HiDALGO2
CENTRE OF EXCELLENCE

Urban Air: Simulating City Air Quality and Air Comfort with HPC

HiDALGO2 Clustering Event

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1. Global challenges of the urban air

Air pollution is above health limits in many cities, due to traffic, or factory emissions (NOx, PM)

- EU regulations
- Current services only at a very coarse resolution

https://www.thelocal.de/20171115/eu-planning-to-sue-germany-over-dirty-air-in-cities-report

Accidental/intentional **toxic gas release** (e.g. from batteries) in cities is a major concern

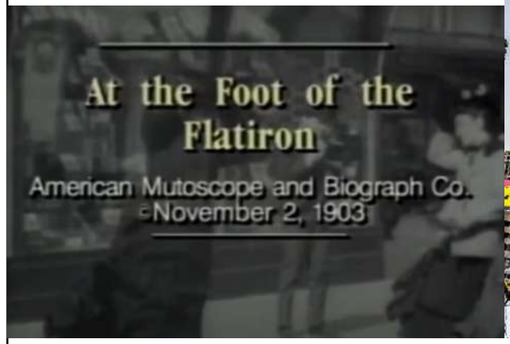
- A very fast operation is needed e.g. for an evacuation

Germany: toxic fumes alert after massive warehouse fire in Hamburg

Police have warned people in the Hamburg to close their windows after a large fire that engulfed several warehouses sent black, chemical-laden smoke drifting over the city.

Pedestrian **wind discomfort** or danger near tall buildings, due to corners' amplification or the channel effect mainly

- E.g. Flatiron Building, NYC
- Standards for building design, e.g. by Lawson, or the NL-standard NEN 8100:2006 - Wind Comfort and Wind Danger in the Built Environment



2. Goals

Develop an HPC application for tackling the urban air challenges:

1. General, easily applicable by non-HPC users, for arbitrary cities
2. Large, real domain: an entire/large part of a city with buildings (e.g. 5 km x 5km x 0.8 km)
3. High spatial resolution: 1-2 meters at street level (for hot spot treatment)
4. (Much) shorter than real-time simulation
5. Accuracy: requested relative error is moderate (5%)

6. Scientific value creation: AI-based surrogate models, UQ (uncertainty quantification), large-scale efficiency
7. Optimized to EuroHPC supercomputers (e.g. 65k CPU cores, FMR, MPI+GPUs)

8. The codes are re-usable for other industrial and societal problems
9. Requirements gathered from real applications (e.g. from the Stockholm simulation)

2. Goals – Solutions and HPC-codes to be developed

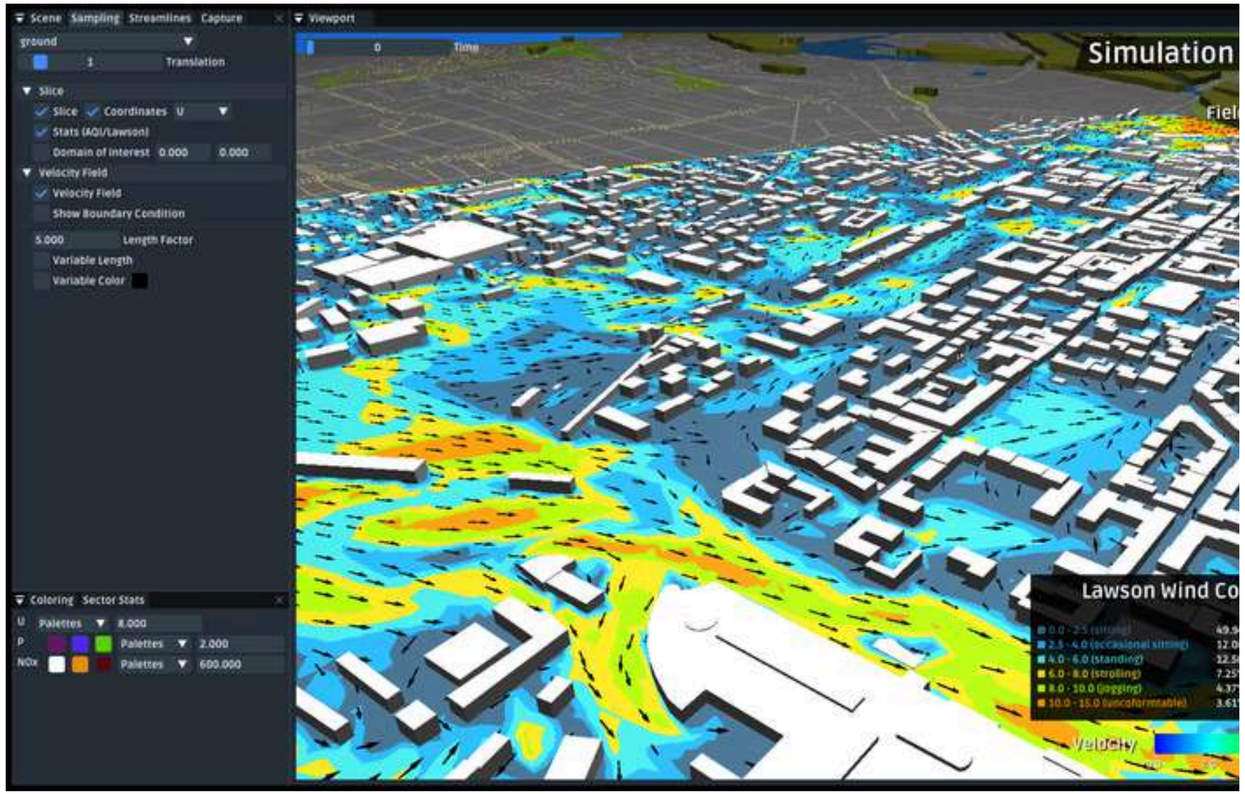
Solutions

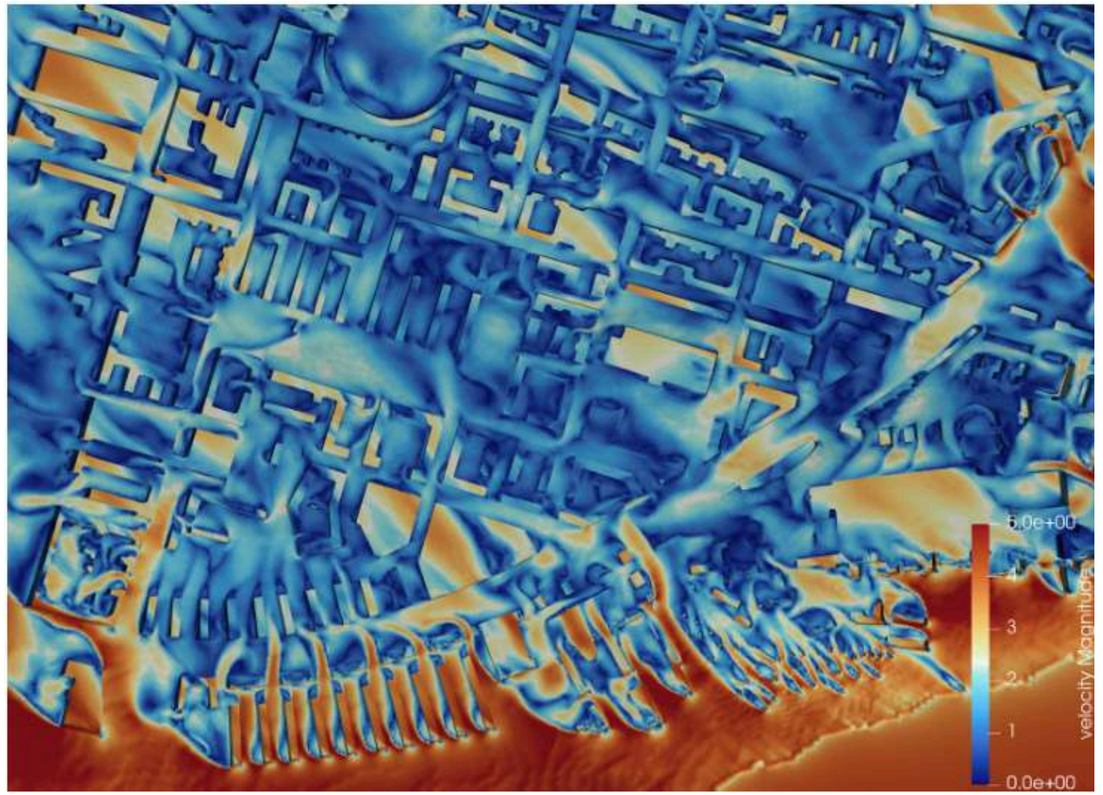
1. Computational tools for the **analysis** of a design: high-resolution (1 meter at ground level) simulation
2. **Reporting tool** according to the EU regulations (e.g. full-year simulation and assessment of air quality)
3. **Decision-making or risk analysis** computational tools for scenario analysis: simulate several options fast
4. **Real-time digital twin** for the airflow / air quality / pollutant concentration (i.e. live simulation that assimilates sensor data continuously to simulation)
5. **Design tool** for urban building planning

HPC-codes

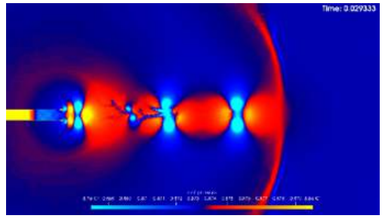
6. CFD-codes optimized to EuroHPC machines CPU, GPU clusters
7. High-performing visualization tool for the web
8. Simple graphical user interfacee for general applications – portal on the web

3. Methods and results: Preview of the results





Urban wind comfort simulation (left) and high resolution simulation (right).



Industrial application for pipe accoustics: https://www.youtube.com/watch?v=rAKsChm9-b8

3. Methods and results: Overview of the HPC codes

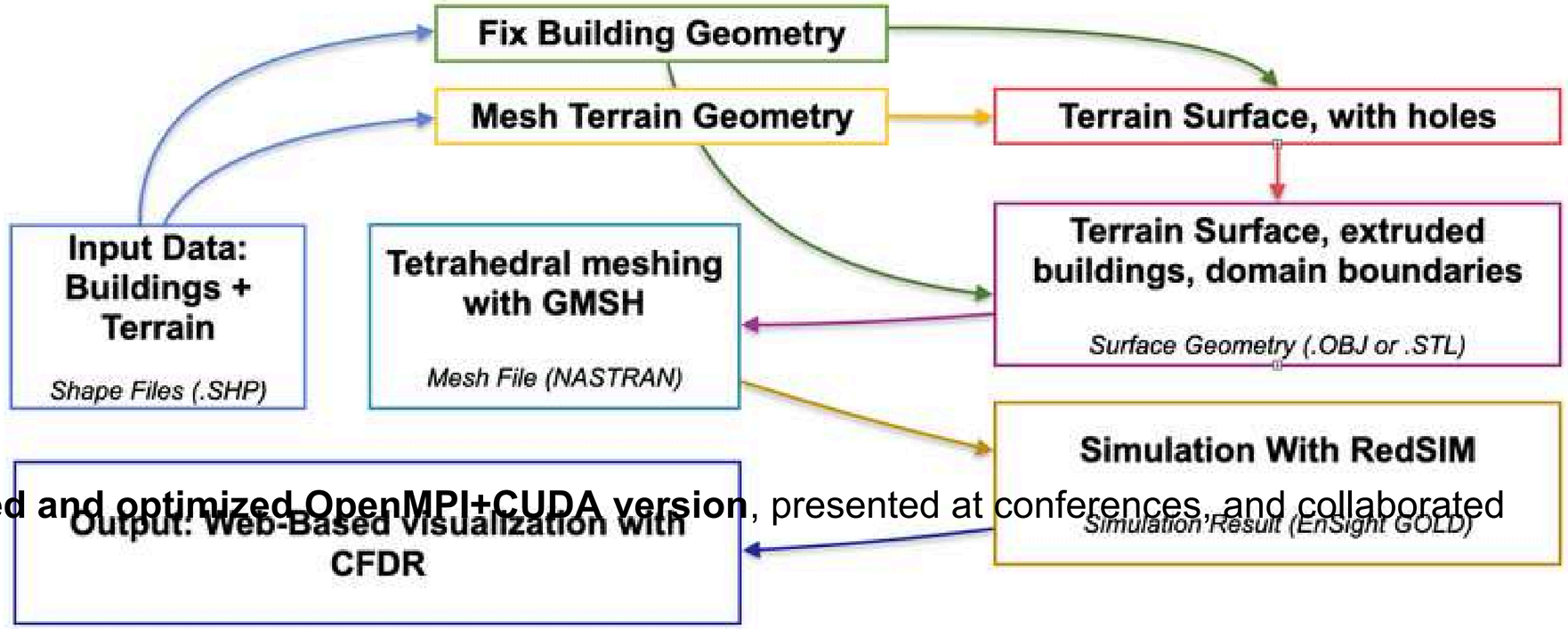
1. **OpenFOAM**
    1. 3D incompressible Navier-Stokes, FVM on unstructured meshes, RANS and URANS, (pimpleFOAM, simpleFOAM), passive scalar (for pollutant dispersion).
    2. Optimized code for CPU (OpenMPI). **Parallel efficiency: >80% (#cells=10M) for 512 nodes of LUMI. GPU-implementation ongoing.**

2. **RedSim**
    1. **Native MPI+GPU** code (from the scratch) for the compressible 2D/3D Euler and Navier-Stokes, 1st & 2nd order FVM, unstructured polyhedral meshes, industrial I/O file formats. Built-in surrogate mode (POD, POD-DEIM).
    2. **Parallel efficiency > 90% with 128 GPUs (KAROLINA). Optimized for many CPU architectures** (ARM, AMD, Intel)
3. Xyst
    1. CFD solver for CPU with different physical air-models and HPC-features (e.g. automated load balancing)
    2. **Hero-run** on LUMI has been performed, scalable up to 196k cores

4. **CFDR**
    1. High-performance CFD visualizer: data rendering on the HPC, visualization from the user's web-browser
5. **MathSO-portal**
    1. Graphical user interface to set up, deploy, execute on HPC, visualize and postprocess results

3. Methods and results: UAP workflow with RedSim

- Workflow with the preprocessing tool with **terrain modelling**, designed to fulfil Stockholm's requirements



- **Implemented and optimized OpenMPI+CUDA version**, presented at conferences, and collaborated in Castiel2

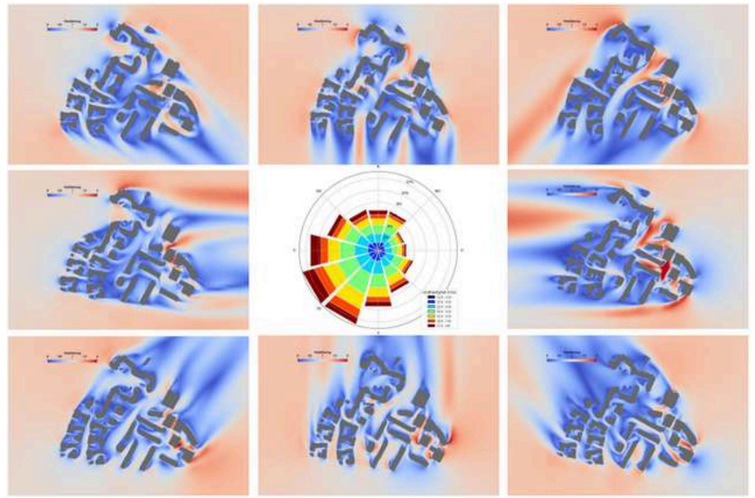
3. Methods and results: Hands-on demonstration of the UAP

Video of a full recorded session with application to Stockholm from OSM:
- Real-time recorded video of 3 min length for a demo area

https://www.youtube.com/watch?v=6vVcnOupfSA

4. Applications: Stockholm wind comfort simulation – the inputs

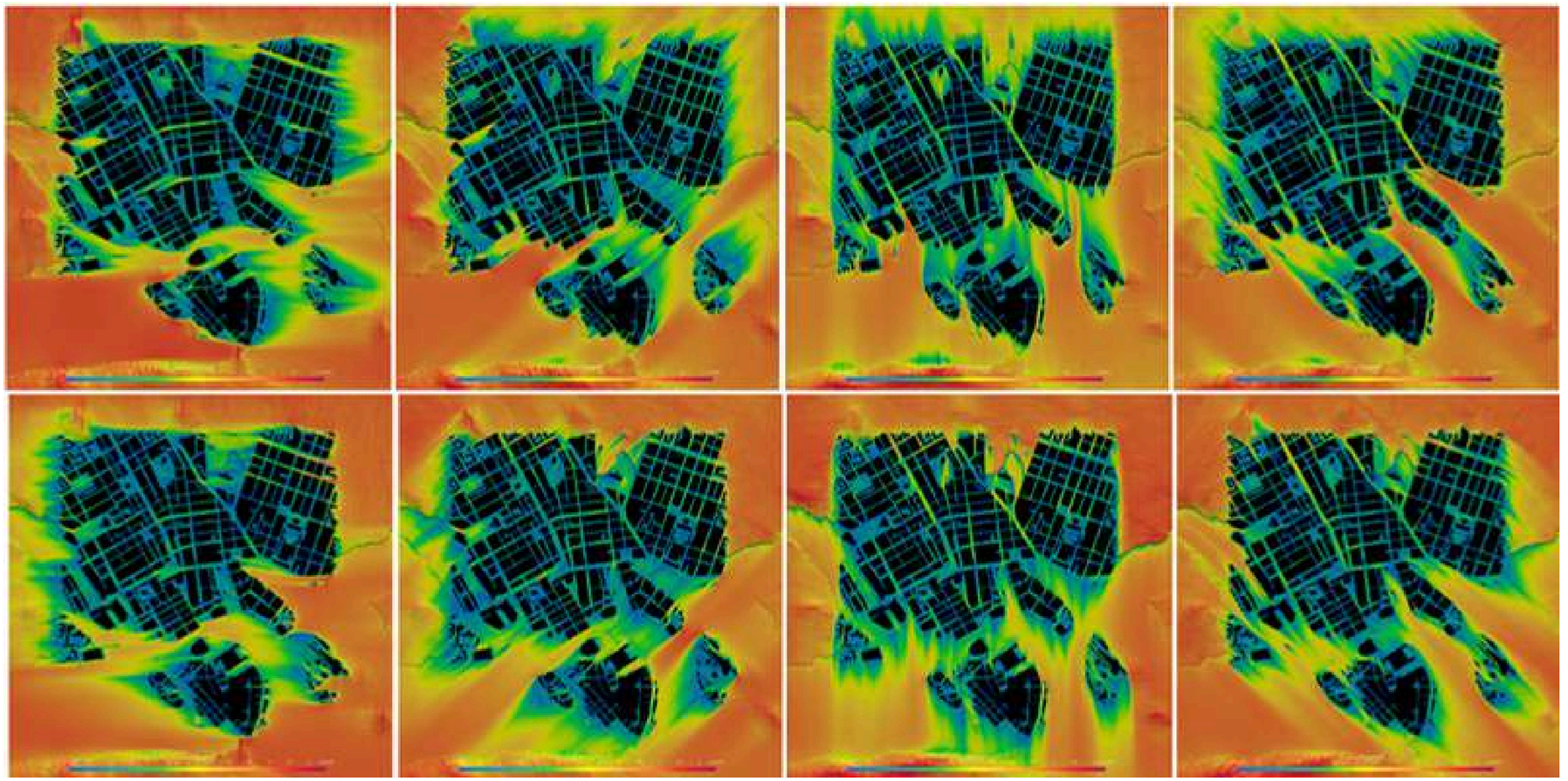
- For Stockholm city, Stockholms Luft- och Bulleranalys (SLB-analys), a unit of the City of Stockholm, is responsible for monitoring outdoor air quality and assists its municipalities with services incl. model calculations. Website: https://www.slb.nu/e/
- SLB-analys' models simulate steady wind for a set of ambient wind directions and
  - Compute steady wind speeds and some standardized indicators for sampled boundary wind directions,
  - The diameter of the simulated domain is 1.6 km,
  - The ground is flat.
- There is an interest at SLB-analys in trying for Stockholm:
  - **simulation for domains that are at least full districts** (cca. 5km-by-5km),
  - **study the effect of the terrain for the modelling** (incl. sea-coastline),
  - **incorporate accurate 3D building models of the city**.
- The EuroCC National Competence Center Sweden (ENCCS) coordinated and assisted the collaboration

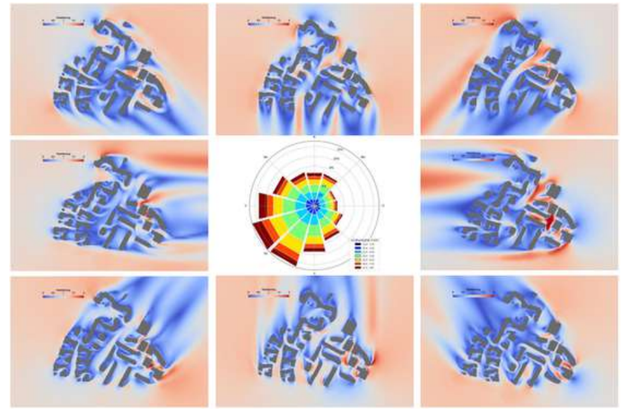


Developmental goals

CFD and dispersion for larger areas (whole Stockholm)?

4. Applications: Stockholm wind comfort simulation – output, wind simulation results for 8 wind directions





HiDALGO2 UAP (left) vs. SLB Analys current solution (right)

4. Applications: Stockholm wind comfort simulation – Success Story with Castiel2

CoE Success Story 7

High-resolution urban wind comfort computation for the entire Stockholm City

CoE HiDALGO2

Partners involved:

SLB Analys: Stockholms Luft- och Bulleranalys (SLB-analys) is a unit at the Environment and Health Administration of the City of Stockholm. The unit is responsible for monitoring outdoor air quality in the city. SLB-analys also runs the regional system of air quality monitoring on behalf of the East Sweden Air Quality Management Association (Östra Sveriges Luftvårdsförbund) and assists its municipalities with services including measurements and model calculations. https://www.slb.nu/el

ENCCS: The EuroCC National Competence Center Sweden (ENCCS) provides high-performance computing training and support for industry, academia and public administration for free.

ENCCS can guide their partners before, during and after they have gotten access to high-performance computers by providing useful knowhow, best practices as well as hands-on support for your code. https://enccs.se/

SZE: The HiDALGO2 partner Széchenyi István University (SZE) is located in Győr, Hungary, in a centre of an industrial region. In HiDALGO2, SZE is developing the Urban Air Project (UAP) and leads the work-package for the applications. The SZE-team is lead by a mathematician and includes a professional scientific programmer and computer scientists, all working for several decades in the field of HPC. https://uni.sze.hu

Codes involved:

RedSim (Reduced Simulations – CFD solution), CFDR (CFD rendering – HPC visualisation), RedSim-Preproc-Urban (preprocessing toolbox for urban air simulations), https://redsim.mathso.sze.hu/.

Technical/Scientific challenge:

Wind in cities has a considerable impact on the comfort and safety of their inhabitants. Especially near tall buildings, wind speeds might be much larger than the average speed, which may cause discomfort, or put pedestrians at risk. Thus, there is a need to evaluate construction plans with respect to their effect on the wind comfort, enabling city planners to optimise construction by evaluating several building scenarios under different weather conditions.

SLB-analys, in need to perform related analyses for Stockholm was put into contact with the HiDALGO2 team through ENCCS, as the challenges are manifold:. The requested resolution (1-2 m horizontally of the full area of 100 km2) requires HPC resources to simulate, combining building and terrain data result in a complex geometry handling challenge, and visualization of terabyte-size simulation data remotely fitting the standard work environment of SLB-analys staff need a scalable solution.

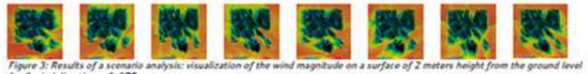


Figure 3: Results of a scenario analysis: visualization of the wind magnitude on a surface of 2 meters height from the ground level for 8 wind directions. © SZE.

CoE Success Story 7

Solution:

To address the technical challenges, the Széchenyi István University (SZE) RedSim-team has adapted their HiDALGO2 Urban Air Project (UAP) solution for Stockholm. The basis for the construction of the computational geometry of the CFD model of the city was a data set provided by SLB-analys containing precise building and terrain data (isolines 0-90 m). The preprocessing toolset has been developed significantly to achieve a computational domain for the city with valid surface geometry and reasonably sized polygons for building floors, using Gmsh for the 3D computational mesh. To provide a sufficiently fast simulation, RedSim, the HiDALGO2 highly optimized multi-GPU CFD-solver has been used. For the visualization of the large amounts of data in a user-friendly way, the team used the HiDALGO2 visualization tool called CFDR that renders the raw CFD-related 3D data residing on the HPC platform in real time and provides visualization on a web browser (even on low-end laptops).

Impact:

The presented work provides city planners and policymakers of the Stockholm area with a fast, high-resolution wind data to guide sustainable urban development. To create the computational geometry of an entire city at 2.5 meters resolution takes less than 15 minutes, surface meshing 6-8 hours, 3D meshing 15 minutes. Simulation of one wind scenario takes 15 minutes on 12 nodes of a HPC machine. This innovative GIS and terrain data process together with the scalable HPC-backed CFD solution created a showcase for other large-scale urban areas (with, e.g. 100 km2 area): Optimized HPC and web-based tools reduce the need for physical testing or third-party software, saving time and resources. There is a commercial potential toolchain, comprised by the scalable CFD engine (RedSim) and visualization tool (CFDR), together with the geometry pre-processing tools (RedSim-Preproc-Urban) which can be offered as commercial services or licensing models for environmental consultancies, city authorities, or industry partners.

Benefits:

- The city's computational model was generated based on precise terrain and building GIS data
- High-resolution simulation of an entire urban district with complex terrain becomes possible, due to scalability of RedSim up to 512 CPU nodes and 32 GPUs
- Time-to-solution became hours for city planners for large-scale scenario analysis, which is not available with other solvers

Figure 1: Region of interest of a test computation. Building data provided by SLB-analys (Stockholm City), layout from the Google Earth. © SLB-analys, Google Earth, SZE (for the overall image).

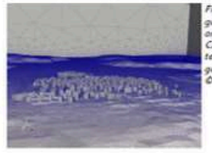


Figure 2: Mesh geometry based on the Stockholm City data of a test computation generated by SZE. © SZE.

Keywords: HPC, CFD, Meshing, CUDA-Acceleration, SIMD-Acceleration, Urban planning, Urban environment, Urban modelling and simulation

Industry Sector: Earth science, Environment/climate/weather, Urban planning

Technology: Python, Shapely, GeoPandas, Gmsh, MPI, manual SIMD, AVX2, AVX512 acceleration on CPU, manual CUDA acceleration on NVIDIA GPUs, WebGL, WASM

Time period: Completed by May 2025

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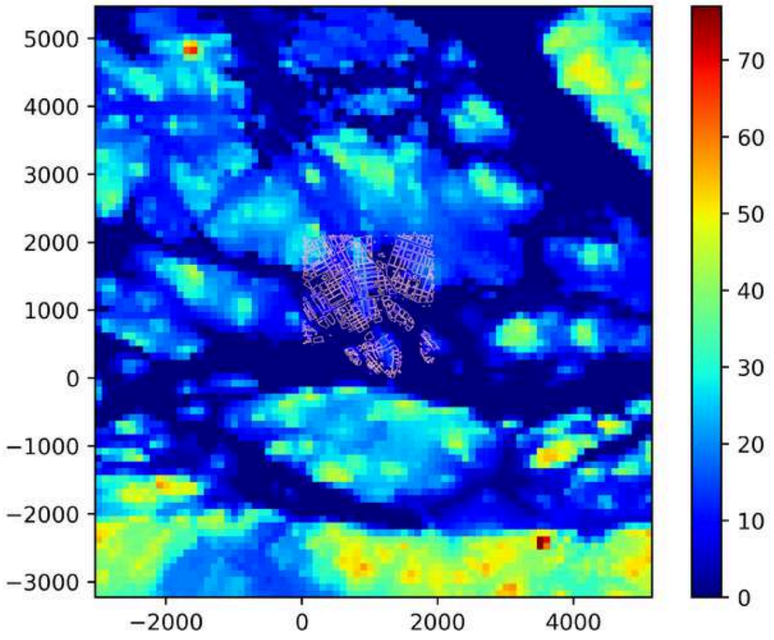
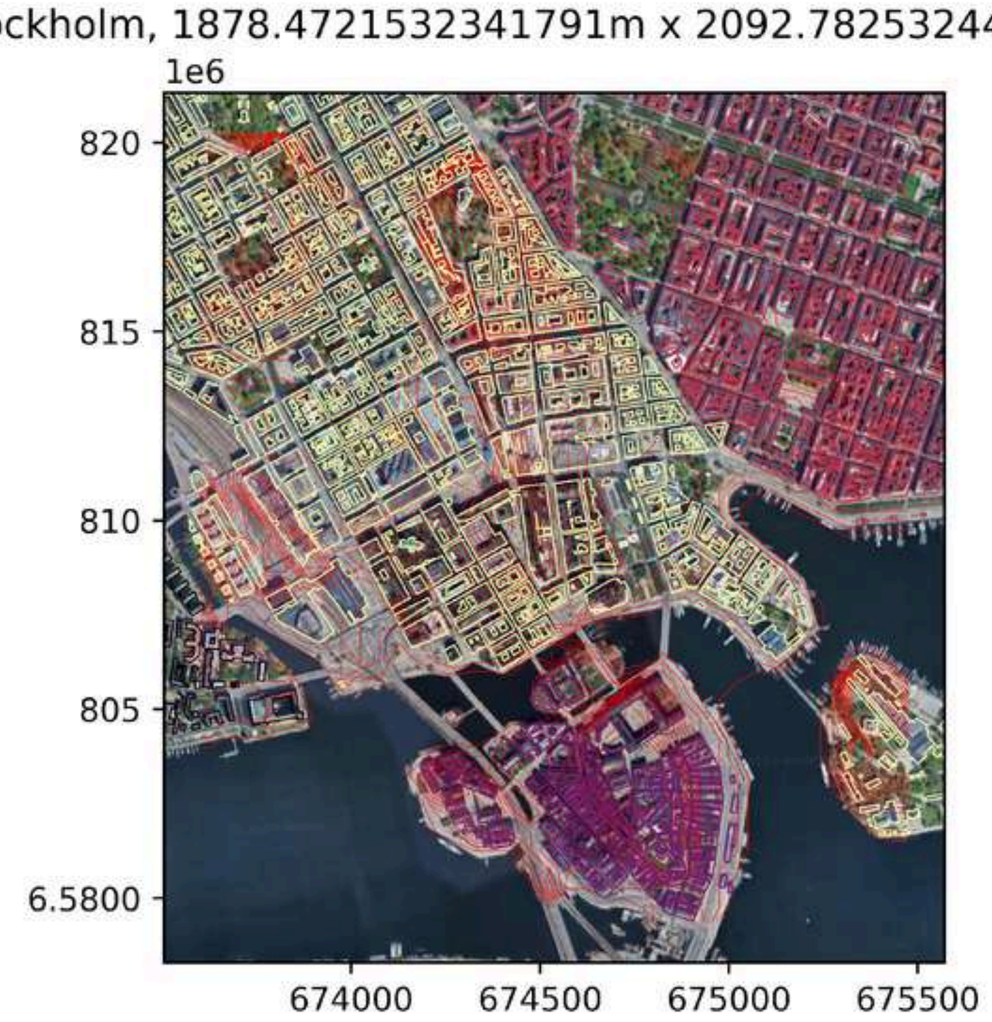
4. Applications: Stockholm wind comfort simulation – the inputs



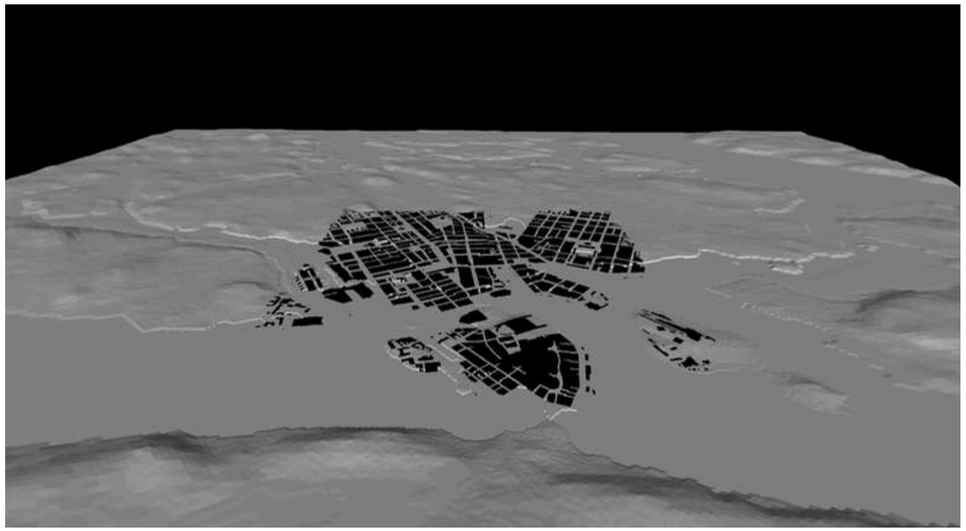
Visualization of Input ISO-LINE Data for terrain modeling

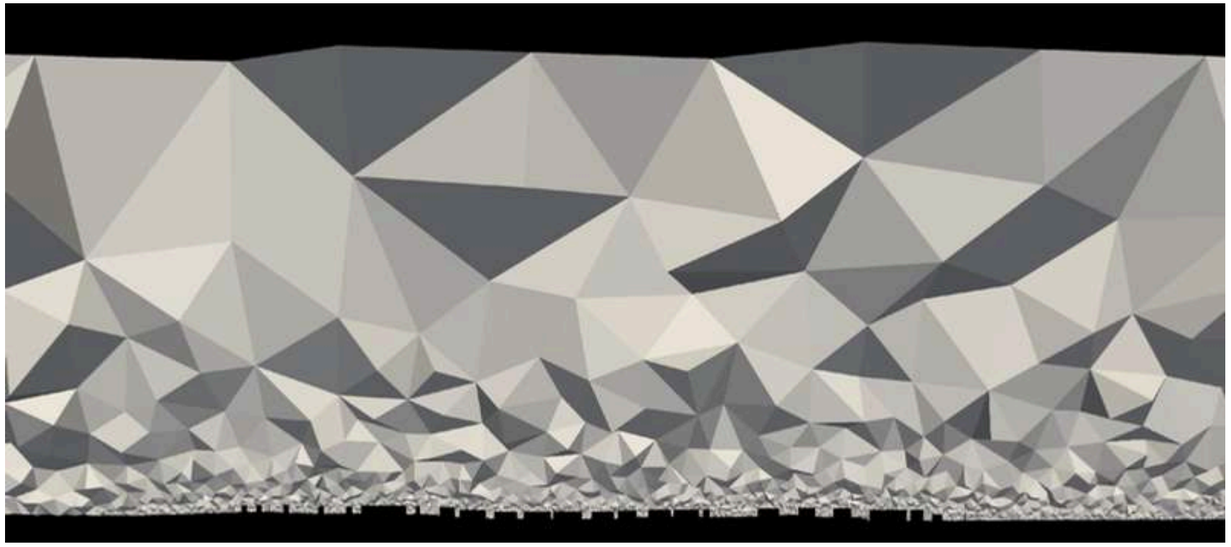


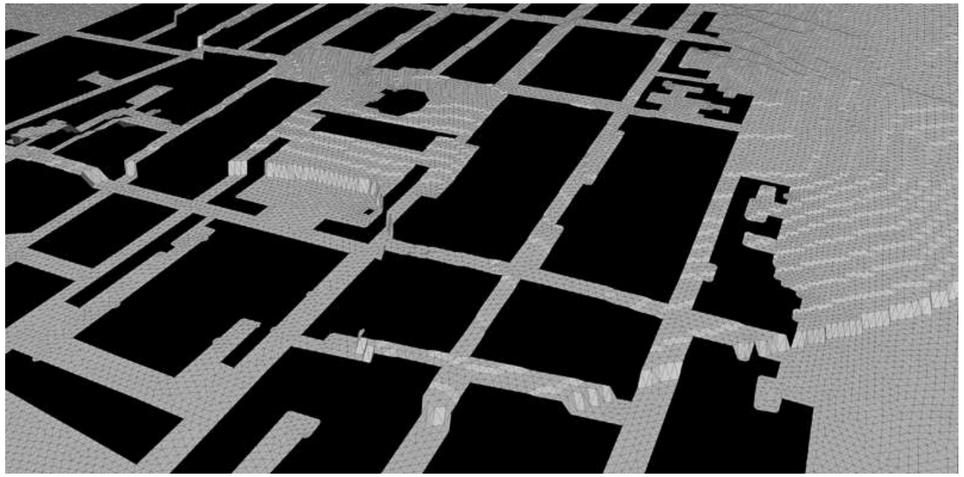
*Input Data from **Shape Files** provided by Stockholm.*

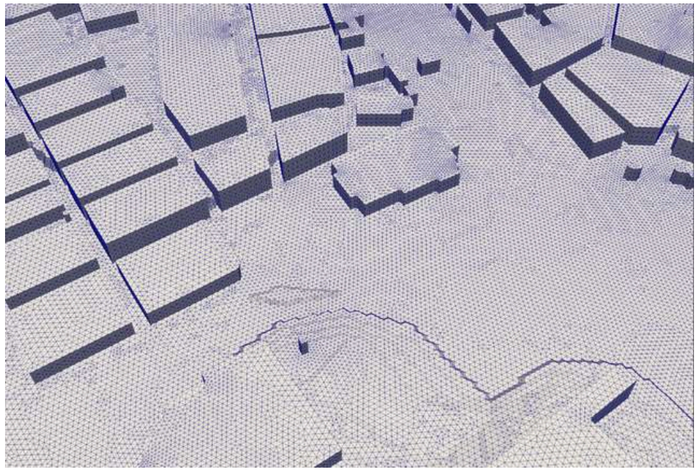
*Overlayed with **Google Earth** Satellite Data.*

4. Applications: Stockholm wind comfort simulation – the surface and volume meshing









Surface geometry and meshing of the ground, with holes for the buildings. 295 830 vertices, 522 664 triangles

Volume mesh using Gmsh, ~= 10 MILLION tetrahedra.

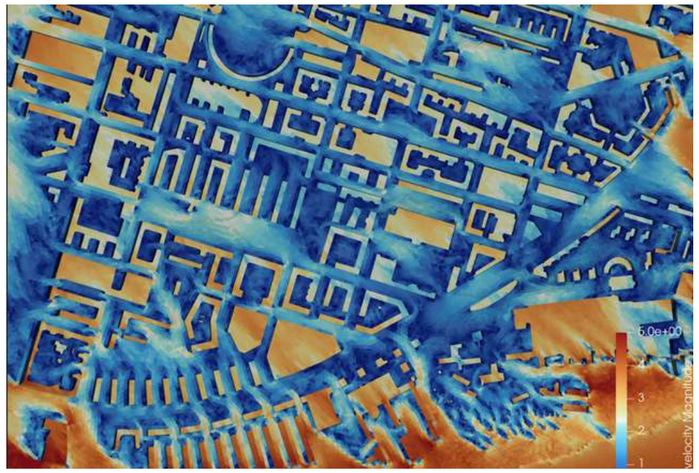
4. Applications: Discussion of RedSim simulation time on HPC vs. physical time

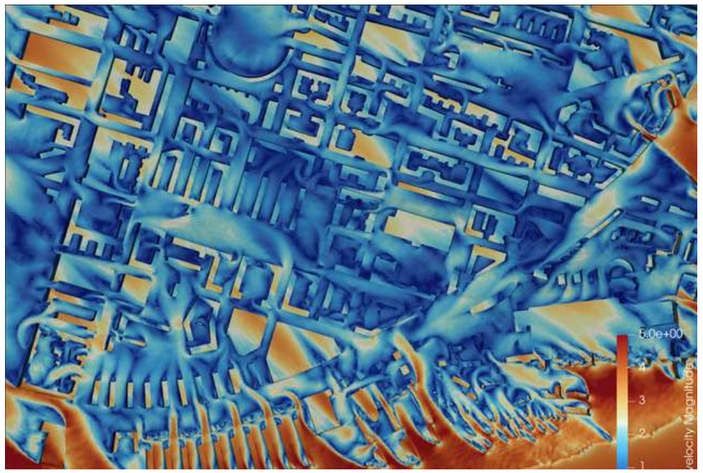
- What value does HPC deliver in addressing global challenges?
  - Simulation time vs. Real time:

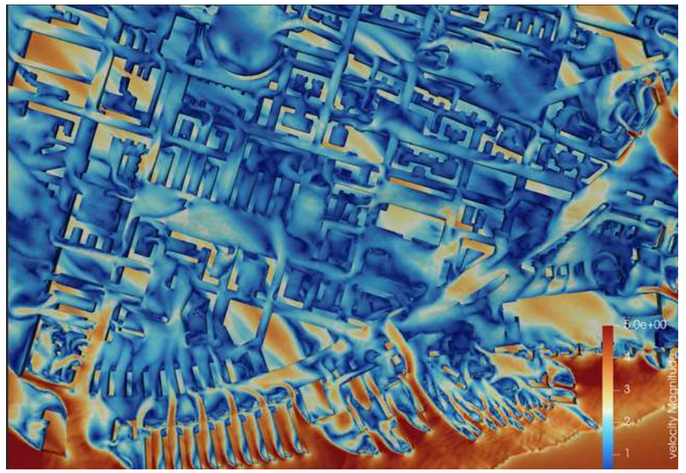
    Conclusion: Simulation of 1 hour on very fine mesh (142M cells) takes 6.5 min on 64 GPUs

Cell #	1,655,758	8,970,472	44,545,194	142,618,800
1 Hour Physical Time (seconds)				
8 GPU	650.504318	-	-	-
16 GPU	-	181.167344	-	-
32 GPU	-	-	592.408632	-
64 GPU	-	-	-	386.3156830
128 GPU	-	-	-	...

  - Accuracy: more resolved wind field on higher resolution meshes (respectively 1.7M, 45M, 142M cells)







5. Roadmap for the next period

- OpenFOAM and RedSim:
  - Participation in **FAIRMODE intercomparision exercise** for Madrid
    - Compare different EU models with vegetation, etc. for a region of Madrid
    - Full urban atmospheric model with **couplings** (UBM, WF, WRF)
  - Detailed application to 3 cities
- RedSim:
  - Release RedSim1.0 and CFDR1.0, with all features requested by the GA of HiDA
    - Simulation of physically relevant use cases above 200k CPU cores and 200-
    - Industrial applications
  - **Surrogate models** with AI (POD-ML)
  - **Real-time digital twin** prototype of the urban air (with sensor data assimilation and prompt visualization)
- Xyst:
  - Application to cities
  - Scalability benchmark above 200k CPUs

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Disclaimer

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