Integrating Modelling, Simulation and Data Management Tools to Create a Planning Support System for the Improvement of Air Quality by Urban Planning Solutions

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Abstract. Urbanization pressure requires urban planners, designers, and policy makers to be more responsive to the challenges related to improving the quality of the urban environment and the living conditions of the inhabitants. One of the many environmental issues that need to be taken into account is urban air pollution. As the process of urban ventilation and air pollution dispersion is significantly affected by the urban layout, the planning and design practice offers some solutions for urban air quality improvement. The paper outlines the most important planning implications for the integrated management of urban ventilation and air quality. The results indicate that the integration of various scale-adaptive modelling, simulation, and data management tools is necessary for the comprehensive assessment of the impact of spatial solutions on urban air quality and the formulation of planning outlines. A case study of the city of Warsaw, Poland, was demonstrated in the paper.

Keywords: Sustainable Cities, Urban Air Quality, Urban Ventilation, Planning support system, Data Management, GIS, CFD.

1 Introduction: theoretical background and the current state of the art

Outdoor air pollution is considered one of the major environmental risks to human health. It is associated with many health problems such as higher risk of strokes, heart diseases, lung cancer, or acute and chronic respiratory diseases, each year leading to several million premature deaths worldwide [1]. Recently it has been also linked with the increase in mental disorders [2]. Therefore, the improvement of urban air quality is one of the key targets in the United Nations' Sustainable Cities and Communities goal [3]. Despite many on-going efforts to reduce pollution emissions in urban areas, remedial measures are still necessary. Poor air quality is usually associated with cities in low- and middle-income countries, but it is estimated that in high-income countries significant part of the population is also exposed to air quality levels that exceed the World Health Organization (WHO) guidelines [4].

The recent lockdown measures have shown that air pollution significantly decreased due to the restrictions of social and economic activities, and especially the significant limitations in traffic [5–7]. However, such drastic changes are not a viable, long-term solution. Implementing sustainable transport measures to reduce pollution emission is a lengthy process, which requires major shifts in the urban mobility systems, local economies, and people's lifestyles. Therefore, it is crucial that other possible measures are also taken into account. According to numerous studies, referenced in the following paragraph, particular urban planning and design solutions can increase the effectiveness of city breathability, thus leading to the improvement of urban air quality.

The relationship between the urban layout and the wind environment, however, is not straightforward to predict and requires scale-adaptive evaluation (Figure 1). At the scale of the entire city, it is crucial to facilitate the air exchange between the more densely-developed urban center, where pollution emission sources are concentrated, and the suburban open areas. To facilitate such process, urban ventilation corridors (passages of undeveloped land) are often introduced and protected within the local planning provisions [8, 9]. Apart from improving city breathability, ventilation corridors can bring other environmental benefits, such as the reduction of surface temperature and the provision of ecosystem services in urban areas [10]. At the district level, the main ventilation corridors should be connected to finer secondary ventilation paths [9, 11]. Then wind environment should be monitored within urban blocs and building complexes as their particular configuration can either allow for air movement and pollution dispersion or create so-called stagnant zones where air exchange is blocked by building arrangements, which leads to local pollution accumulation [12, 13].

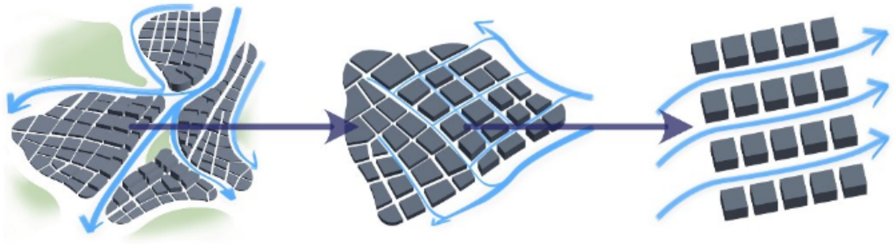

Fig. 1. City breathability management using the scale-adaptive approach should integrate solutions at the city scale (urban ventilation corridors and secondary ventilation paths) with micro-scale solutions, accounting for the impact of urban blocks morphology and buildings layouts on the local wind environment. Source: own elaboration, based on: [14].

The implications listed above can be translated into particular urban planning and design solutions. Although such design solutions should be investigated locally and adjusted to particular spatial conditions, some general examples can be given. This includes adjusting building layouts to the prevailing wind direction, providing sufficient spaces between buildings, or leaving open ground floor plans [15, 16] (Figure 2).

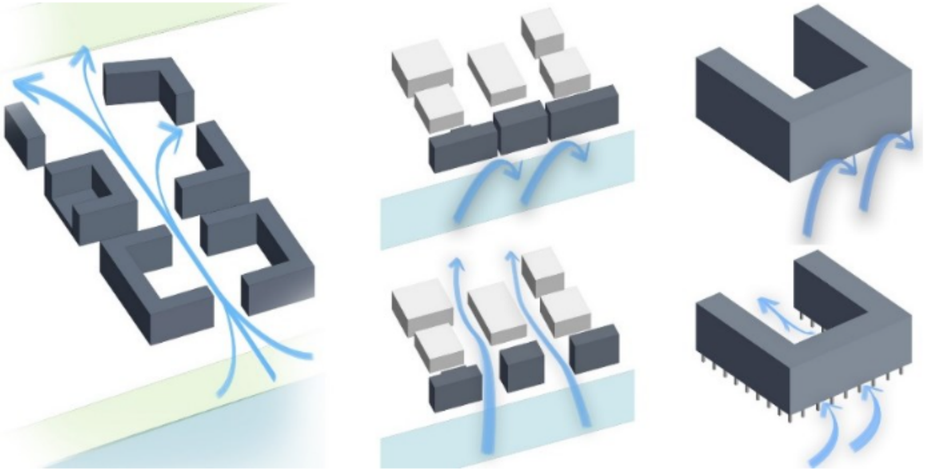

Fig. 2. Particular urban planning and design solutions at the local scale can either block air movement, leading to pollution accumulation, or facilitate the undisturbed flow of air between buildings, facilitating pollution dispersion. Source: own elaboration.

Moreover, many studies indicate that the urban vegetation system is a significant factor shaping the local urban air quality due to the dispersion and adsorption of air pollution. In general, urban greenery help reduce pollution levels. High vegetation as well as green walls, roofs or screens are implemented as a passive system for air pollution control [17–19]. In some cases, however, vegetation can have an adverse effect on local air quality, as trees in dense urban areas, particularly in urban street canyons, can inhibit air flow and lead to increased pollution accumulation [20, 21]. Finally, the impact of outdoor air pollution on the indoor air quality and the living conditions in buildings should also be taken into account in the evaluation process (Figure 3).

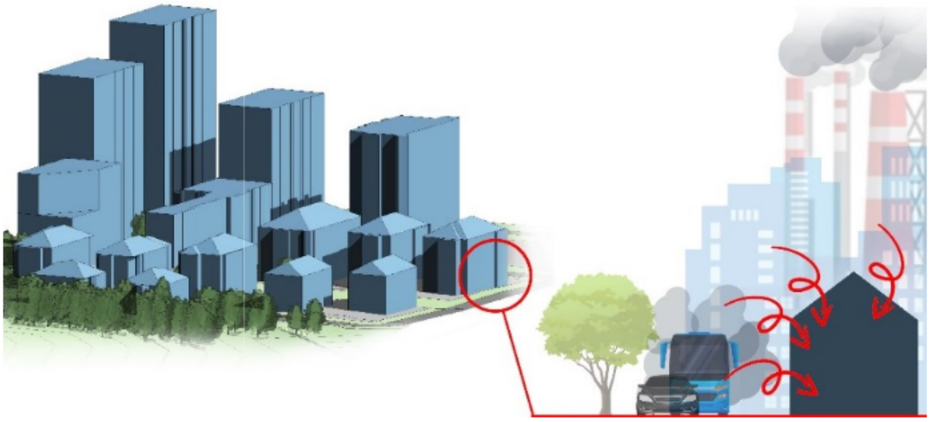

Fig. 3. The interactions between outdoor and indoor air pollution. Source: own elaboration.

As mentioned, particular spatial solutions should be carefully investigated and adopted to local conditions and the existing urban configuration. Many local planning and design guidelines in this respect can be found. For example, in Hong Kong it is required to evaluate the impact of proposed development projects on the local wind environment within the air ventilation assessment (AVA) of Hong Kong guidelines [22]. This technical guide requires the designers to include ventilation simulations and experimental methods (wind tunnel studies) in the design process [15, 23]. The AVA assessment was already applied in several development projects, for example in the Kai Tak Development [24] (Figure 4). Other examples can be also found: the New Taipei City regulations for wind environment control [25], the Chinese national technical guide on Urban Ventilation Corridor (UVC) [9], or the provisions for wind microclimate studies for the City of London [26]. Local guidelines are also developed for the design of urban vegetation systems for air quality improvement, such as the ones issued by the Department of Environment in Flanders and the Greater London Authority [27, 28].

Fig. 4. The Kai Tak Development in Hong Kong – a project, in which the design solutions for urban ventilation enhancement were applied, including open ground floor plans and building voids to facilitate air flow between buildings. Photo: Joanna Badach.

Even if in many urban areas the local guidelines do not exist or are not legally required, designers increasingly often look into this problem. Many particular urban or architectural projects were based on the principles of outdoor ventilation improvement. For example, the Nieuw Zuid district in Antwerp (Figure 5) was designed to provide ventilation paths leading from the waterfront [29]. The same tools used for studying the ventilation process for air quality improvement are used to evaluate the impact of a new project on the pedestrian wind comfort (only in this case the focus is not on maximizing the ventilation efficiency but on not exceeding a certain wind speed limit, which would be uncomfortable for the pedestrians). The OPPO headquarters building by the Zaha Hadid Architects is an example of a project, in which such an evaluation was performed at the early stage of the design process and helped to determine the spatial form of the building [30].

Fig. 5. The construction of the Nieuw Zuid district in Antwerp, the layout of which was designed to facilitate the process of urban ventilation. Photo source: Google maps [31].

Despite the many successful examples of incorporating research on the local urban wind environment in the planning and design process, the principles of urban air quality improvement and the current body of knowledge in this respect is still not sufficiently applied in urban planning and decision-making. The aim of this paper is to summarize the most important results of a multidisciplinary research project aimed at developing new research tools and procedures for the evaluation of the spatial aspects of urban ventilation and air quality management, focusing on their implications for urban planning and design. The applicability of various modelling and simulation tools as well as urban data management systems in the practice of urban planning was investigated. Moreover, the current limitations and directions for further research as well as the integration of city breathability and air quality improvement with urban planning strategies and design solutions were identified.

2 Materials and methods: quantifying the impact of urban form on city breathability and pollution dispersion

2.1 Study area

The aim of the research project was to characterize the wind environment and pollution dispersion in the urban built environment, at different urban scales, using an integrated assessment method, consisting of several modelling, simulation, and data management tools. Their validity was evaluated in several case studies in diverse urban contexts. Here, the Warsaw case study, and in particular, the Bielany district case, is discussed.

Warsaw (52.2297°N, 21.0122°E) is the capital city of Poland, located at the riverbanks of Vistula. It covers an area of approx. 517 km^2 with a population of over 1.7M. The spatial layout of the city is clearly defined by the Vistula river valley and the system of centric ventilation corridors (wedges), which cut into the densely built-up urban center (Figure 6). The ventilation corridors in Warsaw were designated at the beginning of the 20th century. Although some new developments have been recently introduced inside of these corridors due to insufficient planning protection of the system, they are still clearly distinguishable [32].

The Bielany district, now a part of the municipality, was formerly a rural suburban area consisting of several small villages. Its small-scale development was supplemented with large-scale residential buildings constructed after the Second World War based on the modernistic planning principles (Figure 9).

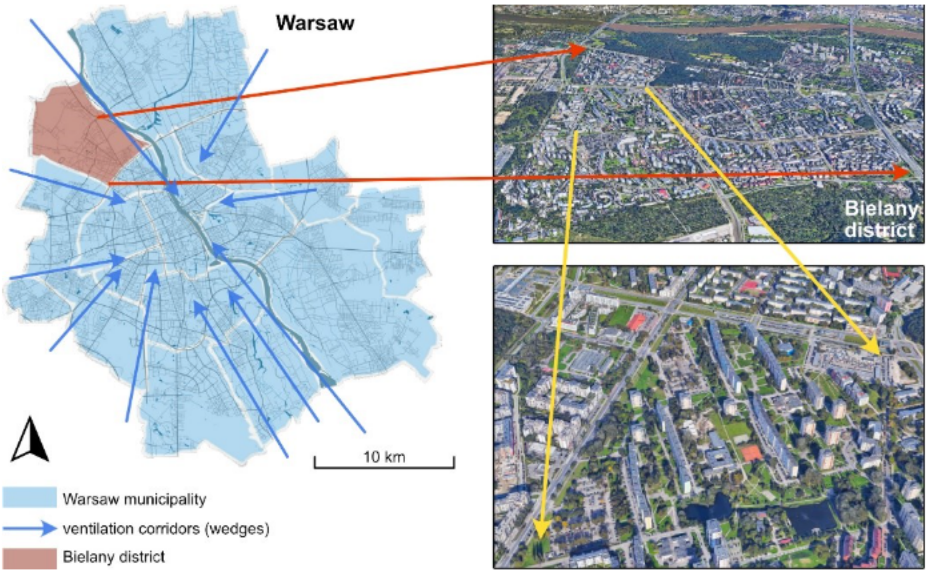

Fig. 6. The municipal city of Warsaw (Poland) and its Bielany district (marked in red), in which the case study was conducted. Blue arrows on the map indicate the location of the main ventilation corridors (wedges). Source: own elaboration, satellite photos: Google maps [31].

2.2 Data sources and processing

The study was preceded by the collection and processing of geospatial data from different sources. Most of the resources were retrieved from Geoportal - the open repository of the Head Office of Geodesy and Cartography in Poland [33] (Figure 7). The 2D Topographic Database was used to obtain information about the built-up structures, e.g., buildings, road networks, etc. (A), and land use (B). Then detailed elevation models were retrieved: the Digital Elevation Model (DEM) (C) and the Digital Surface Model (DSM) (D). These models were created by the Head Office of Geodesy and

Cartography based on LIDAR data from Airborne Laser Scanning (ALS), additionally supplemented by local stereoscopic measurements in urban areas [33]. Normalized DEM (E) was also created by subtracting DEM from DSM. Moreover, the classified raw point clouds with airborne LIDAR data (F) and city GML models, with the second Level of Detail, (G) were also used. Apart from the data from the open resources, a detailed high vegetation database for the area of interest was also retrieved. The database contains the information about the location of each tree as well as the basic parameters of the tree crowns (area, heights and volume), estimated using a dedicated algorithm to process the aerial photos [34] (this data will be presented in another part of this work). ArGIS Pro 3.0, later updated to 3.1 (Esri Inc., Redlands, CA, USA) and standard geoprocessing tools [35] were used to collect and process the data.

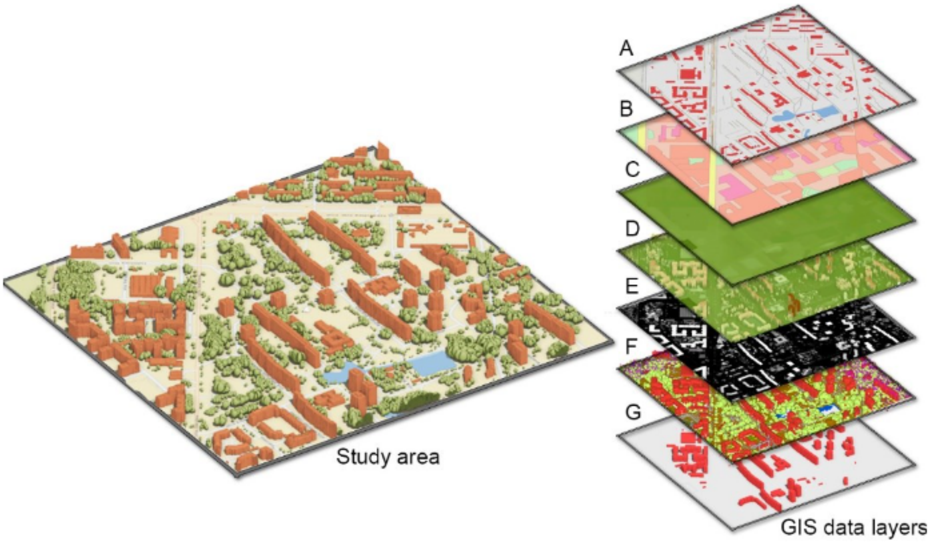

Fig. 7. The 3D model of the existing morphology of the study area and the GIS datasets used in the study (A-G). Source: own elaboration, data source: Geoportal repository [33].

2.3 Modelling, simulation and data management tools

As discussed, the assessment of the impact of urban form on air quality is scale-dependent. Therefore, the case study can be divided into two parts: the analysis at the district level (taking into account the municipal ventilation system) and at the micro-scale level. At each level, different simulation and data management tools were used.

Although many atmospheric dispersion models are available to calculate the spatial and temporal variation of pollution concentration at the city or district level, they do not account accurately for the impact of urban form on ventilation or pollution dispersion [36] and thus, their application as planning tools is limited. Of course, large-scale air quality models and other climatic studies can bring some general implications for designing the urban ventilation system [37], but they require the incorporation of additional tools. In the described research project, the Geographic Information System

(GIS) was used for the characterization of the urban form in relation to the ventilation conditions. In particular, the GIS-based mapping of the frontal area index (FAI) was found useful for the identification of the system of ventilation corridors and paths, following many previous studies [38]. FAI is calculated for a particular wind direction as:

$$\mathrm{FAI} = \lambda f / \lambda p \qquad (1),$$

where λf is the sum of the frontal (projected) façades area (façades facing the selected wind direction) and λp is the total site area. Several calculation methods can be found, in which a set of lines, aligned with a given wind direction, is introduced to the model and intersected with buildings [39, 40] or the buildings façades are projected to planes perpendicular to the wind direction [41]. Dedicated applications to estimate FAI based on input 3D building models are also developed [42]. Here, to make the analysis efficient at the district scale, FAI was calculated using a grid approach and 2D buildings datasets with the information about their height (number of floors). Lines representing cardinal wind directions were introduced and intersected with the buildings polygons. The height of the buildings intersected with a given line, multiplied by the spacing between the wind lines, as well as the unique grid cell ID, were assigned to the wind lines. The Summarize Within tool was used to calculate the total frontal area for each grid cell (based on the grid cell ID) and it was then used to estimate FAI. More details can be found in a previous study by Badach et al. (2022), in which the method was applied to efficiently calculate FAI at the city scale, including the city of Warsaw [14].

The GIS-based analysis made it possible to preliminary estimate the general ventilation conditions for the district and to define the main problem area (as it is discussed in the results section). However, it was not sufficient to capture all the local phenomena related to the local wind environment and pollution dispersion. Thus, it was followed by more detailed analysis at the micro-scale level, in which computational fluid dynamic (CFD) simulations were used. CFD simulations are a well-established numerical tool, which allows to incorporate parametric models of the built environment and to comprehensively account for its impact on the ventilation conditions and pollution dispersion [43–47].

The CFD approaches in this respect are varied. Very often, due to the high computational costs of this method, significantly simplified models of the urban geometries are used [48–50]. In other cases, more realistic urban models are introduced [44, 47]. In this study, the use of different 3D models was considered (Figure 8). Initially, LIDAR data was used to generate the buildings geometries. The Building class was filtered from the classified point clouds (B). Then the buildings footprints were generated using LAS Point Statistic as Raster and Raster to Polygon tools. The polygon layer with buildings footprints and the filtered LAS layer were used to create buildings models using LAS Building Multipatch tool (C). However, the 3D model obtained with this workflow was too detailed. In particular, the detailed roof geometries (indicated in D), which were not significant to the results of the CFD simulations at the pedestrian level, would unnecessarily increase the mesh density. The models were further simplified (E) based on 2D data to increase the efficiency of the simulations, while the LIDAR-based geometries were used for validation.

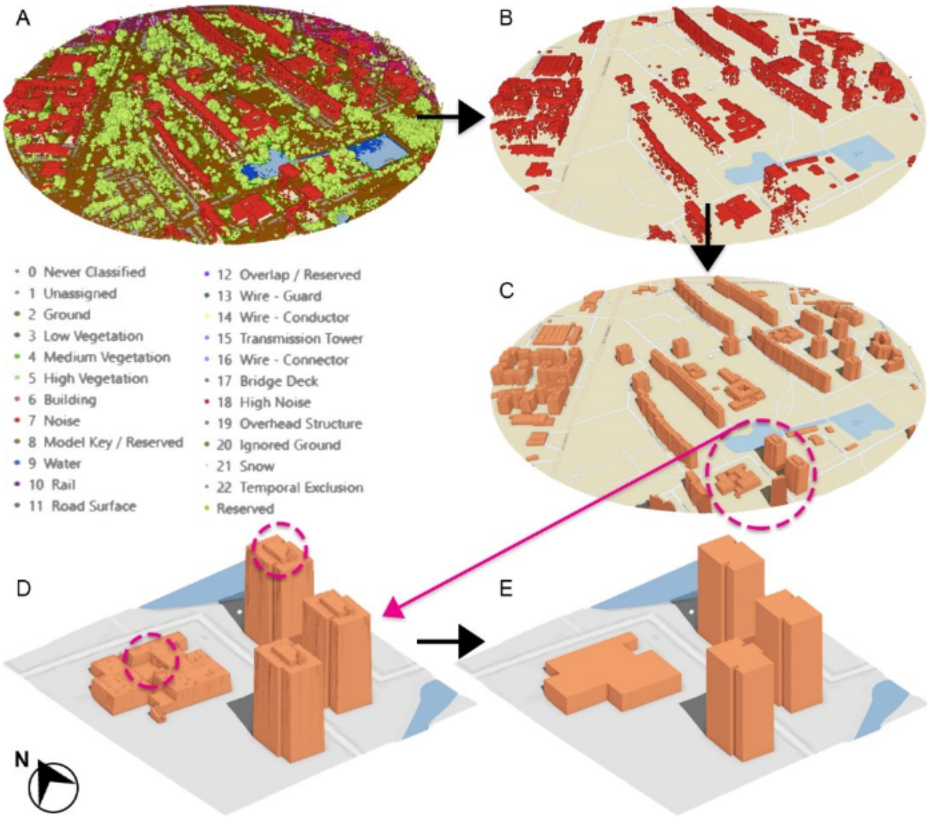

Fig. 8. The processing of the LIDAR data (LAS files) and the development of the 3D model for CFD simulations. Source: own elaboration, data source: Geoportal repository [33].

The adopted approach was previously used to conduct CFD simulations for several urban areas, including the discussed study area (see Badach et al. (2023): [51]). In that work, the main goal was to formulate and retrieve a singular index describing the aerodynamic effects of the micro-scale urban form on pollution dispersion and later investigate its links with urban form features. The steady-state Reynolds-Averaged Navier–Stokes (RANS) simulations were conducted for the cardinal wind directions using Autodesk CFD 2021 software. The simulation boundary conditions and the domain size were based on common standards [52] and validated using the site data and guidelines of the Architectural Institute of Japan [53] (for more details refer to: [51]). In this paper, the spatial distribution of velocity magnitude at the pedestrian level for the selected area of interest was used to estimate how the urban layout impacts the wind conditions, thus affecting local air quality.

The results of the GIS analysis and CFD simulations were briefly outlined, with focus placed instead on their applicability for urban planning and design. The overall goal was to present and discuss the benefits of integrating urban ventilation management with the planning process at various urban scales. The way these tools can be used to formulate planning policies and actions for urban air quality improvement was also analyzed.

3 Results and discussion: implications for urban planning

The results of the GIS mapping of the FAI spatial distribution are shown in Figure 9.

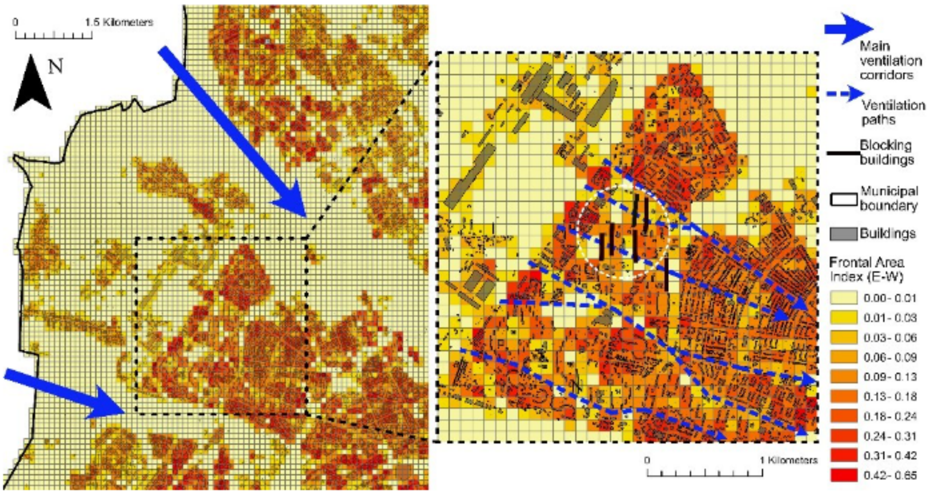

Fig. 9. The results of the FAI mapping (here: west-east wind direction) for part of the Bielany district. The defined area of interest, used for further CFD studies, is indicated with a white circle. Source: own elaboration, based on: [14].

The results indicate that FAI is a useful parameter describing the relationship between urban structure and wind conditions. The GIS calculations allow to rapidly identify areas with lower FAI values, where air flow is less restricted by the spatial obstacles. The Bielany district is located between two main ventilation corridors, but a careful analysis of the FAI distribution allows to identify secondary ventilation paths, which should be conserved in the local planning documents and extended if the district was to be further developed. It can be noticed how these secondary ventilation paths were interrupted by the introduction of the large-scale residential buildings, the positioning of which completely disregarded the previous urban layout (indicated in Figure 9).

Of course, an existing area was subjected to the analysis in this case, but proposed changes in the urban layout and the way they change the spatial distribution of FAI can be also studied. It is important to note, however, that the FAI distribution characterizes the urban form in relation to the wind environment, but not the ventilation conditions as such. In order to more accurately investigate the local wind environment in the area of interest, the results of CFD simulations were used (Figure 10).

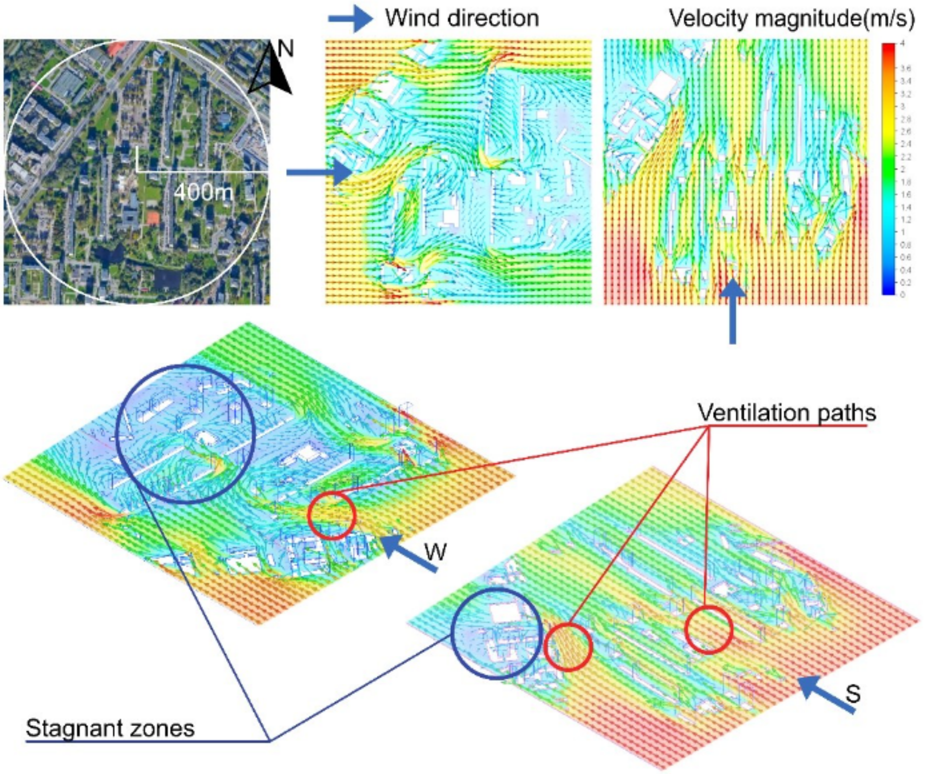

Fig. 10. The results of CFD simulations (velocity magnitude at the height of 2 meters) for selected wind directions (south and west) conducted for the area of interest in the Bielany district. Source: own elaboration, based on: [51].

It can be seen how the long, tall buildings lead to the creation of very strong local ventilation paths for airflow alongside their longer façades (which in some locations may even be causing nuisance for the pedestrians). On the other hand, in case of wind perpendicular to the longer façades, very large air stagnation zones are created, which can contribute to air pollution accumulation.

Many other local ventilation and pollution dispersion phenomena can be identified from the CFD results. Moreover, similarly to the GIS analysis, the CFD simulations were run for an existing layout. However, the same simulations setup can be used to study various design variants and new investments, as it is commonly applied [43] e.g., to assess the impact of new buildings in a given area. Another interesting course of research would be to run the simulations not only to account for the built-up structures (Figure 11, A), but also the vegetation canopy. The high vegetation model based on the National Tree Crowns Map is presented in Figure 11, B. It is visible here how the clusters of high vegetation may inhibit ventilation along the identified paths for west direction. On the other hand, strong ventilation paths were identified for south wind direction (red arrows in Figure 11, B). Although they are generally advantageous for the ventilation of the district, they may contribute to locally decreased pedestrian wind comfort.

Therefore, it would be interesting to study an alternative landscape architecture scenario, where some high vegetation is introduced in these locations to serve as wind breakers. However, this would require further research as accounting for vegetation effects in CFD studies is a complex process, which requires additional validation of the model [20, 54, 55]

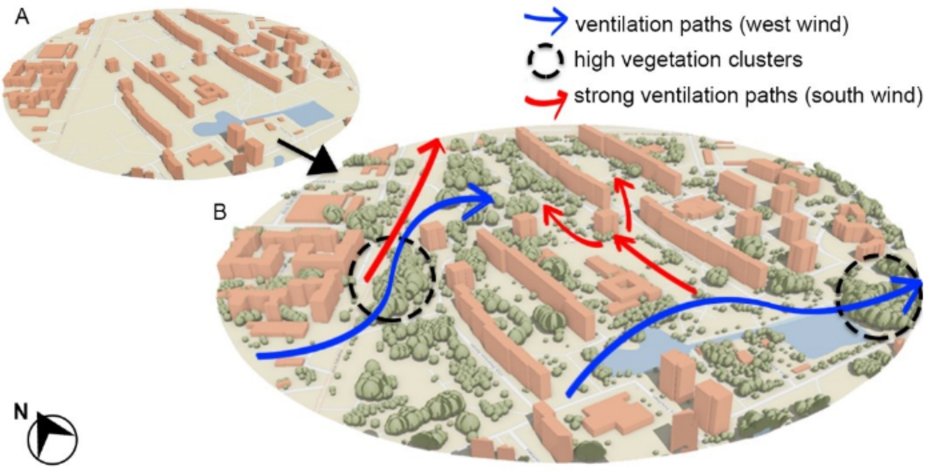

Fig. 11. The previously studied urban geometry (A) and the model supplemented with the vegetation canopy (B). Simulating the effects of high vegetation on the ventilation process is an interesting prospect for further research.

It is important to note, however, that CFD simulations are still computationally expensive and not readily available to non-expert users so it is not always viable to use them in the planning and design practice on regular basis [56, 57]. One way is to use the relatively low-cost steady-state RANS simulations, as described here. They are less accurate than the state-of-the-art Large-Eddy Simulations (LES) [56], but given that a high level of accuracy of the building geometries is very often neglected to improve their efficiency, especially when a large urban area is under investigation [58, 59], they prove to be sufficient. Moreover, there are many simplified CFD plug-ins integrated into design software, ready-to-use with its interface. Although they commonly underestimate the wind speed at the pedestrian level [60], they surely increase the understanding of the planners and designers related to the urban ventilation principles. The future application of the deep learning capabilities to airflow simulations is also discussed in the current literature but there are still many challenges to be addressed [57]. A useful suggestion can be also drawn from this study – that CFD is only used as a follow-up to the GIS approach. If GIS analysis is used at the city or district scale, to identify the main problem areas, then a more detailed micro-scale study using CFD tools may be used to look closely only at selected locations.

The research project took into account several case studies in Polish cities, one of which was discussed here. These case studies allow to describe the relationship between urban layout and the wind environment and to identify some specific problem areas.

However, a more general validity of the procedures was still maintained, allowing for their transferability to other case studies. The proposed multi-scale investigation resulted in the development of new tools and strategies that could facilitate the evaluation of the impact of urban form and various planning solutions on air quality and support its effective management (for details see the reference publications: [14, 51]). Further research is now required to strengthen the planning implications.

What seems to be the most important issue to be resolved in the nearest future is that comparable indicators are necessary both for the GIS and CFD approaches. This would open possibility to cross-compare many urban areas as is the case with the local climate zones (LCZ) [61]. Large, comparable datasets would be also crucial for furthering the prospects of using deep learning in the evaluation of the urban wind environment [58]. While FAI is already a commonly used parameter for urban ventilation planning (with reference values available in subject literature), methods for its calculation and the spatial and spatial resolution vary [14, 38]. Therefore, there is a need for common standards, as in the case of the LCZ. In the case of CFD methods, many various approaches can be used for the interpretation of the results. Therefore, it is crucial that some common parameters derived from the results are also proposed. In the reference project, a singular indicator was proposed to characterize the retention of air pollutants in the selected segment of the urban environment [51]. Such solutions could be further developed so that the results are comparable between different areas. In such a case, the correlation between urban form features and the wind-related and air quality parameters could be examined and compared between many urban areas in order to provide useful guidelines for urban air quality management with reference to urban planning.

Acknowledgements

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