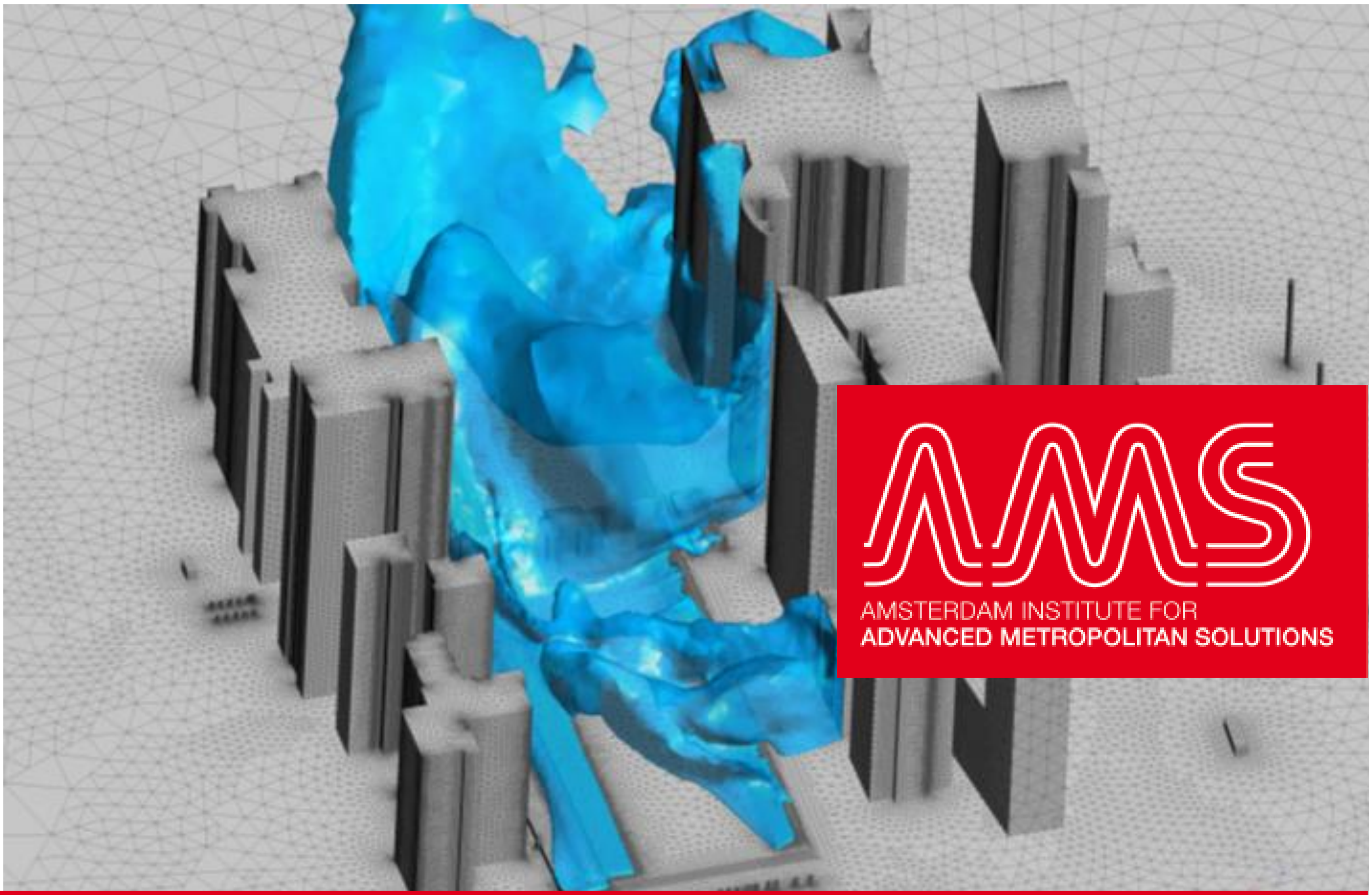

AMSTERDAM INSTITUTE FOR
ADVANCED METROPOLITAN SOLUTIONS

Stimulus Project

Automatic reconstruction of simulation-ready 3D city models

Project report for Stimulus Projects

Project title:	Automatic reconstruction of simulation-ready 3D city models
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Lead Project partner:	Delft University of Technology
Project partners:	CADFEM and virtualcitySYSTEM
Project start date:	1 November 2016
Duration:	12 months
Project end date:	1 November 2017
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1 Project information

1.1 Project title

Automatic reconstruction of simulation-ready 3D city models

1.2 Authors

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1.3 Project partners

Project partners:

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- virtualcitySYSTEMS (Berlin, Germany); Claus Nagel, CTO
- CADFEM (Munich, Germany); Stefan Trometer, New business development
- City of Amsterdam; Dick de Maa, manager information and economy

1.4 Summary

Computer simulation models are very important to assess the impact that environmental factors have in a city, and will have in the future. Traditionally most environmental simulations have been performed by abstracting the 3D world to a 2D ‘flat’ representation (thus on a macro-level, not taking urban 3D characteristic into account), and this while we know that most environment processes are better modelled in 3D because they behave and interact in 3D: noise, air pollution, and temperature are a few examples.

While 3D simulation models have a huge potential to increase the quality of life of citizens, they are in practice seldom used by practitioners because their mandatory input, a 3D city model, are not suitable. Indeed, they often contain geometric errors, eg part of a roof missing, a bridge not connected to the shore, two houses slightly overlapping (known as *slivers*), houses “floating” a few centimetres above the ground, etc. These prevent us from importing them in simulation software (which have strict requirements on the input), and implies that practitioners must spend hours *manually* repairing them. It was estimated that practitioners using 3D models spend as much as 70% of their time fixing the input models.

We demonstrate in this report our results for the automatic reconstruction of simulation-ready 3D city models. Our main result is that we have improved TU Delft’s algorithms (and their implementation into a software), to *automatically* reconstruct semantic 3D city models from publicly available datasets and ensure that these contain as little errors as possible. While the test area is Amsterdam, our methodology and its implementation allows us to reconstruct any area in the Netherlands (and in the world if 2D base data, eg cadastral maps, are available). Also, we have performed experiments to ensure that these 3D models are ready to be used in a simulation software. While the 3D models can be successfully imported, with the current capabilities of the software, many of the details of the 3D models had to be removed and/or simplified so that a simulation is

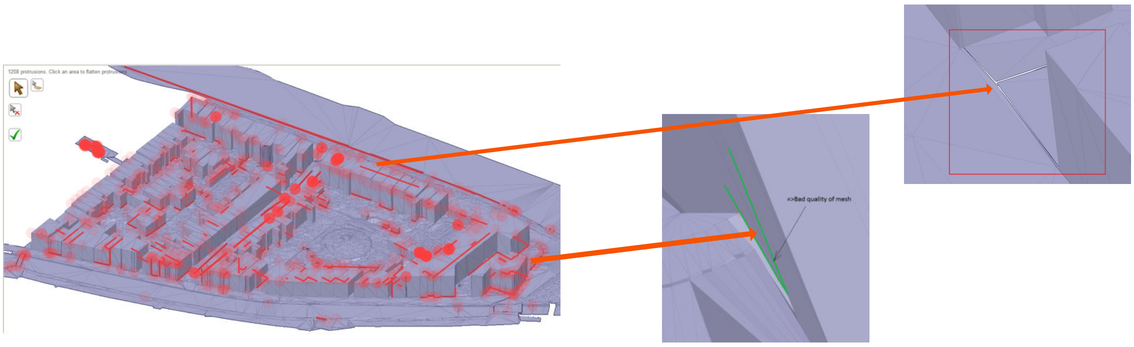

Figure 1: One area in Delft where there were many geometric errors with our first version of the dataset. These errors prevented us from directly importing the dataset in a simulation software. Red highlights are geometrical errors.

performed. We have performed what is called a *turbulent wind field analysis* for assessing the air quality and pollution effects in Amsterdam, as a proof of concept.

Our implementation is open-source and freely available, and so are the datasets that we have created.

2 Project description and results

2.1 Keywords

3D city modelling; simulation; environmental modelling

2.2 Introduction and problem statement

Three-dimensional computer simulation models are essential to assess the impact that environmental factors (noise, air pollution, temperature) have in a city, and have huge potential to increase the quality of life of citizens. However, in practice they are rarely used because currently available 3D city models are not appropriate (they often contain errors, such as those shown in Figure 1), and reconstructing case-specific datasets is a manual operation that is both very costly and labour-expensive. Currently, the hurdles are such that either the simulation models are 2D or rasterised (important information and detail is thus lost), or time-consuming manual repair and enhancements are required.

The aim of this AMS Stimulus project is to investigation methodologies to *automatically* reconstruct simulation-ready 3D city models. In our case, simulation-ready means that the 3D model is free from geometric errors and that it should be for instance watertight, free of intersections, and triangulated (and triangles have certain properties). If this is achieved, then simulation specialists should simply have to perform a “File/Import” without having to spend days fixing the errors.

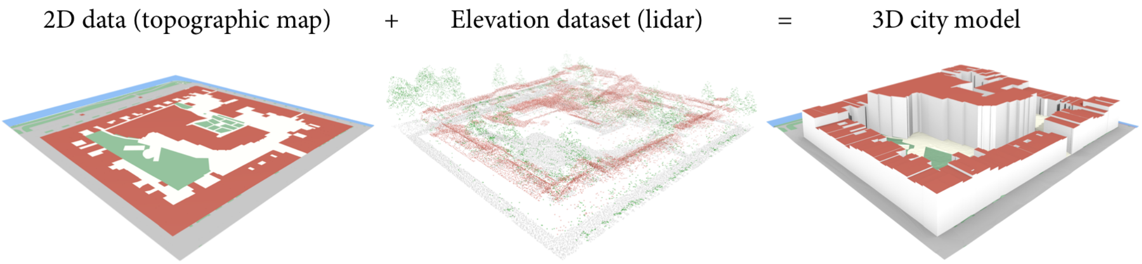

Figure 2: An example of the lifting to 3D that we developed.

2.3 Methods

2.3.1 Automatic reconstruction of the 3D model

The methodology developed is an improvement over that of Oude Elberink et al. (2013). As shown in Figure 2, we use the same idea of lifting each polygon of a 2D topographic map to its height (we used the BGT dataset[1]), but we do not perform any complex operations such as segmentation of the point cloud and plane-fitting. The elevation is obtained from a point cloud (the AHN3 dataset[2]) by vertex to point distance and statistics. The semantics of every polygon is used to perform the lifting and apply correct stitching rules. We defined rules for each of the classes in the 2D topographic map, for instance: water polygons are lifted to horizontal polygons, buildings to blocks, roads as smooth surfaces, forest as surfaces, etc.

To ensure that the model created is free of error, we have designed a methodology that is conceptually the same as that of Ledoux and Meijers (2011) and adapted it to the specificities of the Dutch topographic information. This means that different decisions are taken to “stitch” neighbouring polygons based on the semantic of the neighbours. There is a hierarchical decision tree in which the rules are defined. First of all there are “hard” and “soft” classes in which the man-made structures (e.g. buildings and roads) and water are hard and natural surfaces are soft. The polygons classified as hard generally do not change where the soft ones are moved towards the hard to avoid gaps. Also if the height difference between two polygons is larger then a specified amount, a vertical wall is added. After calculating the hardness rules there are extra options which are incorporated like a building never changes in height. For instance, when terrain is adjacent to a building, the terrain is instead stitched to the building floor. If a road and a forest do not match, then the forest is moved. When two terrains do not match and their height difference is within the given height jump threshold they are averaged.

Because of several errors that are present in the input 2D datasets (BGT), and because of possible shortcomings in 3fdier, we decided to further develop a methodology to fix all the errors automatically and to prepare the 3D model for import in the ANSYS software. One of the main requirements is that the 3D model should be: (1) free of errors such as intersections of surfaces; and (2) forming a closed volume (which is not the case since we only have a surface of an area, see Figure3a). These requirements mean that the spatial extent of the dataset can be *tetrahedralised* (ie subdivided into tetrahedra), which is the first step for performing the simulation. Figure 4 shows an example.

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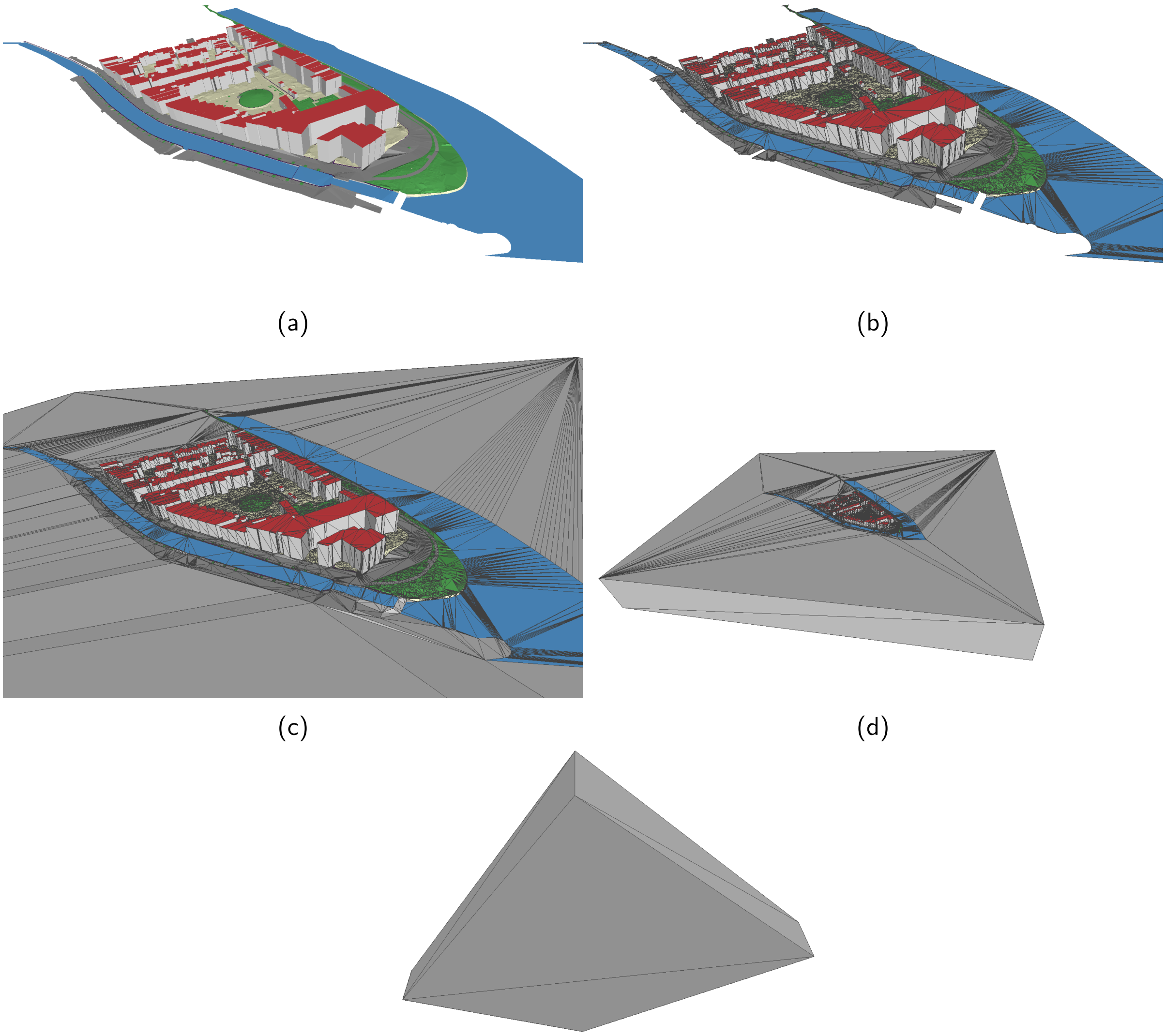
[1] the 1:1,000 topographic dataset of the Netherlands: `http://www.kadaster.nl/web/Themas/Registraties/BGT.htm`

[2] `www.ahn.nl`



(a)

(b)

(c)

(d)

(e) Bottom view of the 3D model

Figure 3: **(a-b)** Output of 3dfier. **(c-e)** Modifications to the 3D models, notice that it forms a closed volume.

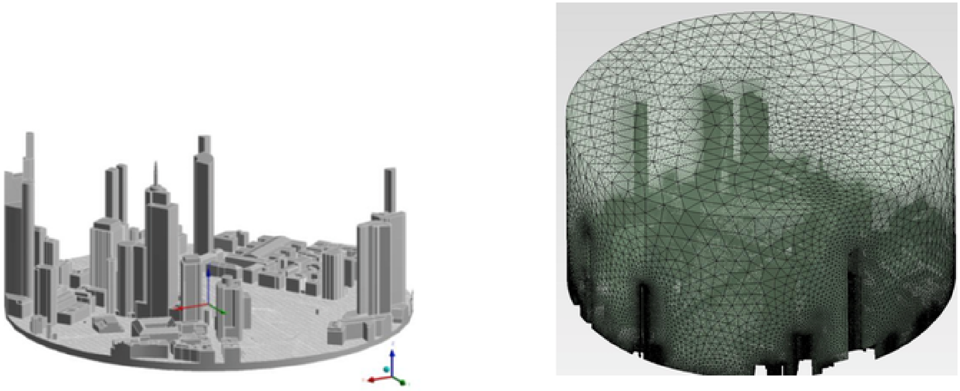


Figure 4: A 3D city model needs to have its 3D domain decomposed into tetrahedra so that it can be used in a simulation.

We have developed a software, which performs the following steps:

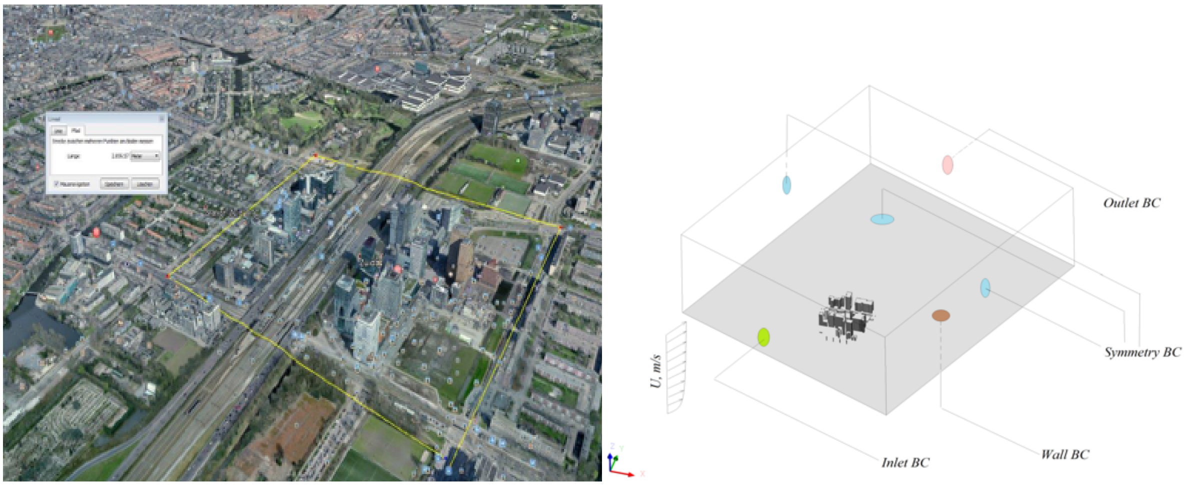
1. the model, which is a surface, is closed to form a volume. This is done by expanding the edges of the dataset by roughly 200m and adding vertices at the elevation zero, and then adding new faces to close the volume. (Figure 3c).
2. the surface of the model is automatically repaired by filling holes in it with new surfaces (which are also triangulated), and by flipping the orientation of the surfaces so that the model is valid. The methodology used is that of Liepa (2003).
3. new surfaces are added to close the volume, and these are triangulated are all triangulated.

Our implementation was developed during the project, and is now available under a GPL-license at `https://github.com/tudelft3d/3dfier/tree/master/resources/3dfier2sim`. The centre of Amsterdam, with around 330,000 features in 2D, was reconstructed. The dataset is openly available at `https://3d.bk.tudelft.nl/opendata/3dfier/`.

2.3.2 Simulation in Amsterdam Zuid

Consider the turbulent multicomponent airflow in the neighbourhood of a building complex located in Amsterdam Zuid (Figure 5a). The numerical simulation was performed using the ANSYS Fluent 18.0 software, using a model of real scale. The maximum height of the buildings was $h_{max} \approx 103m$. The characteristic velocity of air in the core of the wind flow was $U_\infty = 16.9m/s$, and the thickness of the boundary layer, $\delta = 500m$. The free-stream Reynolds number calculated by the characteristic linear scale $L = \delta$ and by the flow velocity U_∞ was Re $\approx$ 5.75E+08. In modelling the flow in the vicinity of building complex under examination a computational domain of height 2δ was treated (Figure 5b). The dimensions of the computational domain were chosen such that the external boundaries exerted no influence on the flow structure in the vicinity of the buildings.

Mathematical model and solution methods. For revealing the flow structure in the neighbourhood of the buildings under neutral atmospheric stratification, we used Reynolds-averaged 3D Navier-Stokes equations written in physical variables. The components of the turbulent stress tensor, necessary for closing the initial equation system, could be calculated from the characteristics of



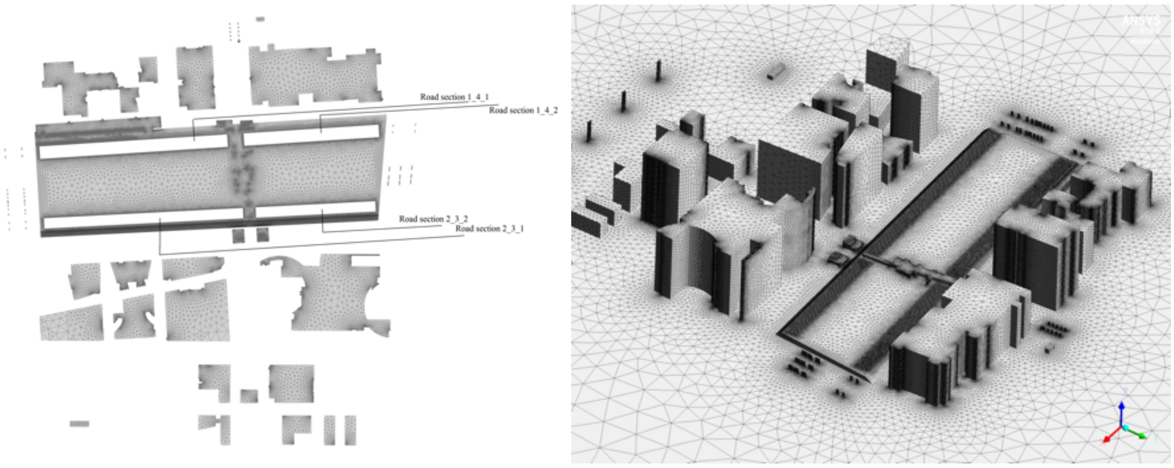
(a) (b)

Figure 5: **(a)** Google map screenshot of the considered district; **(b)** scheme of the computational domain.

the mean flow in line with the Boussinesq hypothesis. For calculating the turbulent viscosity, the k-ω SST turbulence model with the Kato-Launder correction for turbulent kinetic energy (TKE) production was used. Multicomponent flow consists of N_2, O_2, CO_2 and NO_x components. The incompressible ideal gas equation was used as a general equation of state for mixture. The approximate solution of the initial-boundary-value problem was obtained using the finite-volume method. The second-order Upwind scheme for calculating the convective terms was used. For time approximation, an implicit scheme of first-order accuracy was used. In all treated cases described below, a quasi-stationary solution with residuals for all equations reaching a level of as low as 3.10^3 was obtained.

As a characteristic direction of wind (based on yearly average measurements), the SSW direction was chosen, which corresponded to the wind angle α in Figure 6a. At the entrance to the computational domain, stationary profiles of velocity, turbulent kinetic energy, and specific rate of turbulence dissipation were chosen. Mean temperature at the inlet boundary condition was T = 12C. At the exit from the computational domain, the condition of constant static pressure, $\Delta P = P_{st} - P_0 = 0\,atm$, was used. For the upper boundary of the computational domain, the symmetry condition, ensuring the absence of the flow across this boundary, was adopted. On the walls of the flat substrate and buildings, the no-slip boundary condition for a perfectly smooth wall was employed. The Species Transport model without reactions was used to model pollutant transfer process. Additional volumetric sources of NO_x and CO_2 were specifying for regions above the road lines (Figure 6a). The values of volumetric sources were calculated on the basis of the average speed of cars (about 60 km/h) and the average fuel consumption of cars.

Import 3D Model and Preparing the Computational CFD Domain. The preparing CFD model is performed using the *SpaceClaim* software. The source model consists of buildings and landscape data. The original model of relief includes several problem zones, that could be a cause of a bad-quality computational grid near the ground wall of the CFD model. The first example of bad-quality region is shown in Figure 7a. The region is slightly rough and it should be fixing before



(a) (b)

Figure 6: (a) computational domain, top view; (b) a fragment of the calculation grid on buildings

calculation process. The *SpaceClaim* adjusting meshes tools could be used for local fixing the region: smooth/regularize operations. A similar result can be achieved using the *ShrinkWrap* operation in *SpaceClaim* (Figure 7b). The second example of bad-quality region is shown in Figure 7c. The region is not "smooth". The *SpaceClaim* adjusting meshes tools or *ShrinkWrap* operation cannot fix the problem (Figure 7d). At the first stage, the original model was changed in such a way that the surface of the relief was substituted by a flat surface.

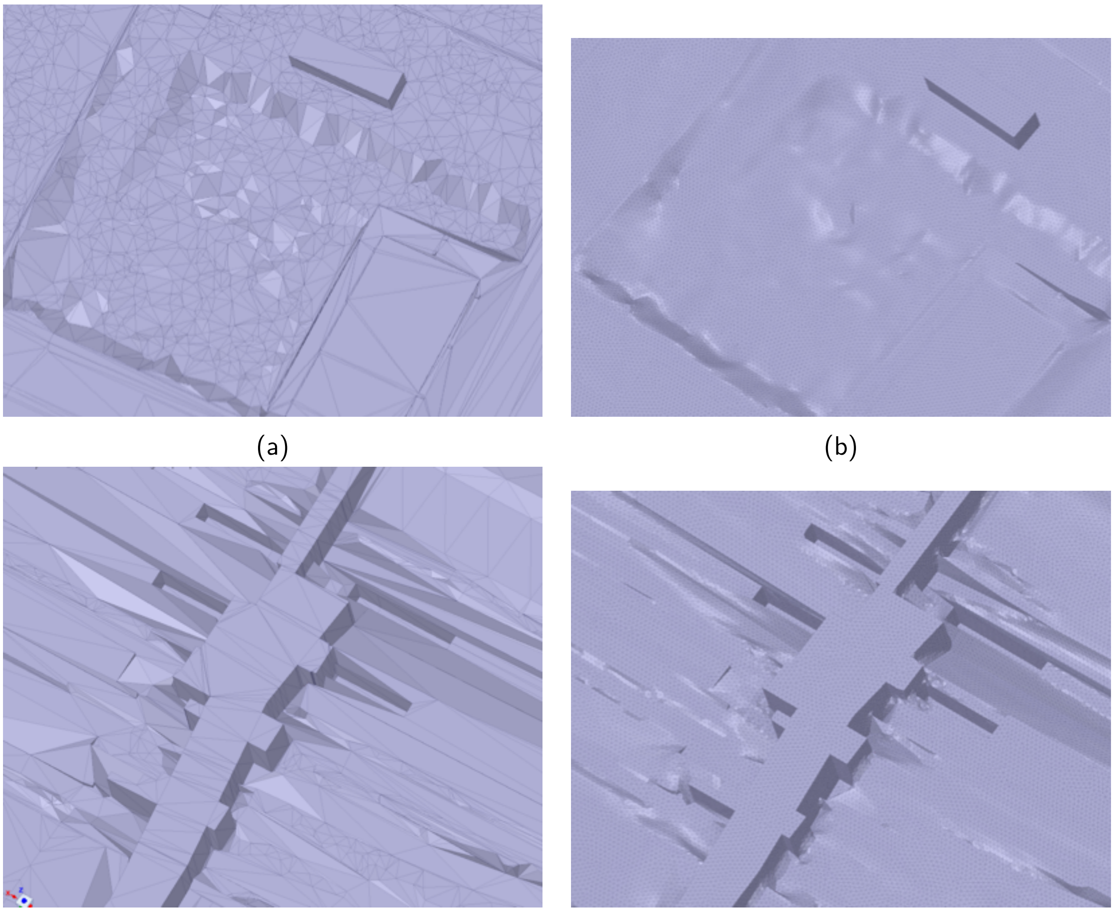
Results and discussion The air flow near the buildings has a complex 3D vortex structure. In Figure 8, the mean velocity fields are presented in several horizontal cross-sections. Under the conditions of SSW wind direction, the vortexes separate from the side edges of the high-rise buildings located on the first line relative to the free stream flow (building's group 1, Figure 8c), it leads to velocity increasing. Roads are open spaces between two lines of buildings, that leads to the formation of the "wind tunnel" effect in this area. High wind velocity is observed around the roads and region of the roads is well ventilated.

In Figure 9, isosurface of NO_x mass concentration at values of 1e-08 (a); 5e-09 (b); 2e-09 (c); 1e-09 (d) are presented. The fields of pollutant concentration allow to estimate the level of air pollution in the considered region taking into account the aerodynamics of buildings, the presence of recirculation zones, and interference effects in the flow. It can also be noted that there is stagnant zone (SR, Figure 8d; 2, Figure 9c) with high concentrations of pollutants.

2.4 Conclusions

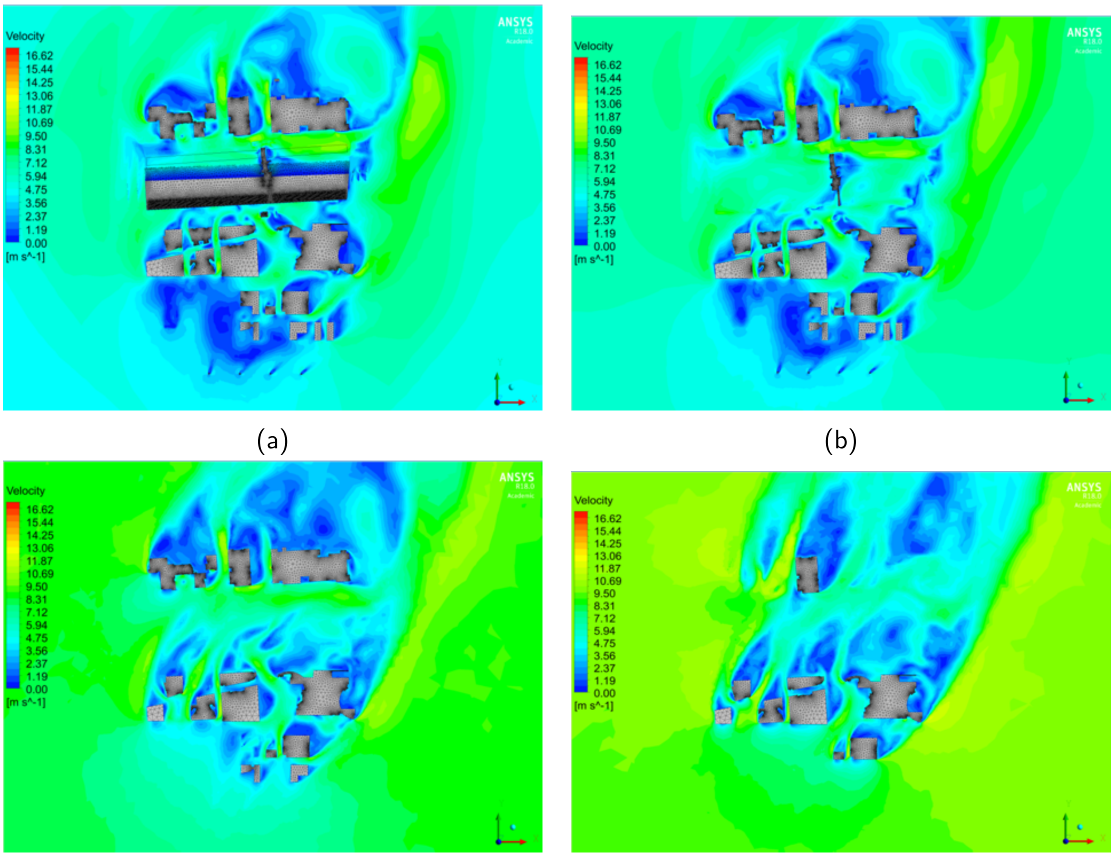
We can reconstruct 3D city models that are error-free and that are, in theory, ready to be imported in complex simulation software. The model of Amsterdam Zuid that we automatically generated allowed the simulation engineers to significantly cut down on the time to import the data, instead of a few days it was brought down to a few hours (the number of manual interventions was minimal).

However, in this case, the software used for the wind turbulence was not able to use the 'rough' terrain that was reconstructed since its shape is of high importance for the quality of the simulation results. We unfortunately had to smooth the terrain at some places, and even replace it with a flat



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

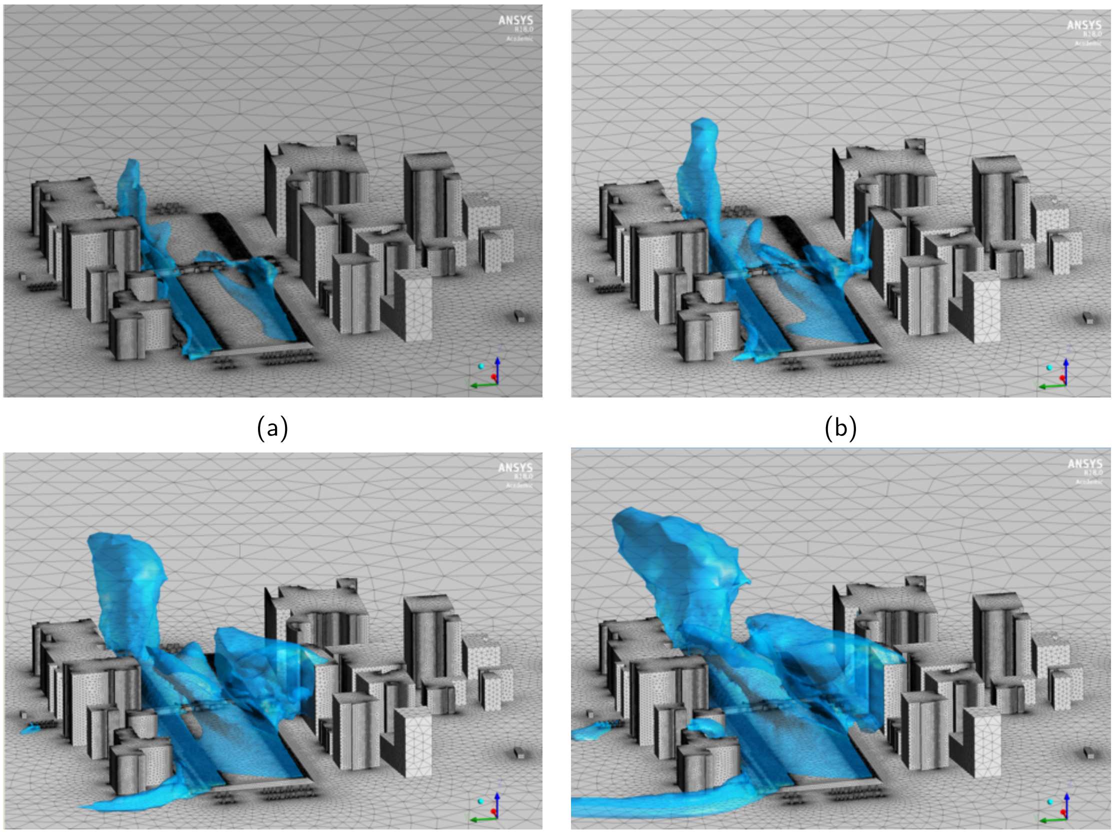
Figure 7: Problem zones of the original model (a,c); the regions obtained using *SpaceClaim* tool (b,d).



(a) (b)

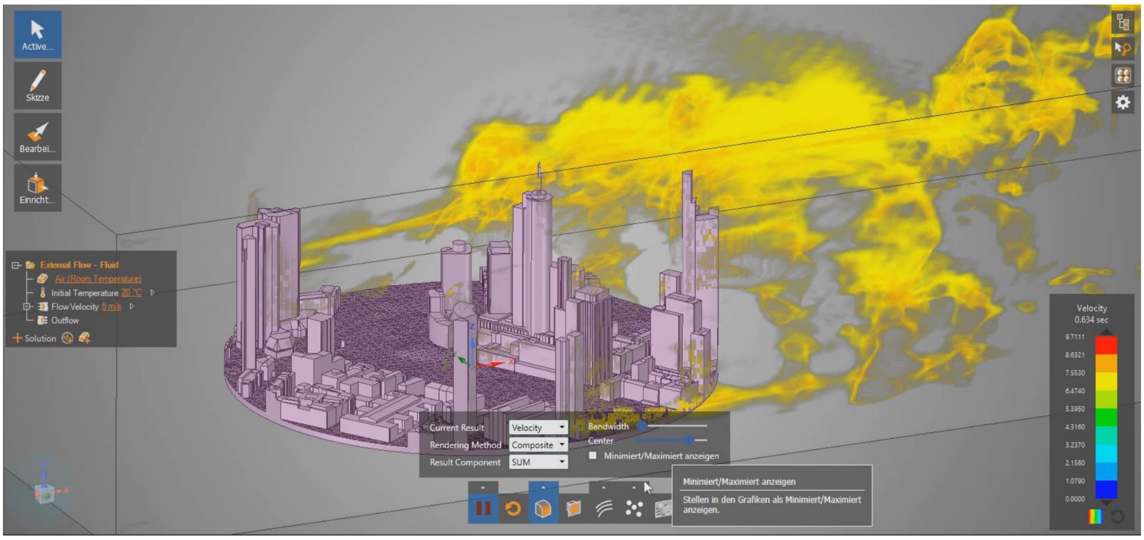
(c) (d)

Figure 8: Velocity fields U, m/s in several horizontal cross-sections: 7m (a); 10m (b); 35m (c); 70m (d)



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

Figure 9: Isosurface of NO_x Mass Concentration at values of 1e-08 (a); 5e-09 (b); 2e-09 (c); 1e-09 (d)



Initial Temperature 20 °C
Flow Velocity 5 m/s
Current Result: Velocity
Rendering Method: Composite
Result Component: SUM

Minimiert/Maximiert anzeigen
Stellen in den Grafiken als Minimiert/Maximiert anzeigen.

Figure 10: New ANSYS product that would allow us to use with less manual operations the output of 3fier.

ground. While this is not wished, this had to be done to perform the simulation with the current version of the software used and the current mathematical equations used.

We see these improvements are part of future work. In the future, we could focus more on the shape of the terrain and aim at removing automatically small objects on it. From a strategic point, it would be advantageous for the simulation to define a certain “smoothening length” for the terrain or the whole model, which is linked to the aim of the simulation and its discretisation.

2.5 Impact and benefits for the Metropolitan Region Amsterdam

Our results would allow the city of Amsterdam to perform other simulations that are currently not feasible, among others: urban heat island problem, wind comfort of pedestrians, crowd movement in case of emergencies, and urban floods (van der Hoeven and Wandl, 2014).

2.6 Spin-off and valorisation

The code of the software to construct and prepare 3D city models for simulation is open-source, and binaries are available on the project website. No patents were filled.

This can be used to construct highly-detailed 3D models of any part of the Netherlands, but currently the use of the models in simulation software is restricted by the amount of details that can be handled.

We believe the potential of our software to be very interesting for the municipality of Amsterdam and other Dutch governmental organisations since the reconstruction of a 3D model, potentially usable for different applications, is fully automatic. Besides saving time and money on using this approach generated 3D models are consistent which allows for comparable results in a simulation.

2.7 Upscaling Plan

In September 2017, ANSYS has launched a new product called *Discovery*, see Figure 10. This tool might allow us to use directly our 3D models without a need for smoothing, it runs more or less in real time, and needs no CFD engineer. We recommend the city of Amsterdam to investigate this solution for future projects.

2.8 Key references

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3 Dissemination activities

1. Ledoux, Commandeur, Biljecki, Stoter (In preparation). *On the automatic generation of simulation-ready 3D city models.* To be submitted to a scientific journal.
2. Commandeur, T. and Ledoux, H. (2017). *3dfier: an open-source software to reconstruct simulation-ready 3D city models*. Cadfem ANSYS Simulation Conference on November 15–16 (Koblenz, Germany)
3. Ledoux, H. (2017). Keynote *How useful are current 3D city models?* at the 102nd OGC Technical Committee meeting. 2017/03/20 (Delft, the Netherlands)
4. Commandeur, T. (2017). Presentation *3dfier open-source software for simulation models* at the 102nd OGC Technical Committee meeting. 2017/03/22 (Delft, the Netherlands)
5. Ledoux, H. (2017). Invited talk *Overview of 3D activities at the TU Delft 3D geoinformation group* at the Geonovum Springplank. 2017/01/23 (Amersfoort, the Netherlands)
6. Commandeur, T. (2017). Presentation *Een open-source toolkit voor het maken van 3D stadsmodellen* at the Nederland 3D Early adopters dag. 2017/03/07 (Zwolle, the Netherlands)
7. Ledoux, H. and Commandeur, T. (2016). Presentation "3dfier: a tool to reconstruct 3D city models automatically" at the *OSGeo.nl dag 2016*. 2016/11/22 (Den Bosch, the Netherlands)

4 Key data-sets realized by project

- the 3D model of Amsterdam is available at `https://3d.bk.tudelft.nl/opendata/3dfier/`