.

Bryson, S. and Levit, C. (1992). The virtual wind tunnel. *IEEE Computer Graphics and Applications*, 12(4):25–34.

Burch, M. (2022). *Eye Tracking and Visual Analytics*. River Publishers.

Burch, M., Wallner, G., Arends, S. T. T., and Beri, P. (2020). Procedural city modeling for AR applications. In et al., E. B., editor, *Proceedings of the 24th International Conference on Information Visualisation, IV*, pages 581–586. IEEE.

Chorin, A. J. (1967). Numerical solution of the navier-stokes equations. *Mathematics of Computation*, 22:745–762.

Deininger, M. E., von der Grün, M., Piepereit, R., Schneider, S., Santhanavanich, T., Coors, V., and Voß, U. (2020). A continuous, semi-automated workflow: From 3d city models with geometric optimization and CFD simulations to visualization of wind in an urban environment. *ISPRS International Journal of Geo-Information*, 9(11):657.

Eidgenossenschaft, S. (2024). Bundesamt für Landestopografie swisstopo.

Forney, G. P., Madrzykowski, D., McGrattan, K. B., and Sheppard, L. (2003). Understanding fire and smoke flow through modeling and visualization. *IEEE Computer Graphics and Applications*, 23(4):6–13.

Kirkil, G. and Lin, C. (2020). Large eddy simulation of wind flow over A realistic urban area. *Computation*, 8(2):47.

Li, Y. and Zhao, H. (2023). Spatial wind flow load and shape optimization for folding grid shell buildings. *IEEE Access*, 11:135304–135322.

Mayo, M., Wakes, S., and Anderson, C. (2018). Neural networks for predicting the output of wind flow simulations over complex topographies. In Wu, X., Ong, Y., Aggarwal, C. C., and Chen, H., editors, *Proceedings of the IEEE International Conference on Big Knowledge, ICBK*, pages 184–191. IEEE Computer Society.

Meinel, G. (2008). High resolution analysis of settlement structure on base of topographic raster maps - method and implementation. In Gervasi, O., Murgante, B., Laganà, A., Taniar, D., Mun, Y., and Gavrilova, M. L., editors, *Computational Science and Its Applications - ICCSA 2008, International Conference, Perugia, Italy, June 30 - July 3, 2008, Proceedings, Part I*, volume 5072 of *Lecture Notes in Computer Science*, pages 16–25. Springer.

Papalexiou, S. and Moussiopoulos, N. (2006). Wind flow and photochemical air pollution in thessaloniki, greece. part II: statistical evaluation of european zooming model's simulation results. *Environmental Modelling and Software*, 21(12):1752–1758.

Paterson, D. and Apelt, C. (1989). Simulation of wind flow around three-dimensional buildings. *Building and Environment*, 24(1):39–50.

Ridzuan, N., Ujang, U., and Azri, S. (2023). 3d vectorization and rasterization of citygml standard in wind simulation. *Earth Science Informatics*, 16(3):2635–2647.

Schlemmer, M., Hotz, I., Hamann, B., Morr, F., and Hagen, H. (2007). Priority streamlines: A context-based visualization of flow fields. In Museth, K., Möller, T., and Ynnerman, A., editors, *Proceedings of the 9th Joint Eurographics - IEEE VGTC Symposium on Visualization, EuroVis*, pages 227–234. Eurographics Association.

Seebacher, D., Miller, M., Polk, T., Fuchs, J., and Keim, D. A. (2019). Visual analytics of volunteered geographic information: Detection and investigation of urban heat islands. *IEEE Computer Graphics and Applications*, 39(5):83–95.

van Wijk, J. J. (1993). Flow visualization with surface particles. *IEEE Computer Graphics and Applications*, 13(4):18–24.

Wang, T., Wang, B., Matekole, E. S., and Atif, M. (2022). Finding hidden patterns in high resolution wind flow model simulations. In Kothe, D. B., Geist, A., Pophale, S., Liu, H., and Parete-Koon, S., editors, *Proceedings of the Accelerating Science and Engineering Discoveries Through Integrated Research Infrastructure for Experiment, Big Data, Modeling and Simulation - 22nd Smoky Mountains Computational Sciences and Engineering Conference, SMC, Revised Selected Papers*, volume 1690 of *Communications in Computer and Information Science*, pages 345–365. Springer.

Wu, A., Deng, D., Chen, M., Liu, S., Keim, D. A., Maciejewski, R., Miksch, S., Strobelt, H., Viégas, F. B., and Wattenberg, M. (2023). Grand challenges in visual analytics applications. *IEEE Computer Graphics and Applications*, 43(5):83–90.

Yan, Z., Chen, R., and Cai, X. (2022). Large eddy simulation of the wind flow in a realistic full-scale urban community with a scalable parallel algorithm. *Computer Physics Communications*, 270:108170.

Yang, Z., Sarkar, P., and Hu, H. (2010). Visualization of flow structures around a gable-roofed building model in tornado-like winds. *Journal of Visualization*, 13(4):285–288.

Yi, J. S., ah Kang, Y., Stasko, J. T., and Jacko, J. A. (2007). Toward a deeper understanding of the role of interaction in information visualization. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1224–1231.

Yin, J., Zhan, Q., Xiao, Y., Wang, T., Che, E., Meng, F., and Qian, Y. (2014). Correlation between urban morphology and wind environment in digital city using GIS and CFD simulations. *International Journal of Online Engineering*, 10(3):42–48.

Zu, G. and Lam, K. M. (2018). LES and wind tunnel test of flow around two tall buildings in staggered arrangement. *Computation*, 6(2):28.