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PARAMETERS OF BUILDING GEOMETRY THAT AFFECT WIND FLOW WITH REGARDS TO THE POSSIBILITIES FOR THEIR IMPLEMENTATION IN URBAN AND ARCHITECTURAL DESIGN IN POLAND

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Abstract

In recent years, there has been a surge in Computational Fluid Dynamics (CFD) research into how urban morphology affects ventilation in cities. However, studies are scattered, with varying parameter definitions, limiting their application in architectural and urban design. This article aims to review and assess the relevance of geometric parameters studied in aerodynamics field to urban planning and architectural design in polish conditions. By reviewing previous publications on morphological parameters in wind studies, it evaluates their recognition and potential for their implementation in urban and architectural design in Polish conditions. Comparisons are made between these parameters and those commonly used in architectural and urban theory and practices in Poland. Results reveal minimal convergence, incorporating other parameters requires interdisciplinary research and significant planning procedure changes. This highlights the need for detailed interdisciplinary research and substantial planning changes to fully integrate CFD results into architectural and urban design practice in Poland.

Keywords: **Sustainable city; Urban climate; Urban morphology; Urban planning; Urban ventilation.**

1. INTRODUCTION

The quality of the living environment in large cities is declining due to increasing air pollution, which has a negative impact on the wellbeing and health of residents. The most important causes for this decrease include climate change and urban area expansion and densification. As a result, air pollution increases, temperatures rise and cases of the urban heat island phenomenon are aggravated. Despite this, the trend of urbanization continues to grow. The changes towards clean technologies in construction and transportation are insufficient for the improvement of the urban environment. While such solutions improve air quality, they do not eliminate existing hazards [1]. The policy to strengthen the resilience of cities is most importantly related to controlling ventilation capacity within urban areas. This allows air to be exchanged and pollutants to be removed, as well as enables cooling in hot periods with the use of natural wind forces. Meanwhile, the increasing intensity of building development makes it difficult for the wind to flow, especially since the wind flow criterion is most often overlooked in the building design process. Only a narrow group of buildings are subject to research requirements regarding their impact on wind flow. Despite the obvious relationship between the shape of development and the ventilation processes of urbanized areas, no widespread implementation of this knowledge in the design practice of urban planners and architects has been seen as yet. There is no clear indication of which geometrical parameters of buildings should be controlled and regulated to favour urban ventilation.

Although the number of publications in the field of aerodynamics on these issues is considerable and growing dynamically, these are scattered, which makes it difficult to get a clear picture of the state of knowledge. Review publications are relatively rare, which hinders the transfer of knowledge to the field of architecture and urban planning. This article aims to provide an initial assessment of the geometric parameters of the developments being investigated in the aerodynamic field for their potential use as a design tool with which to support the regulation of development design regulations applicable in Poland. A review of existing publications concerning morphological parameters of cities used in wind research over the past decades was conducted. The extent to which they are accepted in research and whether the existing state of knowledge allows the formulation of specific design guidelines for architects and urban planners was analysed. The subsequent step was to compare these with the geometric parameters currently used in the Polish urban design practice. The conclusions of this review enabled the selection of a group of parameters worthy of further, more detailed research in terms of their suitability for implementation in urban design in Poland.

2. METHODOLOGY

In the first phase of the review, different sources of information were taken into account, such as articles, books, conference papers, municipal strategies and formal legal documents in which research on the impact of building shape on wind flow is examined. The vast majority of publications are in aerodynamics, with a smaller number of interdisciplinary studies. Afterwards, the search terms were then defined and expanded to the following topic of the article: "city ventilation" + "name of parameter" or "name of parameter" +"airflow". A dynamic increase in the number of publications in this field can be seen over the last thirty years, with a considerable dispersion of research and a lack of consistency in the nomenclature and definition of parameters [2]. After the first search, 126 articles were examined. After a further evaluation of the articles, 70 articles were included in the review. Additionally, a considerable variation in the state of the art of individual parameters can be observed. While some are well or moderately established, others consist in relatively new proposals that remain poorly understood. Publications with review elements on the development of knowledge on known parameters [3,4] and reflections on the potential of new, not yet applied parameters [5] were particularly of value to the authors of the present paper. In [4] 48 different development parameters were gathered and collated; they were also divided into those describing the geometry of the development in one, two or three dimensions. It was also noted that only 15 of these were somewhat "original" parameters, whereas the remaining 33 comprised variations on their numerical interpretation. The review conducted for the present article identified an even larger number of parameters, but it should also be noted that some of these may be seen as simply different ways of recording the same spatial feature.

The present review focuses on practical issues related to urban and architectural design in the face of Polish law and regulations concerning buildings and their location. Therefore, the geometric parameters have been divided according to the scale of the space corresponding to legal requirements applicable in Polish law. The first scale comprises the local scale which corresponds to the size of a settlement, appropriate to the scale of the urban development plan (MPZP), pursuant to the law of 27 March 2003 on spatial planning and development, chapter 1 art. 2 point 22 (Dz. U. 2003. 80.717)[6]. It has its counterpart in climate research as the local climate scale [7]. The second scale is the scale of the immediate neighbourhood of a building, also referred to as the microscale, which corresponds to the size of a building with its surroundings or a small ensemble of buildings (for example the development of an urban quarter). In Poland, it is regulated by the Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions (Dz.U.2022.0.1225)[8]. Similarly, in urban climate studies, the term microclimate is used for a similar scale of space [7]. The scale of the city as a whole has been excluded due to its great complexity and the scale of individual buildings, owing to the fact that the phenomena in their interiors depend on numerous other additional factors.

The very large number of parameters found was reduced to 12 according to the following criteria:

- the strongest research base (known and repeatedly demonstrated relationships between a parameter and wind phenomena),
- number of publications (significant interest by researchers, likelihood of developing research),
- clear indications of the importance of a parameter

in specific, relatively recent publications (studies with selected examples),

- the inclusion of parameters that have not yet been sufficiently researched but which, according to the selected authors, are promising with regards to implementation in design practice (intuitively understandable, similar to commonly used parameters).

In addition, an attempt was made [4], to group parameters that describe similar spatial features by eliminating their variations.

The parameters have been presented in such a way that the description answers the following questions: How was the parameter defined? What alternative names are used? What does it affect? What are the proportions, assumptions and geometric formulae? How extensively has it been researched? What are the main problems and doubts?

This step was followed by a review of the geometric parameters that are used in the field of architecture and urban planning while describing the shape of the development. These parameters appear mainly in legal regulations, but are also used in theory, in design practice and in professional language. The number of these indicators is much smaller than those used in field of aerodynamics. A comparative analysis of both sets was conducted, which allowed a preliminary selection of a group of the most promising parameters to be included in further research on the possibility of implementation in design practice.

3. PARAMETERS OF BUILDING GEOMETRY AND THEIR RELATION TO THE PLOT OF LAND TAKEN INTO ACCOUNT IN STUDIES OF THE VENTILATION POSSIBILITIES OF URBAN SPACES

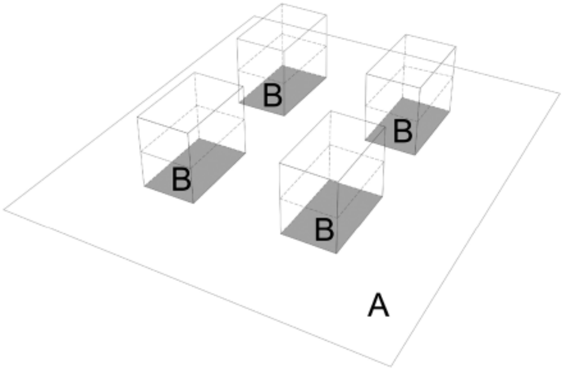
The parameters selected from the review were divided into two groups according to spatial scale. The first scale, i.e. the local scale, is more general and concerns urban design with neighbourhood or housing estate plans (e.g. local development plans, master plans for large areas). In this case, the shapes of buildings, streets, and squares cause changes in airflow (e.g. through channel effects in streets, through the obscuring effects, local accelerations) over a relatively large area. With conscious design decisions, these can be regulated to achieve the best possible wind conditions adapted to the intended use of the individual sites and consistent with the overall city ventilation concept (e.g. ensuring the continuity of wind corridors).

The second scale concerns the immediate building surroundings. It is related to architectural design, which includes the design of individual buildings together with their surroundings. Decisions about the shape of buildings and the spaces around them affect the microclimate within them, including the wind. It is important for building users, affects the energy processes in the buildings and indirectly influences the conditions prevalent over larger areas.

3.1. Local scale

3.1.1. Building coverage ratio

Building coverage ratio (BCR) indicates the area of land occupied by buildings (Fig.1),and is most commonly expressed as a percentage. It is also known as plan area density (PAD) or lot coverage. Its value is calculated as the ratio of the total built-up area (i.e. area occupied by buildings) to the total land area. The building density factor affects the intensity of airflow, particularly at the pedestrian level. In general, the more land occupied by buildings, the weaker the flow and the lower the wind velocity [9], although according to [4], this relationship is most pronounced for buildings with little variation in height. [10] emphasise the importance of this parameter and define a critical value that affects the change in flow. Building density is a relatively well-studied parameter and has long been used in wind studies [11–13].

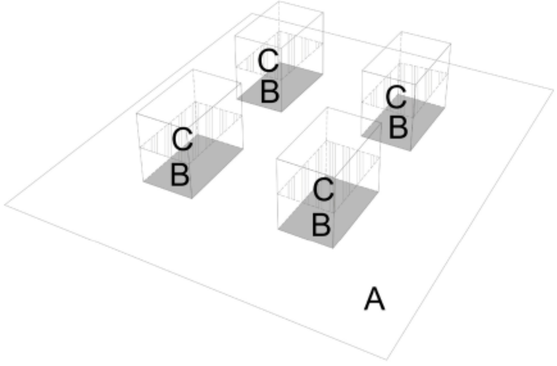


$$BCR = \frac{\text{building area(B)}}{\text{site area(A)}} \times 100\%$$

Figure 1.
BCR scheme and design; by the authors, based on [14]

3.1.2. Floor area ratio

The floor area ratio (FAR) is the ratio of the total built-up area to the total plot area (Fig. 2), expressed numerically. In the literature, the term floor space index FSI [10] can also be found. This parameter is calculated as the ratio of the sum of the surface area of all above-ground floors of buildings to the total land area. It impacts urban ventilation in a similar way as density, but it accounts for the number of storeys. Thus, the height parameter is indirectly incorporated in the FAR. Increasing the FAR in low buildings may result in reduced airflow, just as the BCR will increase. On the other hand, increasing the FAR in tall buildings may result in strong wind gusts and increased airflow towards pedestrians [15]. A variation in the FAR parameter between neighbouring properties has a positive effect on air circulation at the pedestrian level [16]. Studies in which this parameter is used are often found in the wind engineering literature [11–13, 17].

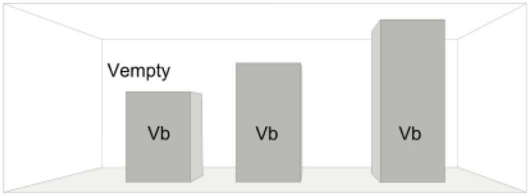


$$FAR = \frac{\text{total area (B + C)}}{\text{site area(A)}}$$

Figure 2.
FAR diagram and formula; by the authors, based on[14]

3.1.3. Porosity

The porosity of a building development is the geometric relationship between the total volume of all the ”empty spaces” in a building development (urban interiors, gaps, gates, arcades, etc.) and the total volume of the space occupied by the development (according to the external contour of the area). The parameter describes a three-dimensional space (Fig. 3). The porosity of development influences the specifics and the intensity of the airflow around it. In general, the more porous the development is, i.e. the more open spaces between the development, the less obstructed and the smoother the flow. Although porosity is a factor that has been studied for a relatively short time, it is beginning to appear in publications with increasing frequency [18]. It is often confused with the two-dimensional permeability parameter, described below. However, the main problem with regards to porosity results from the inconsistency in the way it is calculated. It remains unclear which height should be used to calculate the total volume of built-up area. According to [19] it is assumed to be the height from the ground to the roofs of the tallest buildings, whereas according to [20], height should be calculated from the ground to the roofs of the tallest buildings by adding 10 metres. However, regardless of the calculation method, the value of the porosity coefficient will vary depending on the scale of the area section under study [19, 20]. This makes it difficult to use this parameter as a universal one, as it offers little opportunity for comparative studies. It is necessary that rules for its use are defined depending on the site and the scope of the study.



$$R_{porosity} = \frac{\mathrm{V_{total}} - \sum \mathrm{V_{bi}}}{\mathrm{V_{total}}} = \frac{\mathrm{V_{empty}}}{\mathrm{V_{total}}}$$

($\mathrm{V_{bi}}$- volume of the building)

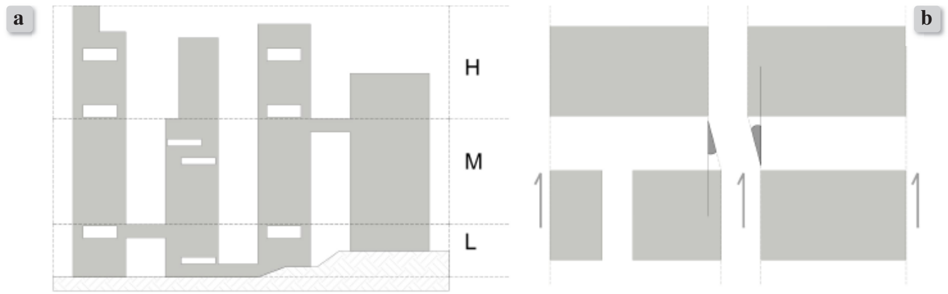
$$P_o = 1 - \frac{\sum \mathrm{V_{oi}} - \sum \mathrm{k_j V_{cj}}}{\mathrm{V_{total}}} = 1 - \frac{\mathrm{V_{empty}}}{\mathrm{V_{total}}}$$

(V_{oi}- volume of the open space;
V_{cj}- volume of courtyard;
k_j- coefficient depends on openness)

Figure 3.
Porosity diagram and patterns; by the authors, based on [19, 20]

3.1.4. Permeability

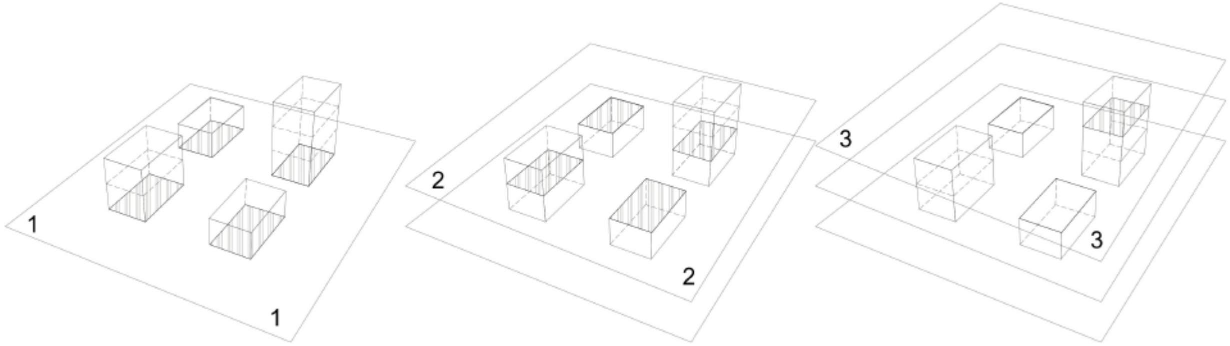
Permeability is defined as the ratio of the void area to the area of the built-up area, determined as a percentage. In the literature, the concept of barrier enclosure or barrier degree (degree of enclosure) can also be found, which is the inverse of permeability [13]. The permeability of an enclosure impacts the intensity of airflow and, in particular, the circulation in the lower zones of the enclosure [21]. Permeability can be referred to in two scales: the local scale (building spacing, urban interiors, ventilation corridors) and the micro-scale(openings in development) [22]. Although the parameter may seem similar parameter to porosity, it differs from it in that it is two-dimensional (it concerns area rather than volume). Permeability is calculated for vertical and horizontal planes (Fig. 4). In order to determine building permeability, the vertical



$$P_e = \frac{A_{void}}{A_{az}} \times 100\%$$

(A_{void} - sum of intervening spaces and permeable elements
A_{az} - area of the assessment zone)

Figure 4.
Schematic and permeability pattern, a. schematic of the vertical plane with division into low, medium and high-rise building zones, b. schematic of the plan view with determination of “wind path”; by the authors, based on [24]



$$O = \frac{1}{N} \sum_{N} \frac{P_{built}}{P_{unbuilt}}$$

Figure 5.
Schematic and pattern of occlusivity, numbers 1–3 indicate horizontal section lines(1 – 1st line of horizontal section, 2 – 2nd horizontal section line, 3 – 3rd horizontal section line); by the authors, based on [20]

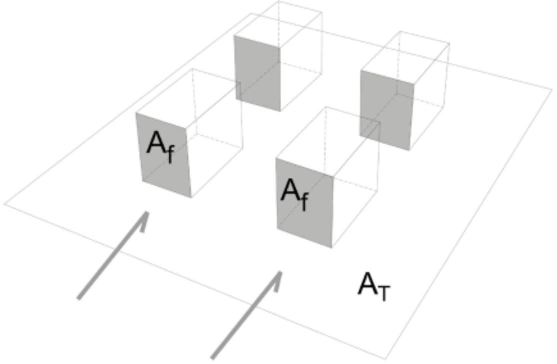
plane of the building or group of buildings is measured. For the horizontal plane, in addition to the ratio of the void area to the built-up area, the straightness of the “wind path” is also important. The layout of buildings that causes excessive deviation to this path slows down the airflow. This parameter is relatively well-studied in the literature (An et al., 2019) and is used in design guidelines [24]. However, the majority of studies are conducted in areas of high-rise building development [23, 25]; thus, there is a lack of knowledge about the suitability of this parameter for lower-rise building development.

3.1.5. Environmental occlusivity

The degree of space enclosure (Latin “occlusio” meaning “closure”) is the arithmetic mean ratio between the perimeters of built-up and open spaces. It is also known as the open spaces indicator, which measures openness to the sky [26]. It is calculated at different heights by making horizontal cross-sections every 3 or 3.5 m, which is the typical storey height (Fig. 5). A higher value of the occlusion coefficient is related to a higher degree of building density and lower permeability. The more enclosed the interior, the worse the airflow. This is a relatively new parameter, but it is increasingly being used in research in urban climate studies. It is used in the context of insolation more commonly than with regards to wind [27, 28].

3.1.6. Frontal aspect ratio

The frontal area ratio characterises the form of development on the windward side (trees are also



$$\lambda_f = \frac{\sum A_f}{A_T}$$

(A_f-windward frontal area;
A_T -total plan area)

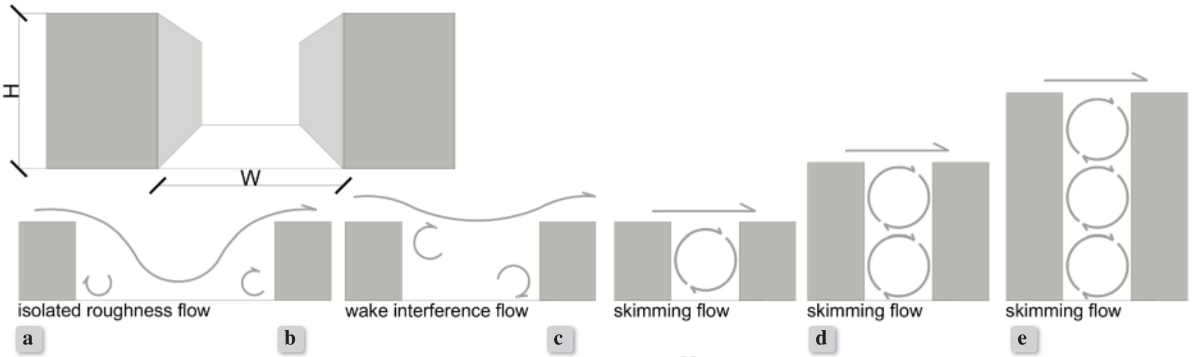
Figure 6.
Frontal aspect ratio diagram and formula; by the authors, based on [7]

included in some calculations). In literature, it is also referred to as the frontal area ratio or frontal area density (frontal area density FAD). It is the ratio of the sum of the windward façade area to the total plot area (Fig. 6). It influences the specifics and intensity of airflow. The greater the area of the wall blocking the wind relative to the built-up area, the more obstructive its effect on the flow. Each block of building development is characterised by several values of this parameter: for different zones of the block and for various wind directions. The parameter is relatively well-studied in the literature [29, 30].

3.2. Scale of the immediate environment (micro)

3.2.1. Aspect ratio H/W

The H/W ratio describes the shape of the vertical cross-section of a street, where H is the height of the buildings and W is the distance between them. In the literature, there is also a version of the inverse of this ratio, W/H, more readily used by architects and urban planners as more intuitive. Regardless of the version, this ratio determines how shallow or deep a street is. This characteristic affects the nature of the airflow, primarily the effectiveness of the ventilation of the street. For the situation where the wind blows perpendicular to the longitudinal axis, five flow variants were distinguished depending on the H/W ratio (Fig. 7). In the studies [31] identified a situation where there was a smooth flow that ventilated the street space, a situation where there was an obstructed flow, and a situation where there was only a whirling movement in the street zone and there was no exchange of air. Subsequent studies have shown that as H/W increases (W/H decreases), the air movement splits into two and three separate vertical vortices[32, 33]. It is difficult to explicitly state the values of the H/W intervals at which these phenomena occur, but the values at which the flow changes have been collected and described in studies [34]. From the most widespread publications, it appears that smooth flow occurs when $W/H>2.4$ and skimming flow when $W/H<1.4$. The street shape factor is the best-described parameter in the literature, used by many researchers [35–37] There are some difficulties in determining the accuracy of the H/W ratio calculation with complex street profile shapes (height differences, different roof shapes, etc.) [38].



$$AR_{HW} = \frac{H}{W}$$

(H − building height, L − building length, W − street width)

Figure 7.
Aspect ratio H/W diagram and main dependent aerodynamic effects, a – isolated roughness flow, b – wake interference flow, c, d, e – skimming flow; by the authors, based on [31]

3.2.2. Aspect ratio L/H

The L/H ratio characterises the shape of the street development in terms of the ratio of its length (without building line breaks) to its height (Fig. 8). This ratio influences the character of the airflow within the street, above all its fluidity (local stagnation and turbulence zones) and ventilation efficiency. Depending on the value of the L/H ratio, a street canyon is defined as short ($L/H \leq 3$), medium ($3<L/H<5$) or long ($L/H>5$). According to [39],the L/H ratio should not exceed 5 in order to avoid disrupting the airflow and creating local vortices. The L/H ratio can also be correlated with the aforementioned five types of flow in perpendicular winds. However, its influence is less than that of the W/H parameter. This relationship is described in [40]. The L/H ratio appears relatively rarely in studies as a stand-alone parameter, it is most often accompanied by the H/W aspect ratio [41].

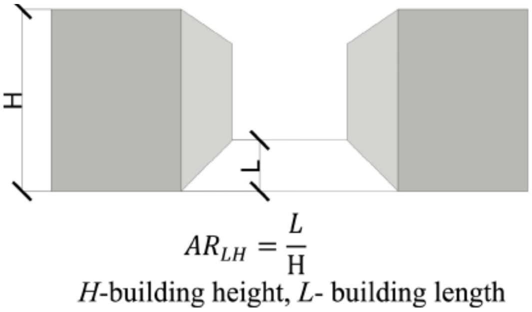


Figure 8.
Aspect ratio L/H diagram; by the authors, based on [39]

3.2.3. Aspect ratio L/W

L/W is another parameter that characterises street geometry. It defines the ratio between the street length (without breaks from the building line) and its width (Fig. 9). This ratio has been studied in relation to its influence on the nature of airflow [41]. However, these studies are rare and provide no clear conclusions. So far, this parameter can be considered insignificant, although it logically completes the group of three coefficients that characterise the street geometry (H/W, L/H, L/W).

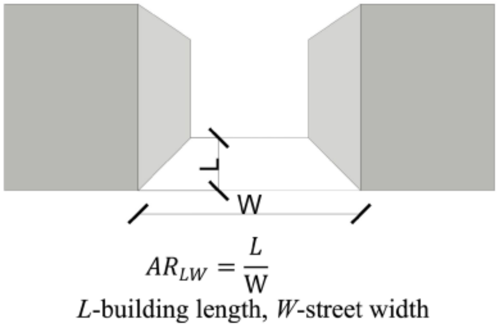


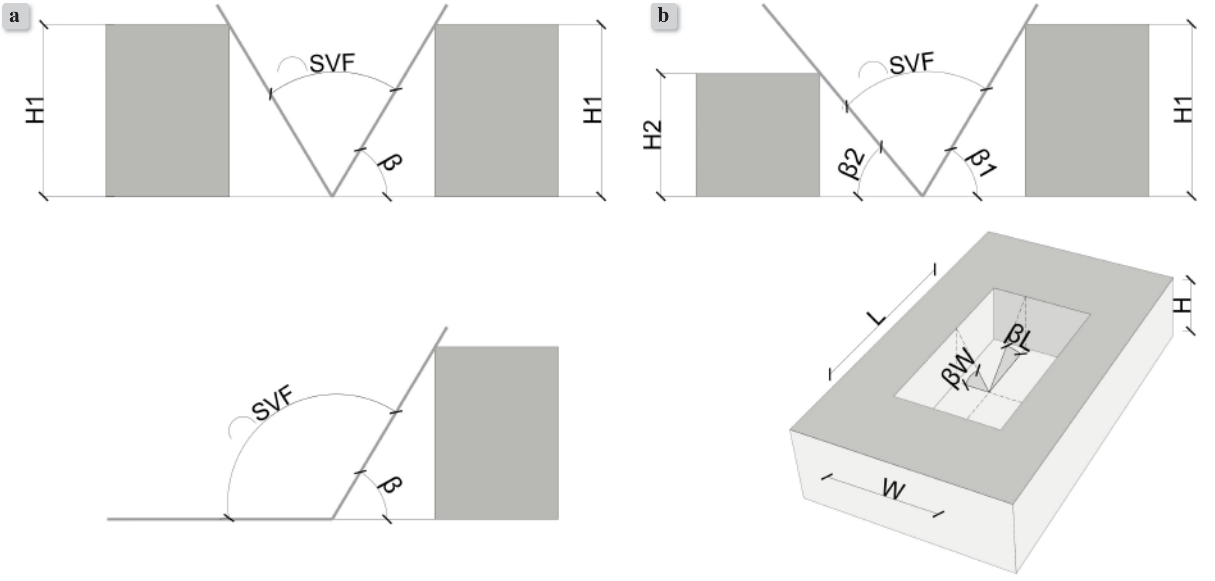
Figure 9.
Aspect ratio L/W diagram; by the author, based on [41]

3.2.4. Sky view factor SVF

The sky view factor is a geometric feature that defines the amount of opening to the sky in the space between buildings (Fig. 10). It is also known as the sky dome ratio. It can be considered another notation version of the aspect ratio H/W. For a simple cross-section, it can be determined using a geometric method. For asymmetrical, complex cross-sections, the so-called fish-eye photography method is used [42]. It captures a panoramic view of the opening of the space to the sky. The SVF ratio, similarly to the H/W ratio, is related to the nature and intensity of the flow. In general, the more open the interiors are (the greater the value of the angle expressed by the SVF), the less the flow is inhibited and disturbed by the building development. The SVF is relatively rarely used as a ventilation parameter, although, for example, according to [43] it may prove useful for ventilation studies at the pedestrian level, and its importance has also been highlighted in [4]. However, it is most commonly used by researchers in the context of daylight access and thermal phenomena, including the urban heat island [44].

3.2.5. The building orientation, sinuosity

The building orientation is one of the basic spatial features of a buildin's development. It defines the position of the plan of buildings, streets and squares relative to the corners of the world. In literature, orientation is also defined in terms of the distribution of local wind directions. The smoothness of air movement (e.g. channel effects, local air turbulence) and the efficiency of ventilation depend on the orientation of buildings and urban interiors. Orienting streets with the prevailing wind directions to intensify ventilation or perpendicular to the wind to protect against it are the best-known ways of regulating the ventilation of urban spaces; such solutions have been used since antiquity [5]. Today, the literature describes numerous examples of designs aimed at optimising airflow that still apply this principle [46, 47]. In [7] ranges for the deviation of street axes from buildings at which certain effects (channel effect or spiral movement away from buildings from the windward side) can occur (Fig. 11) are discussed.



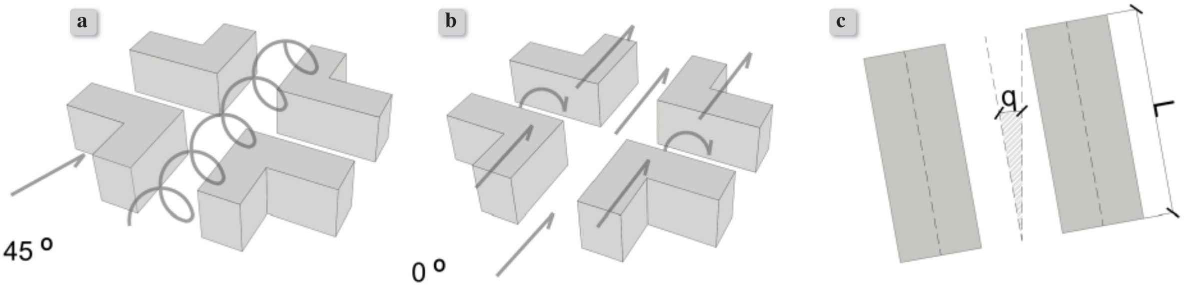
a. Symmetrical street $$SVF = cos_{\beta}$$

b. Asymmetrical street $$SVF = \frac{cos_{\beta1} + cos_{\beta2}}{2}$$

c. Non-street urban spaces $$SVF = \frac{1 + cos_{\beta}}{2}$$

d. Non-street urban spaces (courtyard) $$SVF = cos_{\beta w} \times cos_{\beta L}$$

Figure 10.
SVF diagram and patterns, a – symmetrical street, b – asymmetrical street, c – non-street urban space, d – courtyard; by the authors, based on [45]



$$SI = \frac{L \times cos^2 q}{L}$$

L-length of street; q-angle between wind direction and street axis

Figure 11.
SVF diagram and patterns, a – symmetrical street, b – asymmetrical street, c – non-street urban space, d – courtyard; by the authors, based on [45]

An attempt to describe this feature using the sinuosity parameter was made in [20]. Sinuosity expresses the relationship between the length of a street segment with continuous buildings and the cosine of the angle between the wind direction and the street direction. This parameter is rarely used in research.

3.2.6. Roof shape

A roof shape is a specific geometric shape described by the ridge of the building and the extremities of the junction with the elevations. In airflow studies, roof shapes are most often simplified into three basic types: flat, mono-pitched, and gabled (the latter two may come with different proportions and pitches). The nature of airflow within a street or square, particularly in the roof zone, depends on the shape of the roof. In small urban interiors, the shape of the roof (and therefore the shape of the vertical cross-section of the development) influences the effectiveness of ventilation (Fig. 12). From the research analysed [48] it stems that an increase in roof pitch leads to a decrease in wind velocity i.e. a decrease in ventilation capacity. Studies [49]also show that an increase in pitch increases the risk of two or more vortices. The notion of roof shape is rarely addressed by researchers. In modelling studies, the roof shape is most often simplified to a flat shape. According to [50], roof shape is an underestimated and under-researched parameter and should be considered an essential complement to the important and much better-known H/W parameter.

3.3. Comparative overview

All the parameters described above are summarised in Table 1 below.

Among the parameters appropriate to the scale of large urban areas, BCR and FAR are among the best-known and established. Their continuing popularity is partly due to the fact that these universal indicators have been known for a long time and are used in most countries to describe the efficiency of land use by building development. However, it appears that knowledge with regards to these indicators is developing further as a result of improvements in survey techniques rather than because of the potential of these parameters. They fail to capture variation in building heights; they are most relevant for studies with a high degree of generality over large urban areas.

Figure 12.
Aerodynamic effects within the street depending on roof shape; by the authors, based on[49]

Since the 1990s [2] knowledge of the parameters that capture the third dimension of development, namely frontal aspect ratio and porosity has been developing intensively. The latter parameter, that is porosity, despite the ambiguity of its definition, offers researchers great hope of being able to better than before capture the relationship between the complex morphology of buildings and wind flow. The parameter of permeability is also of interest to researchers, as it is similar and easier to calculate. The occlusivity parameter is difficult to assess unambiguously; on the one hand, it remains somewhat unpopular, but on the

Table 1.
Comparative summary of the geometry of the development and its relationship to the land and parameters used in aerodynamic field

	PARAMETER	DIMENSION/APPLICATION	STATE OF KNOWLEDGE	LITERATURE SOURCES
Local scale – urban planning – local development plans, masterplans for districts, settlements				
1	Building coverage ratio	2D, related to low-rise developments of varying heights	well-established, long-established	[9–11, 13, 51, 51–55]
2	Floor area ratio	3D	well-established, long-established	[11, 13, 16, 17, 47, 55–58]
3	Porosity	3D, related to medium to large building heights	popular recently, of great interest, still imprecise definition	[7, 12, 18, 20, 23, 25, 27, 30, 59–63]
4	Permeability	2D related to buildings with closed layouts and large heights	popular recently, of great interest	[21–24]
5	Occlusivity	2D related to buildings with closed layouts and medium heights	popular recently, of moderate interest	[28, 64, 65]
6	Frontal aspect ratio	3D, related to low-rise developments of varying heights	popular recently, of great interest	[7, 12, 30, 60–63]
Microscale, close surroundings of buildings – urban and architectural design – masterplans, arrangement of the area around buildings				
7	Aspect ratio H/W	2D, related to low-rise developments of varying heights	well-established, long-established, of great interest	[7, 31–38, 66–68]
8	Aspect ratio L/H	2D, related to low-rise developments	long-term, little interest	[10, 39, 41, 69–71]
9	Aspect ratio L/W	2D, related to low-rise developments	long-term, little interest	[10, 41]
10	Sky view factor	2D/3D related to buildings with little of varying heights	well-established, long-established	[42–45, 72, 73]
11	The orientation of the building/sinuosity	2D related tobuildings with medium to large	long-known, difficult to define	[7, 20, 26, 46, 47, 74, 75]
12	Roof shape	3D	poorly researched, rarely considered	[48–50, 76, 77]

other hand, it is the only parameter that enables determining how enclosed a building development is (the model of quartered and therefore enclosed buildings prevails in many cities, causing problems of air stagnation).

At the scale of smaller areas, such as the surroundings of buildings, streets or squares, the aspect ratio H/W, which describes the vertical cross-sectional proportions of urban interiors, has been studied for the longest time [31]. It has generally been the subject of the greatest number of studies, including those that provide design guidance for architects and urban planners. However, as the research review shows, it is too simplistic for the complex geometry of the city. It is difficult to describe asymmetric and geometrically complex cross-sections. The link between this parameter and the shape of the roof seems particularly important. Other variants of the L/H and L/W aspect ratios are similar, although they are less important and less studied than the H/W aspect ratio. However, it seems reasonable to seek design guidelines for the set of these three types of related parameters, as together they form a three-dimensional model of space.

An equally well-established research parameter is the SVF. Although it is less used in the aerodynamics field than the related aspect ratio H/W, it is widely used in urban climate studies. The ability to account for complex geometric layouts through new visualisation techniques is also a major advantage of this parameter.

Other parameters are far less defined and explored, although their potential for future research should be noted.

4. BUILDING GEOMETRY PARAMETERS AND ITS RELATIONSHIP TO THE LAND CONSIDERED IN ARCHITECTURE AND URBAN PLANNING IN POLAND

Compared to the field of aerodynamics, in the field of architecture and urban planning applied in Poland a much smaller range of indicators is used to describe the form of development. Most of these include the parameters used in local laws (i.e. those in force in a given city) that regulate the buildability of new areas. The purpose of these regulations is to make the most efficient use of land and to meet the necessary technical requirements while maintaining the spatial order of a given area of the city. These parameters describe the rules regarding the size of buildings that can be built on a given site and the area of land that should be left undeveloped. They also concern the rules for the location of new buildings (e.g. in the line of existing buildings), the shape of the roof, the maximum height of buildings, height differences (e.g. requiring the creation of a dominant height) or the maximum length of the façade. They may also suggest the type of development indirectly related to its form (e.g. quarter, point). These principles provide a starting point for designers as urban design requirements. Requirements concerning shape are also found in the building regulations that define how buildings are designed in a country and the way they are arranged on a plot. These specify minimum distances from plot boundaries and a minimum percentage of undeveloped land. Distances to other buildings are determined indirectly, e.g. by requirements for minimum insolation conditions, maximum obscuration by neighbouring buildings, fire regulations, and road and access widths. Thus, although the regulations contain many restrictions relating to the form of buildings, most of these guidelines affect the forms of buildings indirectly. A relatively small number of parameters directly describe the geometry of buildings. These include:

- Building coverage ratio- the same parameter as the one described above, used in the field of aerodynamics;
- Floor area ratio – the same parameter as the one described above, used in the field of aerodynamics;
- Percentage of undeveloped biologically active area – describes the percentage of the area that is free of buildings and paved areas (streets, access roads, car parks), and is therefore not the same as the whole area between buildings, but refers only to part of it;
- Building height – this is expressed in metres but is adjusted to a multiple of storeys;
- The difference in building height;
- Façade length;
- Distance to plot boundaries, other buildings, and technical infrastructure elements.

Another source of knowledge on geometric parameters in architecture and urban planning is the theory established and developed in publications, taught under university curricula and used in expert work. It usually deals with issues of composition, human perception of architectural space and the functionality of this space. It considers the size of urban interiors and their distribution relative to each other. As this issue is only partly objectivised, it is difficult to parameterise. Nevertheless, attempts are made to do so. The most commonly used parameters, in addition to those mentioned above, include:

- the proportions of the height and length of buildings to the distance between them, which are expressed by the ratios H/W, L/H and L/W, the most useful being the former, i.e. the H/W aspect ratio known from aerodynamics;
- the central angle express a measure of the extent of the interior, which, as can be seen from a comparison of the figures (Fig. 13 and Fig. 10), is a different type of notation known from the aerodynamics and SVF.

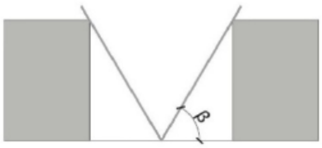


Figure 13.
Diagram of the central angle; by the authors based on [78]

5. BENCHMARKING RESULTS

Table 2 summarises the building geometry parameters and its relationship to the land used in architecture and urban planning in Poland and the corresponding links to the parameters used in aerodynamics.

As the summary above shows, only six of the twelve parameters analysed here and used in aerodynamics studies have direct counterparts in architecture and urban planning. These include BCR, FAR, aspect ratio H/W, SVF, roof shape. Two of these parameters, namely the aspect ratio H/W and the central angle (closely related to the SVF) are not covered in Polish legislation and are therefore of little use in design practice. Roof shape, on the other hand, remains a rather poorly studied parameter. Thus, only BCR and FAR may be seen as a viable bridge connecting aerodynamics and design practice. The potential of the best-studied aspect, that is ratio H/W, remains untapped to date. However, great potential can be seen for linking the two groups of parameters as they operate with similar spatial dimensioning elements. The frontal aspect ratio, the H/W L/W and L/H ratios, the roof shape and the open ground floors could be relatively easily implemented in design practice (provided that more research could be done on their relevance to wind flow), as they fit within the logic of current planning and design procedures in Poland and relate to smaller areas. It would be much more difficult to implement local scale parameters such as permeability, porosity, and sinuosity. The problem lies not only in the ambiguity of how to determine these parameters but also in the need for a comprehensive approach to the building development form, which is not yet present in established urban planning procedures.

6. DISCUSSION AND CONCLUSIONS

A review and analysis of the state of research has shown that, despite the large number of parameters studied in the field of aerodynamics there are still no clear indications of the principles for regulating the shape of buildings with regards to wind in the urban planning, urban design and architectural design process. The existing research can certainly develop design intuition, but this is not sufficient. However, it is possible to focus research on parameters that enable regulating wind processes through rational building design. The range of possible parameters is wide, with all of the 12 parameters described above

Table 2.
Relationships between architecture, its relationship to the land used and geometry building parameters used in aerodynamic

	ARCHITECTURE AND URBAN PLANNING PARAMETERS USED IN POLAND	AERODYNAMICS-RELATED PARAMETERS	
		DIRECTLY	INTERMEDIATE
1	Building coverage ratio	Building coverage ratio	Occlusivity
2	Floor area ratio	Floor area ratio	
3	Percentage of undeveloped biologically active area		Porosity, permeability
4	Building height		Aspect ratio H/W L/H, frontal aspect ratio
5	Height difference		Frontal aspect ratio
6	Façade length		Aspect ratio L/W L/H, frontal aspect ratio, sinuosity
7	Aspect ratio W/H	Aspect ratio H/W	
8	Central angle	Sky view factor	
9	Type of construction		Aspect ratio H/W L/W L/H, sky view factor
10	Building line		Projection orientation, sinuosity
11	Roof shape	Roof shape	
12	Distances to site boundaries, other buildings, technical infrastructure elements	Permeability	Aspect ratio H/W

offering the potential for implementation in Polish design practice. The above review should only be seen as a preliminary assessment. A full analysis of the potential of each parameter requires in-depth research. Clearly, not all of the parameters have an equally strong relationship with wind effects, nor do they all work in all situations (for example, some are best suited to tall buildings or buildings with small variations in height). It is also apparent that the scale of urban planning and design requires different parameters than the architectural design of buildings and small assemblages.

It is noticeable that relatively little convergence occurs in the sets of building morphology parameters used in the aerodynamic and architecture fields in Poland. Only two parameters, namely building coverage ratio and floor area ratio are firmly embedded in both disciplines. The implementation of the remaining parameters (e.g. porosity, permeability, sinuosity, occlusivity) or the strengthening of other ones (e.g. H/W, SVF) requires not only the development of interdisciplinary research in which the existing knowledge would be detailed but also a rethinking of planning procedures used in Poland.

It seems that the development of universal design guidelines for wind regulation is not possible due to the high degree of geometric complexity of Polish cities. It seems more likely that specialised simulation studies could be used at various stages of design to integrate the whole process into a coherent urban climate regulation strategy. These studies could be used to support the development of urban policies, local development plans and other local regulations.

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