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NUMBER

Searching for key variables influencing Upstream Building Effects in Urban CFD Simulations

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***Abstract*—**
In this study, we demonstrate that upstream buildings exert a significant influence on the wind conditions at rooftop levels for energy generation. By systematically removing, adding, and modifying the layout of a section of the University of Alberta North Campus, we conclude that the obstructive effect of upstream buildings is a cumulative phenomenon. This finding adds complexity to urban wind energy assessments that are based on city morphology.

A series of CFD simulations, comparing various building modifications (including the removal of tall obstructions, sheltered structures, and alterations to roof shape) revealed that changes in building inclusion can lead to substantial variations in both wind velocity and energy yields. These variations underscore the importance of understanding the complex interactions between urban structures and the wind.

Following an initial exploration of building interactions, we are performing a systematic CFD simulations aimed at identifying the key variables that govern this cumulative influence. The objective is to characterize how factors such as friction velocity, surface roughness, building width, and relative distance (normalized by a characteristic height difference) affect urban wind flow. The results of this investigation are intended to guide the appropriate inclusion of upstream buildings in CFD simulations, and they highlight the need for further validation through wind tunnel experiments and field measurements.

***Keywords-component*—Urban wind energy; Computational Fluid Dynamics; Upstream building effects; Urban morphology; Wind turbulence.**

I. INTRODUCTION

Urban wind energy is a promising source for distributed generation, offering the potential to harness renewable energy in densely populated areas. Unlike traditional wind farms, often located in remote regions, urban wind energy systems can be integrated into the built environment, providing localized power generation and reducing transmission losses.

The complex interaction between winds and urban structures presents significant challenges in accurately assessing the available energy and the conditions for its extraction. These challenges are strongly present in quantifying the wind's turbulence intensity and velocity, critical variables for ensuring proper working conditions for a wind turbine [1], [2].

One alternative for studying the interaction between winds and urban structures is to perform a systematic study using Computational Fluid Dynamics (CFD). By allowing the isolation of the countless variables that are present in urban wind environments, the simulation helps to identify the most relevant parts of this interaction and even the statistical quantification of potential energy yields [3], [4].

Because the yields are proportional to the cube of the velocity (in equation 1 U is velocity, ρ density, Cp the power coefficient and A the cross-sectional area of the wind turbine), one fundamental part of energy assessment is in representing the environment and setting the boundary conditions of the simulation. In addition to a careful incident profile definition [5], [6], a conscious decision regarding the explicit inclusion of buildings must be taken [7]–[10].

$$E = 0.5\, \rho\, Cp\, A\, U^3 \quad (1)$$

The importance of upstream buildings in wind patterns has been highlighted by multiple authors in the fields of wind-driven rain [11]–[13], ventilation [14], [15], pollutant dispersion [16], wind energy [17]–[21], and general reviews in related areas [23], [24], [27]. Following their findings, it is possible to conclude that significant differences in the wind patterns and behaviour can be obtained depending on the upstream structure height, alignment and shape.

Despite the agreement that upstream buildings' effects should not be underestimated, there is no consensus on how many upstream buildings should be considered and the criteria used for exclude them. For example, Tominaga et al. [27] propose the radius of the height of the building as an area to be considered; Tong et al. [9] suggest 1 to 3 layers of buildings based on the aspect ratio (width to height) of the upstream buildings; Liu et al. 2018 [10] determined times the characteristic length (longest) of the target building should be used; Jianhan-yu et al. [21] suggest a fetch area of 200 m - 450 m radius depending on the type of location. Such differences are understandable considering how complex and diverse urban environments are and their different target variables.

In a previous study of the wind energy simulation of the University of Alberta North Campus (FIG. 1), the authors observed that wind flow at the target building's rooftop is influenced not only by the largest upstream obstacle but also by a chained effect from further upstream structures [20]. In light of these findings, the present study aims to identify the key variables necessary to develop a criterion for assessing the influence of upstream building chains based on their dimensions and relative differences.

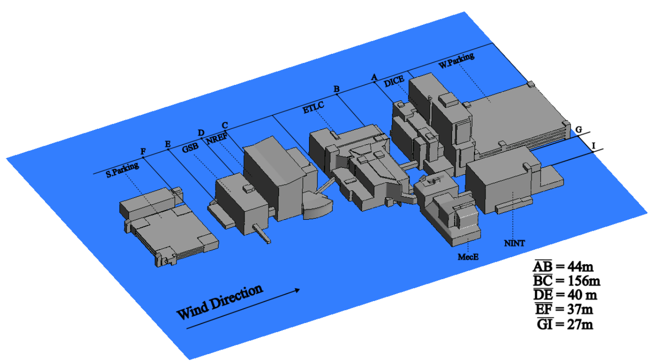

Figure. 1. University of Alberta North Campus CAD (approximated). The buildings for the reference case are the ones aligned with the target building (DICE). Approximated heights: W.Parking:17 m ; DICE: 63 m; ETLC: 27 m; NREF (front): 47 m; GSB:31 m; S.Parking: 9 m; NINT:38 m; MecE:25 m; ChemE:37m

A similar approach was developed by Singh et al. [25], who proposed a parametrization for modelling urban wind patterns to improve the Röckle standard model. According to them, the Röckle model performs a mass-balance correction of parametrized wind pattern predictions. Their algorithm determines the type of interaction between two structures (e.g., isolated, interference, or skimming flow) based on the distance, width, and height ratio between them.

Building on this, in this study a series of CFD simulations is conducted to identify the variables that trigger the cumulative (chained) effects of upstream buildings. The goal is to obtain a list of parameters to develop a criterion for deciding the inclusion of upstream buildings in simulations. Specifically, this research hypothesizes that the influence of further upstream buildings can be characterized on a set of parameters, setting the ground to develop an indicator.

II. Methodology

This is the first part of two rounds of simulations. The first round is a follow-up of a previous work [20], with a different inlet profile, meshing and solving strategy, and focuses on identifying the buildings that significantly influence wind flow patterns in a realistic scenario. The second round will delve further into identifying the key variables that make the upstream buildings interact in their effect towards the target building and quantify their effects.

The relevance of the buildings in this round is determined based on two vertical planes placed on top of DICE (FIG 2) and NREF (3). Their locations are defined based on the uniformity of velocity and local turbulence intensity, whereas the comparison will be based on the average velocity and the total power along the plane without the power coefficient (1). The cases of study and their reasoning are as follows:

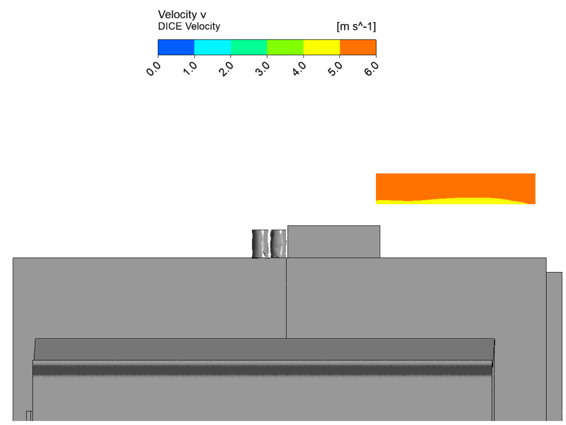

Figure. 2. Location for the comparison plane at DICE showing the normal velocity. Defined based on turbulence intensity and velocity profiles in the reference simulation

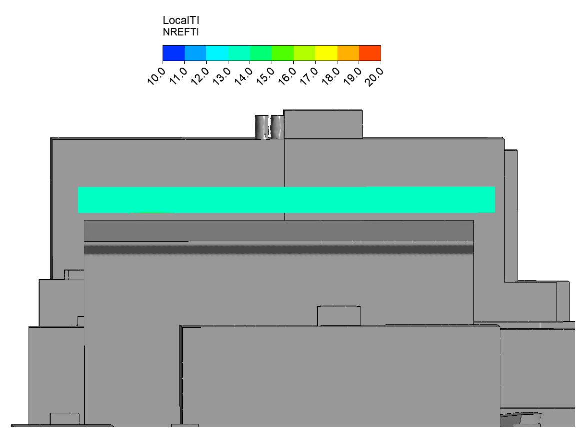

Figure. 3. Location for the comparison plane at NREF showing the turbulence intensity. Defined based on turbulence intensity and velocity profiles in the reference simulation

1) All aligned buildings are present: Reference case (Fig. 1).
2) Removal of the parking lots: Two almost identical buildings located at the start and end of the arrangement. Because of wind sheltering, the downstream is assumed to be not relevant. In contrast, the upstream parking is 36% of the height of the (Natural Resources Engineering Facility, NREF), thus it is likely to indirectly influence the yields in DICE by the obstruction that NREF should have independently.
3) Removal of Engineering Teaching Learning Complex (ETLC) and Chemical Engineering (ChemE): Because these building is in between two tall structures. It is expected for their effects to be negligible due to the height difference with DICE and the shelter from NREF's wind redirection.
4) Removal of General Service Buildings(GSB): This building is in front of the main obstacle (NREF). Due to its disposition, it is expected to be the main contributor to the changes of the influence NREF has in DICE.
5) Removal of Natural Resources Engineering Facility (NREF): The removal of this building will determine if the the General Services building (GSB) has an independent effect on DICE.
6) Flattening the roof of NREF: The V shape of the upstream building could have a significant effect on this interaction. A test is made with the a flat roof, leveling the building to the average height which coincides with the height of the front of the building.
7) Inclusion of National Institute of Nanotechnology (NINT) and Mechanical Engineering (MecE): This buildings are located next to the ETLC and DICE buildings. In-terrain observations of strong gusts at pedestrian level between them hint the presence of pressure gradients.
8) Starting from the tallest obstacle: This case refers to starting to explicitly including the buildings from NREF.

A. Simulations setup

The simulations are set in an environment according to best practice guidelines [26]–[28]. This means using adequate domain dimensions (Lateral and Vertical blockages 14%), measuring horizontal homogeneity (Less than 5% error between inlet and incident (Fig. 4), and using the following boundary conditions: Equations (eqs. 2, 3, 5) for inlet and top boundary condition (streamwise direction); wall shear stress (eq. 6) and sand-grain roughness (eq: 7) for the bottom far from the domain; pressure outlet, and symmetry for the sides.

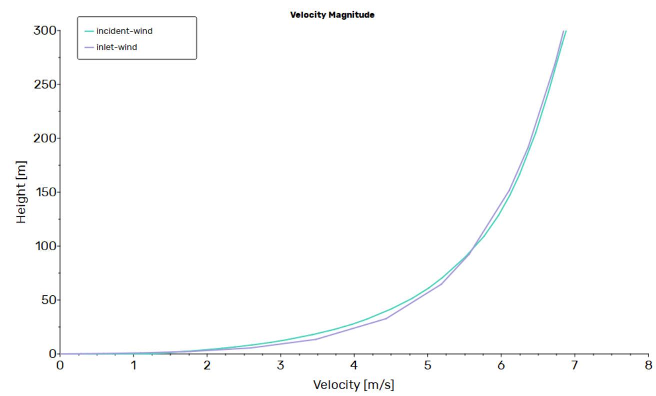

Figure. 4. Comparison between incident and inlet profiles between 0 and 200 m height. Reference velocity of 5.58 m/s at 80 m and z0 = 0.5m. Maximum relative error of 13.8% at 6 m height, average relative error of 5.88%.

$$U = \frac{u_{ABL}}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \quad (2)$$

$$k = \frac{u_{ABL}^2}{\sqrt{c_\mu}} \quad (3)$$

$$\varepsilon = \frac{u_{ABL}^3}{\kappa(z + z_0)} \quad (4)$$

$$\omega = \frac{\varepsilon}{(c_\mu\, k)} \quad (5)$$

$$\tau_w = \rho(u_{ABL})^2 \quad (6)$$

$$Ks = \frac{9.793\, z_0}{Cs} \quad (7)$$

Note that in these equations u_{ABL} is the friction velocity (0.45 m/s), κ is the von-Karman constant ($\approx$ 0.42), c_μ is a model constant (0.09), z_0 is the roughness classification (0.5 m according to local climate zone classification of the upstream urban areas [29]–[31]), k is the turbulence kinetic energy, ε is the turbulence dissipation rate, ω is the specific turbulence dissipation rate, and Ks & Cs are the sand-grain roughness parameters in Fluent. Such equations were set in the version R2023R2 of the program, the mesh was created using the Fluent mesh tool of the same version.

For the mesh generation, a poly-Hexcore method is applied, with refinement zones and prismatic boundary layers (Fig.5). Considering inflation layers and refinement zones for the building proximity and the zones of interest, the number of nodes is between 6-14 million cells, with a minimum of 3 cells per gap and 10 layers of inflation targeting a y+ between 30 and 200.

Turbulence was modelled using $k - \omega$ SST with production limiter, Kato-launder, curvature and corner corrections. SIMPLE and second order gradient approximations were used along with warped face and high order term relaxation. This configuration allowed us to obtain stable residuals of the order of 1e-5 in all simulations.

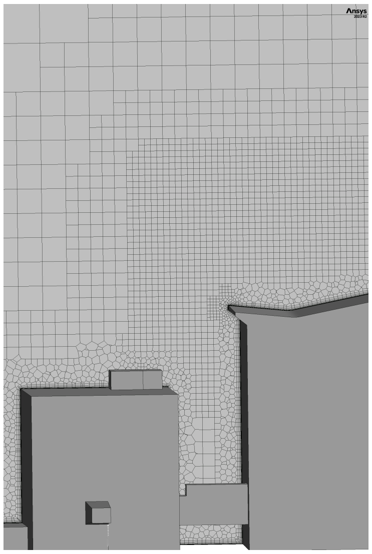

Figure. 5. Side view preview of the mesh close-up to NREF

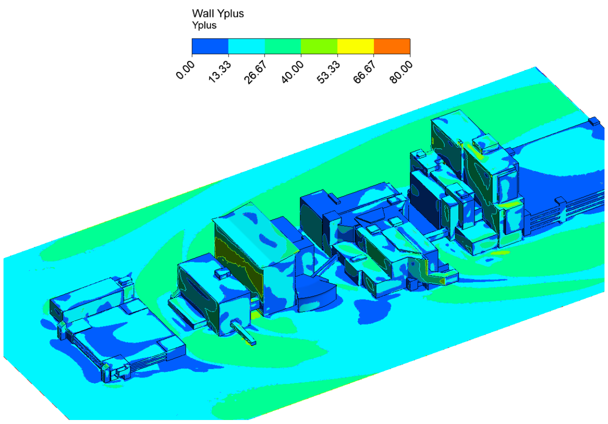

Figure. 6. Yplus in the building proximity in the reference case.

III. Results and Discussion

The changes with respect to the reference case are summarized in table I, the turbulence intensity for all cases is between 13 and 16 % (for an average of 5 m/s), which is considered high for wind turbines. Nonetheless, this is expected for urban wind scenarios. The observations from the first round of simulations are the following:

1) All aligned buildings (reference case): There is a strong observable effect on DICE from the other buildings (Fig. 7). Acceleration is observed from the S.parking to the Removal of General Service Buildings(GSB) into Natural Resources Engineering Facility (NREF), which is sustained by the Engineering Teaching Learning Complex (ETLC).
2) Removal of the parking lots: Downstream parking (W.Parking) is not relevant for the simulation, significant effect was observed from the removal of the upstream parking (S.Parking). It has more effect on the yields of DICE than on NREF.
3) Removal of Engineering Teaching Learning Complex (ETLC): Severe reduction of the velocity at the target spot. This is because it removal also included a building in front of DICE. Both of them have an effect in preventing the flow to recover from NREF effect (Fig. 8).
4) Removal of General Service Buildings(GSB): Without removing the S.Parking lot, the effects of this building are only observed on NREF.
5) Removal of Natural Resources Engineering Facility (NREF): There is a significant effect on DICE from its removal. Its effect is seen in wind velocity that results in a yield increment.
6) Flattening the roof of NREF: There is a change in the wind behaviour, yet is not as high as expected from the shape of the building this is likely due to the sharp corner separation at the building front.
7) Inclusion of National Institute Of Nanotechnology (NINT) and Mechanical Engineering (MecE): There is an increase in DICE velocity likely caused by the width of the canopy increasing the wind obstruction.
8) Starting from the tallest obstacle: The most significant effect observed in DICE yields. main evidence of chained effects of buildings.

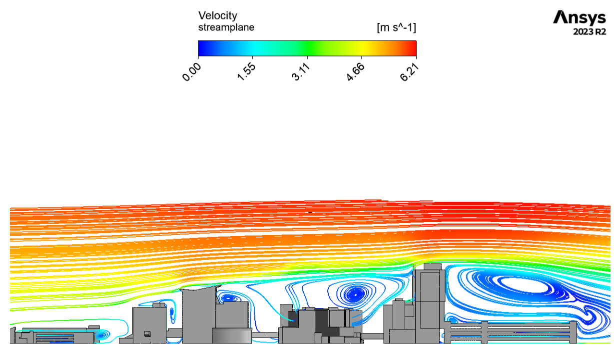

Figure. 7. Streamlines of reference case

Based on these results, the second round of simulations must be redesigned along with the setup of a validation experiment. The second round of simulations will start with a mapping (i.e. orthogonal sampling) of the effects of two simple buildings followed up with the addition of a third. By using the same pattern for the distance between the second and the third building, it should be possible to identify and isolate the combined effects. In contrast, the experiment for validation has the objective of determining the accuracy of the results to strengthen, or refute, these observations.

A wind tunnel experiment of this fraction of the University of Alberta's North campus will be set to validate the current observations. In this experiment, we must determine the accuracy of: (I) the incident wind velocity profile calculation, to validate the wall function corrections; (II) the vertical velocity

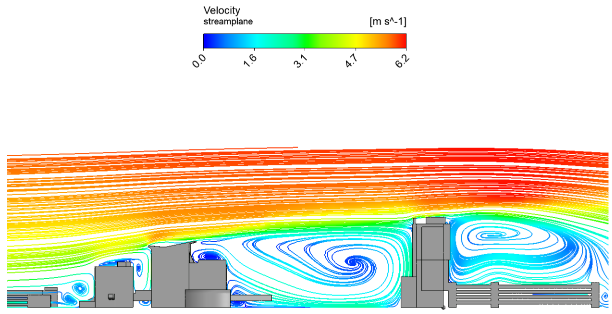

Figure. 8. Streamlines without ETLC and CHEME

TABLE. I
COMPARISON OF AVERAGE VELOCITY AND TOTAL POWER FOR ROUND 1 CASES. FROM EQUATION 1 WITHOUT C_p

Case	Location	Average V [m/s]	Total Power [W]
Main Cases			
Without MecE & NINT (REFERENCE)	DICE	5.77	15020
	NREF	5.33	34558
With MecE & NINT	DICE	5.69	13925
	NREF	5.27	33654
Relative error v/s MecE & NINT	DICE	1.35	7.86
	NREF	1.09	2.69
Relative Error with Respect to Reference [%]			
Without Parkings	DICE	-3.93	-10.72
	NREF	-3.06	-2.14
Without ETLC	DICE	-11.16	-29.27
	NREF	0.4	1.94
Without GSB	DICE	-0.29	0.38
	NREF	-4.88	-7.56
Without NREF	DICE	-1.97	-11.08
	NREF	-7.22	-14.26
Flat NREF	DICE	1.09	2.84
	NREF	-0.43	5.94
Starting from NREF (tallest obstacle)	DICE	-6.78	-17.81
	NREF	-13.47	-29.57

plane of DICE's hot spot (i.e. figure 2), as the main variable for this study; (III) the average turbulence kinetic energy estimated at DICE (i.e. figure 9), which is fundamental for the turbulence model and wind turbine selection. Such measurements involve the most challenging aspects of this type of simulation and hold strong importance in current research efforts in urban wind energy.

IV. CONCLUSION

The simulation results presented in Table I demonstrate that upstream building modifications have a significant impact at the target building. The removal of the Engineering Teaching Learning Complex (ETLC), the stadium parking lot (S.Parking), and Natural Resources Engineering Facility (NREF) produced marked changes in both the average wind velocity and the estimated power yield at DICE, the first two, exceeding the expectations set at the start of this study.

Alterations such as flattening the roof of NREF or the general service building had little impact contrary to what was expected. Given this, and the proof of the interaction between

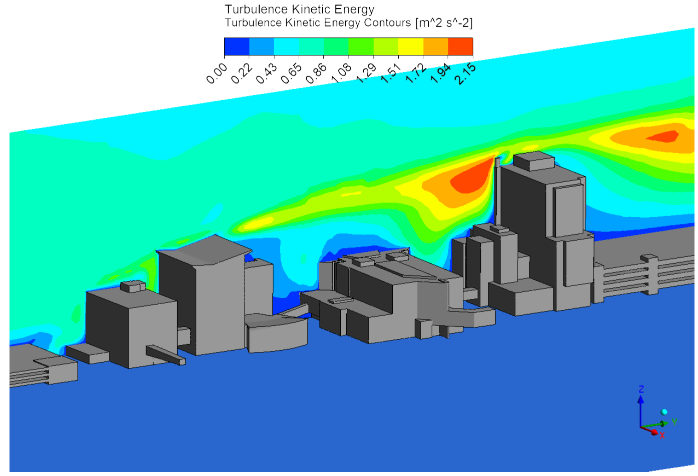

Figure. 9. Turbulence Kinetic energy profiles

the buildings a systematic approach is recommended using simplified versions of the present buildings.

Currently the authors are working on a experimental design for the second-round simulations, which are based on the conditions observed on the University of Alberta North campus. The study is quantifying if a pattern can be identified and parametrizied using 3 aligned buildings (simplified versions of DICE, NREF, and GSB) and measuring the difference on velocity and turbulence. Currently the variables studied are distance, width difference, height difference, surface roughness classification and velocity.

The findings for the second round of simulations are expected to set a foundation towards defining a decision criterion for including upstream buildings in CFD simulations of urban winds. However, the presence of multiple interdependent factors complicates the direct pursuit of a single indicator.

This work needs validation; a wind tunnel experiment is planed to support the observations regarding the influence of the geometrical variables. Additionally, field measurements are recommended to obtain the actual incident velocity profile, addressing the discrepancy in the surface roughness classification and to quantify the impact of removing vegetation and terrain irregularities.

In conclusion, the authors recommend that urban wind energy assessments carefully examine the local context and account for complex interactions such as the ones observed at the University of Alberta North Campus. Doing so is essential for performing more accurate assessments, fundamental for wind energy applications given their sensitivity to the velocity and turbulence demonstrated in by this exercise.

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