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Urban Wind Measurement and Modelling for U-space Operations

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***Abstract*—Urban air mobility can be a potential solution for urban congestion, and high-level concepts of operations (e.g., UTM, U-space) have been developed with the help of large-scale simulations of multi-agent systems. However, one aspect that should be researched more is the effect of wind on the safety and efficiency of missions in an urban environment. While studies that analyse the potential effect of wind on U-space operations exist, they mostly use constant wind fields, or highly simplified wind models.**

The study at hand investigates whether medium-fidelity CFD models can be used to predict and match recorded wind data in the city centre of The Hague. Six locations with distinct urban features were chosen, and wind measurements were recorded on two separate days. Using the rooftop wind properties obtained during the measurement sessions, computational fluid dynamics (CFD) simulations were performed within a large urban model of the city. Results indicate that there are large discrepancies between the simulated and measured values. Some wind phenomena observed within the measured wind data were also replicated by the CFD model. Thus, based on the results presented in this work, future research should focus on improving computer city models and wind measurement methods to ensure the development of concepts of operations that maximise the safety and efficiency of future U-space operations.

***Keywords*—U-space, UTM, drones, urban, mobility, wind**

I. Introduction

With the increase in density of major population centres around the world, solutions for congestion are being investigated across a wide spectrum of domains. Urban air mobility holds the potential to add another mode of transportation for goods and people within high density population centres [1]. To facilitate and create an operational framework for the implementation of urban air mobility, the concept of U-space was developed [2]. This research domain focuses on the study and creation of rules to ensure the safe and efficient operations of aircraft within urban environments.

The main medium through which potential large-scale deployments of aircraft are studied is through multi-agent simulations [3]–[5]. These provide a feasible and fast way of determining the effects of operational decisions on the safety and efficiency of large-scale U-space systems. However, one important element that is typically understudied within such simulations is the effect of wind.

Much of the currently available research on urban wind modelling focuses on other applications and on simplified urban patters or isolated buildings [6], and are thus lacking the global picture of wind patterns at a citywide level. High-fidelity computational fluid dynamics (CFD) simulations have been run on wider areas [7] at the relatively low altitudes at which U-space operations will be conducted. However, the building and terrain models that are used in these are also simplified, and the results themselves are not validated using live-recorded data.

Methods to collect live wind data within cities have been proposed, such as the METSIS project [8], which tested a method through which live hyperlocal wind data can be collected by aircraft in flight. This real-time method is promising for future large-scale operations, and also for the contribution it could make to help develop and verify computer-generated wind models.

However, to study and understand the effect of wind on the safety and efficiency of U-space operations through computer simulations, new wind models may need to be developed specifically for this purpose, with a degree of fidelity high enough to account for most possible scenarios, but limited in complexity as to lower computational requirements and maintain the ability to perform fast-time simulations. Realistic wind models are especially important for testing the capabilities and robustness of both tactical [9] and strategic [10]–[12] conflict detection and resolution algorithms and procedures.

The aim of the research at hand is to investigate whether a medium complexity CFD simulation of an urban area can produce results that are similar to live-recorded data, and determine the requirements for future work in this domain to improve large-scale multi-agent U-space simulations.

II. Methods

The following sections present the methods through which both simulated and live-recorded data were obtained.

A. Urban environment

The city centre of The Hague, Netherlands was chosen as the location for wind measurements. This area has a high degree of variability in terms of urban features, with diverse street widths and building heights. Six locations were chosen for this study, described below as well as presented in Fig. 1:

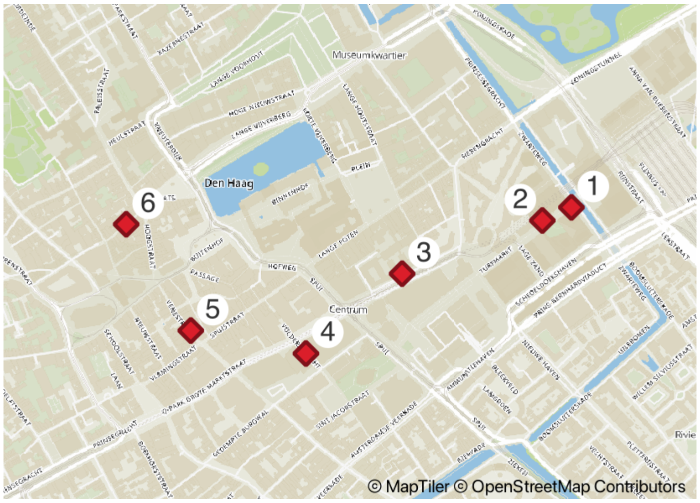


Figure 1. Locations chosen for data collection in The Hague.

1) **Zwartebrug** (52.0798 N, 4.3222 E)
   Open area close to the central station on East-West direction.
2) **Turfmarkt 552** (52.0793 N, 4.3213 E)
   Wide street surrounded by tall buildings on East-West direction.
3) **Kalvermarkt 32** (52.0781 N, 4.3168 E)
   Wide street surrounded by medium-sized buildings on East-West direction.
4) **Voldersgracht 40** (52.0768 N, 4.3138 E)
   More narrow street surrounded by medium-sized buildings on North-South direction.
5) **Venestraat 48** (52.0772 N, 4.3101 E)
   Narrow street surrounded by low buildings on North-South direction.
6) **Papestraat 11** (52.0791 N, 4.3082 E)
   Narrow street surrounded by low buildings on East-West direction.

B. Measurement instrumentation and procedure

The live wind measurements were taken on two relatively windy days of the year 2023: 11^{th} of June and 13^{th} of September. The instrument used to measure the wind magnitude and direction is a Bresser 5-in-1 PC Weather Station, as shown in Fig. 2. The sensor was attached to a pole, raising the direction sensor to a height of 217 cm above ground, and the magnitude sensor at 233 cm, to lessen the ground effects on the measurements. The station was connected to a radio data receiver, which is then connected to a computer.

The weather station was set in an open space and calibrated such that it would point in the geographical North direction. Data measurements would then be started and logged on the laptop for approximately 15 minutes with a frequency of six measurement points per minute. The data of interest within the logs consists of wind direction, wind magnitude, and wind gust level. The global high-altitude wind characteristics would be recorded at the beginning of the measurement using the Meteostat[1] Python package, and is assumed constant throughout the duration of a single measurement.

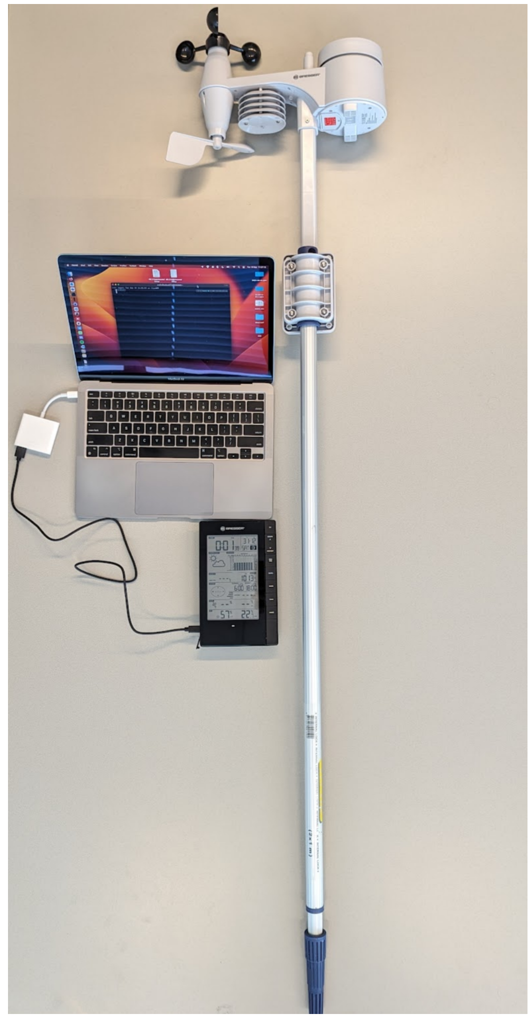


Figure 2. Instruments used to measure wind direction and magnitude: weather station, support pole, USB radio receiver, and a laptop.

C. Computational fluid dynamics wind simulation

An Urban Computational Fluid Dynamics (CFD) simulation was used to attempt to re-create the measured wind values given the same global wind properties. Buildings inside a 1-kilometre radius circle centred in The Hague were included in the simulation. The building models were obtained from [13].

[1]https://github.com/meteostat/meteostat-python (Accessed: 28-09-2023)

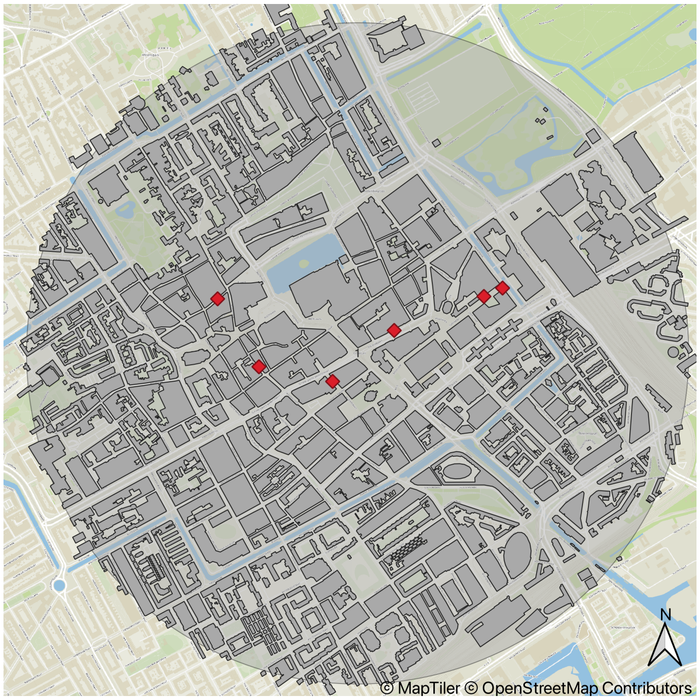


Figure 3. Buildings included for CFD simulations (in grey).

Fig. 3 shows the buildings included in the simulation. The goal was to include enough buildings around the measurement location such that the simulation can capture the effects of the surrounding urban landscape. The buildings were simplified to reduce the complexity of the mesh, and buildings that share a wall were merged.

The height of the buildings were taken from a publicly available government dataset [14]. Additionally, City4CFD [15] was used to generate a 3D model from the building polygons and government dataset.

The CFD domain dimensions were selected using the guidelines from [16]. The ground is assumed to be flat, as the variance in terrain elevation is minimal. An Open-Source CFD software (OpenFOAM [17]) was used to generate a mesh and simulate the global wind conditions of the two measurement days. The mesh contains about 9 million cells. The resolution of the mesh is not constant and increase near the buildings and the ground. Near the buildings and the ground, the horizontal resolution is around 2.5 metres per cell and around 1.3 metres vertical.

Incompressibility can be assumed, as the wind speeds in urban areas are significantly below the speed of sound and below the transonic regime. This work uses the incompressible Reynolds-Averaged Navier Stokes (RANS) Equations, meaning the Navier Stokes equations are separated into mean and fluctuating parts using the Reynolds decomposition. The decomposed equations are then averaged over time. This creates the well-known turbulence closure problem, which requires the use of models.

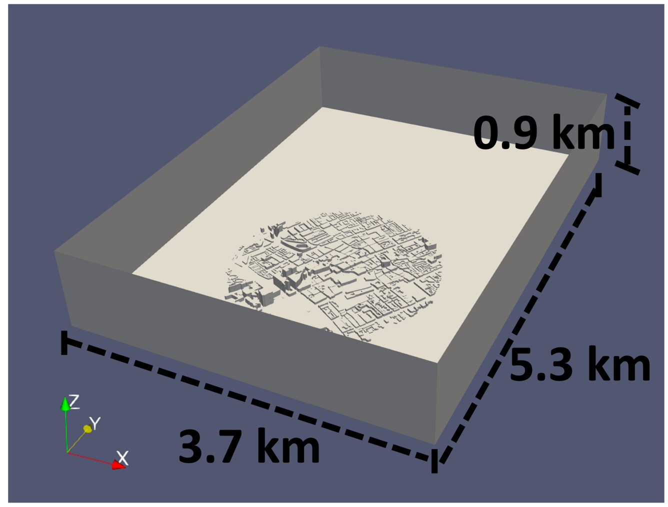


Figure 4. CFD domain, wind is acting in the y-direction.

This is a commonly used approach for solving urban flow problems [16]. The RANS approach solves for the average velocity field and requires the use of a turbulence model. The advantage of the RANS approach over a more accurate model, such as a Large Eddy Simulation (LES), is that it does not use nearly as much computational power and still produces robust results[18], [19]. The main drawback is that RANS cannot resolve the fluctuating components of the velocity field and therefore can only provide a general view of turbulence.

This work uses the standard k - ϵ (k-epsilon) model for turbulence [20], where k is the turbulent kinetic energy and ϵ is the dissipation rate. This is the typical model used for RANS simulations in urban environments, as it can provide an accurate view of the flow field [16]. The turbulent kinetic energy is defined as follows:

$$k = \frac{1}{2}(\langle uu \rangle + \langle vv \rangle + \langle ww \rangle), \tag{1}$$

u, v, and w are instantaneous fluctuations from the average velocities in the 3 Cartesian directions, and $\langle\rangle$ is the average operator. A low value of turbulent kinetic energy at a certain location means that the instantaneous velocity has a higher probability of matching the average velocity. Conversely, a high value of turbulence indicates that the instantaneous velocity has a lower probability of matching the average velocity. This may mean that instantaneous velocities can be significantly higher or lower than the average value.

An inlet boundary condition of a neutral atmospheric boundary layer was used with a wall function from [21]. The reference velocity was set to 8 m/s and 6 m/s for the first and second day, respectively. In both cases, the reference height was set to 10 metres. The area around The Hague is accurately described

TABLE I. AVERAGE GLOBAL WIND VALUES OVER THE COURSE OF THE MEASUREMENT SESSIONS, AND BEAUFORT SCALE EQUIVALENT VALUES.

Day	Speed [m/s]	Gust intensity [m/s]	Direction [deg]	BFT
1	7.9	11.4	217	4-5
2	5.6	9.1	28	3-4

as ”very rough” due to the scattered buildings. However, in accordance to the recommendations in [16], the aerodynamic roughness parameter in the simulations ($z_0 = 0.2$) is set as ”rough” [22]. Thus, the boundary layer is faster at the inlet and thus more conservative.

In accordance to the method described in [16], the simulations were performed with second-order numerical discretisation schemes. The *simpleFOAM* (Semi-Implicit Method for Pressure Linked Equations) solver [23] is used, as it is a steady-state solver for turbulent, incompressible flow that has been used previously in literature [24], [25].

One of the aims of this work is to perform a medium-fidelity simulation with relatively low computational intensity. The solution of a high-fidelity RANS simulation typically requires the flow field variables to reach numerical convergence less than 10^{-4} [16]. In these simulations, the large domain size and computational power limit the resolution of the mesh that would provide a high-fidelity solution. Therefore, the convergence criterium is relaxed to less than 10^{-2}. The velocity, dissipation, and turbulent kinetic energy converged below 10^{-3} and the pressure was less than 10^{-2}. More information about the mesh, boundary conditions, numerical schemes, as well as the source code can be found at [26].

III. RESULTS

A. Global wind data

At the beginning of each measurement session, the global wind field and direction were measured using the Meteostat Python package. As this package provides data with a frequency of one hour, both days only have two data points for this. However, on both days, the global wind did not experience significant variations in magnitude and direction during the measurement sessions, and thus the measured values were averaged, presented in Table I.

B. Measured live wind results

The measured live wind data for each location is presented as wind-rose graphs in Fig. 5. The wind-rose graphs are placed at the approximate locations of the measurements on the map of the centre of The Hague. The radial component of the wind-rose represents the frequency that the wind blows in said direction. The colours in each individual diagram show the measured speeds in the respective direction. Data points with wind speeds below 1 m/s were excluded from the dataset. This exclusion was necessary due to the decreased measurement reliability at low wind velocities, influenced by factors like the wind direction sensor’s moment of inertia and its tendency to remain in its previous position when there is no wind.

The local wind is relatively consistent in direction in most locations on both days. However, some locations experienced low wind and high direction variance: Location 3 on Day 1, and Location 1 on Day 2. Other locations, such as Location 6 on both days, and Location 2 and 4 on Day 2, experienced low wind speeds with a relatively consistent direction.

Overall, in most locations, local the wind direction is consistent with the direction of the global wind mapped onto the street bearing. However, some interesting cases occurred on both days. On the first day, there was little to no wind at Location 3, despite the street being relatively wide and parallel to the streets of Locations 1 and 2. Furthermore, Location 4 experienced local wind that was perpendicular to the street direction, even if the street is relatively narrow and the surrounding buildings relatively tall. On the second day, the local wind directions were mostly matching expectations and were consistent with the street bearings. The only anomaly on that day is seen within the low wind speed magnitude for Location 1, and consequently, the high variance in wind direction.

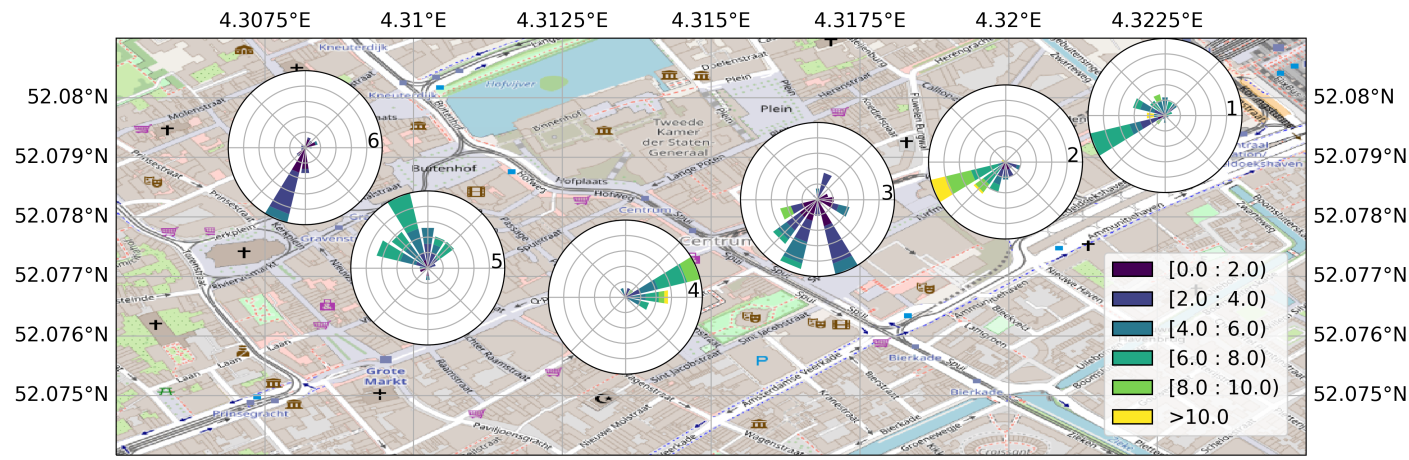
C. Simulated wind results

Fig. 6 shows the results of the CFD simulations that were performed on the city section of The Hague using the global wind properties presented in Table I. In some areas, the wind direction and magnitude are relatively close to the observations, such as Locations 2, 4, and 6 on Day 1, and Locations 2 and 6 on Day 2. However, the other locations show a discrepancy in either magnitude and wind direction between the measured and the simulated values, with the first location showing the largest differences.

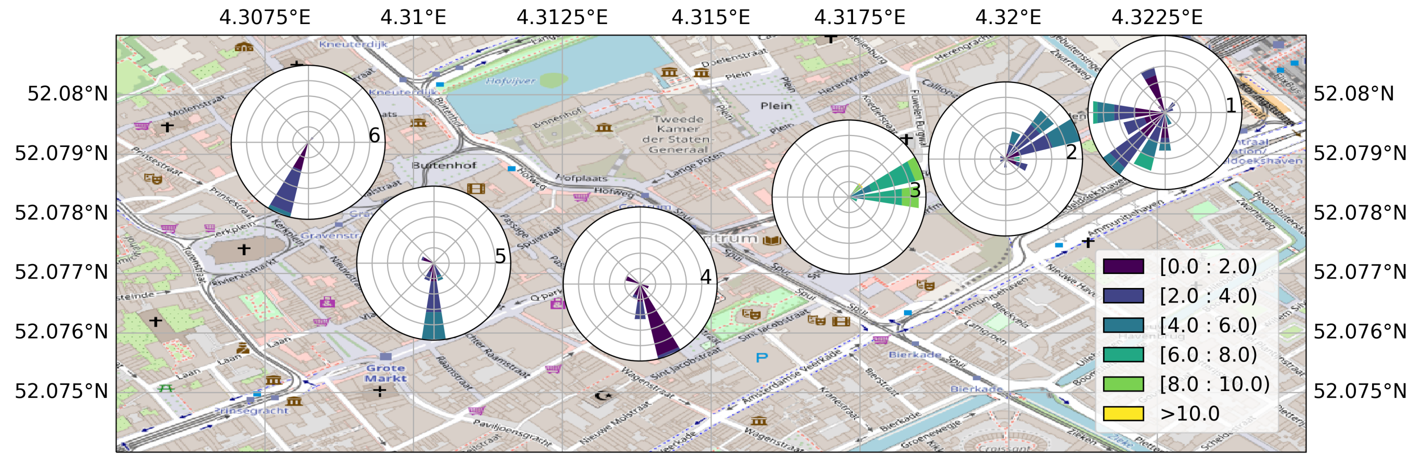
D. Results overview

Table II contains a summary of the measured and simulated wind data properties. The measured wind data is described using the mean (σ) and standard deviation (μ) of the data sets, adjusted to account for the circular properties of the direction. The simulated wind data was obtained by surveying the proximity of the measurement points within the simulated data, and determining the range in which the values for speed, direction and turbulent kinetic energy are found.

The simulated wind turbulence values are also presented in Table II. This metric cannot be reliably computed from the measured live data, as the latter was recorded at a single location for each measurement point, and the wind is recorded in 2 dimensions only. However, it can be related to the variation in the wind properties (variance of speed and direction, gust level).



(a) Measured wind properties for the first day.



(b) Measured wind properties for the second day.

Figure 5. Measured data represented as wind-rose plots, speed represented in metres per second. Map courtesy of OpenStreetMap [13].

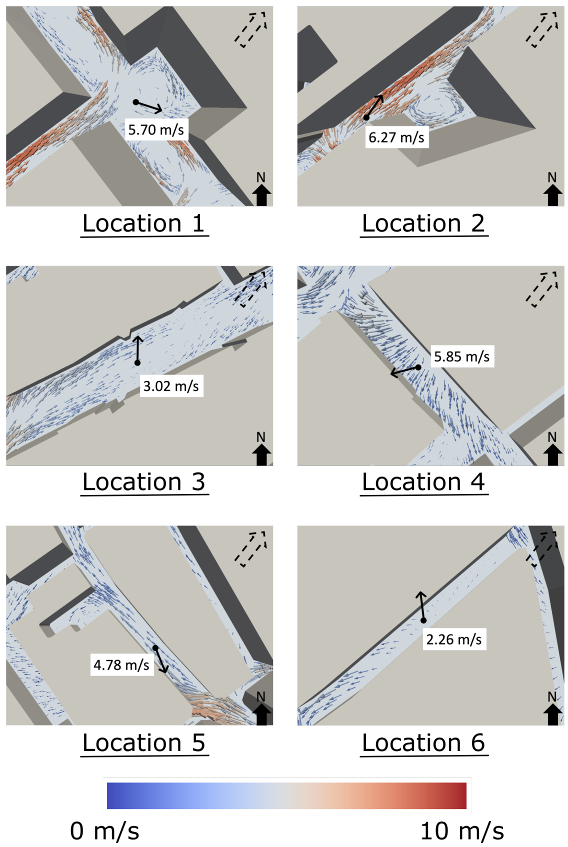
For the first day, the most turbulent Locations were 2 and 4. If compared to the measured data in Table II, these two locations had high gust values as well as the highest variance in wind speed. On the second day, the most turbulent locations were 1 and 2. This is reflected in the values presented Table II, as these locations have the highest variation in wind direction, and relatively high gust levels.

For the first day, only Location 2 has matching measured and simulated results in terms of wind speed, with the other locations being outside the value interval by a relatively large margin. In terms of wind direction, Location 2 is yet again the only point where the simulation is in agreement with the measured values, with the discrepancies being greatest for Locations 5 and 6.

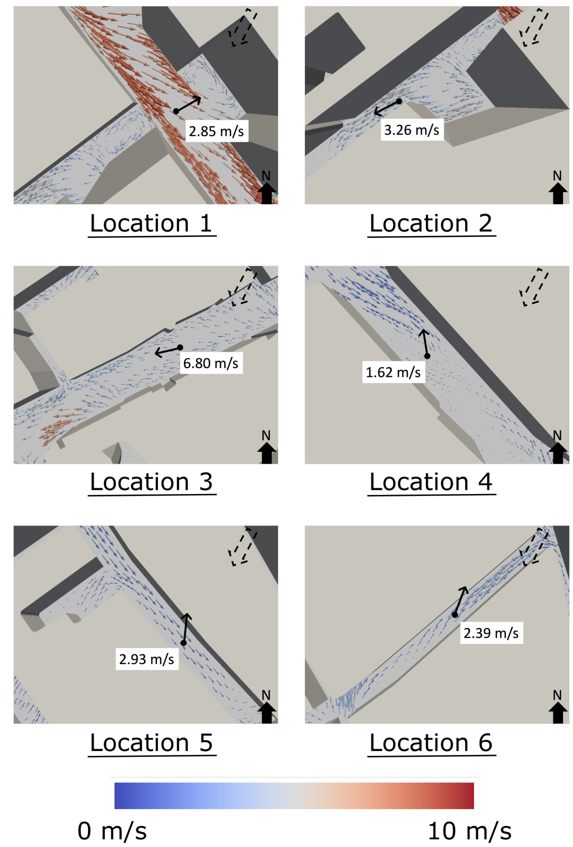
The simulation data for the second day matches the measured data to a higher proportion than for the first day. For wind speed, the measured value for two locations (2 and 6) are contained within the simulated wind speed intervals. Locations 1 and 3 have relatively high discrepancies between simulated and measured values, while the simulated data of the remaining two locations (4 and 5) correctly predicts low wind speeds. In terms of wind direction, 4 locations (1, 2, 3, and 6) have simulated data values that resemble the live measurement values, with the other two locations (4 and 5) having large discrepancies.

IV. Discussion

The results shown in the study at hand show that urban citywide wind models need to be improved to develop a complete set of



(a) Simulated wind data for the first day.



(b) Simulated wind data for the second day.

Figure 6. Simulated wind velocity and direction at the measurement locations for each measurement day. The average measured magnitude and direction are shown as black arrows and labelled. The dotted arrow in each figure represents the direction of the global wind.

TABLE II. Summary of measured and simulated data. The measured data is described using mean, standard deviation and maximum gust values. The simulated data is described using the lower and upper bounds of the data at the mesh points near the locations.

Location	**Measured Data**					**Simulated Data**					
	Speed [m/s]		**Direction [deg]**		**Max gust [m/s]**	**Speed [m/s]**		**Direction [deg]**		**Turbulent kinetic energy [m^2/s^2]**	
	μ	σ	μ	σ		lower bound	upper bound	lower bound	upper bound	lower bound	upper bound
Day 1											
1	5.70	2.02	288	64	13.85	2.0	4.0	110	170	0.1	0.4
2	6.27	3.26	215	44	16.52	5.0	6.9	235	235	1.5	2.0
3	3.02	1.71	181	69	9.82	1.0	2.5	230	250	0.2	0.3
4	5.85	2.25	75	32	12.92	1.4	3.0	30	50	0.7	1.0
5	4.78	1.87	338	51	9.38	2.0	3.5	140	140	0.2	0.4
6	2.26	0.98	173	68	5.59	0.4	1.0	80	105	0.2	0.2
Day 2											
1	2.85	1.53	240	62	7.58	6.6	6.6	300	300	1.3	1.3
2	3.26	1.36	63	45	7.58	2.9	4.5	65	75	0.3	0.4
3	6.80	1.65	77	16	12.05	1.9	2.4	90	90	0.2	0.3
4	1.62	0.62	171	42	4.91	0.2	0.8	330	8	0	0
5	2.93	1.41	186	34	5.59	1.4	1.6	320	320	0	0
6	2.39	1.05	201	33	5.59	1.9	2.7	220	220	0.2	0.2

rules and procedures to ensure the safe and efficient deployment of urban air mobility operations.

In most of the locations where live data was recorded, the simulations did not produce matching values. One of the locations with the greatest discrepancies was Location 1 (Zwartebrug). On the first day, a relatively strong wind with gusts up to 14 m/s was recorded in this location. However, the simulations predict a relatively calm area, with wind speeds of approximately 3 m/s.

This discrepancy may be produced by the mismatch between the real shape of the buildings and the city model. In reality, the building North-East of the measurement point is not fully solid, with a relatively large passageway on the ground level. The lack of this feature could have determined a high-pressure point to form within the simulation of Day 1, which produced lower than expected wind speeds and turbulence, and a large discrepancy in wind direction.

To mitigate this, one option could be the use of city models obtained from the creation of 3D cadastre models for buildings that have complex features should be made and used. These complex features, such as the large passageway at Location 1, affect the local wind flow, and need to be better studied. The development of such models has been underway for several years, with a steadily increasing interest [27]. However, the presence of legal, technological, and organisational impediments means that accessible citywide high-fidelity models are unavailable publicly.

In some cases, the simulations correctly predicted the magnitude and direction of the wind, most notably for Location 4 of the first day. The measurements for this day were surprising, as the wind direction was both inconsistent with the street bearing and the global wind direction. However, the simulation correctly predicted that wind in this area would not be directed along the street, like observed in other areas. This result shows that complex wind phenomena might indeed be captured within medium-fidelity simulations, and can provide valuable information about expected wind behaviour in urban environments, which should be accounted for when developing U-space concepts of operations. However, more measurements at this location are needed to confirm this.

Another notable finding of this study is that, for many measurement points, the direction of local wind was consistent with expectations based on mapping the global wind onto the bearing of the street. This can be seen for Locations 1 and 2 on Day 1 and Locations 2 and 3 on Day 2 (Fig. 5). Wind on streets that were less aligned to the global wind direction had a higher chance of having local wind that goes against expectations (e.g., Location 5 on both days). Thus, with more live measurements and data analysis, a set of general considerations could be developed that would help estimate expected urban wind level on streets without the need to run computationally intensive simulations.

Despite the discrepancies between measured and simulated wind values for each location, an overview of the results shows that simulations produced data within the range of measured values. Thus, realistic models can indeed be created by only using medium-fidelity CFD methods, which would serve the purpose of better understanding the effects that wind has on aircraft within urban environments. However, a wider range of conditions need to be simulated to account for a larger variety of possible wind intensities and directions.

V. Conclusion

The study presented in this work aimed to investigate whether current computational fluid dynamics (CFD) methods applied on a large citywide scale can reliably predict and match wind data recorded at street level in an urban environment. Live wind data was recorded at six locations within The Hague on two different days, and compared to models generated using OpenFOAM.

Results indicate that there are large discrepancies between recorded and simulated values in terms of wind speed and direction at most of the locations. However, some unexpected observed phenomena (i.e., wind blowing perpendicular to the street bearing and opposite of rooftop wind direction at location 4 on Day 1) were correctly predicted, and the simulations provided values within the order of magnitude of the recorded values. Thus, despite some discrepancies, CFD simulations prove to be a good tool for studying wind patterns in urban environments, and for creating realistic wind models that can then be used to simulate and develop large-scale U-space operations.

More research and development is needed in several aspects of the problem at hand to produce better wind data for urban environments. Firstly, the methodology can be improved in several ways, one of which would be the use of better 3D city models to more accurately capture wind patterns in areas with complex building shapes. Most large-scale building model data sets are created by using aircraft, and are thus limited to capturing the 2D footprint of buildings. Terrain features should also be included in the analysis, such as changes in elevation and natural features (e.g., trees). The data quality for rooftop wind should also be improved, preferably with live measurements taken from tall buildings and vantage points, thus improving the potential accuracy of CFD simulations. Also, uncertainty in the boundary conditions, namely the reference height, velocity, and roughness parameter can affect the accuracy of the CFD results. Therefore, the methodology of the comparison can also be improved by using more accurate instruments at higher elevations than in this study to set improved boundary conditions.

Future research should pursue the development of better urban wind models and methods to capture live wind data. As wind is expected to affect U-space operations greatly, this information could be important in the development of operational concepts, with major implications in safety-critical systems (e.g., strategic and tactical conflict resolution) as well as flight planning and flow management.

Acknowledgments

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