Building and Environment 174 (2020) 106743

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

A framework for Air Quality Management Zones - Useful GIS-based tool for urban planning: Case studies in Antwerp and Gdańsk

Joanna Badach [a,*], Dimitri Voordeckers [b], Lucyna Nyka [a], Maarten Van Acker [b]

[a] Department of Urban Architecture and Waterscapes, Faculty of Architecture, Gdańsk University of Technology, 11/12 Narutowicza Street, 80-233, Gdańsk, Poland
[b] Research Group for Urban Development, Department of Architecture, Interior Design and Urban Planning, Faculty of Design Sciences, University of Antwerp, Mutsaardstraat 31, 2000, Antwerp, Belgium

ARTICLE INFO

Keywords:
Air quality management
Urban ventilation
Urban planning
Urban morphology
GIS-Based analysis

ABSTRACT

There is a growing recognition of the importance of proper urban design in the improvement of air flow and pollution dispersion and in reducing human exposure to air pollution. However, a limited number of studies have been published so far focusing on the development of standard procedures which could be applied by urban planners to effectively evaluate urban conditions with respect to air quality. To fill this gap, a new approach for the determination of urban Air Quality Management Zones (AQMZs) was proposed and presented based on two case studies: Antwerp, Belgium and Gdańsk, Poland. The main objectives of the study were to 1) formulate a theoretical framework for the management of urban ventilation potential and human exposure to air pollution and to 2) develop methods for its implementation by means of a geographic information system (GIS). As a result of the analysis, the typologies that may be associated with decreased ventilation potential and the areas that require close monitoring due to potential human exposure to air pollution were identified for both cities. It is advocated that delimiting these typologies – combined with investigating local climate, wind and topography conditions and air pollution characteristics – could constitute a preliminary step in the urban planning process aimed at air quality improvement. These methods can be further applied to other urban areas in order to indicate where detailed studies are required and to facilitate the development of planning guidelines. Moreover, the directions for further research and urban planning strategies were discussed.

1. Introduction

It is becoming evident that the issue of urban air pollution requires immediate solutions. Despite reductions in emissions of air pollutants, a significant proportion of European residents still live in places where the air quality standards defined by the experts from the World Health Organisation (WHO) are exceeded, which poses a threat to human health [1,2]. According to a recent extensive study, it is estimated that current levels of air pollution in Europe are leading to a decrease in the average life expectancy of over two years [3]. Therefore, improving air quality in urban areas is a subject of growing interest among researchers, urban planners and policy makers. Numerous studies have shown that urban morphology influences the process of atmospheric pollution dispersion, and although this phenomenon remains insufficiently explored [4], considerable advancements in this field have been made recently.

Despite the developments, the integration of theoretical findings with urban planning procedures is still insufficient. Local planning instruments offer good prospects for addressing environmental issues in a flexible, area-oriented approach [5], which is also related to ventilation and atmospheric pollution dispersion management. However, in order to integrate environmental and urban planning, also to address air quality concerns, it is necessary to define area-specific objectives and to develop differentiated approaches adopted to the local conditions [6]. Therefore, the implementation of air quality improvement measures in spatial policies and planning decisions needs to be further examined [7]. Effective air pollution mitigation by urban planners and policy-makers requires appropriate procedures to quantify the urban structure [8–10], which will facilitate the development of area-specific policies.

In this article the prospects of air quality management within the process of urban planning and spatial development were examined. The focus of this work was placed on combining the current knowledge of urban air quality management with the practice of urban planning in order to develop a practical decision support tool. Such a tool should be

* Corresponding author.
E-mail address: joanna.badach@pg.edu.pl (J. Badach).

https://doi.org/10.1016/j.buildenv.2020.106743
Received 2 December 2019; Received in revised form 20 January 2020; Accepted 10 February 2020
Available online 26 February 2020

easily and quickly applicable by urban planners, informing them of the factors which are crucial for improving ventilation conditions and reducing human exposure to pollution. It should also allow them to delimit the main problem areas in terms of air quality management and to indicate where further local studies are needed. Moreover, the parameters of the urban form used in air quality studies, often conducted on idealised models, were referred to two existing cities' distinct urban typologies.

The analysis of morphological urban attributes, which impact the air flow within urban areas, has been already suggested as a vital tool to supplement systematic air flow studies [9]. He et al. [8] designed a study aimed at establishing a protocol for the determination of precinct ventilation zones, in which three main aspects are taken into account: urban form compactness, height of buildings, and patterns of streets. The study is an important contribution to the development of ventilation-performance-based urban planning. However, based on the literature review, it is evident that additional parameters should be taken into account in order to perform the evaluation of the urban structure for the purpose of urban air quality management. Thus, while the framework for the precinct ventilation zone system constitutes a valuable tool, there is a need to develop new methods for its practical application and to include new parameters which could be based on existing municipal data and geographic information system (GIS)-based analysis. This study was aimed at filling this gap and further developing the presented morphology-based approach towards urban air quality management.

In the initial stage a theoretical framework was formulated, aimed at developing a set of urban form indicators connected with two main aspects: ventilation potential and potential human exposure to air pollution. Then, calculation methods – ready-to-use by urban planners – and the boundary values for each indicator were provided. These methods were tested by means of GIS-based tools in two empirical case studies in Antwerp, Belgium and Gdańsk, Poland. The two cities were selected for the analysis because they differ significantly in terms of their spatial structure. Moreover, they also vary in terms of the characteristics of air pollution, the monitoring of it, and mitigation strategies. Further indications to develop effective air quality management strategies for these two cities were also drawn from interviews with local planners, decision-makers, and academics. As a result, the main urban form typologies for air-quality-related issues were identified. The ultimate objective was to propose a systematic approach towards air quality management based on the morphology of urban areas (see Fig. 1).

2. Development of the framework for Air Quality Management Zones

The concept of Air Quality Management Zones (AQMZs), proposed in this study, is related to the widely discussed urban climate zones – see, e.g. Refs. [11–13], – defined as areas with similar combination of factors that influence the local climate, e.g., altitude or urban geometry. However, local modifications in climatic conditions still occur within these zones. Similarly, the intention of this study was to designate zones with similar parameters of the urban form, which in turn have an impact on two main factors: ventilation potential (summarised in the air circulation classes) and human exposure to air pollution (summarised in potential increased exposure zones). The AQMZs can be an effective tool for the assessment of the morphological features of the urban form, which may affect these processes. Yet, the ventilation conditions or pollution concentration levels may vary within these zones, as they are affected by local conditions. The concept of AQMZs was developed based on a review of recent relevant studies. The most important factors for air quality management in relation to the parameters of the urban form were summarised, with an emphasis on the practical application of the reported results and on the suitability of particular indicators used in air quality studies for the practice of urban planning at the municipal scale.

The aim of the review was to develop a set of indicators of the urban form for the delimitation of AQMZs. The following criteria for choosing these indicators were pre-defined: the availability of resources and data, their versatility and simplicity of application. It was assumed that it should be possible to calculate the indicators with commonly available tools and standard municipal geospatial data, without the need to collect a large number of new datasets or to perform field inventories. Moreover, the intention was to provide a set of indicators applicable to various urban areas. Finally, the aim of this research was to develop tools which could be easily applied by all urban planners, within their knowledge and expertise. In the second stage of the study, GIS-based tools were used to map the selected indicators. Two case studies were then performed to confirm that the pre-defined criteria were met and that these indicators may be used for urban development and management of the city's parameters for the purpose air quality improvement.

2.1. Air circulation classes

There are many indications in the existing body of research that a dense matrix of buildings is strongly related to decreased ventilation potential [4,14,15]. On the contrary, a high proportion of open spaces or appropriately arranged ones (e.g., linked to create minor and major air pathways) can improve ventilation and the dispersion of pollutants accumulating in congested structures [16]. Therefore, in order to enhance ventilation potential in high-density areas, it is beneficial to increase buildings' height while decreasing their footprint – as demonstrated in a study by Guo et al. [15]. Based on these indications, the **plan area density (λ_P)** indicator (the ratio between the footprint area of buildings and the site area) was included in the maps to account for urban structure compactness (also referred to as packing building density or site coverage ratio; see, e.g. Refs. [17,18]).

Another factor to consider is the buildings' 3-dimensional structure. For example, Yang et al. [19] established that the wind velocity ratio can increase even by 7%–8% when the locally applied indicator – sky view

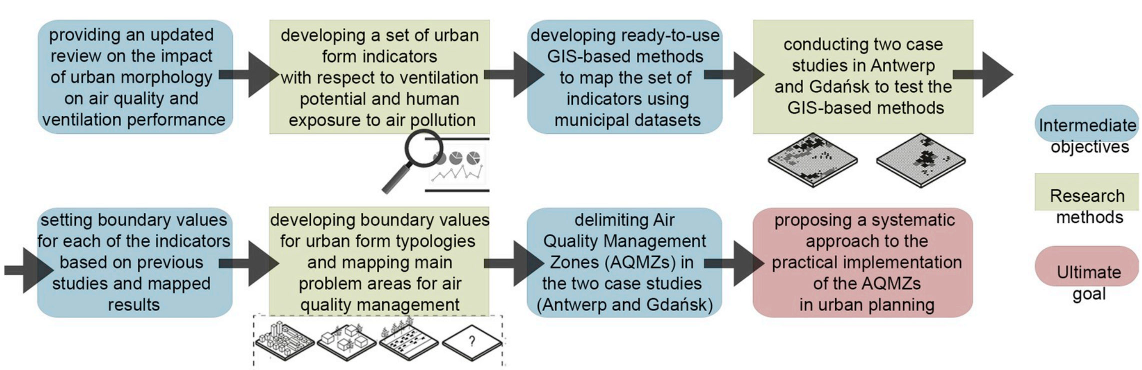

Fig. 1. The methodological approach used in this study.

factor (the ratio of visible sky to the overlying hemisphere in a sky view image from a given point) – is increased by 10%. Ventilation potential was also investigated using an indicator based on the building frontal area (frontal façade facing the wind), referred to as frontal area density or the frontal area index [17,18]. However, this indicator is dependent on the local wind conditions and is unsuitable for a municipal scale. The particular indicator included in the maps of air circulation classes is **gross floor area ratio (λ_{GFA}),** being the most straightforward to calculate using basic municipal data (also called floor area ratio, the ratio between the buildings' gross floor area and the site area; see, e.g., Refs. [20,21]).

Another important factor affecting urban ventilation potential is the variation in building height, which can generally be associated with improved overall ventilation conditions. For example, Lau and Ngan [22] established that the effect of fresh air entrainment increases by approx. 80% in case of non-uniform models and the capability of pollutants removal increases by app. 30% when building height varies 33%. However, a study by Chen et al. [17] suggested that this phenomenon may be more complex, since improved ventilation around taller buildings was observed, but it worsens around neighbouring lower ones due to a shelter effect. Although this connection remains incompletely explored, there are clear indications that this factor should be included in the urban morphological analysis with respect to ventilation potential. **Height variability (σ_H),** calculated as the standard deviation of buildings height, was therefore included in the maps of air circulation classes.

The geometry of street canyons, a fundamental component of the urban tissue, has a particular impact on the accumulation of various atmospheric pollutants, especially traffic-related ones. This effect is especially severe in high-density cities, where the width-to-height (W/H) ratio of a street canyon) is very low [23]. The relationships between this indicator and ventilation potential or pollution dispersion have been investigated in many local studies by means of numerical modelling or simplified parametric modelling (see, e.g. Ref. [24]). Therefore, identifying the location of street canyon geometries at the scale of the entire municipality is indispensable to air quality management strategies. The mapped distribution and proportions of street canyons are included in the air circulation classes in the form of the **street canyon density (σ_{SC})** indicator, which was newly developed for the purpose of this study and is calculated as the ratio between total length of street canyons and the site area, based on the commonly-used road density indicator.

Finally, trees, often omitted in ventilation studies due to their low frontal area in comparison with buildings [25], were considered. They constitute an aerodynamic barrier, reducing wind speed, so their arrangement should be considered in urban planning [26]. It is especially important in street canyons due to the observed disturbance of flow and the reduction in wind speed [27]. Therefore, an indicator which can be easily computed with the available datasets was included within the air circulation classes – **tall vegetation area density (λ_{TV})** – also referred to as urban tree cover [28] and calculated as the ratio between the tall vegetation cover and the site area.

2.2. *Potential increased exposure zones*

Growing attention in the current research agenda is paid to evaluating personal exposure to pollution, also due to new techniques and tools allowing for more accurate estimations based on the spatial–temporal characteristics of air pollution and human mobility patterns [29]. However, detailed census data is not always available and actual resident's exposure to pollution can be difficult to be accurately measured [30]. In such a case, urban function and infrastructural parameters can serve only as a proxy rather than as actual human exposure indicators [31], although this relationship is not easily parameterised. To account for this aspect, increased exposure zones were added to the analysis.

Frank and Engelke [32] showed that increased residential density not only exacerbates traffic congestion, but also increases human exposure to harmful emissions. Therefore, **the gross floor area ratio for residential and commercial functions (λ_{RC})** was taken into account as a proxy to estimate potential increased exposure to air pollution.

Not only dense residential or commercial areas are related to increased exposure to air pollution, but so are specific urban functions which bring together vulnerable segments of the population such as schools, nursing homes, and hospitals. Various studies have been conducted on schools as a function related to groups which are vulnerable to pollution. For example, a study by Van Brusselen et al. [33] showed that within a 500-m perimeter of the ring road in Antwerp, where increased pollution levels were measured, 55 schools, hospitals, and nursing homes were located. However, no study for the entire city of Antwerp or Gdańsk was conducted. For this study, the **plan area density for urban functions related to groups vulnerable to air pollution (λ_{UF})** (the ratio between the footprint area of buildings containing relevant functions and the site area) was used. Schools, educational facilities, hospitals and nursing homes were included.

Active travel (cycling and walking) should also be taken into account, especially when it takes place in the proximity of traffic-related emissions, depending on the type of road and the traffic intensity [34]. Studies by Tainio et al. [35] and de Hartog et al. [36] indicated that air pollution may reduce the health benefits of active travel, though in most urban environments the benefits of active travel outweighed the detrimental effects of exposure to air pollution. Due the fact that it is time-consuming and expensive to map movement patterns on a large scale, this study focused on mapping the cycling infrastructure as a proxy related to the higher amount of cyclists and other users. Therefore, another indicator was included in the potential increased exposure zone map: **cycling infrastructure density (σ_C),** the ratio between the total length of the cycling infrastructure and the site area. This parameter might be an aid in municipal infrastructural decisions, also regarding reductions in traffic intensity, and – when linked with mapped traffic intensity – can lead to interesting results.

Carlisle and Sharp [37] reviewed a wide range of ambient air pollutants and their potential impact on the health of outdoor athletes or exercisers. The study suggested avoiding roads with high traffic intensity for outdoor activities. Therefore, outdoor sports facilities and parks were mapped in the study, expressed by the **urban parks and outdoor facilities area density (λ_{PO})** (the ratio between the floor area with urban parks and outdoor facilities and the site area) as a proxy for increased human outdoor activity, and so, a potential increased exposure to air pollution.

The final set of indicators included in the concept of AQMZs, compared with the indicators used by He at al [8]. is shown in Fig. 2.

3. Air Quality Management Zones in application

3.1. *Study areas*

Two cities were selected for the comparative study to test the applicability of the chosen indicators: Antwerp, Begium and Gdańsk, Poland (see Fig. 3). Antwerp (51.22° N, 4.40° E), the Belgian city located on the River Scheldt and connected to the North Sea, manages one of the biggest ports in Europe. It covers an area of 204.5 km^2 and has a population of over 520,000 residents. Gdańsk (54.35° N, 18.65° E), a Polish city on the Baltic coast, manages the largest seaport in Poland. It covers an area of 262 km^2 and has a population of over 460,000 residents.

The determination of topography units was performed using available numerical elevation models for Antwerp and Gdańsk, with reference grids of 25 m and 100 m, respectively (retrieved from the Departement Omgeving [38] and from the Head Office of Geodesy and Cartography [39]), using a methodology for topography analysis adopted from Alcoforado et al. [11] (see Fig. 4). Additionally, waterfront units were also distinguished, adopting a 200-m border from the banks of rivers and surface waters, given the crucial role of waterfront

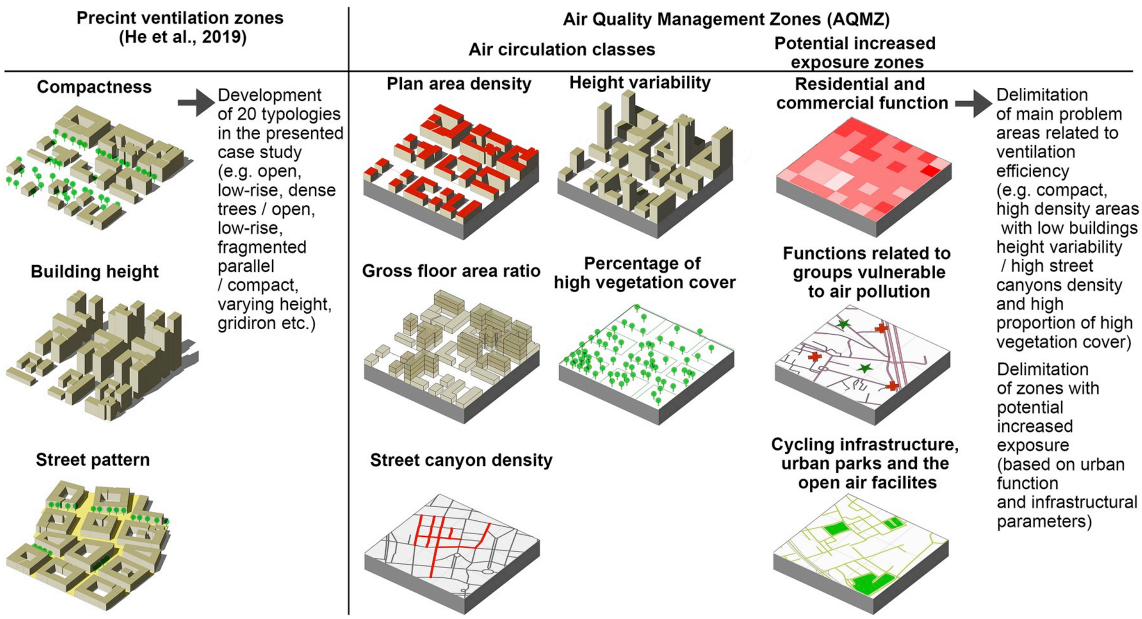

Fig. 2. The set of indicators for precinct ventilation zones and the Air Quality Management Zones (AQMZs).

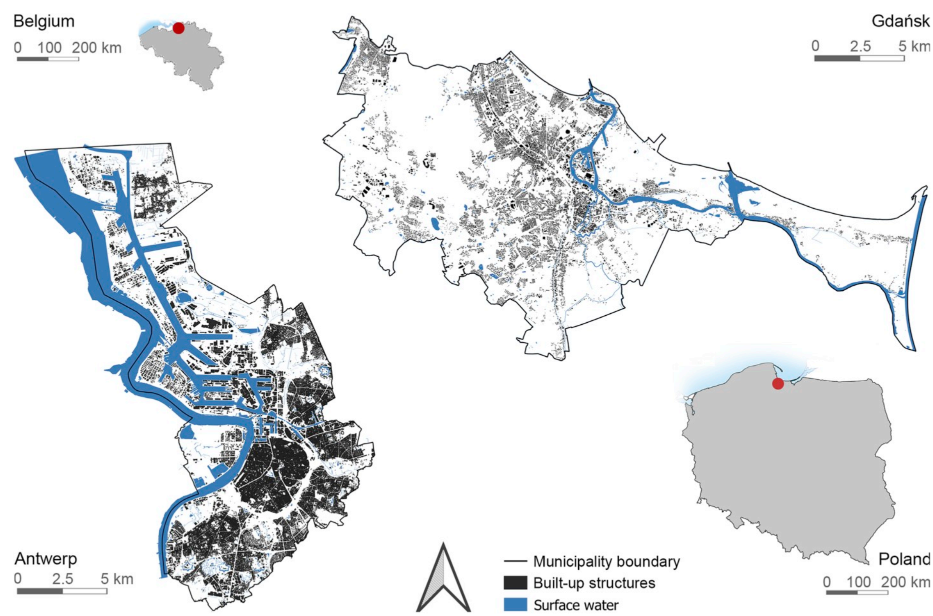

Fig. 3. The locations of the study areas: Antwerp, Belgium and Gdańsk, Poland.

sea and land breezes in city breathability [16]. In Antwerp, a low-altitude zone prevails with very small and dispersed sloped areas. In Gdańsk, the topography is more complex, with all of the predefined units identified. In Antwerp the waterfront unit covers a significant proportion of the municipality (approx. 33%), whereas in Gdańsk it is approx. 14%.

Existing wind and air quality conditions were also analysed for the two cities. The wind roses indicate a clear prevailing wind direction for Antwerp from 180° to 247.5° (southerly and west-southwesterly) with an average yearly wind speed of 4.12 m/s (measured at Antwerp Airport from 2001 to 2019). In Gdańsk, there are predominantly southerly, southwesterly and westerly winds with an average yearly wind speed of 2.6 m/s (measured at Gdańsk Stogi Station in 2018). The location of monitoring stations and yearly wind roses are presented in Fig. 5 (data retrieved from Windfinder [40] for Antwerp and from ARMAAG Foundation [41] for Gdańsk).

Antwerp is one of the cities with the highest loss of life expectancy due to air pollution in Europe [42]. Air quality studies have shown a strong focus on traffic-related pollution [43,44]. However, a study by the Flemish Institute for Technological Research (VITO) [43] showed that more than 70% of the particulate matter (PM) concentration can be allocated to sources outside the country's borders. In Antwerp, a large-scale measurement campaign revealed high levels of NO_2 (50–60 μg/m^3) in the city centre, raising awareness of air pollution [44]. The data was used to validate the results of air quality modelling by the Belgian Interregional Environment Agency (Ircel–Celine) and VITO [45]. The air quality models based on the ATMO-street model – already validated in two Belgian cities, Antwerp and Ghent – were made for NO_2, $PM_{2.5}$, PM_{10}, and black carbon (BC) concentrations [46]. The models indicate specific zones of high air pollution, pointing out the ring

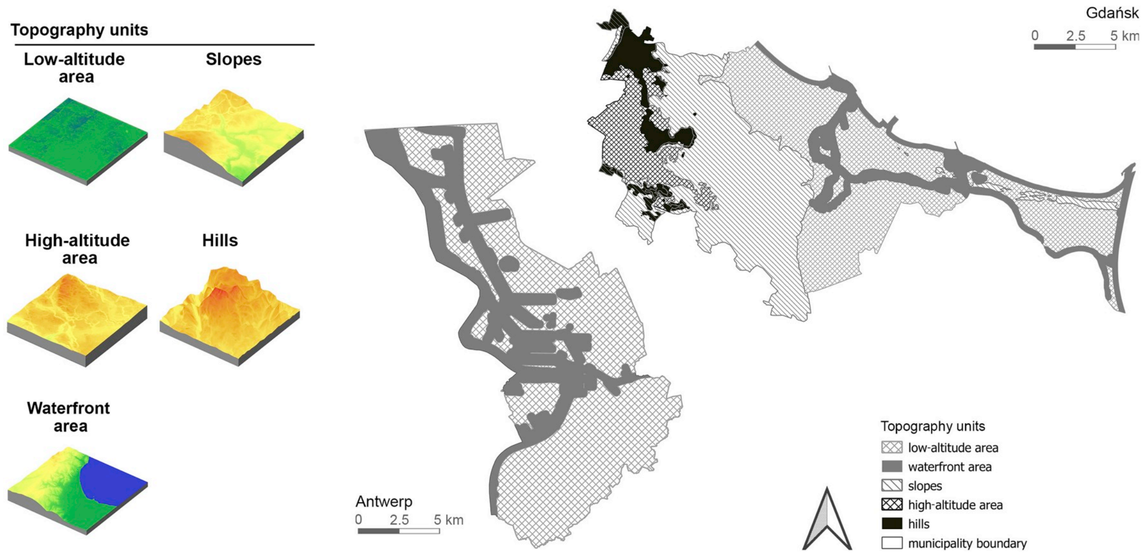

Fig. 4. Antwerp and Gdańsk – mapped topography units.

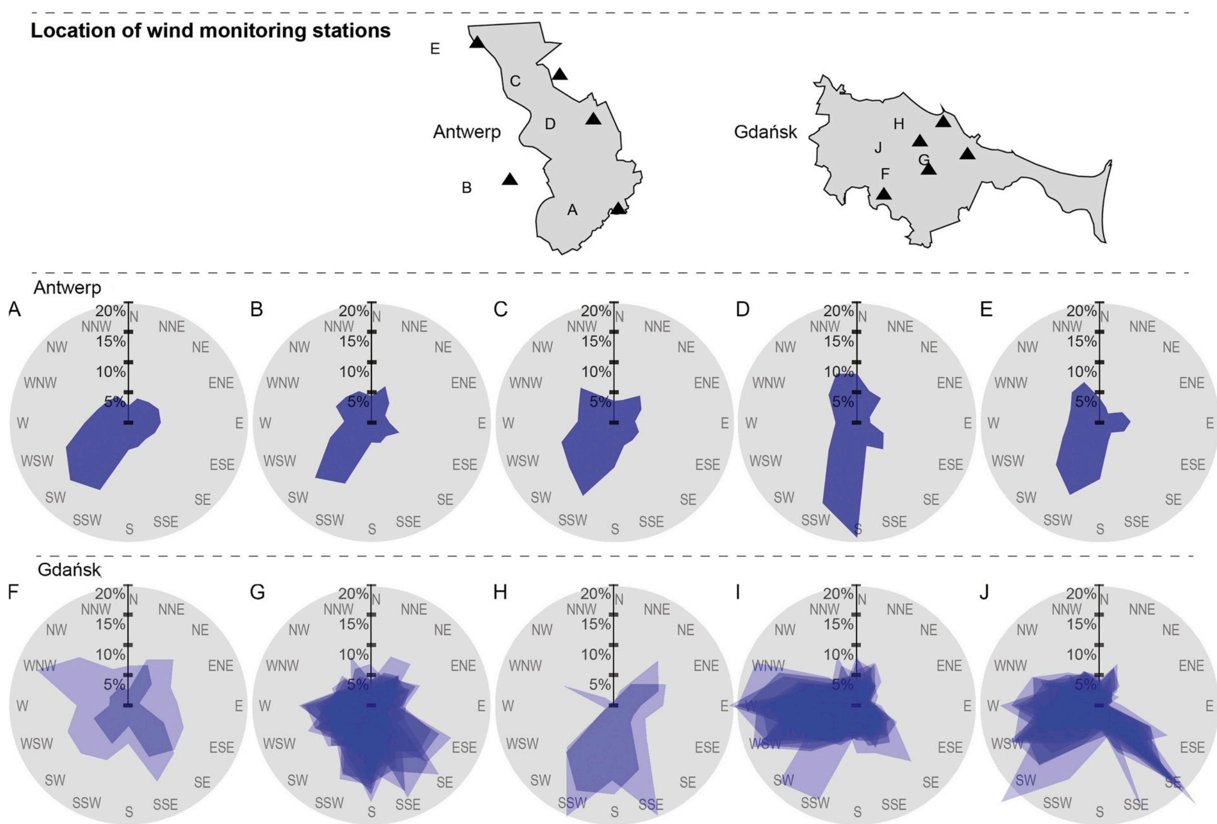

Fig. 5. Wind roses for Antwerp (2001–2019) and Gdańsk (2000–2017).

road and several street canyons as problematic areas where pollution concentration levels are higher than the European standards.

For Gdańsk, the issue is mainly with PM (especially PM_{10}), emitted by the household sector and traffic. High PM concentrations are also connected with high levels of benzo(a)pyrene [41]. According to recent reports, a long-term trend of exceeding the maximum 24-h concentration of both PM_{10} and benzo(a)pyrene occurs in many districts, despite recent mitigation measures [47]. The air quality models are carried out by different research institutes. Paciorek [48] used CALPUFF dispersion modelling for NO_2, SO_2, and PM; however, the model was not validated by in situ measurements. Another model was made by Ramacher and Karl [49] for NO_2 levels, based on a CityChem simulation and validated by measurements of the eight stations in the metropolitan area of the cities of Gdańsk, Gdynia and Sopot, but not by on-site measurements. Although these models lack clear validation, similar spatial patterns can be found. Both show an increase in air pollution concentration levels in the proximity of the main road and in the city centre.

Maps based on the above-mentioned air pollution models are presented in Fig. 6. Conclusions should be drawn carefully from comparison of these maps, since the colour codes related to air pollution levels differ from map to map.

3.2. Data sources

The geospatial datasets were retrieved from the Databank Ondergrond Vlaanderen (DOV) database for Antwerp [38] and provided by the Head Office of Geodesy and Cartography in Poland on an individual request for Gdańsk. Additional data on the cycling infrastructure and outdoor facilities was collected from the Opendata Geoportal of the city of Antwerp [50] and the cycling map available from the Gdańsk city portal [51]. Moreover, further information was also sought from local planning documents or air quality plans and reports.

3.3. Grid selection

Open-source QGIS V.3.6.0 software was used in the study. In order to delimit different zones with common features, a grid approach was applied. Recent studies showed that the grid size is related to the size of the study area and the desired accuracy. At a city scale, Smith [52] used a squared, 500 × 500 m grid to illustrate the office floor space density for the city of London. In order to get detailed insight into global population density, Freire et al. [53] used a 250 × 250 m grid. Since this GIS analysis aimed to map Air Quality Management Zones at the a city scale, a grid size of 200 × 200 m was applied (see Appendix A, Figure A.1). To calculate each indicator, the relevant input layer was intersected with the grid layer, which allowed unique grid IDs to be assigned to the elements (or their parts) located within a particular grid cell.

3.4. Air circulation classes in application

λ_P was calculated for each grid cell, using the *Group Stats* QGIS tool. The information on the plan area was available in the municipal layers with buildings. The unique cell ID was used as an additional filter to obtain the sum of the total plan area of buildings for each grid cell. The calculated values were then added as an additional field for the grid layer and divided by the grids surface. λ_{GFA} was calculated using the same approach. New information on the gross floor area was added to the layer by multiplying the total plan area by the number of buildings floors. It is important to note that corresponding data on buildings' height was not available in both cases. In Antwerp more accurate data on buildings heights is available. However, in Gdańsk only the number of floors is indicated so an approximation of the building's height was used to obtain the missing data (number of floors multiplied by 3.5 m). Then σ_H was calculated using the standard deviation of the height of all buildings for a given grid cell ID with the use of *Group Stats* tool.

Detailed mapping of the street canyons (enclosed streets with a W/H ratio of <1.4) was first conducted to obtain σ_{sc} with an accuracy of 5 m. The input layers for this analysis included layers with buildings (for buildings heights) and road infrastructure (for the central axes for every street). Each street axis was divided into 5-m segments. For every segment, the perpendicular distance to the nearest facade was calculated on both sides of the axis by using the *Intersect* tool in QGIS to retrieve the buildings' height associated with each segment. Thus, the W/H ratio could be determined, resulting in a detailed street canyon map (see Fig. 7). This street canyon analysis is more detailed than the one conducted by the Department of Environment in Flanders [54] where the W/H ratio was calculated for an entire street. σ_{sc} could then be calculated for a given grid cell ID using the *Group Stats* GIS tool.

λ_{TV} was also calculated using the *Group Stats* tool. The municipal layers with greenery were used for input data. In Gdańsk a separate layer with areas covered with tall vegetation was available, which made it possible to calculate the sum of their total plan area for each grid cell using the *Group Stats* QGIS tool. However, for Antwerp an additional step was required due to the lack of vector layers. A raster file including the following areas was used as input: tall vegetation, low vegetation, agricultural areas, lack of vegetation or lack of data. In order to extract the areas with tall greenery and to obtain their surface, a point layer was created with a reference grid of 10 m. By using the *Add Raster Values to Points* QGIS tool, all points located within the tall vegetation clusters (characterised by the colour assigned to tall vegetation) were determined. By doing this, λ_{TV} could be estimated as a percentage of the number of points within the high vegetation area to the total amount of points (400) in every grid cell (see Fig. 8). All of the mapped indicators for air circulation classes are shown in Appendix A, Figure A.1.

3.5. Identification of potential increased exposure zones

A similar approach was adopted for λ_{RC} as for λ_{GFA} but only buildings with the required residential and commercial functions were extracted from the layer based on the attributes assigned to each building. For λ_{UF} and λ_{PO} a similar approach was adopted as for λ_P, and again only buildings and facilities with the required functions, according to each case, were extracted. It is important to note that due to the lack of corresponding data, municipal layers were supplemented by other data sources. The layers for urban parks and outdoor facilities were collected using data from the Opendata Geoportal of the city of Antwerp [50]. Relevant information for Gdańsk was extracted of the following geospatial layers in the municipal datasets: (1) sports and recreational complexes, (2) sports infrastructure as well as (3) various forms of low greenery. The indicators were subsequently calculated for each grid cell, using the unique cell ID and the *Group Stats* tool. For σ_C, the total bicycle infrastructure length per grid cell was calculated using the *Group Stats* tool. Next, σ_C was determined by calculating the ratio of the total length of bicycle infrastructure in every grid, using the unique cell ID and the *Group Stats* tool. The cycling infrastructure was collected using data from the Opendata Geoportal of the city of Antwerp [50]. In case of cycling infrastructure for Gdańsk, some of the cycling routes were mapped within the municipal datasets. Additionally, the cycling map available from the Gdańsk City Portal [51] was used. All of the mapped indicators for potential increased exposure zones are presented in

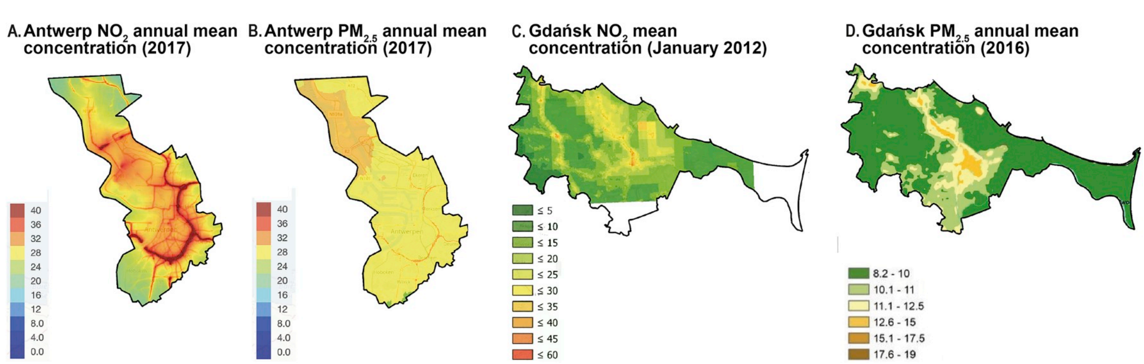

Fig. 6. Modelled air quality maps: (A and B) modelled NO_2 and $PM_{2.5}$ concentrations for Antwerp, (C and D) modelled NO_2 and $PM_{2.5}$ concentrations for Gdańsk.

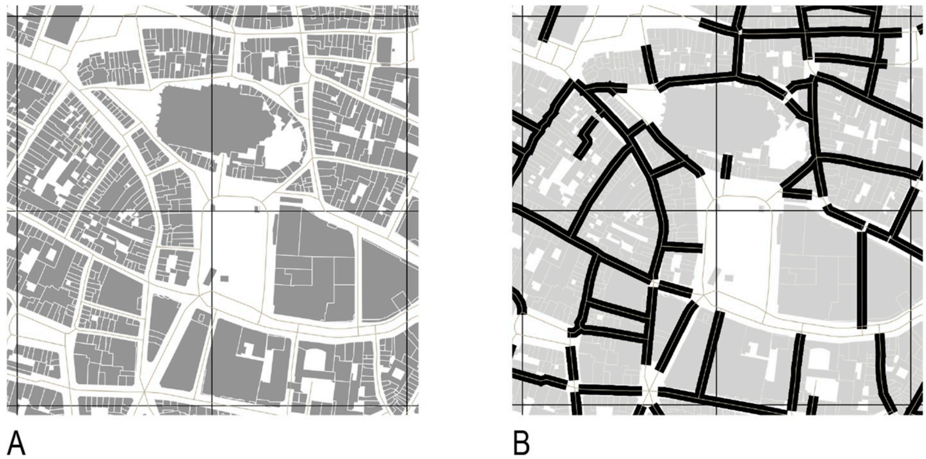

Fig. 7. (A) the available data layers on building geometry and street axes and (B) the calculation of the W/H ratio and the designation of every street segment of 5 m with a W/H ratio lower than 1.4.

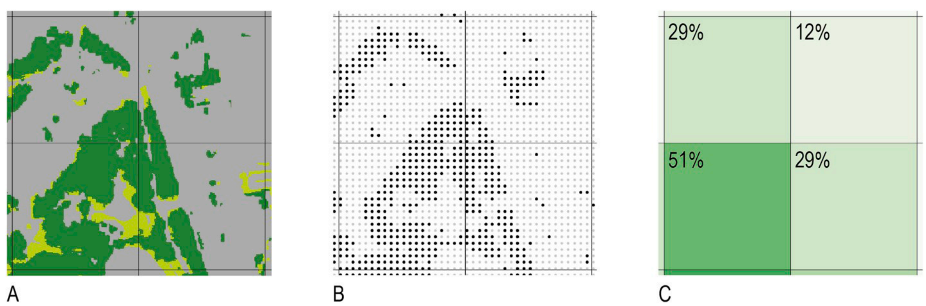

Fig. 8. The approach to calculate tall vegetation area density in Antwerp: (A) the input raster layer (B) the point vector layer (C) the finally obtained results.

Appendix A, Figure A.1.

4. Results – Boundary values for the AQMZs typologies

Further categorisation of urban form indicators was conducted by determining boundary values to create sample typologies for the main problem areas. It is important to note, however, that the boundary values should be reconsidered and adjusted in order to be applied for the morphology of high-density metropolitan cities [8].

4.1. Air circulation classes: Boundary values

The following λ_P can be found in studies by Mei et al. [18] and Chen at al [17]: 25% for medium and 44% for compact urban development. Although in both cities the maximum λ_P exceed 95%, in the municipality of Gdańsk only approx. 1.9% of the total area ranges between the above-mentioned λ_P of 25% and 44%, while in Antwerp approx. 15% does so. In another study the lowest λ_P of 4% was applied, defined as 'almost isolated buildings', and the λ_P of 44% was also used to define dense structures [55]. Therefore, the threshold for medium density λ_P was lowered to 15%.

In a study by Wang et al. [56], three values of plot ratio (here λ_{GFA}) were used: 3, 5, and 8. The maximum value calculated for Antwerp is 8.9, but areas with a λ_{GFA} of more than 5 cover less than 0.3% of the municipal area. For Gdańsk these values are 5.8 and 0.1%, respectively. Therefore, 3 and 1 were selected as boundary values for high- and medium-density development. The values lower than 1 were classified as low densities.

Hang et al. [57] and Chen et al. [17] investigated idealised building array models and showed that the flow rate increases with the increase of building height variability. In studies of existing cities, the standard deviation of the height of the roughness elements ranged from 2.9 m to 12.7 m for various urban structure typologies in the high-density city of Hong Kong [58], or from 5.6 m even up to 83.6 m for downtown Houston districts [59], but in the latter case values from 13.9 m to 29.2 m were obtained for other districts. The standard deviation of buildings height obtained in the analysis for the entire municipality was 5.95 m (with relative standard deviation of 58.7%) for Antwerp and 5.42 m (68.7%), for Gdańsk. The following values of σ_H were adopted based on an approximation of a single floor height: low - below 3.5 m, medium - between 3.5 m and 10.5 m, and large - above 10.5 m.

σ_{SC} is a new indicator developed for the purpose of this study, so there are no reference values available in the literature. However, road density (σ_R), expressed by the ratio between the total road length and the site area, is commonly used. Therefore, the obtained values of σ_{SC} were referred to the average values of σ_R obtained for both cities: 8.15 km/km^2 in Antwerp and 9.96 km/km^2 in Gdańsk. The total length of street canyons constitutes approx. 13.5% of the total road length in Antwerp, but only 0.9% in Gdańsk. Based on these values, the following classification of σ_{SC} was adopted: 6.5 km/km^2 for high density (which constitutes approx. 80% of the average σ_R in Antwerp) and between 2.5 and 6.5 km/km^2 for medium density (approx. 30%–80%, respectively). The values below 2.5 km/km^2 were classified as low density.

In a study by McDonald et al. [60], the tree planting cover in West Midlands and Glasgow, UK was quantified between 1.1% and 1.3% for dense urban and suburban areas and 2.0%–4.4% for less dense suburban areas. The areas with an average tree planting cover of 42.6% were classified as wooded. Based on this study, the λ_{TV} of over 40% was classified as high tree cover. Approx. 53% of the municipality in Antwerp and 39% of Gdańsk fall below this percentage, so the medium threshold of 20% was adopted for medium λ_{TV} based on the average tree cover for the Greater London Authority, as reported by Tallis et al. [61].

Table 1
The adopted boundary values of the air circulation class indicators for the AQMZs maps.

Indicator				
plan area density (λ_P)	gross floor area ratio (λ_{GFA})	height variability (σ_H)	street canyon density (σ_{SC})	tall vegetation area density (λ_{TV})
Sparse: <15%	Low-density: <1.0	Low: <3.5	Low-density: <2.5	Low tree cover: <20%
Medium: 15%–43%	Medium-density: 1.0–3.0	Medium: 3.5–10.5	Medium-density: 2.5–6.5	Medium tree cover: 20%–40%
Compact: >43%	High-density: >3.0	Large: >10.5	High-density: >6.5	High tree cover: >40%

The final boundary values are listed in Table 1. Mapped results are shown in Fig. 9 for Antwerp and in Fig. 10 for Gdańsk.

4.2. Potential increased exposure zones: Boundary values

Because of the close similarity to $\boldsymbol{\lambda_{GFA}}$, the same boundary limits were taken into account for $\boldsymbol{\lambda_{RC}}$. For Antwerp, $\boldsymbol{\sigma_C}$ per grid cell varies from 0 to 2.88 km/km^2 and for Gdańsk from 0 to 4.85 km/km^2. The analysis also revealed a $\boldsymbol{\sigma_C}$ of 2.65 km/km^2 for the entire area of Antwerp, which is approx. one-third of the road density of Antwerp (8.15 km/km^2). For Gdańsk, the calculated $\boldsymbol{\sigma_C}$ is 3.83 km/km^2, which is about 38% of the overall road density (9.96 km/km^2). The study for Flanders showed density values for the bicycle network ranging from 0.50 to 3.05 km/km^2 [62]. A study for Montreal, Canada showed different levels of density in different neighbourhood typologies, indicating 8.08 km/km^2 for downtown areas, 4.22 km/km^2 for urbanised areas, and 3.24 km/km^2 for the suburban region [63]. An average $\boldsymbol{\sigma_C}$ of 1.74 km/km^2 was calculated for 74 US cities, with a minimum of 0.03 km/km^2, a maximum of 18.67 km/km^2 [64]. Based on these studies, any density lower than 0.80 km/km^2 was labelled as low $\boldsymbol{\sigma_C}$. The boundary levels for medium $\boldsymbol{\sigma_C}$ were set to 0.80–4.40 km/km^2 and for high $\boldsymbol{\sigma_C}$, the boundary level was over 4.40 km/km^2.

No relevant studies were found for $\boldsymbol{\lambda_{UF}}$ and $\boldsymbol{\lambda_{PO}}$, so the calculated percentages were analysed. The class division was automated with Microsoft Excel (V16.26). The histogram clearly indicated a high amount (609) of relatively low percentages of $\boldsymbol{\lambda_{UF}}$ (0%–3.2%). A moderate frequency (212) ranged from 3.2% to 8.0%. From a $\boldsymbol{\lambda_{UF}}$ of 8%, the amount drops off strongly; therefore, $\boldsymbol{\lambda_{UF}}$ >8.0% was labelled as high $\boldsymbol{\lambda_{UF}}$. The same analysis was conducted for $\boldsymbol{\lambda_{PO}}$, resulting in a high frequency (897) of low percentages (0.0%–8.9%), a mediocre frequency (164) ranging from 8.9% to 17.8%, and a low frequency (lower than 90) of $\boldsymbol{\lambda_{PO}}$ >17.8%.

The final boundary values are listed in Table 2. The mapped results are shown in Fig. 11 for Antwerp and in Fig. 12 for Gdańsk. Four levels of potential exposure to pollution were delimited: low, moderate, high and highest. The grid cells labelled 'low' are those with low levels for $\boldsymbol{\lambda_{RC}}$, $\boldsymbol{\lambda_{UF}}$, $\boldsymbol{\sigma_C}$, and $\boldsymbol{\lambda_{PO}}$. Once one or more of the indicators reaches the medium level the grid cell is labelled 'moderate' and once one of the indicators reaches a high level, the grid cell is labelled 'high'. A fourth level (highest) was added for the potential increased exposure zones. The grid cells labelled 'highest' are those where not one, but two or more indicators reached the high level.

5. Conclusions and recommendations

5.1. Summary of findings

AQMZs were proposed as a preliminary tool for delimiting the main problem areas in terms of air quality management during the initial stage of policy development. The key conclusions from the conducted study are as follows:

- The set of indicators meets the pre-defined criteria, which was confirmed by two case studies. It was possible to calculate all the indicators with the available resources, although in some cases municipal geospatial datasets were supplemented with additional open source data. The method is applicable to different urban areas and allows for cross-comparing the results. The indicators can be calculated with standard GIS-based tools which are already commonly utilised by urban planners.
- In the case of air circulation classes, Antwerp has low height variability and tall vegetation clusters are dispersed, indicating lower

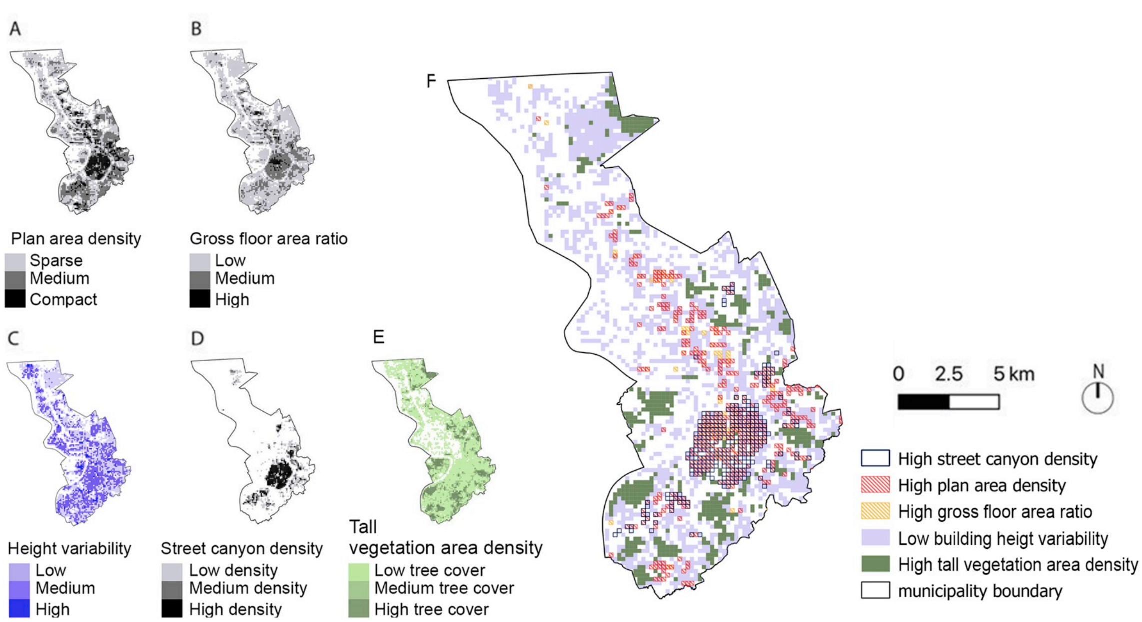

Fig. 9. Antwerp – mapped air circulation classes: (A) – plan area density ($\boldsymbol{\lambda_P}$), (B) – gross floor area ratio ($\boldsymbol{\lambda_{GFA}}$), (C) – height variability ($\boldsymbol{\sigma_H}$), (D) – street canyon density ($\boldsymbol{\sigma_{SC}}$), (E) – tall vegetation area density ($\boldsymbol{\lambda_{TV}}$), (F) – final main problem area typologies.

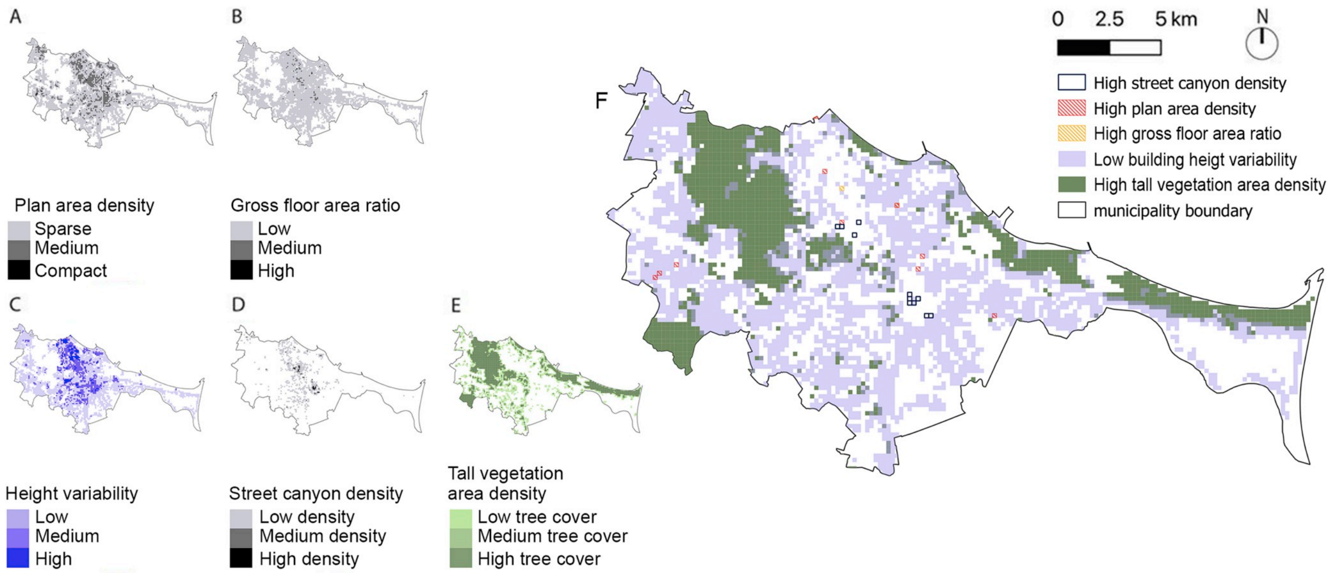

Fig. 10. Gdańsk – mapped air circulation classes: (A) – plan area density (λ_P), (B) – gross floor area ratio (λ_{GFA}), (C) – height variability (σ_H), (D) – street canyon density (σ_{SC}), (E) – tall vegetation area density (λ_{TV}), (F) – final main problem area typologies.

potential to form aerodynamic limits. The areas characterised by high λ_P, λ_{GFA}, and σ_{sc} are located mainly in the historic centre and they should be given particular consideration when developing local design scenarios. Solutions to improve ventilation potential in these areas may include regulating the urban grid, buildings' arrangement and shapes, height variability or built density for new developments [65–67]. Moreover, implementing particular solutions within the existing structures can be considered, e.g., in street canyons, such as arcade design or half-open spaces [68,69]. Planting new tall vegetation in the densely built-up inner city areas should be avoided or carefully considered in the course of air flow studies. Instead, other forms of urban greenery may be recommended such as green walls and green roofs [70–72].

- In Gdańsk, the built-up structures are more dispersed and less dense. Two main problems should be addressed and cautiously considered in the spatial development strategies: the low height variability of the built-up structures and large clusters of tall vegetation. The latter, together with the distribution of sloped areas can constitute significant aerodynamic limits (see, e.g. Ref. [11]) and should therefore be cautiously considered in the development of spatial strategies. The proposed solution is to develop an urban ventilation corridor plan to enhance air exchange and ventilation conditions in the inner city areas [73]. Many methods for identifying such ventilation corridors have already been developed, including GIS or integrated GIS and CFD approaches based on building frontal area index [25,74–76]. Topography should be also included in this analysis [77], especially in the complex terrain in the discussed case scenario. Moreover, in the future more accurate indicators might be considered to account for the aerodynamic effects of tall vegetation such as vegetation volume but this would require detailed vegetation inventories.
- In the case of the maps of increased potential exposure areas, both cities show large zones marked as 'low', mostly corresponding with large natural areas or industrial sites. For the areas marked as 'moderate', 'high', and 'highest', a spatial difference between Antwerp and Gdańsk is visible. In Antwerp, these areas have clearer boundaries, corresponding with the urban fabric. In Gdańsk, the delimitation of this zone is more scattered. For both cities, no large areas with the highest exposure levels were detected – only a few single grid cells. The first recommended step for the management of human exposure to air pollution is to establish more detailed spatial–temporal patterns of exposure and pollution concentration levels in the areas marked as 'high' and 'highest', e.g., by means of mobile monitoring [78–80]. Data collected in such an approach would also allow to provide the residents with more comprehensive information about their exposure to air pollution.

5.2. Limitations

Some limitations to the interpretation of these results should be mentioned. Firstly, all maps were computed based on the available municipal data, so if some data were inaccurate or out-dated, the maps should be revised. In terms of data quality, some cases of significant data shortages were revealed. On such occasions additional data sources were used, which poses some methodological difficulties resulting from the differences in the datasets. This may lead to inaccuracies in data processing and the final calculations. Therefore, the established AQMZs for the two cities may require updating in the future and should not be treated as conclusive. For the purpose of air quality management within spatial planning policies at the municipal scale, the above-mentioned limitations can be counteracted by using better quality geospatial data or applying new techniques to supplement the available municipal datasets, such as remote sensing [12].

Table 2
The boundary values of the increased potential exposure indicators for the AQMZs maps.

the gross floor area ratio for residential and commercial functions (λ_{RC})	plan area density for urban functions related to groups vulnerable to air pollution (λ_{UF})	cycling infrastructure density (σ_C)	urban parks and outdoor facilities area density (λ_{PO})
Low-density: <1.0 Medium-density: 1.0–3.0 High-density: >3.0	Low: <3.2% Medium: 3.2%–8.0% High: >8.0%	Low: <0.80 Medium: 0.80–4.40 High: >4.40	Low: < 8.9% Medium: 8.9%–17.8% High: >17.8%

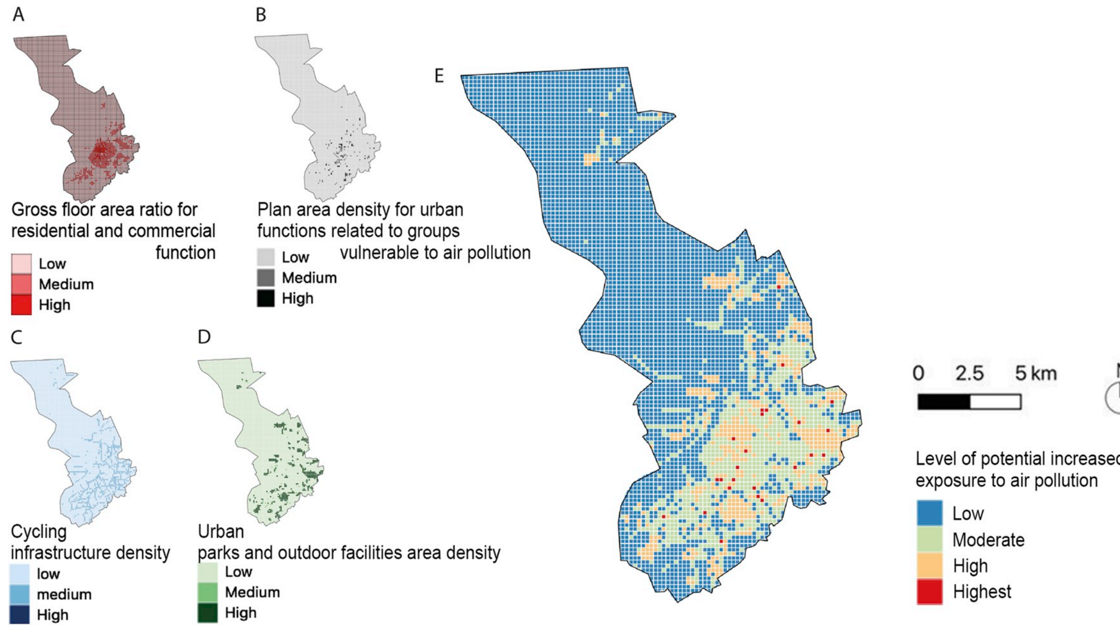

Fig. 11. Antwerp – mapped potential increased exposure zones: (A) – the gross floor area ratio for residential and commercial functions (λ_{RC}), (B) – plan area density for urban functions related to groups vulnerable to air pollution (λ_{UF}), (C) – cycling infrastructure density (σ_C), (D) – urban parks and outdoor facilities area density (λ_{PO}), (E) – the merged map.

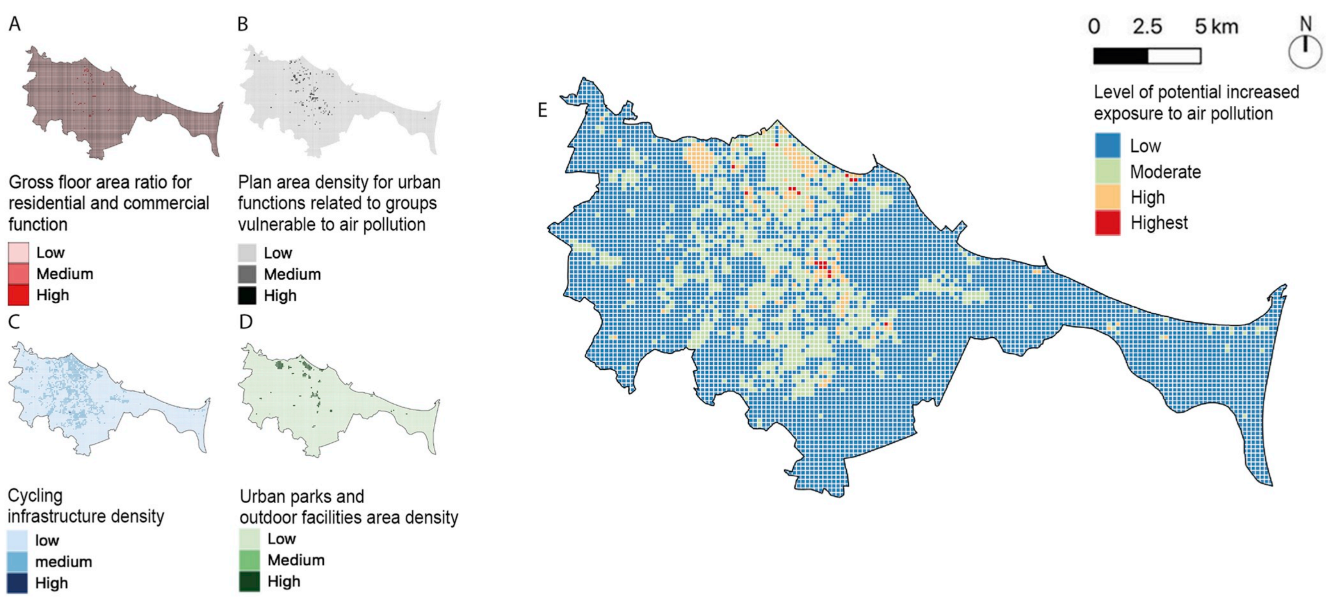

Fig. 12. Gdańsk–mapped potential increased exposure zones: (A) – the gross floor area ratio for residential and commercial functions (λ_{RC}), (B) – plan area density for urban functions related to groups vulnerable to air pollution (λ_{UF}), (C) – cycling infrastructure density (σ_C), (D) – urban parks and outdoor facilities area density (λ_{PO}), (E) – the merged map.

Secondly, the application of the grid approach, besides the discussed benefits, has also some disadvantages as the obtained values would slightly vary if a different grid size or positioning were used. However, a very high level of accuracy is not required for this tool, as it is aimed at controlling certain geometrical and infrastructural parameters which are relevant to ventilation potential and human exposure to air pollution at the city scale, in order to draw attention to certain hot spots and areas in which further detailed studies are required. It is important to note that apart from the morphological analysis at the municipal scale, further detailed local studies should also follow [81,82].

5.3. Recommendations and further directions

The developed set of methods could constitute a preliminary step for municipal planning aimed at improved air quality, underlying more detailed studies regarding ventilation conditions and pollution dispersion. Although a set of indicators was selected to present the proposed approach for AQMZs, they can be replaced and supplemented by other indicators in future case studies. Further typologies can be also created, according to which particular aspects need to be considered. Moreover, the developed indicators can be easily combined with other data, also due to the application of the grid approach. This can be illustrated by the following example: the results of the mapping can be cross-referenced

Fig. 13. Application of the potential increased exposure map for the Koning Albertpark in Antwerp, with (A) the mapping of the potential increase exposure zones, (B) the combination of the potential increased exposure zones and the urban fabric and (C) the NO_2 pollution level model [45].

with the air pollution models, as shown for the area of the Koning Albertpark in Antwerp (see Fig. 13). Grid cells with the high and highest level of potential increased exposure to air pollution were indicated for this area. When comparing with the pollution model for NO_2 [45], its increased annual levels close to the EU limit value of 40 $\mu g/m^3$ are visible in the same location. It should also be noted that these levels are annual, and therefore higher levels can occur for short periods of times. The map of potential increased exposure to pollution combined with the detection of high pollution concentration levels may be used to indicate areas which require 'fast response' in spatial planning policies.

The developed AQMZs can have further applications in other urban areas:

- for preliminarily identifying problem areas within municipal development strategies and outlining directions for drafting further procedures for air quality management,
- as a planning and design tool for formulating a set of general guidelines and recommendations, and
- as a background for further, more detailed studies.

The method itself can be further developed and updated based on new developments in this research areas. Rule-based modelling tools can be also considered to create rapid models of urban development scenarios for the purpose of ventilation evaluation in general and detailed studies [10,83]. The following prospects for further research can be also considered: 1) creating AQMZs databases for many cities and using big data analysis to compare the existing conditions in various urban areas in order to draft novel strategies and 2) developing a corresponding set of methods to map the parameters which are connected with other environmental problems. Therefore, the proposed optimisation of the use of available geospatial datasets to map AQMZs can be used in order to successfully account for air quality improvement in the process of urban planning. Moreover, some area-specific recommendations can be based on the results obtained with this tool, as briefly discussed in section 5.1, providing directions for further studies and policy development. If comprehensive databases are available for many cities, it may be useful for drawing comparisons and developing common strategies for the improvement of air quality. Similarly, data on urban mobility [84] or data for urban climate models [85] are collected for various cities. However, the collected data need to be consistent and comparable [85]. In case of a lack of corresponding data in the geospatial municipal datasets data processing and incorporating additional data sources is necessary, which was demonstrated in the conducted case studies. The proposed AQMZs are a useful tool for this purpose.

In the case studies presented herein, some consideration of urban air quality can be found in certain existing planning strategies, such as the proposal by the city of Antwerp to improve air quality through four main sustainable mobility strategies [86]. Moreover, the 'Antwerpen Nieuw Zuid' represents one of the first projects in Belgium to incorporate spatial strategies for tackling low air quality. Located in the close proximity of a motorway crossroad complex, this residential project used vegetated slopes to reduce direct exposure to air pollution. The project was also developed on a strict grid in order to improve ventilation. Functions related to groups vulnerable to air pollution, such as schools, were located at a distance of at least 300 m from the motorway [87]. However, despite these promising strategies, the MER (Environment Effect Report) of Arcadis [88] indicated that the impact of the project on air quality would be negligible. Still, the project represents an interesting effort to implement urban design strategies in order to improve local air quality.

It can be concluded that further policy changes are needed in order to achieve the best possible quality of the urban environment. To this end, novel planning tools are needed, such as the AQMZs framework. Therefore, the proposed approach to use available geospatial datasets and GIS tools to map AQMZs in order to account for air quality improvement in the process of urban planning may prove useful for drawing comparisons between various cities and developing common strategies.

Funding

This work was funded by a Special Research Fund (BOF) provided by the Flemish Government and the University of Antwerp, Belgium, Doctoral project ID: 37035, and statutory funds of the Gdańsk University of Technology, Faculty of Architecture, Poland.

Declaration of competing interest

There are no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

Acknowledgements

This research was part of an interdisciplinary doctoral project in collaboration with Research Group for Urban Development of Antwerp. The authors also gratefully acknowledge the support from the participants of the community study, and from the local stakeholders for providing the municipal datasets.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2020.106743.

References

[1] M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, R. Sandler, W. Schöpp, F. Wagner, W. Winiwarter, Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications, Environ. Model. Software 26 (2011) 1489–1501, https://doi.org/10.1016/j.envsoft.2011.07.012.

[2] Eurostat, Urban Europe: Statistics on Cities, Towns and Suburbs. 2016 Edition, Publications office of the European Union, Luxembourg, 2016, https://doi.org/10.2785/91120.

[3] J. Lelieveld, K. Klingmüller, A. Pozzer, U. Pöschl, M. Fnais, A. Daiber, T. Münzel, Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions, Eur. Heart J. 40 (2019) 1590–1596, https://doi.org/10.1093/eurheartj/ehz135.

[4] C. Yuan, E. Ng, L.K. Norford, Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies, Build. Environ. 71 (2014) 245–258, https://doi.org/10.1016/j.buildenv.2013.10.008.

[5] M. Weber, P.P.J. Driessen, Environmental policy integration: the role of policy windows in the integration of noise and spatial planning, Environ. Plann. C Govern. Pol. 28 (2010) 1120–1134, https://doi.org/10.1068/c0997.

[6] H. Runhaar, P.P.J. Driessen, L. Soer, Sustainable urban development and the challenge of policy integration: an assessment of planning tools for integrating spatial and environmental planning in The Netherlands, Environ. Plann. Plann. Des. 36 (2009) 417–431, https://doi.org/10.1068/b34052.

[7] M. Cárdenas Rodríguez, L. Dupont-Courtade, W. Oueslati, Air pollution and urban structure linkages: evidence from European cities, Renew. Sustain. Energy Rev. 53 (2016) 1–9, https://doi.org/10.1016/j.rser.2015.07.190.

[8] B.-J. He, L. Ding, D. Prasad, Enhancing urban ventilation performance through the development of precinct ventilation zones: a case study based on the Greater Sydney, Australia, Sustain. Cities Soc. 47 (2019), 101472, https://doi.org/10.1016/j.scs.2019.101472.

[9] L. Merlier, F. Kuznik, G. Rusaouën, S. Salat, Derivation of generic typologies for microscale urban airflow studies, Sustain. Cities Soc. 36 (2018) 71–80, https://doi.org/10.1016/j.scs.2017.09.017.

[10] Y. Luo, J. He, Y. Ni, Analysis of urban ventilation potential using rule-based modeling, Comput. Environ. Urban Syst. 66 (2017) 13–22, https://doi.org/10.1016/j.compenvurbsys.2017.07.005.

[11] M.J. Alcoforado, H. Andrade, A. Lopes, J. Vasconcelos, Application of climatic guidelines to urban planning. The example of Lisbon (Portugal), Landsc. Urban Plann. 90 (2009) 56–65, https://doi.org/10.1016/j.landurbplan.2008.10.006.

[12] T. Houet, G. Pigeon, Mapping urban climate zones and quantifying climate behaviors - an application on Toulouse urban area (France), Environ. Pollut. 159 (2011) 2180–2192, https://doi.org/10.1016/j.envpol.2010.12.027.

[13] I.D. Stewart, T.R. Oke, Local climate zones for urban temperature studies, Bull. Am. Meteorol. Soc. 93 (2012) 1879–1900, https://doi.org/10.1175/BAMS-D-11-00019.1.

[14] E. Ng, C. Yuan, L. Chen, C. Ren, J.C.H. Fung, Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong, Landsc. Urban Plann. 101 (2011) 59–74, https://doi.org/10.1016/j.landurbplan.2011.01.004.

[15] F. Guo, P. Zhu, S. Wang, D. Duan, Y. Jin, Improving natural ventilation performance in a high-density urban district: a building morphology method, Procedia Eng 205 (2017) 952–958, https://doi.org/10.1016/j.proeng.2017.10.149.

[16] E. Ng, Policies and technical guidelines for urban planning of high-density cities - air ventilation assessment (AVA) of Hong Kong, Build. Environ. 44 (2009) 1478–1488, https://doi.org/10.1016/j.buildenv.2008.06.013.

[17] L. Chen, J. Hang, M. Sandberg, L. Claesson, S. Di Sabatino, H. Wigo, The impacts of building height variations and building packing densities on flow adjustment and city breathability in idealized urban models, Build. Environ. 118 (2017) 344–361, https://doi.org/10.1016/j.buildenv.2017.03.042.

[18] S.J. Mei, J.T. Hu, D. Liu, F.Y. Zhao, Y. Li, Y. Wang, H.Q. Wang, Wind driven natural ventilation in the idealized building block arrays with multiple urban morphologies and unique package building density, Energy Build. 155 (2017) 324–338, https://doi.org/10.1016/j.enbuild.2017.09.019.

[19] F. Yang, F. Qian, S.S.Y. Lau, Urban form and density as indicators for summertime outdoor ventilation potential: a case study on high-rise housing in Shanghai, Build. Environ. Times 70 (2013) 122–137, https://doi.org/10.1016/j.buildenv.2013.08.019.

[20] T. Kubota, M. Miura, Y. Tominaga, A. Mochida, Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: development of guidelines for realizing acceptable wind environment in residential neighborhoods, Build. Environ. Times 43 (2008) 1699–1708, https://doi.org/10.1016/j.buildenv.2007.10.015.

[21] Y. Peng, Z. Gao, W. Ding, An approach on the correlation between urban morphological parameters and ventilation performance, Energy Procedia 142 (2017) 2884–2891, https://doi.org/10.1016/j.egypro.2017.12.412.

[22] G.E. Lau, K. Ngan, Analysing urban ventilation in building arrays with the age spectrum and mean age of pollutants, Build. Environ. 131 (2018) 288–305, https://doi.org/10.1016/j.buildenv.2018.01.010.

[23] X. Xie, Z. Huang, J.S. Wang, Impact of building configuration on air quality in street canyon, Atmos. Environ. 39 (2005) 4519–4530, https://doi.org/10.1016/j.atmosenv.2005.03.043.

[24] J. Zhong, X.M. Cai, W.J. Bloss, Coupling dynamics and chemistry in the air pollution modelling of street canyons: a review, Environ. Pollut. 214 (2016) 690–704, https://doi.org/10.1016/j.envpol.2016.04.052.

[25] M.S. Wong, J.E. Nichol, P.H. To, J. Wang, A simple method for designation of urban ventilation corridors and its application to urban heat island analysis, Build. Environ. 45 (2010) 1880–1889, https://doi.org/10.1016/j.buildenv.2010.02.019.

[26] J.H. Amorim, V. Rodrigues, R. Tavares, J. Valente, C. Borrego, CFD modelling of the aerodynamic effect of trees on urban air pollution dispersion, Sci. Total Environ. 461–462 (2013) 541–551, https://doi.org/10.1016/j.scitotenv.2013.05.031.

[27] A. Wania, M. Bruse, N. Blond, C. Weber, Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations, J. Environ. Manag. 94 (2012) 91–101, https://doi.org/10.1016/j.jenvman.2011.06.036.

[28] D.J. Nowak, E.J. Greenfield, Tree and impervious cover change in U.S. cities, Urban For. Urban Green. 11 (2012) 21–30, https://doi.org/10.1016/j.ufug.2011.11.005.

[29] Y.M. Park, M.P. Kwan, Individual exposure estimates may be erroneous when spatiotemporal variability of air pollution and human mobility are ignored, Health Place 43 (2017) 85–94, https://doi.org/10.1016/j.healthplace.2016.10.002.

[30] L. Guo, J. Luo, M. Yuan, Y. Huang, H. Shen, T. Li, The influence of urban planning factors on PM2.5 pollution exposure and implications: a case study in China based on remote sensing, LBS, and GIS data, Sci. Total Environ. 659 (2019) 1585–1596, https://doi.org/10.1016/j.scitotenv.2018.12.448.

[31] N. Rose, C. Cowie, R. Gillett, G.B. Marks, Weighted road density: a simple way of assigning traffic-related air pollution exposure, Atmos. Environ. 43 (2009) 5009–5014, https://doi.org/10.1016/j.atmosenv.2009.06.049.

[32] L.D. Frank, P. Engelke, Multiple impacts of the built environment on public health: walkable places and the exposure to air pollution, Int. Reg. Sci. Rev. 28 (2005) 193–216, https://doi.org/10.1177/0160017604273853.

[33] D. Van Brusselen, W. Arrazola de Oñate, B. Maiheu, S. Vranckx, W. Lefebvre, S. Janssen, T.S. Nawrot, B. Nemery, D. Avonts, Health impact assessment of a predicted air quality change by moving traffic from an urban ring road into a tunnel. The case of Antwerp, Belgium, PloS One 11 (2016), e0154052, https://doi.org/10.1371/journal.pone.0154052.

[34] J. Luo, K. Boriboonsomsin, M. Barth, Reducing pedestrians' inhalation of traffic-related air pollution through route choices: case study in California suburb, J. Transp. Heal. 10 (2018) 111–123, https://doi.org/10.1016/j.jth.2018.06.008.

[35] M. Tainio, A.J. de Nazelle, T. Götschi, S. Kahlmeier, D. Rojas-Rueda, M. J. Nieuwenhuijsen, T.H. de Sá, P. Kelly, J. Woodcock, Can air pollution negate the health benefits of cycling and walking? Prev. Med. 87 (2016) 233–236, https://doi.org/10.1016/j.ypmed.2016.02.002.

[36] J.J. de Hartog, H. Boogaard, H. Nijland, G. Hoek, Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118 (2010) 1109–1116, https://doi.org/10.1289/ehp.0901747.

[37] A.J. Carlisle, N.C.C. Sharp, Exercise and outdoor ambient air pollution, Br. J. Sports Med. 35 (2001) 214–222, https://doi.org/10.1136/bjsm.35.4.214.

[38] Departement Omgeving, Databank Ondergrond Vlaanderen [in Flemish], 2019. www.dov.vlaanderen.be/.

[39] Head Office of Geodesy and Cartography, General Geographic Database [in Polish], 2019. http://www.gugik.gov.pl/strona-glowna.

[40] Windfinder. www.windfinder.com, 2019.

[41] Armaag Foundation, [in polish]. http://armaag.gda.pl/en/index.htm, 2018.

[42] J. Lelieveld, J.S. Evans, M. Fnais, D. Giannadaki, A. Pozzer, The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature 525 (2015) 367–371, https://doi.org/10.1038/nature15371.

[43] S. Janssen, W. Lefebvre, C. Mensink, B. Degraeuwe, The multi-scale character of air pollution: impact of local measures in relation to European and regional policies - a case study in Antwerp, Belgium, Int. J. Environ. Pollut. 54 (2014) 203, https://doi.org/10.1504/IJEP.2014.065121.

[44] University of Antwerp & VMM, Curiezeneuzencampagen. https://curieuzeneuzen.be/in-english/, 2018.

[45] Ircel-Celine, VITO, Air Pollution High Resolution Maps, 2017. http://www.irceline.be/en/air-quality/measurements.

[46] VITO, ATMO-Street, Mapping Air Quality to Street Level, 2019. https://vito.be/en/atmo-street.

[47] Sejmik of Pomorskie Voivodeship, The Update of the Programme of Air Quality Protection for the Tri-city Agglomaration Zone in Which the Maximum Level of PM10 and the Target Level of Benzo(a)pyrene Was Exceeded [in Polish], 2017. https://armaag.gda.pl/files/208/49/74_pop_strona.pdf.

[48] M. Paciorek, Tri-City air quality assessment driven by SECA regulation, results of 2014 and 2016 local model calculation, Ekometria Environmental Studies and Monitoring Centre, 2018. https://static1.squarespace.com/static/56a0c84dfb36b1be19213613/t/5ba8df81eef1a16551ba3af7/1537793941379/Paciorek%2BEKOMETRIA.pdf.

[49] M.O.P. Ramacher, M. Karl, Population exposure to emissions from ships and residential heating in the urban area of Gdansk-Gdynia, in: SHEBA Sustainable Shipping and Environment of the Baltic Sea region, Helmholtz-Zentrum Geesthacht, 2017. http://shipping-and-the-environment-2017.ivl.se/download/18.1369484715f59ce4bab1d67/1512051096965/Ramacher_AP08.pdf.

[50] The City of Antwerp, Geospatial Data - Antwerp [in Flemish], 2019. http://portaal-stadantwerpen.opendata.arcgis.com/.

[51] Gdańsk City Portal, Find Cycling Routes in the City. Collect New Cycling Map of Gdańsk [in Polish], 2016. https://www.gdansk.pl/wiadomosci/znajdz-drogi-rowerowe-w-miescie-odbierz-nowa-mape-rowerowa-gdanska,a,59317.

[52] D.A. Smith, Polycentricity and Sustainable Urban Form. An Intra-urban Study of Accessibility, Employment and Travel Sustainability for the Strategic Planning of the London Region, Doctor of Philosophy Doctoral Thesis, Univ. Coll. London, 2011.

[53] S. Freire, K. MacManus, M. Pesaresi, E. Doxsey-Whitfield, J. Mills, Development of New Open and Free Multi-temporal Global Population Grids at 250 m Resolution, in: Proceedings of the 19th AGILE Conference on Geographic Information Science, 2016. June 14–17, Helsinki.

[54] Department of Environment in Flanders, Expert Assignment on Street Clusters of Water, Sound, Air, Heat and Energy [in Flemish], Departement Omgeving, 2018. https://archief.onderzoek.omgeving.vlaanderen.be/Onderzoek-2089208.
[55] J. Liu, M. Heidarinejad, S. Gracik, J. Srebric, The impact of exterior surface convective heat transfer coefficients on the building energy consumption in urban neighborhoods with different plan area densities, Energy Build. 86 (2015) 449–463, https://doi.org/10.1016/j.enbuild.2014.10.062.
[56] W. Wang, E. Ng, C. Yuan, S. Raasch, Large-eddy simulations of ventilation for thermal comfort — a parametric study of generic urban configurations with perpendicular approaching winds, Urban Clim 20 (2017) 202–227, https://doi.org/10.1016/j.uclim.2017.04.007.
[57] J. Hang, Y. Li, M. Sandberg, R. Buccolieri, S. Di Sabatino, The influence of building height variability on pollutant dispersion and pedestrian ventilation in idealized high-rise urban areas, Build. Environ. 56 (2012) 346–360, https://doi.org/10.1016/j.buildenv.2012.03.023.
[58] Y. Zheng, C. Ren, Y. Xu, R. Wang, J. Ho, K. Lau, E. Ng, GIS-based mapping of Local Climate Zone in the high-density city of Hong Kong, Urban Clim 24 (2018) 419–448, https://doi.org/10.1016/j.uclim.2017.05.008.
[59] B. Yu, H. Liu, J. Wu, Y. Hu, L. Zhang, Automated derivation of urban building density information using airborne LiDAR data and object-based method, Landsc. Urban Plann. 98 (2010) 210–219, https://doi.org/10.1016/j.landurbplan.2010.08.004.
[60] A.G. McDonald, W.J. Bealey, D. Fowler, U. Dragosits, U. Skiba, R.I. Smith, R. G. Donovan, H.E. Brett, C.N. Hewitt, E. Nemitz, Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations, Atmos. Environ. 41 (2007) 8455–8467, https://doi.org/10.1016/j.atmosenv.2007.07.025.
[61] M. Tallis, G. Taylor, D. Sinnett, P. Freer-Smith, Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments, Landsc. Urban Plann. 103 (2011) 129–138, https://doi.org/10.1016/j.landurbplan.2011.07.003.
[62] S. Willems, Bicycle Paths and Routes in Flanders: Analysis of Current Design Practice [in Flemish], Master's Thesis, Univ. Ghent, 2015.
[63] S.A.H. Zahabi, A. Chang, L.F. Miranda-Moreno, Z. Patterson, Exploring the link between the neighborhood typologies, bicycle infrastructure and commuting cycling over time and the potential impact on commuter GHG emissions, Transport. Res. Transport Environ. 47 (2016) 89–103, https://doi.org/10.1016/j.trd.2016.05.008.
[64] J.E. Schoner, D.M. Levinson, The missing link: bicycle infrastructure networks and ridership in 74 US cities, Transportation 41 (2014) 1187–1204, https://doi.org/10.1007/s11116-014-9538-1.
[65] J. Hang, Y. Li, M. Sandberg, Experimental and numerical studies of flows through and within high-rise building arrays and their link to ventilation strategy, J. Wind Eng. Ind. Aerod. 99 (2011) 1036–1055, https://doi.org/10.1016/j.jweia.2011.07.004.
[66] M. Lin, J. Hang, Y. Li, Z. Luo, M. Sandberg, Quantitative ventilation assessments of idealized urban canopy layers with various urban layouts and the same building packing density, Build. Environ. 79 (2014) 152–167, https://doi.org/10.1016/j.buildenv.2014.05.008.
[67] M. Llaguno-Munitxa, E. Bou-Zeid, M. Hultmark, The influence of building geometry on street canyon air flow: validation of large eddy simulations against wind tunnel experiments, J. Wind Eng. Ind. Aerod. 165 (2017) 115–130, https://doi.org/10.1016/j.jweia.2017.03.007.
[68] Y.H. Juan, A.S. Yang, C.Y. Wen, Y.T. Lee, P.C. Wang, Optimization procedures for enhancement of city breathability using arcade design in a realistic high-rise urban area, Build. Environ. 121 (2017) 247–261, https://doi.org/10.1016/j.buildenv.2017.05.035.
[69] C.Y. Wen, Y.H. Juan, A.S. Yang, Enhancement of city breathability with half open spaces in ideal urban street canyons, Build. Environ. 112 (2017) 322–336, https://doi.org/10.1016/j.buildenv.2016.11.048.
[70] H. Feng, K. Hewage, Lifecycle assessment of living walls: air purification and energy performance, J. Clean. Prod. 69 (2014) 91–99, https://doi.org/10.1016/j.jclepro.2014.01.041.
[71] R. Kessler, Green walls could cut street-canyon air pollution, Environ. Health Perspect. 121 (2013), https://doi.org/10.1289/ehp.121-a14, 2013.
[72] J. Yang, Q. Yu, P. Gong, Quantifying air pollution removal by green roofs in Chicago, Atmos. Environ. Times 42 (2008) 7266–7273, https://doi.org/10.1016/j.atmosenv.2008.07.003.
[73] C. Ren, R. Yang, C. Cheng, P. Xing, X. Fang, S. Zhang, H. Wang, Y. Shi, X. Zhang, Y. T. Kwok, E. Ng, Creating breathing cities by adopting urban ventilation assessment and wind corridor plan – the implementation in Chinese cities, J. Wind Eng. Ind. Aerod. 182 (2018) 170–188, https://doi.org/10.1016/j.jweia.2018.09.023.
[74] M.S. Wong, J. Nichol, E. Ng, A study of the " wall effect" caused by proliferation of high-rise buildings using GIS techniques, Landsc. Urban Plann. 102 (2011) 245–253, https://doi.org/10.1016/j.landurbplan.2011.05.003.
[75] C.M. Hsieh, H.C. Huang, Mitigating urban heat islands: a method to identify potential wind corridor for cooling and ventilation, Comput. Environ. Urban Syst. 57 (2016) 130–143, https://doi.org/10.1016/j.compenvurbsys.2016.02.005.
[76] S. Chang, Q. Jiang, Y. Zhao, Integrating CFD and GIS into the development of urban ventilation corridors: a case study in changchun city, China, Sustainability 10 (2018) 1814, https://doi.org/10.3390/su10061814.
[77] F. Guo, H. Zhang, Y. Fan, P. Zhu, S. Wang, X. Lu, Y. Jin, Detection and evaluation of a ventilation path in a mountainous city for a sea breeze: the case of Dalian, Build. Environ. 145 (2018) 177–195, https://doi.org/10.1016/j.buildenv.2018.09.010.
[78] J. Van den Bossche, J. Peters, J. Verwaeren, D. Botteldooren, J. Theunis, B. De Baets, Mobile monitoring for mapping spatial variation in urban air quality: development and validation of a methodology based on an extensive dataset, Atmos. Environ. 105 (2015) 148–161, https://doi.org/10.1016/j.atmosenv.2015.01.017.
[79] J. Van den Bossche, J. Theunis, B. Elen, J. Peters, D. Botteldooren, B. De Baets, Opportunistic mobile air pollution monitoring: a case study with city wardens in Antwerp, Atmos. Environ. 141 (2016) 408–421, https://doi.org/10.1016/j.atmosenv.2016.06.063.
[80] S. Steinle, S. Reis, C.E. Sabel, Quantifying human exposure to air pollution-Moving from static monitoring to spatio-temporally resolved personal exposure assessment, Sci. Total Environ. 443 (2013) 184–193, https://doi.org/10.1016/j.scitotenv.2012.10.098.
[81] R.X. Lee, S.K. Jusuf, N.H. Wong, The study of height variation on outdoor ventilation for Singapore's high-rise residential housing estates, Int. J. Low Carbon Technol. 10 (2015) 15–33, https://doi.org/10.1093/ijlct/ctt013.
[82] C. Ortolani, M. Vitale, The importance of local scale for assessing, monitoring and predicting of air quality in urban areas, Sustain. Cities Soc. 26 (2016) 150–160, https://doi.org/10.1016/j.scs.2016.06.001.
[83] Y. Luo, J. He, Y. He, A rule-based city modeling method for supporting district protective planning, Sustain. Cities Soc. 28 (2017) 277–286, https://doi.org/10.1016/j.scs.2016.10.003.
[84] HERE Technologies, Urban Mobility Index City Data, 2019. https://urbanmobilityindex.here.com/.
[85] B. Bechtel, P.J. Alexander, C. Beck, J. Böhner, O. Brousse, J. Ching, M. Demuzere, C. Fonte, T. Gál, J. Hidalgo, P. Hoffmann, A. Middel, G. Mills, C. Ren, L. See, P. Sismanidis, M.L. Verdonck, G. Xu, Y. Xu, Generating WUDAPT Level 0 data – current status of production and evaluation, Urban Clim 27 (2019) 24–45, https://doi.org/10.1016/j.uclim.2018.10.001.
[86] Stad Antwerpen, OVAM, Departement Omgeving, Havenbedrijf Antwerpen NV, Team Vlaams Bouwmeester, Metabolism of Antwerp: the city of flows. Final report [in Flemish], 2018. https://issuu.com/fabrications/docs/metabolisme-van-antwerpen-stad-van-.
[87] Antwerpen Stad, RUP Nieuw Zuid, Toelichtingsnota [in Flemish], 2014. https://www.antwerpen.be/docs/Stad/Stadsvernieuwing/Bestemmingsplannen/RUP_11002_214_10014_00001/RUP_11002_214_10014_00001_0006ONTWIKKELINGSVIS_tn.html.
[88] Arcadis, Plan-MER, Masterplan Nieuw Zuide Te Antwerpen [in Flemish], 2013. https://mer.lne.be/merdatabank/uploads/merntech2924.pdf.