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Integrating Wind Flow Analysis in Early Urban Design: Guidelines for Practitioners

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ABSTRACT

The research focused on simulating wind patterns in urban planning design offers substantial contributions to both the social and economic aspects of the urban planning and design field. To begin with, it addresses a critical factor in urban development, especially in Mediterranean climates, where natural ventilation significantly influences summer comfort. By incorporating predictive numerical simulations of urban wind patterns, this study provides valuable insights into improving outdoor thermal comfort within urban areas. This holds particular importance in the context of adapting to climate change, as it equips urban planners and architects with informed decision-making tools to create more sustainable and comfortable urban environments. Additionally, this research makes an economic contribution by presenting guidelines for iterative wind simulations in the early stages of designing medium-scale urban projects. Through the validation of a simulation workflow, it streamlines the design process, potentially reducing the time and resources required for urban planning and architectural design. This enhanced efficiency can result in cost savings during project development. Moreover, the study's recommendations concerning simulation parameters, such as wind tunnel cell size and refinement levels, offer practical insights for optimizing simulation processes, potentially lowering computational expenses and improving the overall economic viability of urban design projects. To summarize, this research effectively addresses climate-related challenges, benefiting both social well-being and economic efficiency in the field of urban planning and design, while also providing guidance for more efficient simulation-driven design procedures.

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Highlights:	Contribution to the field statement:
To develop a coherent urban planning approach that aligns with our current challenges, it is imperative to identify and account for the key variables that significantly influence the microclimate. This study aims to provide guidelines for architects, urban planners, and landscapers to conduct iterative CFD simulations during early design stages. These simulations focus on integrating microclimatic parameters, particularly wind flow, by investigating various model sizes and two primary parameters: simulation time and accuracy. This research has underscored two crucial factors: the necessity of considering a broader context in all directions and the adoption of a moderate level of refinement for the urban morphology.	-The research focused on simulating wind patterns in urban planning design offers substantial contributions to both the social and economic aspects of the urban planning and design field. -This research effectively addresses climate-related challenges, benefiting both social well-being and economic efficiency in the field of urban planning and design, while also providing guidance for more efficient simulation-driven design procedures

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1. Introduction

The ecological transition intends to redefine the relationship of sustainable balance between human activities and the environment. It must simultaneously address the challenges of mitigating climate change, as well as the scarcity of resources, the accelerated loss of biodiversity, and the multiplication of health and environmental risks. At the territorial level, the threats arise from both the manifestations of ecological upheavals and the structure of the socio-economic systems within territory. Territorial analysis should enable a transversal and multi-scalar diagnosis of the environment and the society in which the project takes place, leading to urban and architectural adaptation solutions. Cities concentrate wealth and populations and are responsible for numerous sources of pollution. Analyzing the true impact of cities is challenging, as it is the result of the chosen and desired societal model. Some studies suggest that cities are responsible for 40% of greenhouse emissions, with these urban areas accounting for 70% of energy consumption, a demand that could increase by another 50% by 2050. Presently, over three and a half billion people reside in urban areas globally, and according to the UN, this trend is on the rise. The current urban model not only contributes to the degradation of several planetary boundaries but also heightens certain risks. The challenge of the 21st century will be to accommodate more people in cities while reducing their overall impact and improving the current quality of life. Planning urbanism and architecture in harmony with a territorial project that integrates planetary limits becomes crucial. Preliminary design decisions influence the entire life cycle of a building and the uses of its inhabitants and must not neglect these aspects.

Territorial urbanization has altered the local climate, through land use, urban morphology, the thermo-physical properties of construction materials, roads, and other infrastructures, as well as the heat generated by human activities. These changes induce microclimatic phenomena specific to build environments. Alterations in temperature, relative humidity and air flow influence the well-being of inhabitants, the use of public space, energy consumption and the preservation of biodiversity. Emerging urban design methods are taking into account these microclimatic parameters. The research conducted by Emanuele Naboni on the implementation of an urban regenerative design, as well as the architectural projects undertaken by the sustainable design and engineering agency "Franck Boutté Consultants" reflect a similar multi-criteria environmental analysis approach. The proposed workflow involves an iterative process of simulating various parameters affecting climate, energy, biodiversity, resource consumption and human well-being (Naboni et al., 2019). Although many policies and recommendations advocate for such methodologies, it remains challenging to find concrete examples of their implementation at the urban scale. This type of project remains the prerogative of a few companies or institutions with significant human and material resources. Typically, considerations related to exterior or interior thermal comfort and energy consumption come into play during the final design phases (Mauree et al., 2019). Simulations of microclimatic parameters are essential to validate hypotheses in the early design stages and meet energy consumption requirements (Mackey et al., 2017). Simulations also help integrate future scenarios into project forecasts. However, the difficulty of performing certain simulations, the time required and the specific knowledge needed to interpret results hinder the adoption of these simulations in the architectural and urban professional practice.

In this work, our focus lies on the urban wind pattern, one of the primary factors influencing urban thermal comfort. The main objective is to propose guidelines for carrying out iterative Computational Fluid Dynamics (CFD) simulations for architects, urban planners and landscapers during early design stages. Most of these professionals may not possess the technical knowledge to easily execute accurate simulations. For this, we will use a previously considered case study, the Village Grec, in Leucate, France (Paris et al., 2022) which represents medium urban density housing near the Mediterranean Sea. While all microclimate variables are important, wind flow requires specific attention. Firstly,the urban wind model represents the second most significant parameter in simulating the UTCI comfort index, following the impact of the heat exchange model of the sky (Mackey et al., 2017). Furthermore, CFD simulations are very time-consuming, and do not align with design schedules. Finally, wind plays a vital role in achieving and sustaining acceptable comfort levels during periods of high heat in the Mediterranean regions. A previous study on evaluating outdoor thermal comfort through the Physiologically Equivalent Temperature (PET) highlighted the importance of wind accessibility (Paris et al., 2022). Measurement points with air speed greater than 0.5 m/s are the most comfortable never reaching the very hot zone during the day. In contrast, a measurement point with a consistent air velocity below 0.1 m/s remains in the very hot zone 87.5% of the time. The figure below illustrates the significance of precise wind simulations for each urban context. Data from meteorological stations often provides values significantly higher by 5 to 10 m/s compared to wind speeds measured at specific urban points 1, 2, 3, 4, 7 and 9 (Figure 1). After logarithmic regression of the wind speed, to consider the height difference between the weather station and the measurement site, the values remain very different.

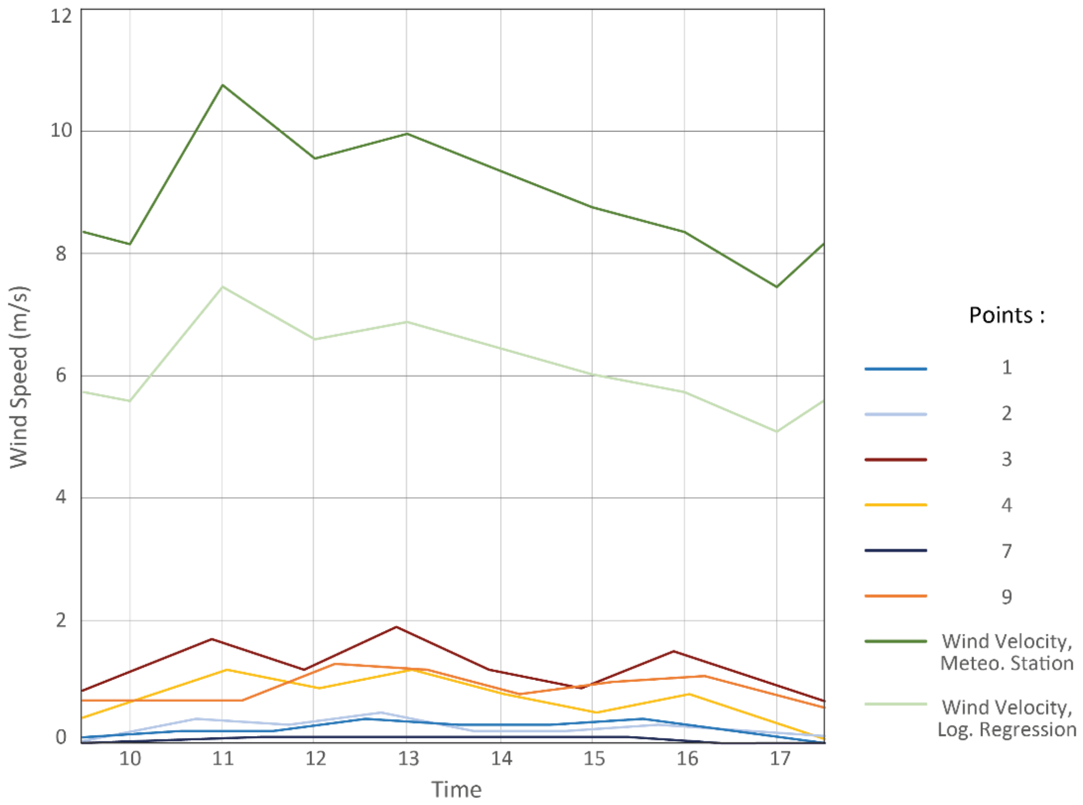

Figure 1. Wind profile on the measuring points and data from the Meteorological Station.

The study carried out here involves simulating the wind flow at the measurement site using wind data from the specific day as input, and then comparing the results obtained with the actual measured values. We examine how varying the context around the measurement points and the level of refinement in morphology impact the time required and the accuracy of the results. Through this validation of a simulation workflow, we will be able to provide recommendations applicable to urban projects of a similar scale.

2. Material and Methods

To offer CFD workflow recommendations to architects, urban planners and other designers, we have established a four stages approach:

- Selecting simulation software based on our criteria
- Configuring the study parameters and selecting the study variables
- Describing the workflow
- Evaluating the results obtained

The study is then conducted by following the steps depicted in figure 2.

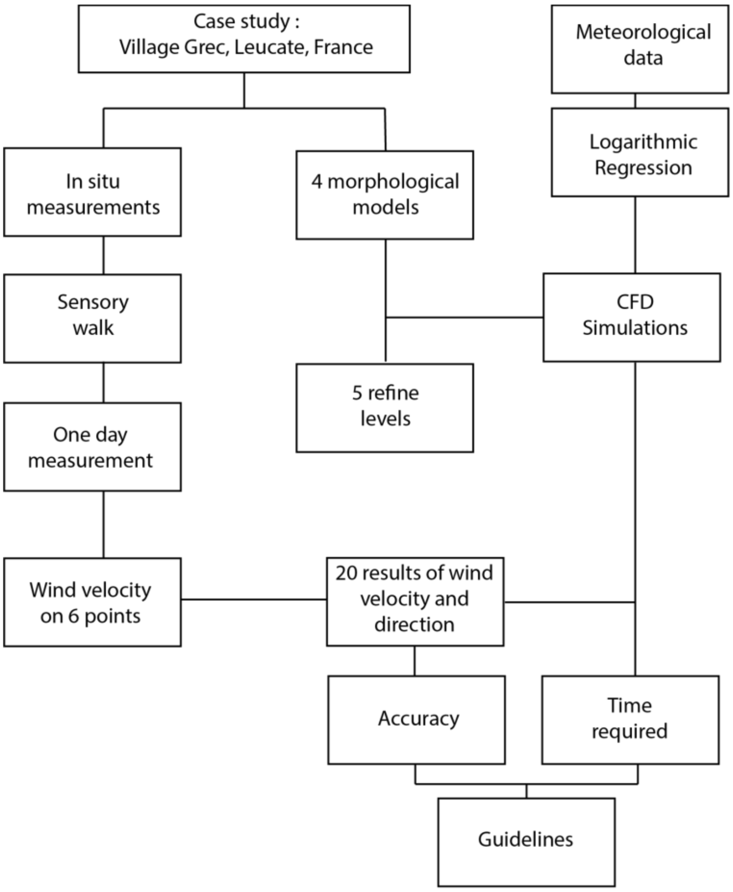

Figure 2. Workflow of the methodology.

2.1 CFD Parametric Simulation Tools

The use of CFD simulation tools in the design of public spaces and buildings is experiencing a rapid increase. This is particularly evident in the proliferation of scientific articles published on this subject over the past two years (Hu et al., 2022). Furthermore, there is a growing demand for coupling radiation and energy simulations. Combining these results enables a thorough evaluation of project assumptions during the design phases. Most of these simulations can be directly visualized through the interfaces of design platforms such as Autodesk Revit, Rhino or SketchUp. Currently, there are more than a dozen plug-ins or applications associated with design programs. Given the recent surge of interest in the integration of CFD simulation into urban and architectural projects, our primary consideration for selecting a CFD simulation tool is based on the study conducted by Hu Y. (2022) on *"Application of CFD plug-ins integrated into urban and building design platforms for performance simulations: A literature review"*. Our objectives are to secure a CFD simulation tool that can:

- Be coupled with other simulations relating to the urban microclimate
- Deliver reliable and accurate results
- Handle diverset scales within urban and architectural design
- Be easily customizable to suit specific project requirements

The Rhino modeling software, with its plug-in platform Grasshopper, provides a wide range of CFD plug-ins that have been developed in Open Source. This ensures their continual development and expansion over time (McNeel, 2010). As a result, we have chosen to work with one of the tools available within Grasshopper. The main options include Butterfly from Ladybug Tools, Swift, Eddy3D, proceduralCS, ixCube CFD, GH_Wind, WS-Snake and FlowDesigner. Parametric design platforms like Rhinoceros and Grasshopper offer users greater flexibility in conducting wind simulations. This coupling of simulations with other microclimatic analysis allows for in-depth studies. Moreover, these platforms provide and ideal environment for organizing and expanding the functionality of plug-ins. The three most notable free tools in recent times are Butterfly, Swift, and Eddy3D. All of them utilize the validated external CFD solver OpenFOAM, to ensure accuracy and efficiency (Chronis et al., 2017). These tools can also be integrated with other simulations. Swift, in particular, stands out for its user-friendly graphical interface making it more accessible for architects, urban planners or landscapers with limited expertise in the field. On the other hand, Butterfly, which appears to be more tailored to engineers (Mackey et al., 2017) is the most widely used plugin on Grasshopper, accounting for approximately40% simulations on this platform. In recent years, numerous studies have validated the simulation capabilities of Ladybug tools (Sun et al., 2020; De Luca et al., 2019; Ibrahim et al., 2021) across various scales and with various microclimatic parameters. This validates our choice to opt for Grasshopper in 2023.Among the CFD plugins available on Grasshopper, Butterfly has been extensively used for wind pattern analysis in medium-density urban environments. Many studies published recently employ multi-criteria simulations using Butterfly and other components of Ladybug Tool. (Chronis et al., 2017; Elwy et al., 2018; Ibrahim et al., 2021; Loh and Bhiwapurkar, 2022). It's important to note that Ladybug Tools supports flexible coupling between Butterfly and other validated simulation modules, such as EnergyPlus/OpenStudio (Roudsari et al., 2013).

2.2 CFD Simulation Guidelines

To conduct precise CFD simulations for urban spaces, a wealth of reference studies have provided invaluable simulation recommendations and guidelines (Blocken et al., 2015; Ferziger and Peric, 2002; Tamura et al., 2008; Tominaga et al., 2008; Toparlar et al., 2017; Franke et al., 2011). These authors provided important information regarding the turbulence model, the boundary conditions, the grid resolution, and the computational domain (Blocken et al., 2012). Butterfly offers a wide range of options for selecting the turbulence model and the mathematical model, allowing us to parameterize the wind tunnel mesh and geometry as desired. Therefore, we will rely on the studies cited above to define the simulation parameters. Some general parameters will be fixed, while others will be variable to be studied. These three parameters will remain unchanged:

- Mathematical model: steady RANS; 169 out of 176 (96%) of CFD analysis processed between 1998 and 2015 used this model. The literature demonstrates that the accuracy of the RANS model is sufficient, and the additional time required for using the LES model is not justified (Toparlar et al., 2017).
- Turbulence model: RNG k-epsilon; the second most popular turbulence model is the standard k-ε model, used in 45 studies out of 176 (25%). Advanced models like the Renormalization Group (RNG) k-ε have shown a similar popularity and are increasingly employed (Toparlar et al., 2017; Franke et al., 2004). The most widely used model according to the 2017 study owes its popularity to its exclusivity in certain programs such as ENVI-Met and is not available in Butterfly. Thus, the RNG k-epsilon model is the best available.
- Computational domain: Top, Lateral, Inlet Boundaries: 5H (with H the height of the tallest building) (Tominaga et al., 2008); or a Blockage Ratio <3% ; in order to avoid an artificial acceleration of wind speed (Franke et al., 2004).

These 3 parameters will be study variables in order to see their impact on time and accuracy:

- Wind tunnel size: 1 and 2-meter; in a medium urban densities, streets and alleys can be narrow, which limits us from meshing the geometry with dimensions exceeding 2 meters to achieve accurate results while adhering to minimum refinement guidelines (Franke et al., 2011)
- Grid resolution: 0 to 4 refine levels; in the area of interest, it is recommended to have at least 10 cells per cube root of the building volume (Franke et al., 2011; Tominanga et al., 2008). In the case study, the buildings have a volume close to 1000 cubic meters. Therefore, the recommended minimum number of cells is one per cubic meter.
- Residuals reduction: 3 to 5 orders of magnitude; some studies recommend 3 or 4 (Ferziger and Peric, 2002; Tominaga et al., 2008), others 5 (Franke et al., 2004). There appears to be no consensus on this value for CFD urban simulations. Consequently, one of the conclusions involves establishing our position in this regard.

2.3 CFD Workflow

2.3.1 Initial Wind Input

Wind is a crucial parameter in urban physics (Blocken et al., 2015). However, obtaining wind data in a specific context requires either conducting measurements or performing accurate simulations. Most of the available data are derived from weather stations at the nearest airports. Often, these data do not represent the topographical context of the area under study, and let alone the flow modifications generated by urban built environment This discrepancy is evident in measurements conducted in *Village Grec*. There are significant differences between the daily weather data and the values measured between 9:33 a.m. and 5:23 p.m. (Figure 1, Table 1). The provided measurements are averages over 5-minutes intervals (Sansen et al., 2021). A first approximation of the wind speed at the station to the speed in the urban space involves applying a logarithmic regression that corresponds to the roughness of the geographical context.

Table 1. Wind speed and direction from the Meteorological Station, wind speed after logarithmic regression, and data obtained at each point, hour per hour during 22/06/2020.

Meteorological station data			**Log Reg.**	**Point 1**		**Point 2**		**Point 3**		**Point 4**		**Point 7**		**Point 9**	
Time	Wind direction *(°)*	Wind speed *(m/s)*	Wind speed *(m/s)*	Time	Wind speed *(m/s)*	Time	Wind speed	Time	Wind speed *(m/s)*	Time	Wind speed *(m/s)*	Time	Wind speed *(m/s)*	Time	Wind speed *(m/s)*
9h	310	8	5,7												
10h	320	7,8	5,5	9h33	0,1	9h43	0,1	9h53	1,1	10h03	0,7	10h23	0	10h13	0,7
11h	320	10,4	7,4	10h33	0,2	10h43	0,4	10h53	1,7	11h03	1,2	11h26	0,1	11h13	0,7
12h	320	9,2	6,5	11h33	0,2	11h43	0,3	11h53	1,2	12h03	0,9	12h23	0,1	12h13	1,3
13h	320	9,6	6,8	12h33	0,4	12h43	0,5	12h53	1,9	13h03	1,2	13h23	0,1	13h13	1,2
14h	320	9	6,4	13h33	0,3	13h43	0,2	13h53	1,2	14h03	0,8	14h23	0,1	14h13	0,8
15h	320	8,4	5,9	14h33	0,3	14h43	0,2	14h53	0,9	15h03	0,5	15h23	0,1	15h13	1
16h	320	8	5,7	15h33	0,4	15h43	0,3	15h53	1,5	16h03	0,8	16h24	0	16h13	1,1
17h	310	7,1	5,0	16h33	0,2	16h43	0,2	16h53	1	17h03	0,3	17h23	0	17h13	0,7
18h	310	7,8	5,5												
Average:		**8,5**	**6,03**		**0,3**		**0,3**		**1,3**		**0,8**		**0,1**		**0,9**

For the CFD simulations of this study, we choose the initial input values:

- Reference wind height: 10 m.
- Wind speed: 6.03 m/s
- Wind direction: 40º North West
- Landscape roughness: 0.5' (very rough)

2.3.2 Model

To quantify the influence of the context and refinement levels on time and accuracy, we analyzed four models. These models depict an expanding environment around the target street (Figure 3). The goal of this method is to understand the influence of the context and its significance in achieving accurate results. Morphology 1 includes only the building to the west of the street, obstructing direct wind from the northwest. Morphology 2 incorporates the second building, forming the streets's walls and creating the urban canyon. The third adds the two buildings to the north of the street, creating a physical barrier for the wind. Finally, morphology 4 encompasses the entire built structure of the *Village Grec*. These different models are represented in figure 3, labeled from 1 to 4.

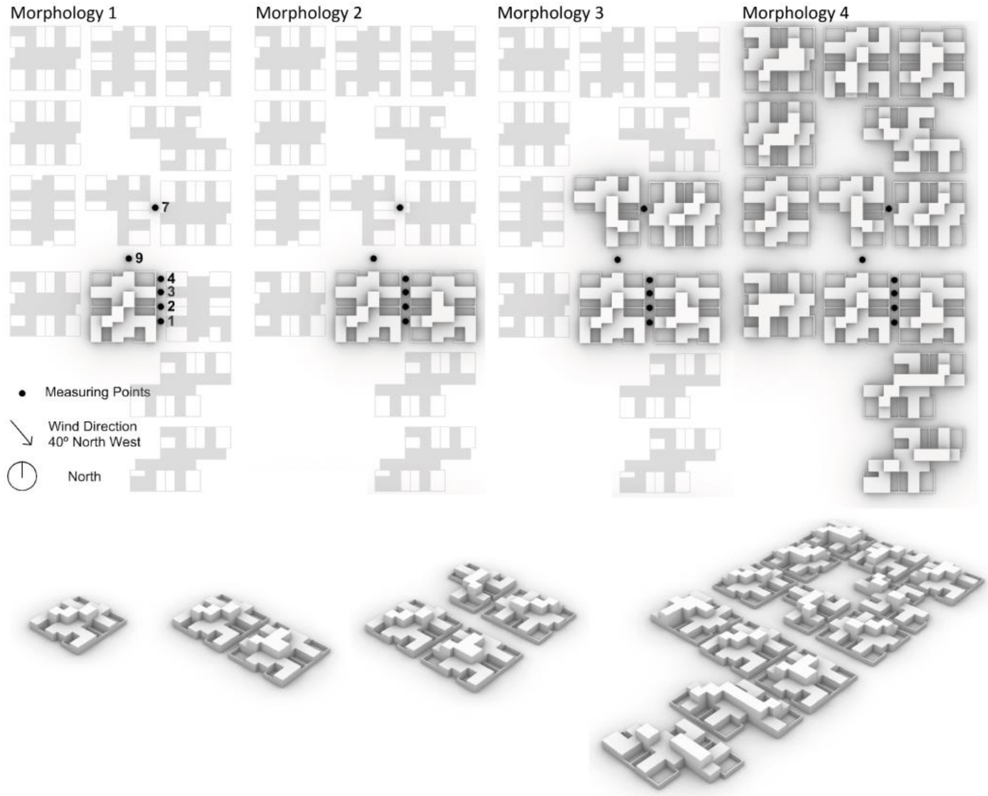

Figure 3. 3D representations of morphologies 1 to 4.

Each of these four morphologies will be refined across several progressive levels, ranging from 0 to 4 (Figure 4). At each level, the base cell size in the wind tunnel is halved, decreasing from1 meter to 0.0625 meter. Following the recommendations provided in part 2.2, level 0 corresponds to the minimum recommended refinement. Subsequently, cell sizes were further reduced to accurately represent the 1.60-meter-high walls of the patios that form the streets. Field observations (Sansen et al., 2021) and preliminary studies indicate the pivotal role played by these patios in influencing the wind patterns.

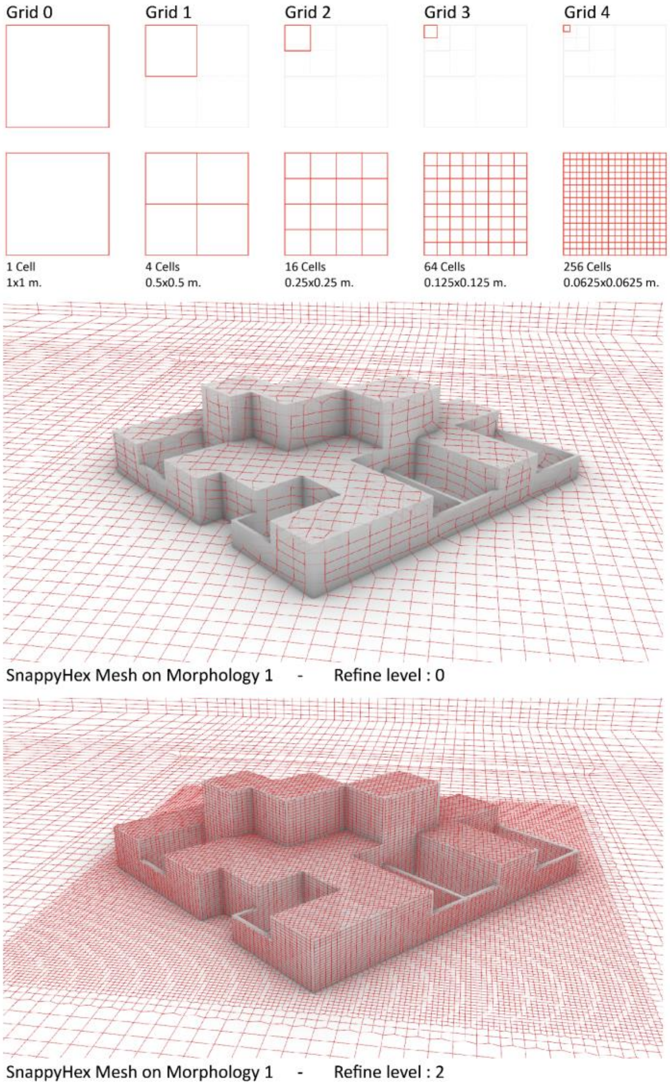

Figure 4. Visual representation of growing refine levels.

2.3.3 Verification Tests

Our goal is to approximate the simulated values to the measured values while maintaining consistent simulation times. To achieve this, we will investigate the following:

- Time required to obtain wind speed results based on different morphologies and levels of refinement
- Convergence of the simulated parameters to ensure the reliability of the results. Theseparameters include the three wind vectors, the values of k and epsilon, as well as three pressure values. Simulations were initially performed with a 5-order of reduction, and subsequently with 4, for all parameters.
- Root Mean Square (RMS) error according to refinement levels to assess the impact of mesh refinement. This enables us to estimate the discretisation error of each coarser grid compared to grid 4. Verification tests are crucial in determining the accuracy of each simulation.
- Wind speed at measuring points for comparison purposes.

3. Results

The primary objective of this work is to provide guidelines for architects and other designers. As a result, the findings are presented in a format that allows us to draw conclusions regarding simulation parameters and context depending on the time and precision of the results. The initial observation in terms of morphological context is depicted in Figure 5. In this figure, the top image illustrates the wind flow results without soil, while the bottom image shows results with soil. Notably, there are numerous additional recirculation effects. Although Butterfly does not provide the capability to assign roughness values to the different materials, tests carried out indicate more accurate results with the presence of soil. For this study, all simulations were conducted with both configurations. However, for the subsequent results, only those with the presence of soil were considered.

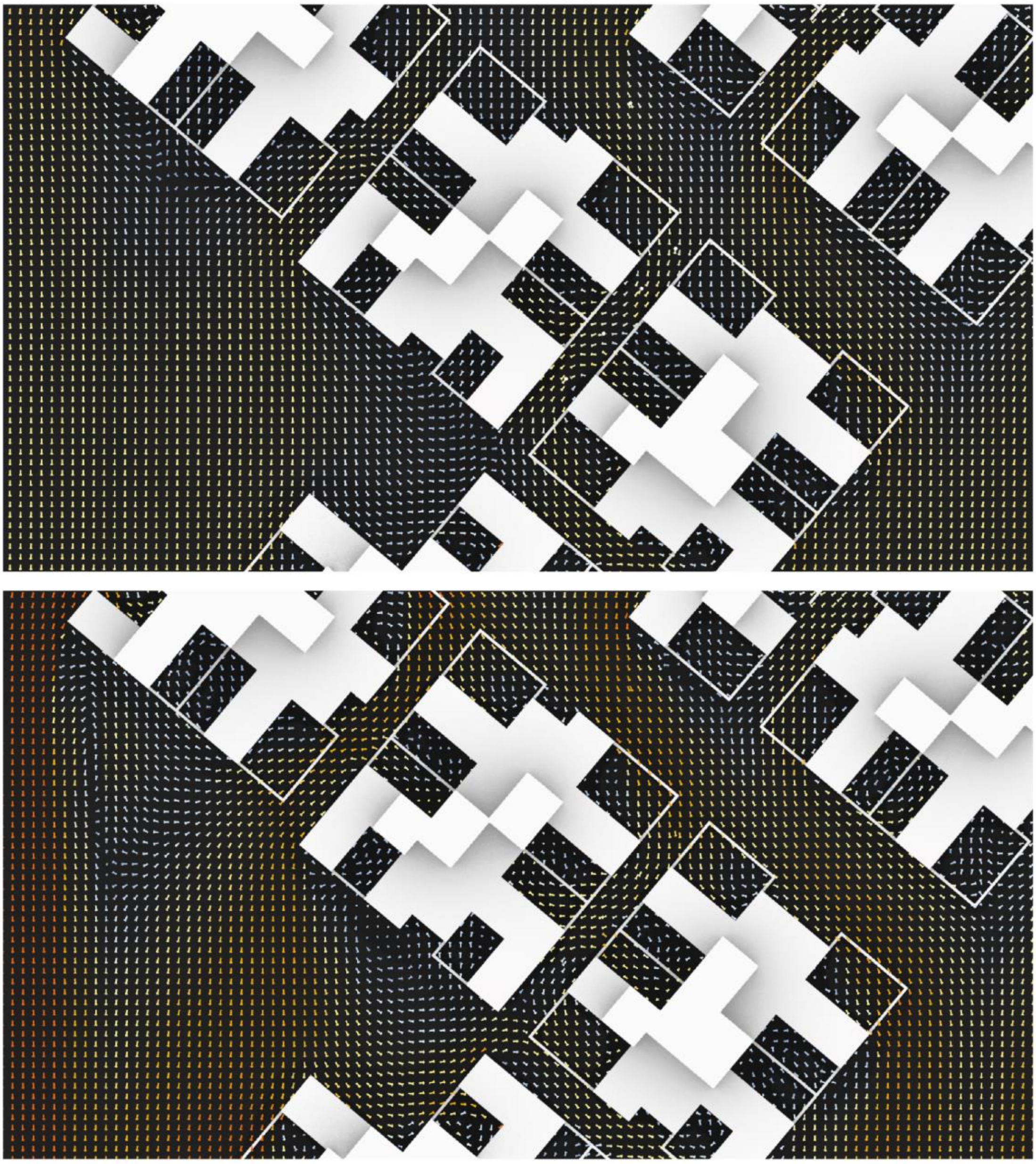

Figure 5. Representation of wind speed vectors for simulations on morphology 4, without soil (top), and with soil (down).

3.1 Time versus Accuracy

The initial comparison step concerns the computation time, which can be divided into two components; meshing time and solution time, representing respectively 10-20% and 80-90% of the total time (Table 2). It is important to note that as the volumetry complexity increases, the solution time becomes dominant over the total time (Maffessanti et al., 2019). Depending on the simulation programs and the associated graphical interfaces, we could also consider parameterization time. However, Butterfly allows many iterations, enabling quick and easy modification of initial parameters or morphology. Consequently, we consider parameterization time insignificant in this study. An exponential increase time is observed with the refinement of the model (Figure 6). The left side of the figure represents simulation time for a wind tunnel with 1-meter base cells, while the right side depicts results with 2-meter cells. Notably, the accuracy over the surveyed area remains consistent, albeit with varying levels of refinement. In other words, refinement 2 in part a. corresponds to the same level of precision as refinement 3 of part b. Comparing these two graphs reveals that, at the same level of refinement, the size of the wind tunnel cells has a minimal impact on computation time. For the lower refinement levels (0 and 1), computation time is reduced by 40 to 70%. However, starting from refinement level 2, computation time becomes roughly equal. In quantitative terms, it is evident that the time increases according to the size of the considered context. For non-isolated morphologies, such as 3 and 4, calculation time quickly becomes substantial. For morphology 3, it requires approximately 15 minutes for refinement level 2 and 65 minutes for level 3. For morphology 4, these times increase to 65 and 290 minutes respectively.

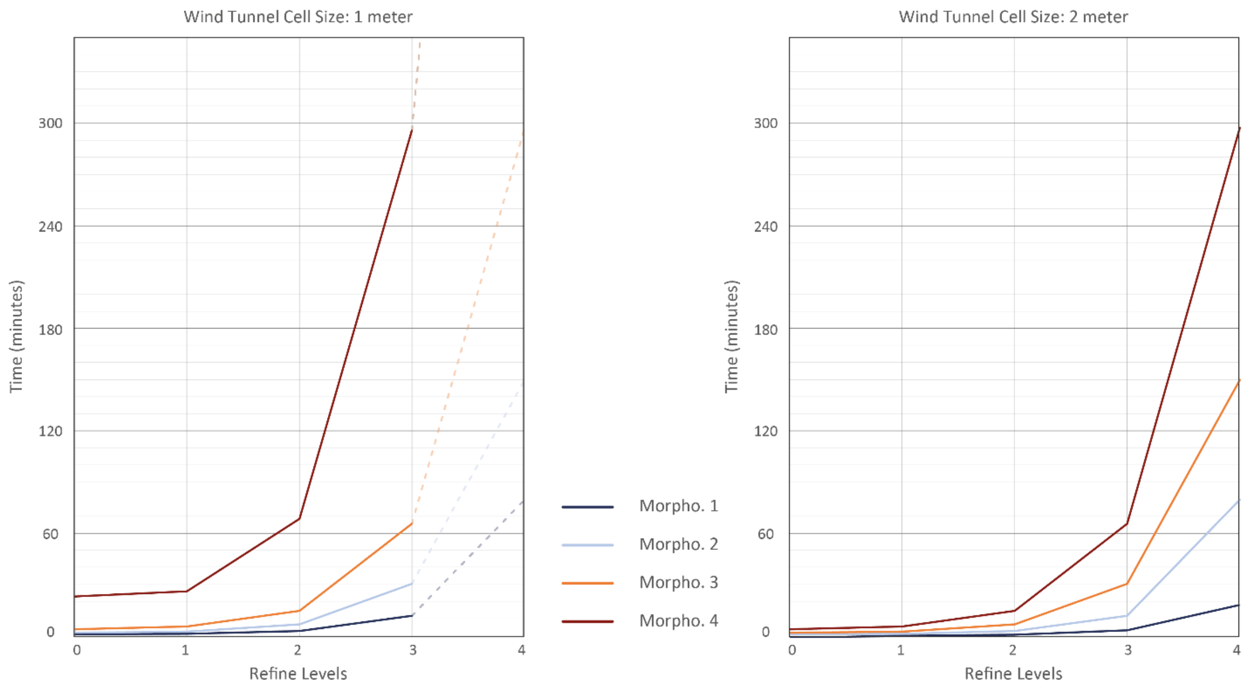

Figure 6. Time versus accuracy diagram.

Based on these simulation times, it can be concluded that refinement levels 0, 1 and probably 2 allow for an iterative process. At refinement level 3, particularly with an extended context, computation time becomes relatively long but remains manageable. However, it can still be considered within the study's scope. On the other hand, refinement level 4, for 1-meter wind tunnel cells, is excluded from the study. The calculation times associated with this level do not permit an iterative process between architectural design and the verification of morphological hypotheses. Approximations and tests conducted indicate that computation times range from a few hours for simple morphologies to several tens of hours for the most complex.

Table 2. Total time to obtain results for all morphologies and refine levels, with 1- and 2-meter Wind tunnel cell size.

Wind Tunnel Cell Size	Refine lvl.	Morpho. 1	Morpho. 2	Morpho. 3	Morpho. 4
1 meter		*Time (min.)*	*Time (min.)*	*Time (min.)*	*Time (min.)*
	0	1,2	2,2	4,2	23,4
	1	1,5	2,9	5,8	26,5
	2	3,2	7,1	15,0	68,8
	3	12,1	30,8	66,0	295,9
Wind Tunnel Cell Size 2 meter	**Refine lvl.**	**Morpho. 1**	**Morpho. 2**	**Morpho. 3**	**Morpho. 4**
	0	0,4	0,6	1,0	3,4
	1	0,4	0,8	1,2	3,8
	2	0,7	1,8	2,6	11,9
	3	2,7	7,2	13,0	59,0
	4	12,8	38,4	65,8	286,7

Only the results for the 1-meter wind tunnel cells are presented below. Given that the values and orders of magnitude are very similar, the conclusions drawn from the subsequent results remain unchanged, regardless of the wind tunnel mesh.

3.2 Residual Reduction

The second stage involves verifying the convergence of the simulation parameters, indicating how much the error has reduced (Franke et al., 2004). In the majority of our simulations, one pressure parameter never reaches the 5th order of magnitude (Figure 7). In a few instances, the first and second pressure parameters as well as the wind vector U(x) never reaches the 5th order of magnitude. Consequently, we have chosen to adopt the 4th order of magnitude as convergence criterion which is considered acceptable for urban simulations (Tominaga et al., 2008).

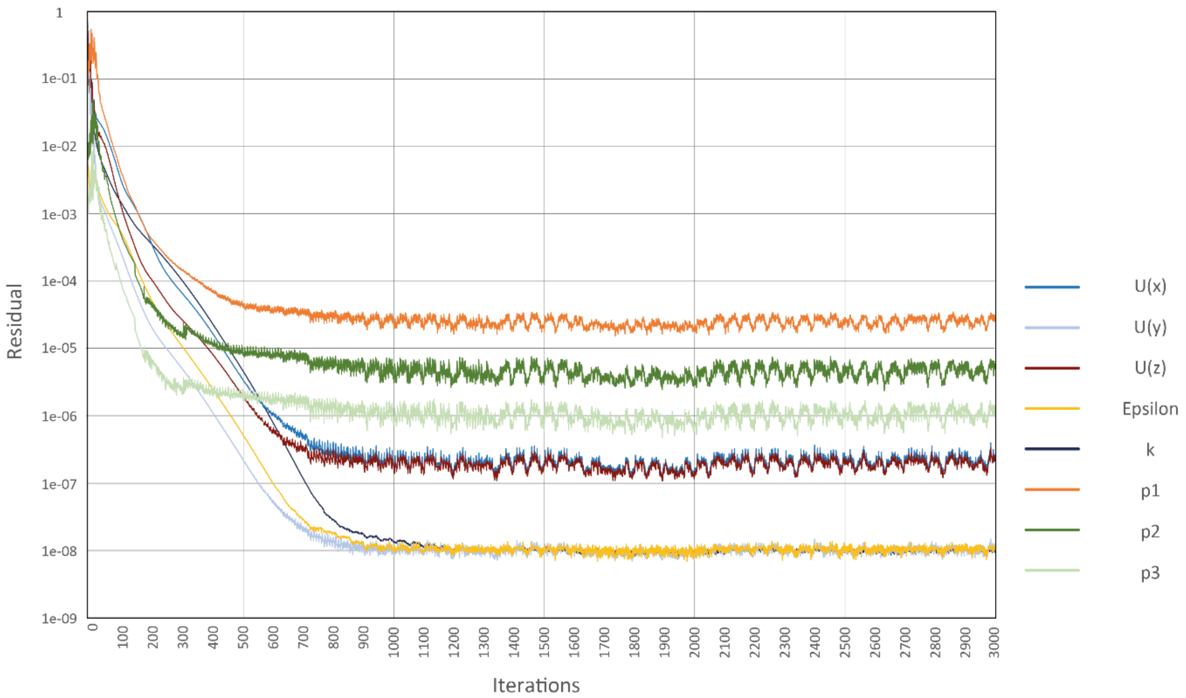

Figure 7. Residual Logarithmic graph for Morphology 2, Refine level 2.

3.2 RMS Error

The third stage of the results analysis concerns the significance of refinement levels, involving the calculation of the RMS error of each grid by comparing it to the most refined (Franke et al., 2011). These calculations were performed for the three wind vectors U(x), U(y) and U(z). It is worth noting that the trends presented for U(z) (Figure 8) are consistent with those obtained for the other two directions. The RMS error was computed based on three sets of different points: a first point grid on the enlarged model, a second on the street, and the last on a 1-meter-wide strip in the center of the street.

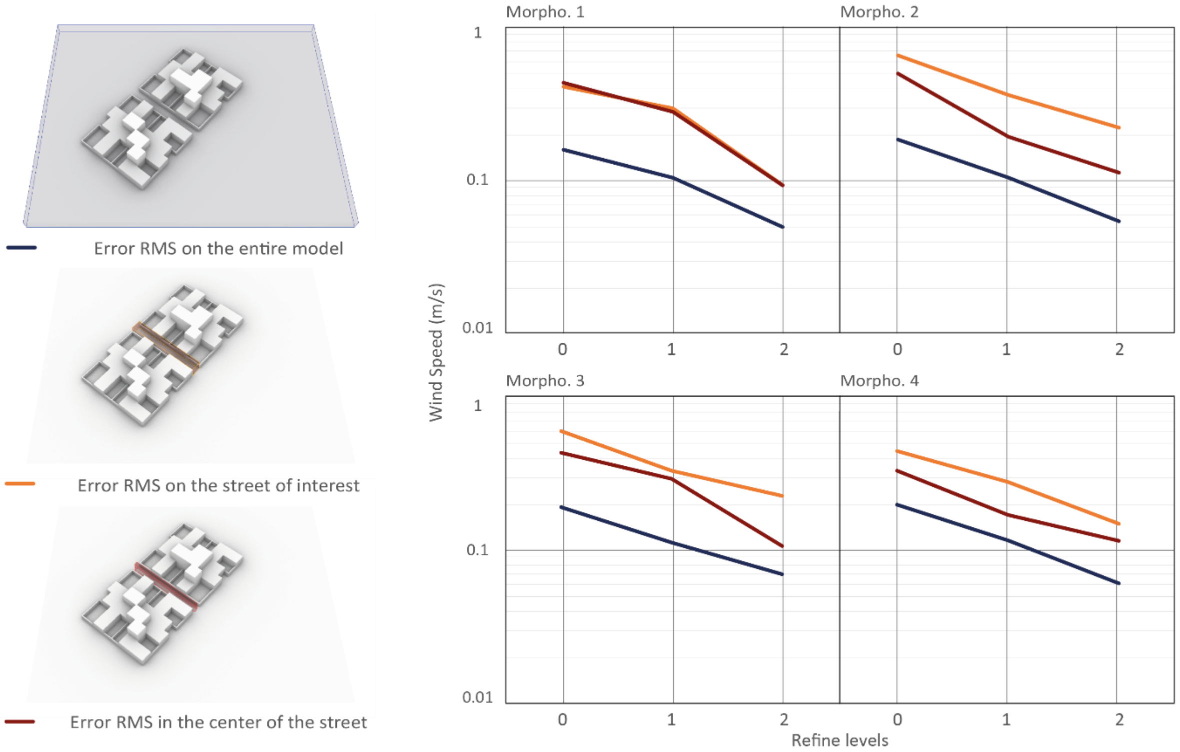

Figure 8. Error RMS graph: velocity U(z), for the 4 morphologies.

As expected, the results demonstrate improved accuracy as the level of refinement increases (Maffessanti et al., 2019). Notably, there is a tenfold improvement between levels 0 and 2, which amounts to approximately 0.1 for all morphologies. We notice a slightly better precision for the values in the center of the street compared to the entire street. This observation underscores that effects closely associated with buildings are significantly more accurate with higher refinement levels. Furthermore, the results for the entire model are consistently more accurate on average. This can be attributed to the large number of points situated between the village and the wind tunnel boundaries, which are unaffected by the geometry.

Table 3. Root Mean Square error.

		Morpho. 1			Morpho. 2			Morpho. 3			Morpho. 4		
	Ref. lvl	*Model*	*Street*	*Center*	*Model*	*Street*	*Center*	*Model*	*Street*	*Center*	*Model*	*Street*	*Center*
U(x)	*0*	0,2	0,5	0,5	0,2	0,4	0,4	0,2	0,5	0,4	0,2	0,5	0,5
	1	0,1	0,4	0,4	0,1	0,3	0,3	0,1	0,3	0,3	0,1	0,3	0,3
	2	0,1	0,1	0,1	0,1	0,2	0,1	0,1	0,1	0,1	0,1	0,2	0,1
U(y)	*0*	0,5	1,3	1,3	0,4	0,6	0,4	0,4	0,6	0,7	0,4	0,7	0,6
	1	0,2	0,6	0,7	0,2	0,4	0,3	0,2	0,4	0,4	0,2	0,3	0,3
	2	0,1	0,2	0,2	0,1	0,2	0,2	0,1	0,2	0,2	0,1	0,2	0,1
U(z)	*0*	0,2	0,4	0,4	0,2	0,7	0,5	0,2	0,6	0,4	0,2	0,4	0,3
	1	0,1	0,3	0,3	0,1	0,4	0,2	0,1	0,3	0,3	0,1	0,3	0,2
	2	0,0	0,1	0,1	0,1	0,2	0,1	0,1	0,2	0,1	0,1	0,2	0,1

Following the provided guidelines, it is evident that the chosen levels of refinement do not entirely eliminate grid dependence. The results show a reduction of only one order of magnitude, whereas the recommended practice is to achieve a reduction of two orders of magnitude (Ferziger and Peric, 2002; Franke et al., 2007; Tominaga et al., 2008). However, it is important to consider that disciplines accustomed to CFD simulations need much more precise results than those required for a bioclimatic architectural approach during the early design stages.

3.3 Wind Velocity

In the final stage of the results analysis, we compare the values obtained across different morphologies and refinement levels with the measurement points. The wind speed values provided in the table and displayed on the graphs represent the average of measurements taken at each point during the campaign, between 9:30 a.m. and 5:30 p.m. The graphs depict the simulated values at various points for each morphology (see Figure 9), with the shades of color indicating the different levels of refinement. Notably, Point 7 is not considered for the first and second morphologies due to its location outside the geometric model, rendering the values irrelevant.

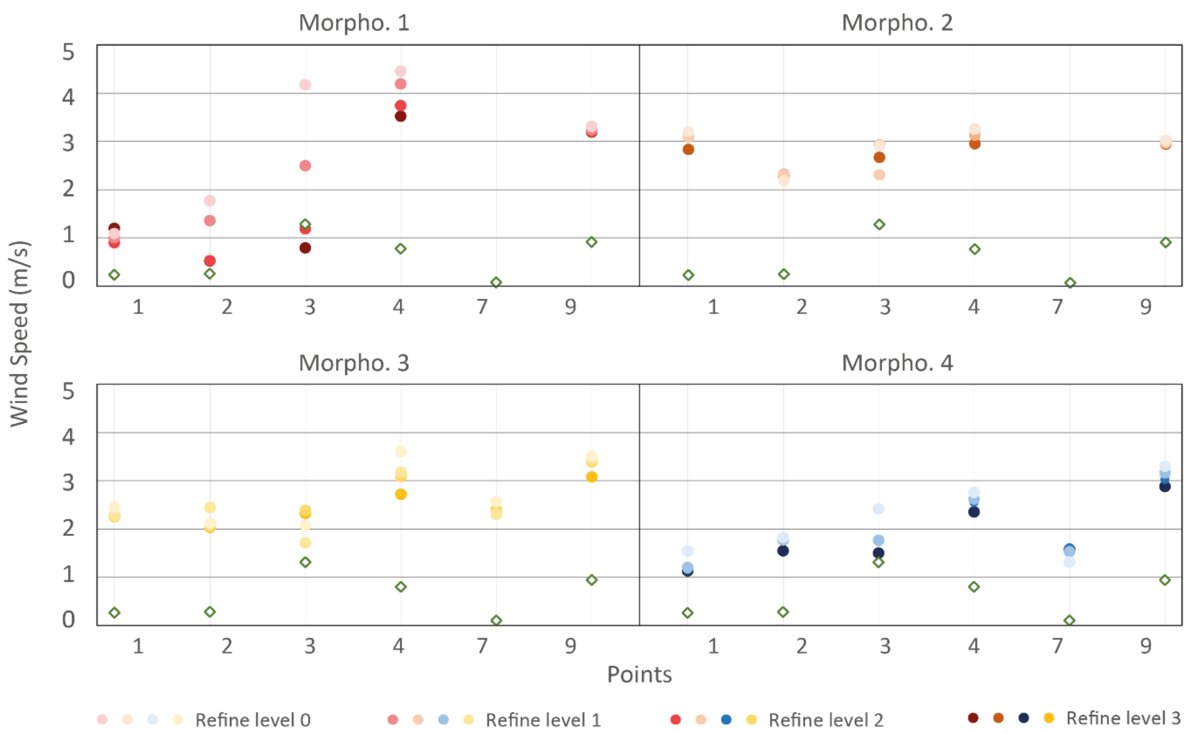

Figure 9. Comparison of the measured wind speed in green, with those simulated.

In the case of morphology 1, although some values closely approach the measured values, the most notable observation is the significant variation in values based on refinements levels. For instance, at point 3, which exhibits the greatest amplitude for all morphologies, the wind speed varies from 4.2 m/s at level 0 to 0.5 m/s at refinement 3. For morphologies 2 and 3, the trends are highly similar. The amplitude between the values at point 3 in these two cases ranges from 3.0 m/s to 2.7 /ms, and 2.1 m/s to 2.3m/s, respectively. In contrast, morphology 4 displays a trend and values that are closer to the measurements. Unlike the first morphology, the variation in values appears to be less dependent on the refinement levels. In this case, the amplitude at point 3 ranges from 2.4 m/s to1.5 m/s.

Table 4. Wind speed (m/s) calculated with Butterfly for the 4 morphologies and the 5 refine levels, compared to measures.

Ref. lvl	**0**						**1**						**2**						**3**					
Points	*1*	*2*	*3*	*4*	*7*	*9*	*1*	*2*	*3*	*4*	*7*	*9*	*1*	*2*	*3*	*4*	*7*	*9*	*1*	*2*	*3*	*4*	*7*	*9*
Morpho. 1	1,1	1,8	4,2	4,5	-	3,3	1,0	1,4	2,5	4,2	-	3,3	0,9	0,6	1,2	3,8	-	3,2	1,2	0,5	0,8	3,6	-	3,2
Morpho. 2	3,2	2,2	3,0	3,3	-	3,1	3,1	2,3	2,3	3,3	-	3,0	3,2	2,4	3,0	3,2	-	3,0	2,9	2,3	2,7	3,0	-	3,0
Morpho. 3	2,4	2,1	2,1	3,6	2,6	3,5	2,3	2,4	1,7	3,2	2,3	3,5	2,3	2,1	2,4	3,1	2,4	3,4	2,3	2,0	2,3	2,7	2,4	3,1
Morpho. 4	1,5	1,8	2,4	2,8	1,3	3,3	1,2	1,8	1,8	2,6	1,5	3,2	1,1	1,8	1,7	2,5	1,6	3,0	1,1	1,5	1,5	2,4	1,6	2,9
Measures																			0,3	0,3	1,3	0,8	0,1	0,9

These results underscore the significant influence of the context on the accuracy of the obtained results. Employing the visualization interface (Figure 5), we can elucidate the majority of the findings. In the case of the first morphology, the obtained values can be attributed to a potent corner effect resulting from the pressure differential between the nearby building walls, particularly close to Point 4. Morphologies 2 and 3 comprise the urban canyon surrounding the measurement points. The corner effect is no longer dominant, and instead, we observe a Venturi effect that elevates the values at Points 1, 2, and 3. Notably, in Morphology 3, there is a general decrease at all points, approximately 10% less compared to the previous morphology. The presence of the two buildings to the North serves as a barrier, reducing the wind speed. In the case of Morphology 4, the entire context slows down the overall speed. What stands out is the presence of buildings to the south of the street of interest, which induces a contrary recirculation effect. This recirculation effect decreases the wind speed at Points 1, 2, and 3, making the results more closely align with reality. Overall, increasing the level of refinement leads to values that are closer to the measurements. However, when we focus on Morphology 4, which appears to be the most suitable, the differences between values at different refinement levels are relatively small. Therefore, Level 2 may be considered satisfactory.

4. Discussion

The simulations carried out and the analysis of results in terms of both time and precision, provide valuable insights for CFD simulation in cases of medium urban density.

4.1 Influence of context

From observation in Figure 5, 9 and the data presented in Table 4, it is evident that the context is an essential element for having accurate simulations. Firstly, for simulations related to human scale comfort, the inclusion of the ground is indispensable (Blocken et al., 2011). The ground not only facilitates the coupling of CFD simulations with thermal simulations to yield comfort-related outcomes but also adds a more realistic dimension to wind patterns (Mauree et al., 2019). Furthermore, we have witnessed the substantial influence of the context on result accuracy. In the case of the broader morphology encompassing the study area, the results are in closer agreement with the measurements. Even buildings situated behind the direction of the prevailing wind have a significant impact. Notably, in Figure 5, there is evidence of wind recirculation behind the measurement points, primarily moving in a northward direction. Therefore, it is strongly recommended to ensure the accurate representation of the immediate context by generously expanding the radius of the simulation domain. Achieving this may necessitate multiple simulations. Visualization of the results in software such as Rhino enables a quick assessment of the contextual influence before delving into a thorough analysis of the result values. In our specific case, the buildings have a height of 5.8 meters and are situated within a radius of approximately 60 meters around the street of interest in Morphology 4. Compared to the study conducted by Naboni in 2019, which employed a radius of 150 meters for 40-meter-high buildings, our approach covers a larger influence area. It is important to acknowledge that the models used in this study, as in the majority of comparison studies, adopt a simplified urban morphology represented by blocks without architectural details (Naboni et al., 2019; Maffessanti et al., 2019). Additionally, the vegetation was not considered due to program limitations.

4.2 Choice of simulation parameters

Employing wind simulation in a parametric environment offers the advantage of reducing the initial modeling time, and facilitates the integration of wind considerations into projects analyzing other microclimatic parameters. However, considerable time was still required for accurate simulations. To optimize this process, we recommend the following settings:

- Wind Tunnel Cell Size: 1-meter large. Based on the observations from Figure 6, using larger cells while maintaining the same level of refinement for the studied morphology does not lead to a significant change in simulation time. For the refinement levels 0 and 1, the computation time is reduced by 40 to 70%. However, for refinement level 2, the computation time becomes equal again.
- Cell to Cell Expansion Ratio: 1.2. Likewise, when adjusting this parameter, the time savings achieved are minimal even with an increased value. Increasing the ratio to 1.3 resulted in an

insignificant reduction in simulation time. Therefore, it is advisable to adhere to the literature's recommendations and maintain the suggested expansion ratio (Franke et al., 2004).

- Residual Reduction: 4 orders of magnitude. While the literature often recommends 5 orders of magnitude, it is notable that most simulations fall short of this level for at least one of the six calculated parameters. The parameters subjected to verification are depicted in figure 7 and encompass the three wind vectors, the values of k and epsilon, as well as three pressure values. In the majority of simulated scenarios, p1, p2 and U(x) attain the 5th order of magnitude after extended periods of simulation. (Franke et al., 2004; Tominaga et al., 2008). It is worth considering that disciplines accustomed to CFD simulations may demand results of higher precision than those necessitated by urban design and architectural detail considerations. Therefore, targeting a 4th order of magnitude for residual reduction is more aligned with practical project timelines.
- Refine Level: 2 or 3. The choice between these levels will depend on both the model size and the complexity and precision of the architectural elements. In our study, Level 2 appears to be the most suitable refinement level. The differences between Level 2 and Level 3 simulations are on the order of 0.1 m/s, whereas the error between the most precise simulations and the measurements averages 1.2 m/s. Additionally, the computation time between Refinement Level 3 and Level 2 is roughly reduced by a factor of 4, providing the opportunity for more iterations.

4.3 Topics to explore

The streets of the *Village Grec* are lined with hedges, approximately 2 meters in high. This vegetation is a common feature in most streets. In more open areas, grass covers the ground, and a few trees are scattered about. Integrating this vegetation and its associated roughness parameters into the simulations is likely to reduce simulated wind velocities. Additionally, the roughness of building walls and floors, and architectural facade details o would undoubtedly yield different results. However, the available literature on the precision provided by these elements is limited. The influence of air temperature and buoyancy on the wind pattern was not considered. While previous research suggests that these effects are negligible when urban wind speed exceeds 4 m/s (Magnusson et al., 2014), it would be interesting to incorporate these effects in a case study where wind speeds measured in the urban context are very low. These three elements represent significant avenues for improving result precision. Regarding simulation time, it is essential to focus on refinement. Further analysis on the required areas of refinement should be conducted. Several software uses automatic meshing processes which could be introduced in Butterfly (Ma et al., 2019; Mirzaei et al., 2021).

5. Conclusions

Climate change and its impact on urban microclimates directly and indirectly affect human well-being and energy consumption. To develop a coherent urban planning approach that aligns with our current challenges, it is imperative to identify and account for the key variables that significantly influence the microclimate. This study aims to provide guidelines for architects, urban planners, and landscapers to conduct iterative CFD simulations during early design stages. These simulations focus on integrating microclimatic parameters, particularly wind flow, by investigating various model sizes and two primary parameters: simulation time and accuracy. This research has underscored two crucial factors: the necessity of considering a broader context in all directions and the adoption of a moderate level of refinement for the urban morphology. The findings in this paper offer modeling and simulation recommendations that facilitate an iterative design process better suited to real-world scenarios. However, further research is warranted to explore the impact of dense vegetation in a medium-density urban setting, the influence of building materials and facade details, as well as the coupling of microclimatic criteria with other aspects. Given the environmental challenges facing humanity, studies on urban microclimates are essential for mitigation and adaptation to climate change. Numerical simulations serve as essential tools for evaluating various planning solutions in both present and potential future climates. Beyond the need for technical advancements to achieve faster and more accurate results, there is a growing need to integrate this data into the design process. Architects and urban planners require methods and practical case studies to push the boundaries of their projects. Parametric CFD tools are making their way into the design process alongside other environmental tools. In addition to technical expertise and resource requirements, the integration of these calculations into the design process must be given greater consideration.

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