Preliminary Research Concept on Urban Micrometeorology for AAM

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1. Introduction

Micrometeorology is a part of meteorology that deals with observations and processes at small scales of time and space, approximately smaller than 1 km and one day (Foken et al., 2008). This region is characterized by different small-scale meteorological processes such as turbulence, wind shear, wind gusts, surface friction, and wind load. These processes affect UAV operations in dense urban airspaces. Wind shear and turbulence caused by buildings in the vicinity of airports have been identified as causes of aircraft instability during landing and takeoff for some time (Krüs et al., 2003). Therefore, in order to realize safe flight operations, careful study of turbulence modeling, simulation, and validation, as well as taking these processes into account in the design of advanced air mobility systems, is essential. In this concept note, I describe my understanding of these processes one by one.

2. Atmospheric Turbulence

2.1 Governing Equations (RANS)

Atmospheric turbulence is initially represented by the Navier–Stokes equation, which is derived from Newton's second law of motion. This law states that the acceleration of the atmosphere is equal to the summation of the forces causing motion in the atmosphere. These forces are the pressure gradient force, gravitational force, friction (viscous force), and Coriolis force

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial x} + f\,v + \nu\,\nabla^2 u$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial y} - f\,u + \nu\,\nabla^2 v$$

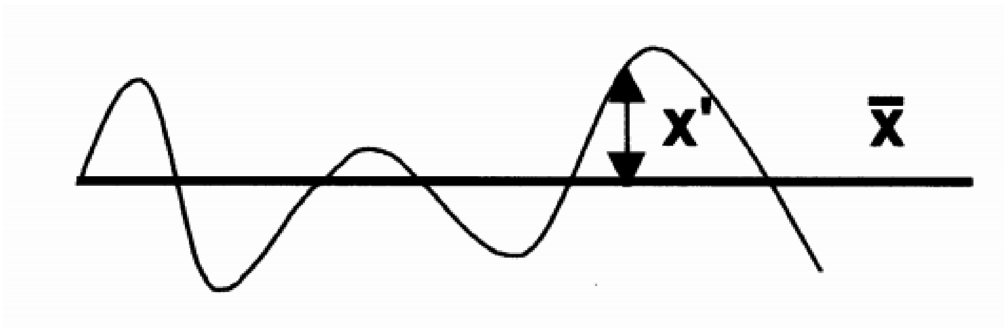
$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} + g + \nu\,\nabla^2 w$$

.

Even though the above equation represents motion in the atmosphere for zonal, meridional, and vertical components, it lacks turbulent representation; therefore, modification has to take place by introducing Reynolds's decomposition, as indicated by Foken et al. (2008).

$$\mathrm{x} = \overline{\mathrm{x}} + x' .$$

The application of Reynolds's decomposition requires some averaging rules for the turbulent value x' (a represents a constant), which are termed Reynolds's postulates:



$$
\begin{array}{ll}
I & \overline{x'} = 0 \\
II & \overline{x\,y} = \overline{x}\,\overline{y} + \overline{x'\,y'} \\
III & \overline{\overline{x}\,y} = \overline{x}\,\overline{y} \\
IV & \overline{a\,x} = a\,\overline{x} \\
V & \overline{x + y} = \overline{x} + \overline{y}
\end{array}
$$

After applying Reynolds's decomposition, Reynolds averaging rules (postulates), the Boussinesq approximation, and Einstein summation notation to the Navier–Stokes equations, we obtain the turbulent equations (RANS) (Foken et al., 2008).

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u_j}\,\overline{u_i} + \overline{u_j'u_i'}\right) = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu\frac{\partial^2 \overline{u_i}}{\partial {x_i}^2} + g\delta_{i3} + \varepsilon_{ijk} f\,\overline{u_k}$$

2.2 Computational Fluid Dynamics (CFD)

CFD numerically solves the governing Navier–Stokes equations to simulate fluid motion, and turbulence is either directly resolved or parameterized using approaches such as Reynolds-Averaged Navier–Stokes (RANS) or Large Eddy Simulation (LES), depending on the desired level of temporal and spatial resolution and computational cost (Al-Khalidy.. et al 2018)

2.3 Turbulence Modeling and Closure

The quality of CFD simulation depends on the selected turbulence model. In practical problems the turbulence model should be as simple as the relevant physics will permit For most real world building problems turbulence is, in principle, described by the Reynolds Averaged Navier-Stokes (RANS) equations

According to publication by… the three-dimensional Reynolds-Averaged Navier–Stokes (RANS) using the k–e turbulence model is one of the most suitable numerical methods for built environment simulations. The model solves for two governing equations, the kinetic energy and turbulent dissipation.

2.3.1 Closure Techniques

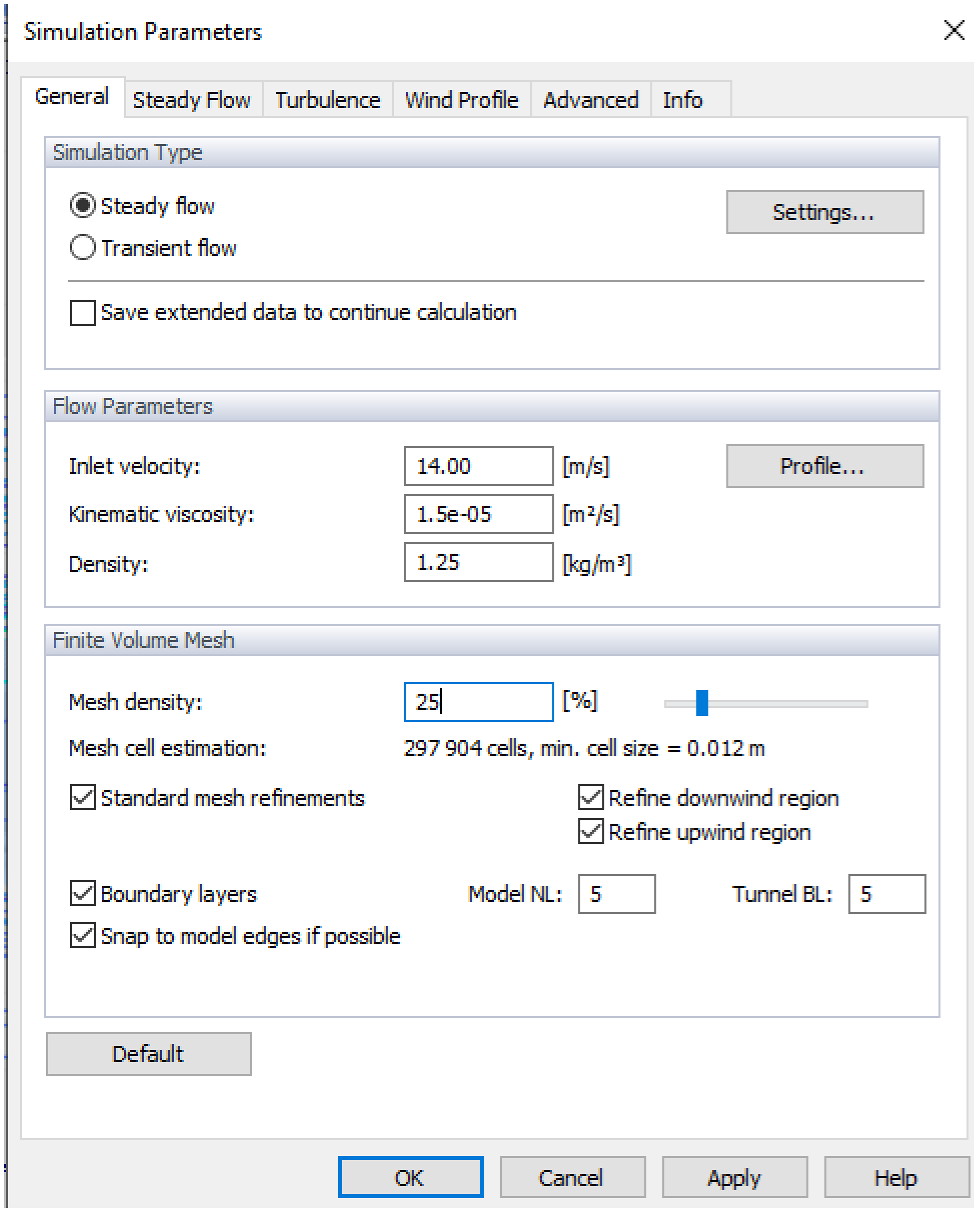
The transition from the equation of motion for the mean stream to the turbulent flow gives a system of differential equations with more unknown parameters than equations. To solve the system of equations, assumptions have to be made to calculate the unknown parameters. These assumptions, for example the covariance terms, are called closure techniques (Foken et al., 2008).

After Reynolds averaging, the RANS equations contain more unknowns than equations. This is called the closure problem. The assumptions used to model these unknown turbulent terms are called closure techniques. In RWIND, closure is achieved using turbulence models such as k -ε and k-ω, which replace unknown turbulent terms with modeled expressions.

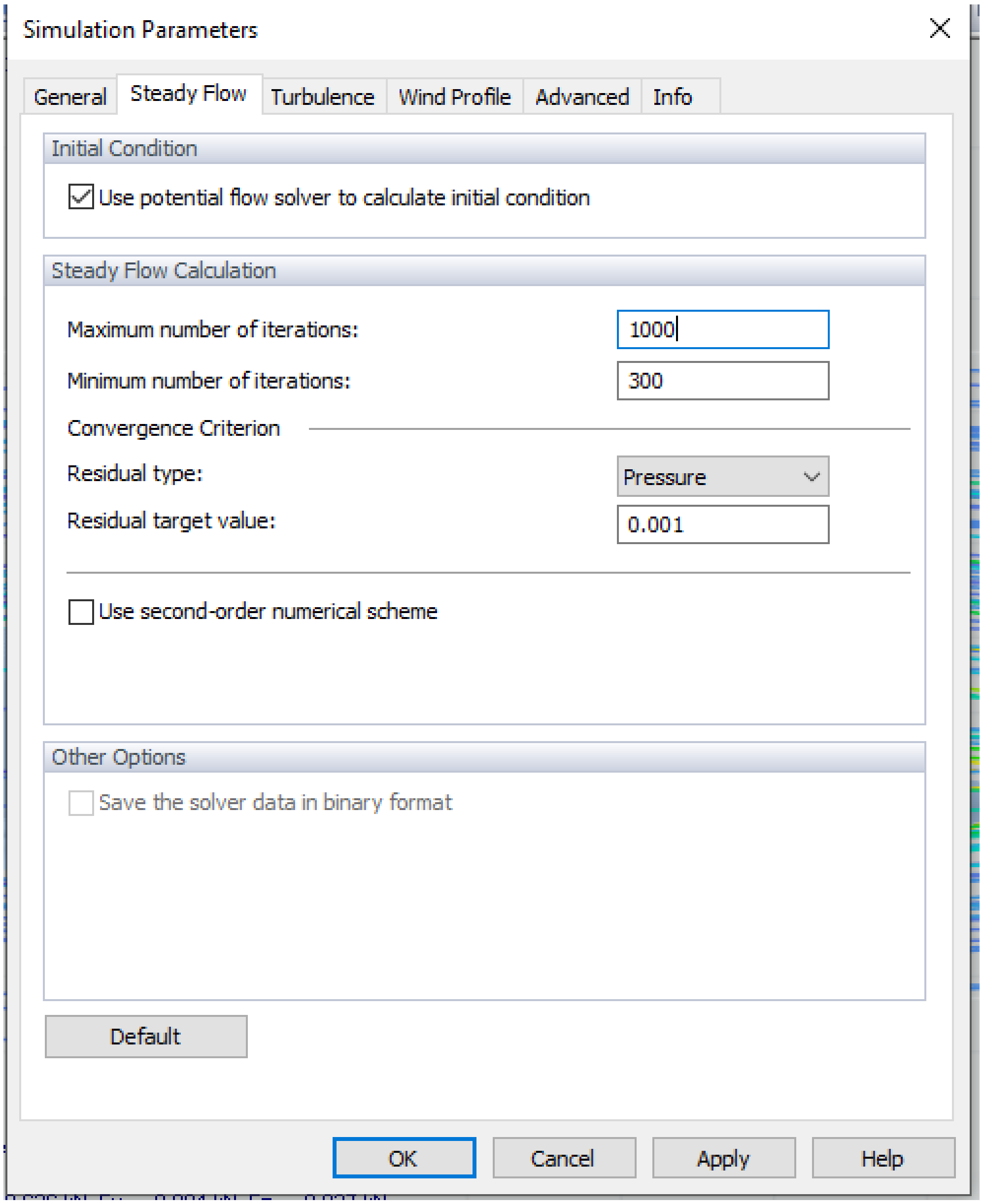
The Reynolds-averaged Navier–Stokes equations contain unknown Reynolds stress terms, leading to the closure problem. Closure techniques, such as the k-ε and k-ω models used in RWIND, parameterize these terms by relating them to mean flow variables through an eddy-viscosity assumption.

2.4 RWIND-Based Urban Flow Simulation

2.4.1 Initial and Boundary Conditions

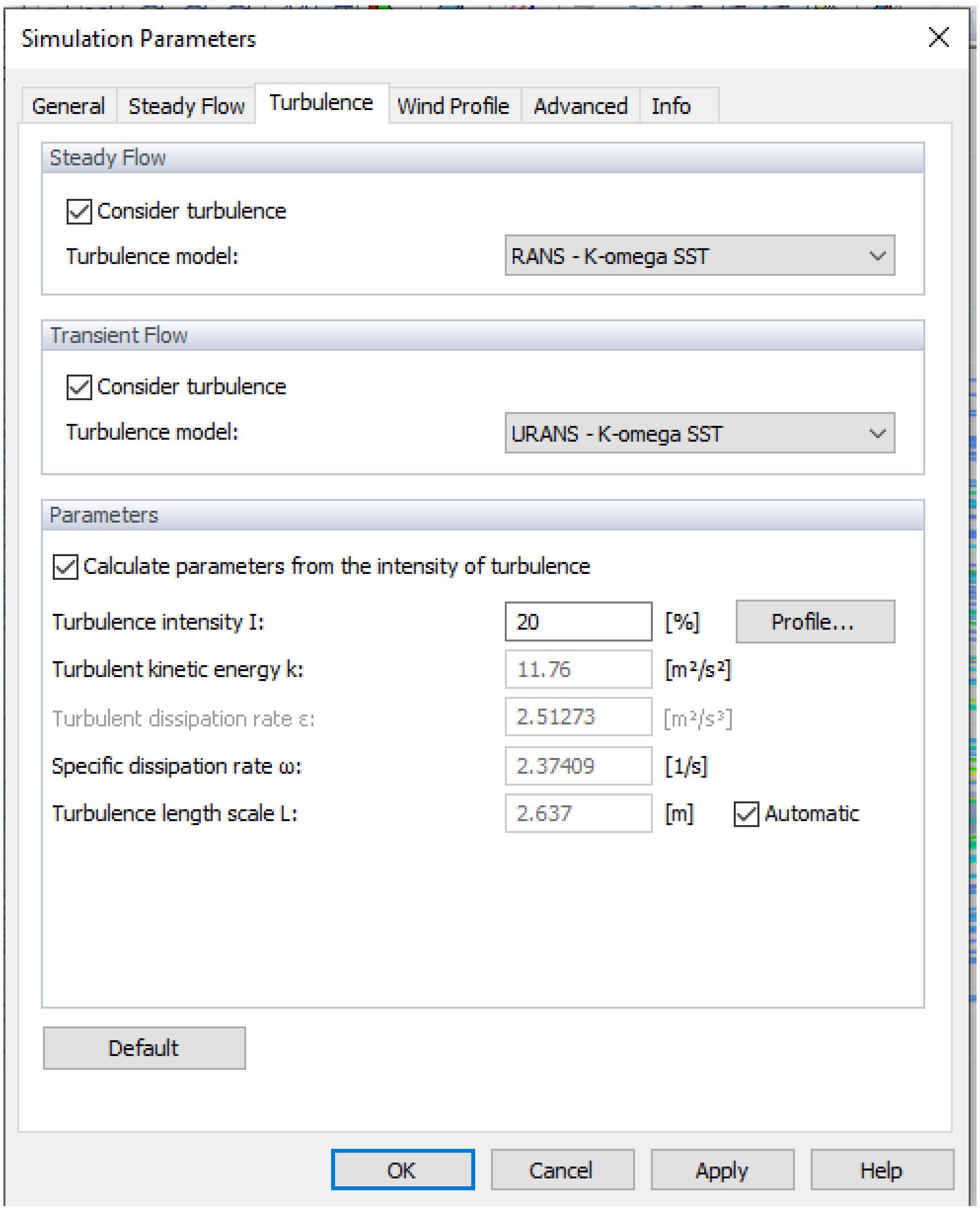


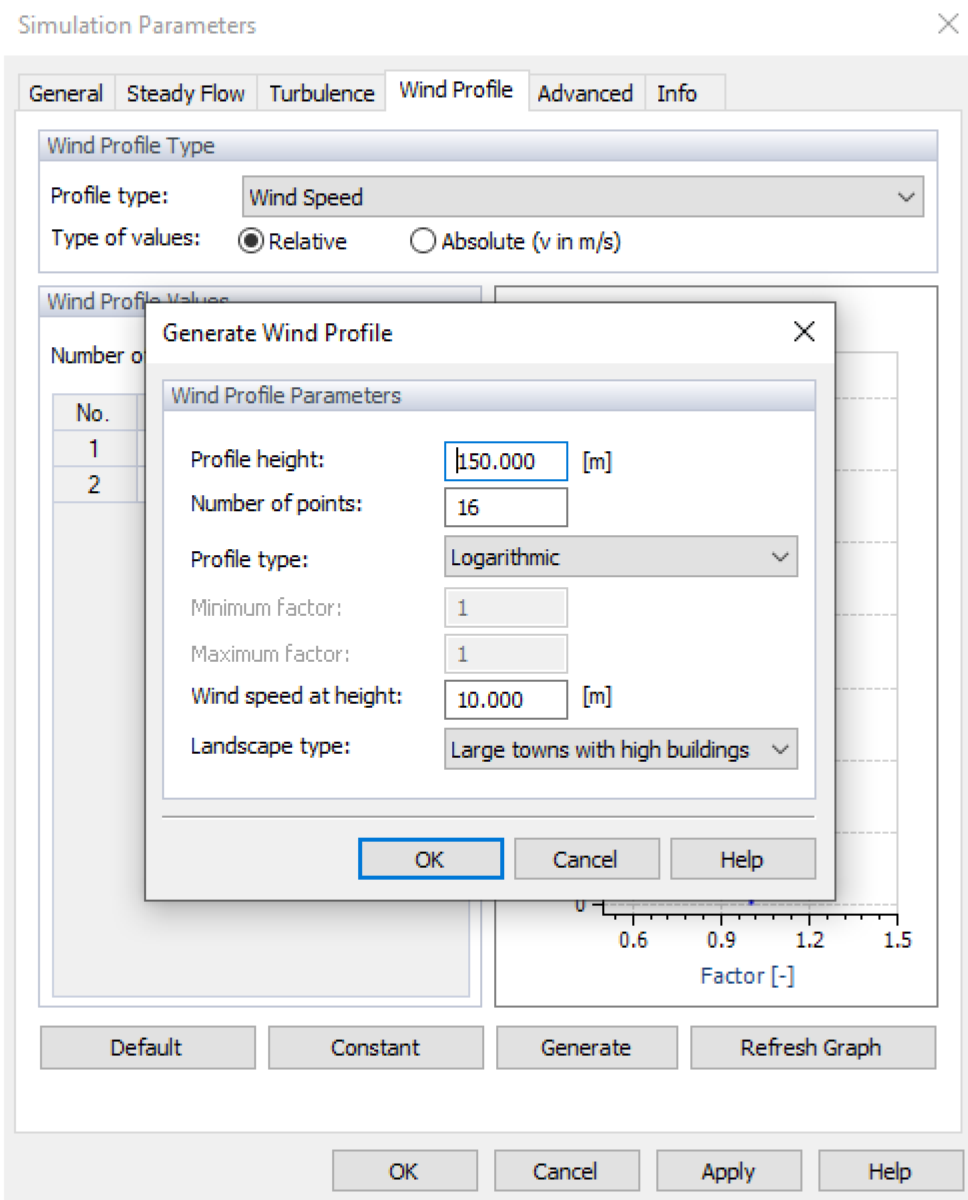
All the required initial condition for this simulation is based on RWING3 guide line obtained from https://www.dlubal.com/en/downloads-and-information/documents/online-manuals/rwind-3/005631

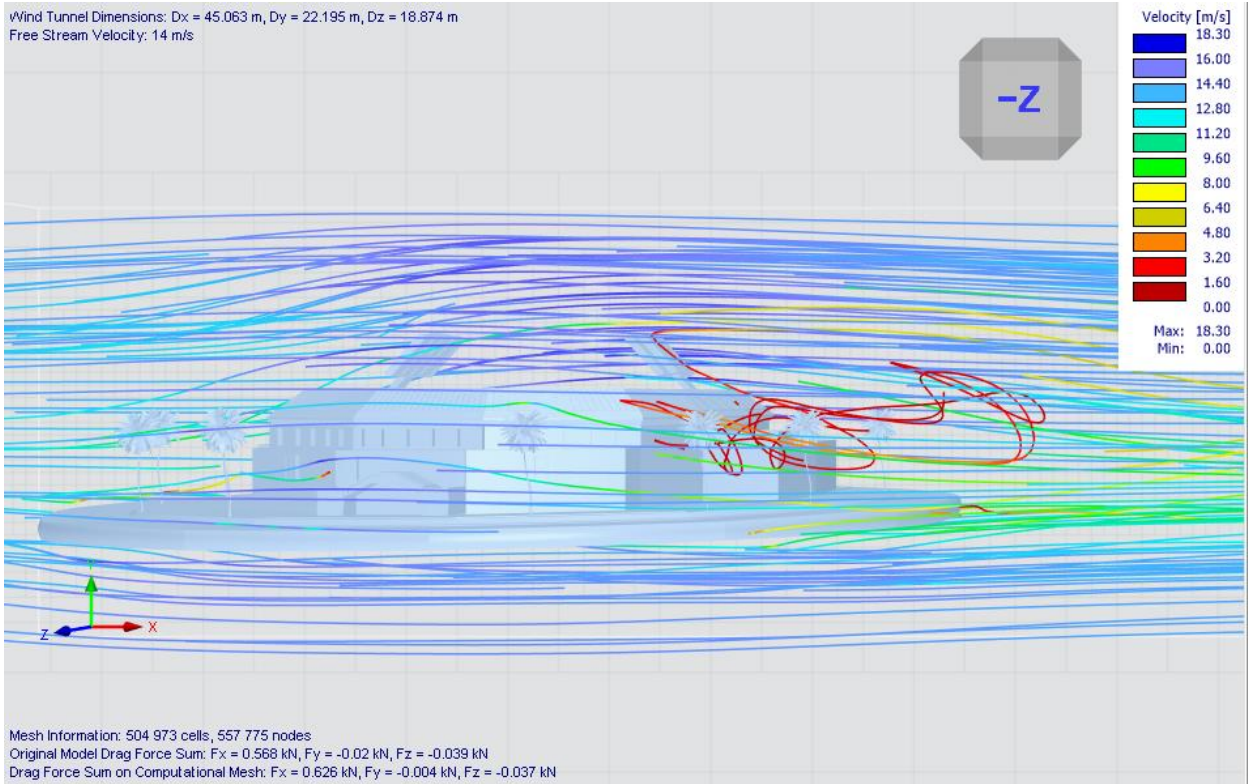


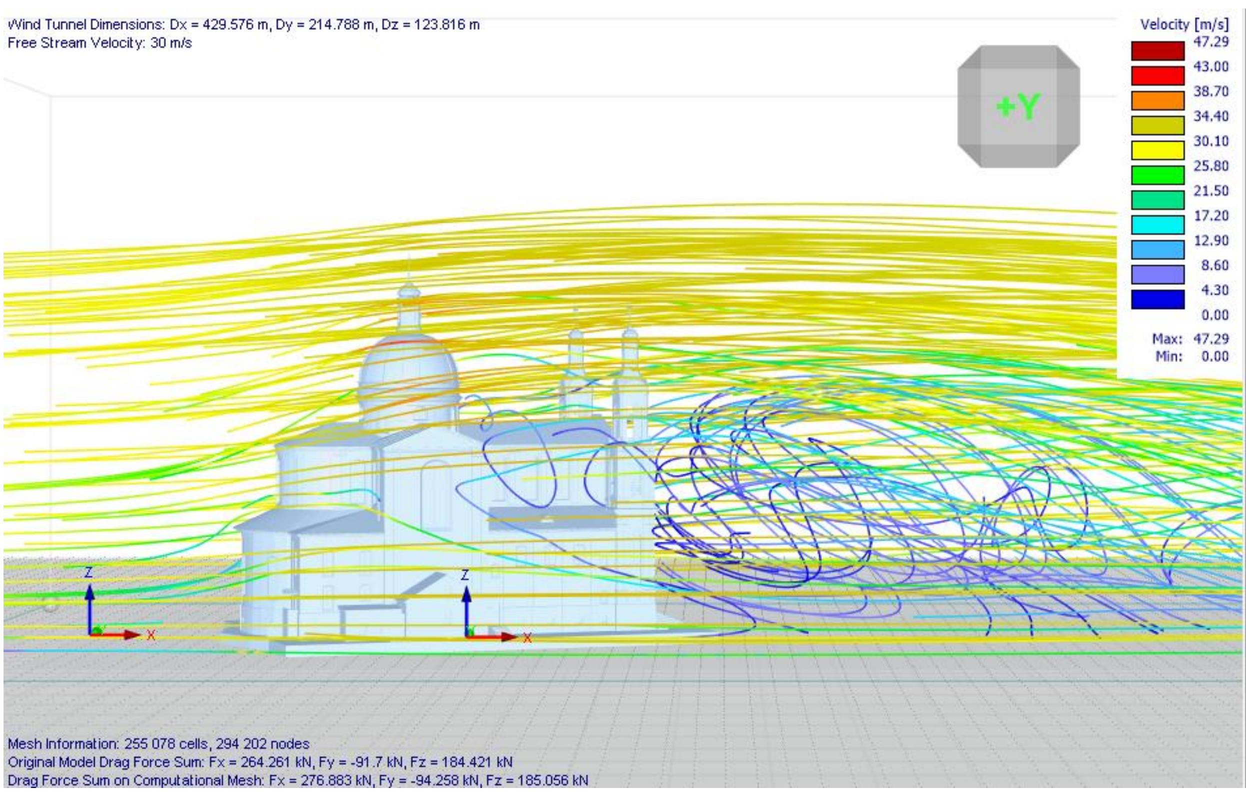
Use potential flow solver to calculate initial condition Check this box (ON) This is standard practice in RANS simulations (especially in wind engineering) because: *RWIND*

3 Manual mentions using potential flow for initial field helps solver start from a physically meaningful state. RWIND 3 Online Manual (Dlubal) — see “Initial condition” section https://www.dlubal.com/en/downloads-and-information/documents/online-manuals/rwind-3/005640




Simulation Parameters
General
Steady Flow
Turbulence
Wind Profile
Advanced
Info
Wind Profile Type
Profile type:
Wind Speed
Type of values:
Relative
Absolute (v in m/s)
Wind Profile Values
No.
1
2
Generate Wind Profile
Wind Profile Parameters
Profile height:
150.000
[m]
Number of points:
16
Profile type:
Logarithmic
Minimum factor:
1
Maximum factor:
1
Wind speed at height:
10.000
[m]
Landscape type:
Large towns with high buildings
OK
Cancel
Help
0.6
0.9
1.2
1.5
Factor [-]
Default
Constant
Generate
Refresh Graph
OK
Cancel
Apply
Help


Wind Tunnel Dimensions: Dx = 45.063 m, Dy = 22.195 m, Dz = 18.874 m
Free Stream Velocity: 14 m/s
-Z
Velocity [m/s]
18.30
16.00
14.40
12.80
11.20
9.60
8.00
6.40
4.80
3.20
1.60
0.00
Max: 18.30
Min: 0.00
Z
X
Mesh Information: 504 973 cells, 557 775 nodes
Original Model Drag Force Sum: Fx = 0.568 kN, Fy = -0.02 kN, Fz = -0.039 kN
Drag Force Sum on Computational Mesh: Fx = 0.626 kN, Fy = -0.004 kN, Fz = -0.037 kN


Wind Tunnel Dimensions: Dx = 429.576 m, Dy = 214.788 m, Dz = 123.816 m
Free Stream Velocity: 30 m/s
+Y
Velocity [m/s]
47.29
43.00
38.70
34.40
30.10
25.80
21.50
17.20
12.90
8.60
4.30
0.00
Max: 47.29
Min: 0.00
Z
X
Z
X
Mesh Information: 255 078 cells, 294 202 nodes
Original Model Drag Force Sum: Fx = 264.261 kN, Fy = -91.7 kN, Fz = 184.421 kN
Drag Force Sum on Computational Mesh: Fx = 276.883 kN, Fy = -94.258 kN, Fz = 185.056 kN

2.5 Conceptual framework

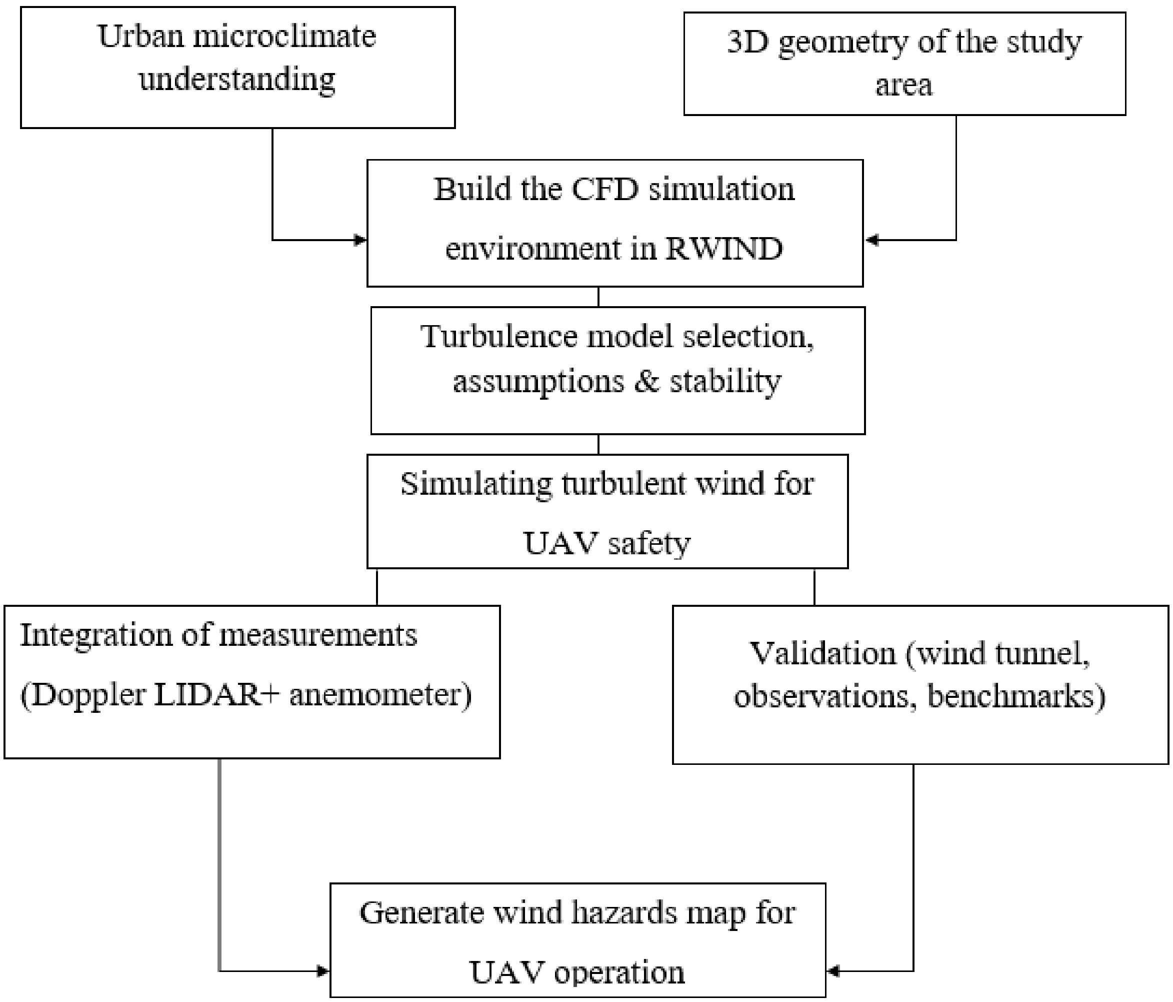


Figure 1 Conceptual framework linking urban micrometeorology, CFD modeling, and UAV wind safety assessment.

The CFD framework is based on the Reynolds-Averaged Navier–Stokes (RANS) equations with appropriate turbulence closure models (e.g., $k-\varepsilon$ and k-ω.) Atmospheric stability assumptions and model uncertainties are considered when interpreting turbulence intensity and wind hazard maps for UAV operations.

References

Al-Khalidy, N. (2018). Building Generated Wind Shear and Turbulence Prediction Utilising Computational Fluid Dynamics. *WSEAS Transactions on Fluid Mechanics*, *13*, 126-135

Foken, T., & Mauder, M. (2008). *Micrometeorology* (Vol. 2, p. 306). Berlin: Springer.

https://www.dlubal.com/en/downloads-and-information/documents/online-manuals/rwind-3/005640?utm_

Krüs, H. W., Haanstra, J. O., Van Der Ham, R., & Schreur, B. W. (2003). Numerical simulations of wind measurements at Amsterdam Airport Schiphol. *Journal of Wind Engineering and Industrial Aerodynamics*, *91*(10), 1215-1223.

RWIND 3 Online Manual (Dlubal) — see "Initial condition" section
https://www.dlubal.com/en/downloads-and-information/documents/online-manuals/rwind-3/005640