Wind and Urban Spaces. Evaluation of a CFD Parametric Framework for Early-Stage Design

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Abstract

Outdoor comfort and microclimate have recently garnered growing interest as important factors determining the success of urban open spaces. Increasing urban density, amongst the consequences of global urbanisation, is considered environmentally positive, but can also have a negative impact on outdoor comfort and on the Urban Heat Island (UHI). Wind plays an important role in alleviating UHI and ensuring comfortable outdoor conditions. However, accelerated winds around tall buildings can cause down-draughts, negatively affecting pedestrian comfort and safety. Monitoring airflow behaviours from the earliest design stages is crucial to adjusting the design accordingly. Expensive physical wind tunnels and sophisticated Computational Fluid Dynamics (CFD) are mainly the domain of wind engineers, while there is an overall lack of fast, intuitive, and yet accurate tools for non-specialists, such as urban designers and architects, particularly involved in the first design phases, to test several design options. Recently, CFD has been fully integrated within the user-friendly and fast-responsive Parametric Design platform, where several environmental simulations can be combined. The aim of this work is to evaluate CFD parametric tools from an *accuracy* and *speed* point of view, as a possible solution for non-specialist designers to simulate wind. A CFD parametric framework describing the systematic process to correctly perform airflow simulations with these tools was set-up and included best practice guidelines, a CFD parametric model construction and verification tests. Time was recorded across all simulations. Coupling CFD and parametric design proved positive, in terms of high accuracy and modelling time reduction, thanks to the automatization of some steps. However, the simulations required a long time and some CFD specialist knowledge, limiting the use by non-specialists. Improvements to this technology, computing time reduction strategies and future research were proposed.

1. Introduction

The progressive growth in global population since the 1950s has induced the phenomenon of urbanisation, which is predicted to rise to 68% by 2050 (UNDESA, 2018), with consequential urban expansion and densification (Rose et al., 2015). Environmentally, increasing density is considered positive compared to urban expansion, as it limits land exploitation and optimizes energy efficiency and infrastructures (Rakha et al., 2017; Rose et al., 2015). However, density also entails, among other things, worsening the outdoor air quality and the solar access of open spaces and buildings, and increases the Urban Heat Island (UHI) (Du et al., 2017), negatively affecting the quality of neighbourhoods and open spaces. It is therefore important to ensure comfortable outdoor environmental conditions within the urban context (Rakha et al., 2017) and considering wind from early design stages is fundamental to improving outdoor comfort and ensuring pedestrian safety. In hot climates, shaping urban developments to encourage airflow at pedestrian level strongly improves outdoor comfort (Du et al., 2017). On the other hand, especially in colder climates, high-rise buildings cause down-draughts at pedestrian level which can affect both pedestrian comfort and safety (Blocken et al., 2012).

However, the complexity of airflow phenomena has limited wind studies and simulations to the wind engineering discipline. Expensive physical wind tunnels and Computer Fluid Dynamics (CFD), a highly accurate but time consuming technology, require specialist knowledge (Blocken et al., 2012), and are usually used at later design stages. Early-stage design is characterised by testing several design options, and therefore fast environmental simulations are vital. Faster and easy-to-

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use wind simulation software exist, for example, Autodesk Flow Design or ODS-studio, but compared to CFD software (Phoenics), they were found to be either very limited in their options of modelling and grid resolution, or difficult because they involved other software. Furthermore, although flow patterns were similar, their numerical accuracy was found to be very poor compared to CFD (Sousa et al., 2015). The CFD engine Phoenics (developed by CHAM) can be connected to the Rhinoceros 3D modelling platform through the plugin RhinoCFD, which is a useful starting point for neophytes. However, the Rhinoceros platform can run only a limited number of other environmental plugins and RhinoCFD does not allow iterative optimization processes. Furthermore, it is not a freely available software and its development depends on CHAM (Chronis et al., 2017). Overall, there is a lack of fast-responsive, easy-to-use, and accurate wind simulation tools, which can also be easily combined with other environmental plugins, and be used by non-specialist designers, such as architects and urban designers, to inform early-stage design, when main decisions are made and cannot be easily adjusted at later stages (Bottema, 1999).

A possible solution was recently offered by the integration of the Computational Fluid Dynamics (CFD) technology, which requires accurate inputs and modelling to be reliable, into the user-friendly and dynamic Parametric Design tools. These tools are particularly valid because they allow for real-time geometry modification and for optimisation. Parametric design is experiencing growing success among the design community, and also in relation to the wide range of open source environmental tools made available to a very diverse public of professionals (Sadeghipour Roudsari et al., 2013). However, very limited literature is currently available on CFD parametric tools. Mackey et al., 2017, studied the impact on a case-study of four main environmental factors defining outdoor comfort, including wind, simulated through Butterfly, a CFD parametric tool. In Chronis et al., 2017, Butterfly was technically compared to two other CFD tools (Rhino-CFD and Processing FFD), and defined as promising, but currently limited by its solver's complexity and by installation difficulties, (Mackey, 2019) which are now mostly overcome.

The main aim of this work is therefore to assess how quickly, easily, and accurately, CFD wind analysis within the parametric modelling environment can be performed by non-specialist designers at early urban design stages. In order to do this, two main criteria are specifically focused on:

- *Accuracy*, in terms of the tool's ability to provide reliable and realistic results;
- *Speed*, intended both as short simulation time, fundamental during the iterative and dynamic design early-stages, and as learning time required by non-specialists.

To meet requirements for *accuracy*, a framework outlining the systematic process to correctly perform CFD parametric simulations was developed, and also represents the novelty of this work. Necessary *time* was evaluated throughout the process.

2. Methods and Simulation

The evaluation of this emerging technology was performed through four main steps:

- Review of CFD tools compatible with Grasshopper, parametric plugin of Rhinoceros (3D modelling software).
- Research of CFD Best Practice Guidelines (BPG's), to identify recommended inputs for CFD cases set-up.
- CFD parametric framework set-up, including initial inputs, CFD parametric model construction, and verification tests.
- Testing the framework using a case-study, including qualitative and quantitative results, CFD convergence and grid-independence tests, and time recording for each simulation.

2.1 CFD Parametric Tools Review

A limited number of plugins coupling CFD and parametric design (Grasshopper) were identified within literature. They were compared using the same criteria, (Table 1) where possible, to identify the tool for this work.

Table 1 – Comparison of CFD plugins for Grasshopper (GH)

Criteria	Ansys-CFX	FFD	Swift	Butterfly
Integration into GH	Script required (Python)	Plugin required	Yes	Yes
Speed	n/a	Faster than CFD	Slower than FFD	Slower than FFD
Accuracy	High	Lower	High	High
Cost	Not free	n/a	Free	Free
Customisation (language)	n/a	Yes (Programming)	Yes (C++)	Yes (Phyton, easier)
Learning material	n/a	n/a	Less	More

Butterfly was selected, based on the following considerations. Ansys-CFX requires an auto-run Python script (Chronis et al., 2017; Taleb and Musleh, 2015). Fast Fluid Dynamics requires an additional plugin and, despite being much faster than CFD, is inaccurate (Chronis et al., 2017). Swift (by ODS engineering) is fully integrated in Grasshopper, is freely available, and is based on OpenFOAM which is an established and accurate open source CFD engine. However, there are only few example files, a video, and an inactive forum (https://www.ods-engineering.com/tools/ods-swift/). Butterfly has similar characteristics to Swift, but is written and customisable in Python, an easier programming language. It also has few example files and videos but it does have an active and responsive forum and forms part of the Ladybug Tools, an extensive spectrum of environmental plugins (Chronis et al., 2017).

2.2 CFD Best Practice Guidelines (BPG)

To reduce CFD user errors, best practice guidelines were developed by groups of international researchers to properly set-up CFD simulations. Three different sources were compared due to their availability and recent date: European COST Action 732 (Franke et al., 2007), German Association of Engineers guidelines (VDI 3783 Part 9, 2005) and AIJ the Architecture Institute of Japan publication (Tominaga et al., 2008).

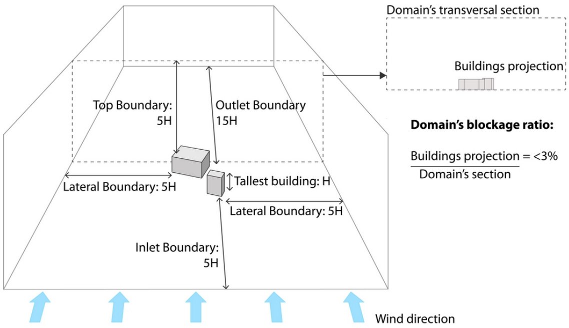

Fig. 1 – Selected domain's dimensions criteria

Criteria for this work were selected following a conservative approach (Fig. 1, Table 2) and used for setting-up the parametric model.

Table 2 – BPGs selected criteria for this work

BPG's Criteria	Selected Criteria
Mathematical Model	steady RANS
Turbulence Model	RNG k-ε
Blockage Ratio	<3% (priority on BPG's domain's dimensions)
Top Boundary	5H (H= tallest building's height)
Lateral Boundary	5H
Inlet Boundary	5H
Outlet Boundary	15H
Wind profile	Logarithmic Law
Min. grid resolution	Expansion ratio between 2 consecutive cells= max.1.3. Area of interest: min.10cells per building side and 10cells per volume cube root of volume.
Cells shape	Hexahedra
Refinement grid	Number of refined cells: 8 times the coarser one (2 per side); to test: min. 3 refinement levels
Probes extraction	At 1.75 m pedestrian height
Residuals reduction (CFD convergence)	Min. 5 orders of magnitude (Ferziger and Perić, 2002)

In the case-study, it was observed that using the guidelines' recommended factors, by which the tallest building height is multiplied to set all domain dimensions (Table 2: boundaries), the blockage ratio was greater than 3%, due to the blockage width resulting from the chosen wind direction. The 3% blockage ratio was therefore prioritised and the domain's dimensions were increased accordingly.

2.3 Parametric CFD Framework Definition

A CFD parametric framework was developed based on Butterfly's functionalities and BPG's, providing the necessary steps to perform a CFD parametric simulation (Fig. 2). The framework presents in grey the steps which can be parametrically set-up and in pink those which also belong to traditional CFD. It is horizontally divided in three parts: Initial inputs, CFD parametric model construction and Verification tests.

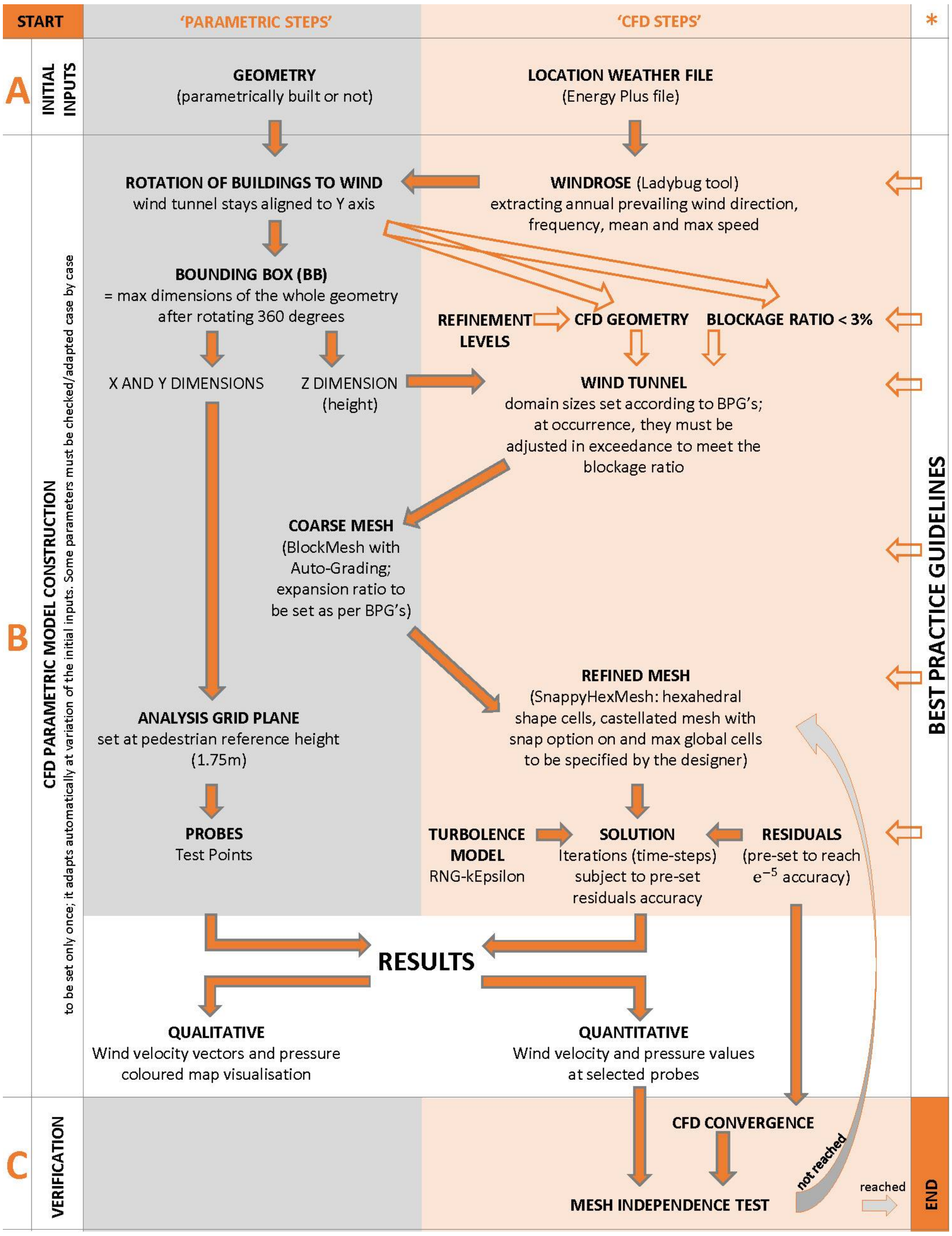

Fig. 2 – CFD Parametric framework

2.3.1 A: Initial inputs

To focus on the tool functionality, two small simplified buildings were used as a case study (Fig. 3) (https://github.com/ladybug-tools/butterfly-plus/tree/master/plugin/grasshopper/examplefiles).

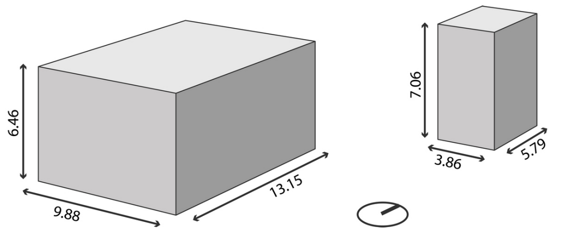

Fig. 3 – Case-study dimensions (meters) and orientation

Prevailing winds from London Gatwick Energy plus weather file were extracted with Ladybug component 'Windrose'. Average wind speed 3.45 m/s from 70 degrees direction was used.

2.3.2 B: CFD parametric model

A CFD model was built by combining existing Butterfly and Ladybug workflows, further parametrically tuned. The resulting model is a pre-set workflow, where the weather file and wind characteristics, geometry, and refined grid settings are the sole inputs to be updated for each case-study, while most functionalities automatically update. For example, the geometry is set to automatically rotate by the chosen wind direction angle (Fig. 4).

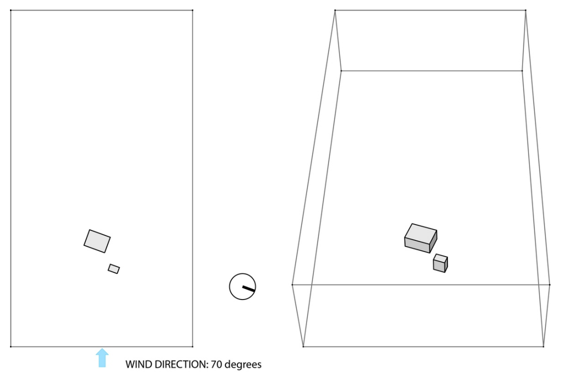

Fig. 4 – Automatic rotation of the geometry to the wind

Furthermore, the domain's dimensions, which depend on the height of the tallest building, are parametrically linked to it and automatically adjust at height variation.

The recently implemented Autograding component parametrically generates the Openfoam coarse grid: denser (in this case-study: 1 m cell size) around the case-study and progressively less dense towards the domain's top and ends, following the set expansion ratio of 1.2 (Fig. 5).

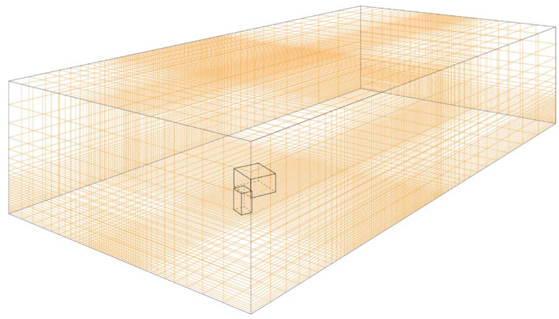

Fig. 5 – Coarse grid generated by the Autograding component

On the area of interest, Openfoam also requires the application of a refined hexahedral grid (SnappyHexMesh) which is, instead, case-specific. To define an appropriate grid refinement, six progressively finer grids were tested by setting the maximum global cells to 10 million, and by changing the BF 'refineLevels_' parameter in the "createBFGeometry" component, using the values: (0,0), (1,1), (2,2), (3,3), (4,4) and (5,5) (Fig. 6), leaving all other parameters as "default". Consequentially, in each test, the number of global cells progressively increased with the grid refinement.

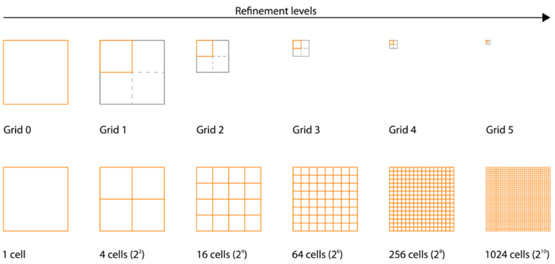

Fig. 6 - Refinement levels tested in the case-study

2.3.3 C: Verification tests

CFD solutions are only approximate to reality as they are based on the discretisation method. It is therefore crucial to perform verification tests to quantify uncertainty and ensure numerically accurate results (Roache, 1997). For each simulation, CFD convergence and grid independence tests were performed. The first are necessary to control the extent of iterative errors and ensure that each solution ran through enough iterations to achieve results close to reality. Logarithmic graphs of the residuals were plotted to verify convergence. Grid independence tests must be performed on at least three different grids to ensure that results only depend on boundary conditions and not on the grid refinement (Ferziger and Perić, 2002). Velocity and pressure values were extracted for each of the six grids tested in this work, and the error Root Mean Square (RMS) was calculated to estimate the discretisation error of each coarser grid compared to grid 5, the finest grid. Verification tests are key to determine each simulation's *accuracy*.

2.4 Framework Test on Case Study

The framework was tested in the case study, qualitative and quantitative results were extracted, and verification tests performed for each simulation. *Time* spent on meshing and solution processing was recorded to observe its variation with the increase in grid resolution. An appropriate grid refinement was then identified for this case study, which could reach the fastest solution without excessively compromising on accuracy.

3. Result Analysis and Discussion

The aim of this work was to assess CFD parametric tools for non-specialists at early design stage, focusing on *accuracy* and *speed*. A framework representing the correct simulation process was set up and tested on a case-study, and simulation time was recorded.

3.1 Result Analysis

Test results were used to evaluate the whole process from the point of view of *accuracy* and *speed.* In terms of *accuracy*, CFD parametric tools are interfaces of CFD engines, and therefore they also match their high accuracy. However, comparing quantitative and qualitative results of 6 different grids, it emerged that correctly setting-up and verifying simulations was important in order to avoid compromising results. CFD convergence was achieved for the first 5 coarser grids, reaching the 5th order of magnitude (Table 2), meaning that the CFD solution process was complete and correctly representing reality. On the residuals graph of the most refined grid 5, pressure residual only reached a 4th order of magnitude, fluctuating horizontally after almost 8 simulation hours. To exclude the risk of divergence, the solution ran for a total of 17 hours and 39 minutes (3082 iterations), compared to 1.5 hours for grid 4 and 10 minutes for grid 0 (approximately 1250 iterations) (Fig. 7).

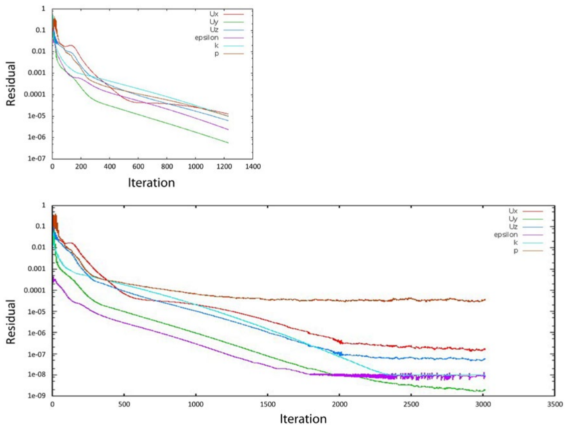

Fig. 7 – Residuals logarithmic graphs: grid 0, above, grid 5, below

Grid independence tests, calculating error RMS for each grid compared to the most refined, showed that the error progressively decreased with the increase in the grid's refinement (Fig. 8, 9, 10). Grid 4 was the coarsest grid maintaining an acceptable numerical error, and its results were therefore considered grid-independent.

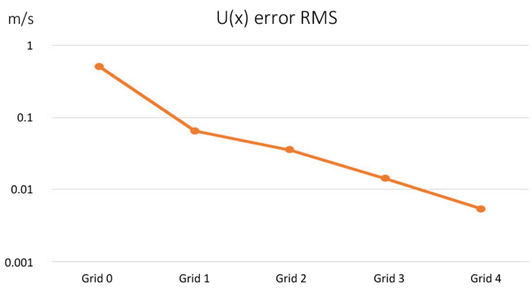

Fig. 8 – Error RMS graph: velocity U(x)

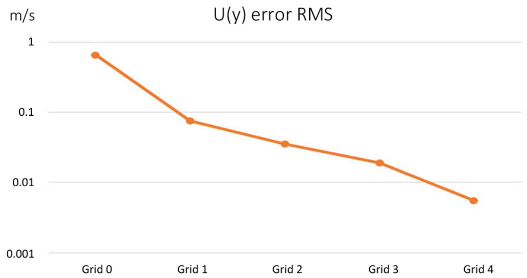

Fig. 9 – Error RMS graph: velocity U(y)

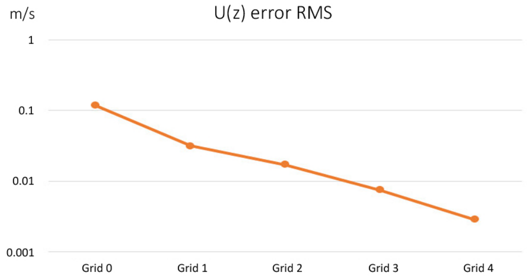

Fig. 10 – Error RMS graph: velocity U(z)

Differences across the six grids were also visually noticeable when comparing qualitative maps, particularly around the building corners and despite the low wind speed simulated (Fig. 11).

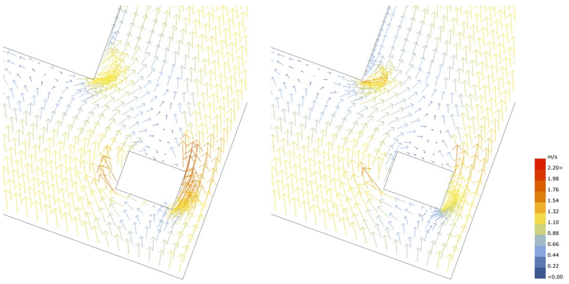

Fig. 11 – Velocity vectors: grid 0, left, and grid 5, right

Numerical and visual errors could be explained by observing the quality of the grids 0 and 5 applied on the modelled buildings (Fig. 12, in orange); grid 0 deformed the geometries of the buildings, particularly in the corners, confirming visually to be too coarse.

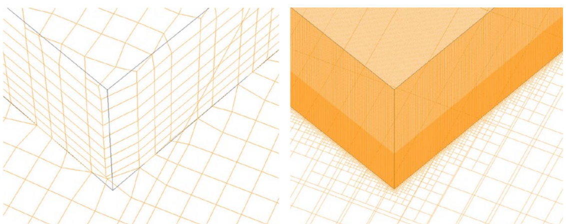

Fig. 12 – Refined grid: refinement level 0, left, and level 5, right

In terms of *speed*, modelling time was reduced thanks to parametric tool: once the framework is correctly set-up, it can be applied to several cases by only updating the inputs and tuning a few parameters. However, time required for both meshing and CFD solution exponentially increased with the grid refinement (Fig. 13).

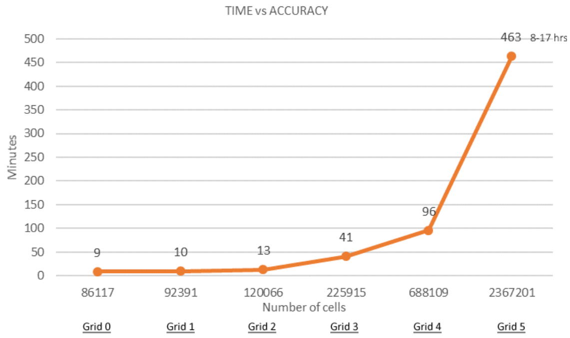

Fig. 13 – Time versus Accuracy diagram

Total time spent on performing the whole simulation was about 20 hours, which are a significant amount for a small case study and low wind speed. Grid 4 achieved reliable results in a reasonable time, and was consequently considered appropriate for this case study.

3.2 Discussion

Computational Fluid Dynamics is generally a time-consuming technology during modelling, meshing, running the solution and verification. The integration of CFD into the parametric design meant a considerable reduction of the initial modelling time, as once set-up the first time, the model can be re-used by only adjusting a small number of parameters. Furthermore, wind simulations can be included more easily in studies involving other environmental tools, for example for assessing outdoor comfort. However, considerable time was still required for accurate simulations, heavily affecting the use of these tools during early design stages, when simulation time should ideally not exceed a few minutes, particularly when testing design options, combining various environmental analyses or performing design optimization. Computational cost mainly depends on the speed of current computers for meshing and running the solution, and on a long verification process, which, however, was demonstrated to be fundamental; using too coarse grids to speed-up the process may cause misleading results.

3.2.1 'Speed *versus* Accuracy' dilemma: a matter of technological progress

Possible time-reduction strategies to overcome CFD bottlenecks were therefore investigated.

Reducing number of CFD simulations

For long annual hourly simulations, for instance, Ladybug tools developers suggest the use of so-called Wind Factors: only 36 simulations were run to cover the wind rose directions, and results divided by the correspondent weather file wind speed. For each direction, multiplying the wind factor by any meteorological wind speed, the local wind speed could be obtained without re-running CFD simulations each time. It was also noted that reducing the 36 simulations to only 2, the Universal Thermal Comfort Index (UTCI) results were very similar (Mackey et al., 2017). Further testing of this method may provide interesting results.

Adaptive grid refinement

An existing technology to identify the best grid refinement is the *adaptive grid refinement*, which predicts the wind pattern and refines the grid only where required (Kim and Boysan, 1999). This function is already available in Openfoam (Berce 2010; Karlsson, 2012), and could be implemented in CFD parametric tools using this engine.

Computational technologies

For this work's case study, the same simulation ran for 1.5 hours on a laptop (Windows 10, 64 bit, 4 CPU, base speed: 2.0 GHz) and in 25 minutes on a desktop (Windows 10, 6 CPU; base speed: 3.7 GHz); computer speed and performance are crucial. Running simulations in parallel, meaning on more computer processors at the same time and combining results in post-processing (Greenshields, 2018), is a common function available both in Openfoam and Butterfly. The future of CFD technology greatly depends on High-Performance Computers, especially with parallel and hybrid computing architectures. Emerging technologies linked to quantum computing and advanced 3D memory are also promising (Slotnick et al., 2014). Artificial Intelligence (AI) was recently implemented for the creation of digital twins, which, through algorithms, can predict and reproduce virtual representations of airflow around buildings in real-time, with speeds 1000 greater than anything else currently available (Akselos, 2019). Finally, combining CFD with animation software using Langrarian Fluid (e.g. Autodesk Maya) or Eulerian approaches (e.g. SideFX Houdini) may greatly improve computational cost; however, meshing and results quality requir e further verification (Kaushik and Janssen, 2015).

3.2.2 Another type of 'Speed *versus* Accuracy' dilemma: a matter of purpose

Despite the reduced modelling time, substantial *time* and effort are required for running simulations and also for neophytes to sufficiently learn CFD, the parametric tool and its correct use. Indeed, the tool's accuracy cannot be compromised; however, the *accuracy* of the results could be evaluated against reality by assessing an 'acceptable error' in relation to the purpose and scale of the simulation. Unlike other disciplines (e.g. aeronautical engineering) that require a high degree of accuracy, a greater error compared to reality may be tolerable in wind simulations for urban comfort. However, for early-stage design, although characterized by a simplified representation of urban context and architecture, wind simulation tools should be sufficiently accurate to correctly reproduce wind phenomena around and between buildings, and model turbulence, particularly in the presence of tall buildings, to provide correct indications for the design development. Consistent comparison of results of simpler and faster wind simulation tools with reality and CFD could verify these conditions and help define an acceptable error, leading to interesting findings on available technologies for non-specialists to consider wind as a driver of early-stage urban design.

4. Conclusion

This work aimed to evaluate CFD parametric tools for non-specialists to quickly, easily, and accurately simulate wind behaviour in early-stage urban design iterations. The necessary process to carry out simulations correctly and ensure accuracy of results was researched and a CFD parametric framework was set-up and tested. Although CFD parametric tools are equivalent in *accuracy* to their established CFD engines, the results demonstrated how their correct use is crucial. Regarding *speed*, CFD parametric tools can considerably reduce the modelling time and be integrated with other environmental plugins. However, significant time was still required to run simulations and perform verification tests, despite the small scale of the case study and low wind speed used. Existing simulation time reduction strategies, and ongoing and future developments of computer technology were explored. Finally, reflecting on the level of accuracy required for urban scale studies, further research could focus on faster and yet sufficiently accurate tools for designers to correctly simulate wind from the earliest stages of urban design.

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