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Determining the optimal distance between buildings based on the solar altitude angle to facilitate appropriate illumination in residential interiors in accordance with current legislation

Introduction

One can get the impression that in recent years, in which energy saving and sustainable development have become one of the main topics, sunlight has been seen as the predominant alternative source of energy. It seems that, somehow, many other benefits and positive effects of light have been neglected, all the benefits that the hygienists, scientists and architects called for and emphasized at the turn of the 19th and 20th centuries. The concept of *light, air and sun*, which became one of the most important slogans of modernism in the 1920s and 1930s, was supported by medical research. At the beginning of the 19th century, it was discovered that sunlight is a beneficial factor in preventing rickets. One of the first to raise this issue was Polish doctor Jędrzej Śniadecki. In 1822 in his work on bringing up children, he wrote that rickets […] *is not as common in the country as in the city* and that children should be allowed to stay […] *in the sun, which impacts the body in the most effective way to prevent the disease and facilitate healing* [1, p. 184–186]. In subsequent years, it was discovered that sunlight can destroy bacteria [2]. In 1890, at the 10th International Congress of Medicine in Berlin, Robert Koch presented the results of studies that proved that tuberculosis bacteria die within a few minutes of being exposed to sunlight. In case of diffused light this process is extended to several hours, however, light still has bactericidal properties [3]. In 1903, Danish doctor Niels Finsen received the Nobel Prize in medicine for the introduction and use of sunlight to treat some skin diseases and tuberculosis. In 1876, in his book on urban development, which in 1880 became a textbook of urban planning in Germany, urban engineer Reinhard Baumaister emphasized that […] *sunlight and clean air were necessary for human well-being* [4, p. 16]. At the same time, he pointed out the reasons for the poor health of the society of that time as: […] *bad quality of air in small, overcrowded rooms, the narrowness of buildings around the courtyards and very small windows* [4, p. 16].

Perhaps, paradoxically, advances in medicine (antibiotics and the tuberculosis vaccine) initiated the gradual devaluation of the antiseptic power of sunlight in the 1940s [5]. However, for several dozen years, care was taken to provide natural sunlight to residential interiors. In many countries the rules for constructing new buildings are based on regulations aimed at securing the access to light.

The amount of sunlight penetrating the residential interiors depends on several factors. These factors can be grouped into two basic categories: variables dependent on us, those which we can influence, and the independent variables (Table 1).

Table 1. The list of factors that determine the amount of daylight in residential interiors categorized into dependent and independent variables (elaborated by M. Bartnicka)
Tabela 1. Zestawienie czynników, od których zależy ilość światła dziennego we wnętrzach mieszkalnych w rozbiciu na czynniki zależne i niezależne (oprac. M. Bartnicka)

Factors that determine the penetration of daylight into residential interiors	
independent	dependent
Latitude (φ) sun declination (δ) height of sun = solar altitude angle (α)	orientation of the building size of the window opening distance between buildings

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One of the very important dependent factors listed above needed to facilitate good lighting is the correct distance between buildings. According to the author, one can assess and establish an optimal distance between buildings facilitating proper light conditions in the interiors without having to create a 3D model and a computer simulation. The only physical data to be established in relation to the building is its position with reference to the north. This paper describes the way to calculate the appropriate distance between buildings using two variables: the orientation of the building relatively to the world directions (E/W/N/S) and the time at which such an optimal distance is checked.

Although this topic may seem less significant in the era of various computer programs, it must be noted that not all software can track and assess lighting and lighting conditions accurately. The most used CAD programs are Autodesk Revit, 3dMAX, SketchUp (Plugin Sun Hours), SolidWorks, Elite CAD and 2016 and AutoCAD. These programs require geographical location, date, and time. Moreover, on top of the high prices of software, there is no way for the user to verify the results obtained. There are many reviews in which it has been pointed out that the software may display discrepancies in the position of the Sun they apply and the data available in Solar Calculators. These differences can reach up to several degrees resulting in misleading calculations.

It should be noted that in the case of software lighting analysis, the analysis can be carried out only after 3D spaces are modeled. On the contrary, with the proposed calculations, the following information can be determined before the design phase:

– optimal distance between buildings depending on the planned height of the building and the orientation of the building overshadowing the building in question,

– approximate height of the designed building/s depending on the expected distance between them.

State of research

The article deals with revision and revitalization of approaches to daylight that have been changing for several years now. Year 2015 was declared the International Year of Light by the UN General Assembly. It was named so to raise public and international political awareness of the importance of light for the future of global society. In the same year the 6th Daylight Symposium "Daylight as a driver of change" was held in London. The renewed interest in daylight in recent years reflects the acknowledgement of its potential not only in terms of energy saving, but also the extent of impact daylight has on the users of spaces. The benefits of daylight are not only emphasized and seen in health, but also in the general well-being of individuals and public.

Studies of urban spaces in terms of buildings obscuring daylight grow in importance in relation to the access of light to the residential interiors. More and more high-rise architecture and the increase in the density of buildings in urban spaces have a restrictive effect on the amount of sunlight entering residential interiors. Simultaneously, such dense urban planning reduces the potential for passive use of solar energy [6]. In the paper quoted, Paul Littlefair presents guidelines for designing outdoor environments that facilitate good access to daylight, sunlight, and solar energy [6]. The author proposes a method of determining the area of the sky in which no physical obstacle should be placed. This area is defined horizontally by an angle of 90° delimited at the level of the center of the window approximately facing south (45° eastwards and westwards from the south), and vertically through the limit of the maximum height of buildings, which depends on the latitude. This method helps determine the optimal height of buildings in the designated zones. It does not define the distance between buildings, nor their position in relation to each other.

Another way to determine the relationship between buildings is to determine the ratio between the height of the obscuring building (H) and the distance between the buildings in question (W). Attempts to determine the optimal H/W ratio between buildings were made by numerous researchers who used various methods, such as for example:

– "The daylight access rule" where the basis for determining the proportion was to maintain accurate Daylight Factor (DF) in the interior. In this way, the ratio of height and distance between atrial buildings was proposed [7],

– Unobstructed Vision Area Method in which the authors estimated the distance between the tall buildings by providing the appropriate Vertical Daylight Factor (VDF) [8].

An important and often discussed topic is the H/W relation considered in terms of the so-called street canyons. Geometry of "urban canyons" is a key factor in energy consumption in buildings. Positioning and distances between buildings determine both the amount of light and energy that comes into the interiors of the buildings and, at the same time, affect the ability to reflect light and increase the amount of daylight between buildings [9]. As Andrea Vallati and his team pointed out, the distance between buildings also means decisions regarding the possibility of ventilating the area resulting from wind movement, including that caused by convection [10]. According to these authors, the scale of the phenomenon of convection is directly proportional to the distance between buildings.

If the H/W ratio is high between buildings, then such urban planning contributes to the formation of Urban Heat Island (UHI) in the cities. Temperature increases with the increase of the value, the highest levels are observed in the range of $H/W > 1.5$ ($W < 0.66H$) [11]. The above mentioned studies and calculations were performed in temperate areas (Europe and USA). In countries with hot and dry climates, a strategy of using compact buildings and deep urban canyons is more recommended ($H/W = 2.2$; $W = 0.45H$), as to alleviate the impact of UHI and achieve thermal comfort inside and outside [12].

In the discussion about the distance between buildings depending on solar exposure and sky view factor Gerard Mills [13] presents an interesting viewpoint, but his conclusions seem controversial. The article contains various charts that show the amount of light on the facades every day of the year and the *sky view factor* depending on the dimensions of buildings and latitude. According to these tests, at 0° N latitude, the optimal solution is to use high freestanding buildings spaced relatively to each other so that $H/W > 1.0$ ($W = H$); at 30° N latitude rectangular structures (10 × 5) at spacing $0.5 < H/W < 1.0$ ($2H > W > H$) are optimal according to Mills; and at 60° latitude, rectangular structures (10 × 5 or 5 × 10) with spacing of $H/W = 2.0$ should perform best. This proportion means that buildings should stand relative to each other at a distance $W = 0.5H$, which although it would mean buildings with large widths would likely minimize heat loss and maximize heat gain in spring and summer time, they would be unlikely to achieve such results in the winter months.

Another view related to determining the optimal H/W ratio is presented in the work on optimization of the urban building efficiency potential using a genetic algorithm approach [14]. The authors present certain methodology for optimizing the building energy efficiency potential in urban forms based on the genetic algorithm approach. The authors investigated optimal shapes and positioning of buildings at various latitudes to facilitate maximum absorption of solar radiation in winter and as low as possible results in the summer. According to the conclusions presented, architects of the buildings at all latitudes should strive to reduce the length of the building base. The northbound orientated buildings (located on the width of 50° N) should be in the range from –45 to +45°. The recommended H/W aspect ratio should be between 0.25 and 0.7, i.e. $4H > W > 1.4H$.

All the above-mentioned types of research and studies were carried out using various types of programs to simulate the levels of insolation, such as software used for internal and external thermal analyses e.g., Ecotect and Dialux Evo. Authors who employ optimization methods in their research often use Rhinoceros, alongside its plug ins – Grasshopper (used for parametric design), as well as a well-known, thanks to You Tube, Ladybug, which is a solar lighting simulator utilizing a Climate-Based Daylight Modeling (CBDM) method to predict several measures of daylight based on sky conditions acquired from location specific meteorological data. Additionally, evolutionary algorithms are also used, e.g. Galapagos (built into Grasshopper) [15], [16].

The Polish contribution to the field of this kind of software allowing the analysis of solar lighting of spaces is called PRC Analysis and was developed by Jacek Markusiewicz. It enables the analysis of windows and entire apartments for compliance with local solar regulations [17]. Thanks to the software and additional preliminary analyses, a method was developed to check the interference of the planned building with the lighting cast onto the windows of the existing building/s [18].

Although all the quoted studies have a common denominator – estimating the distance between buildings taking into account the effects of sunlight – the research paths vary. The author of this paper would like to propose a different viewpoint on this issue.

The solution proposed in this paper comes from a graphic approach to analyzing the amount of sunlight in urban spaces and residential interiors. In Poland, one of the best-known publications on this subject is the book by Mieczysław Twarowski *Słońce w architekturze* [Sun in Architecture] from 1960 [19]. The author, referring to the research of the team including professors from the Warsaw University of Technology and dating back to the occupation during World War II, presented graphic ways of determining the access of sunlight to urban and residential spaces. The charts were made using the sun path diagram MT (also known as daylight analysis diagram or sundial) estimated for the selected latitude.

Twarowski's book included diagrams for the latitudes of 50°, 52.2° (Warsaw) and 54°. Based on these charts, one can plot the shadows of the obscuring object projected onto other blocks on a specific day (usually during the equinox), at specific times. The author shows how to check the extent of insolation of the interior and proposes a method for plotting contour lines with reference to insolation, with which one can specify the permissible height of neighboring buildings that will not cause shading to the building/s in question. This proposed method has been used in Poland to determine the shadow cast from the designed building or to demonstrate the lack of shading in accordance with the regulations.

The difficulties in the use of diagrams printed on tracing paper were eventually overcome by introducing a plug-in to AutoCAD (version 15 onward). At the same time, as mentioned previously, it is necessary to use a CAD program, and in this case its full version, because the plug-in does not work with the AutoCAD LT version. The decals attached to Twarowski's book are limited and cannot be used with the above-mentioned latitudes. One can, of course, calculate the data to plot a local sun ruler, based on formulas (2) and (3) or (4) – *vide infra*. The author of this paper proposes a transformation of the graphic drawing of the shadow into algebraic calculation of the distance between buildings and the permissible height of the obscuring object (building).

Method

To be able to calculate the optimal distance between buildings on a specific day of the year, you need to calculate and establish several values that become fixed factors. The basic constant value is the latitude (local latitude) (φ) of the place where we make calculations for. The day of the year (n) in which we check the optimal distance is another constant value. Connected to the day of the year (n) is the declination of the sun, i.e. the angular position of the sun at solar noon with respect to the plane of the equator (north positive); $-23.45° \le \delta \le 23.45°$. Declination can be calculated using the formula (1) [20]. In the case of equinox, which is often referenced in many building regulations, the sun declination is zero, $\delta = 0$.

$$\delta = 23.45° \cdot \sin\left(360 \cdot \frac{n + 284}{365}\right), \quad (1)$$

where:
n – the following day of the year.

First, two following formulas should be used: for *solar altitude angle* (α) (2) and *solar azimuth angle* (γ) (3) [21] or (4) [22] related to the hourly angle (ω). The solar altitude angle is the angle between the horizontal and the

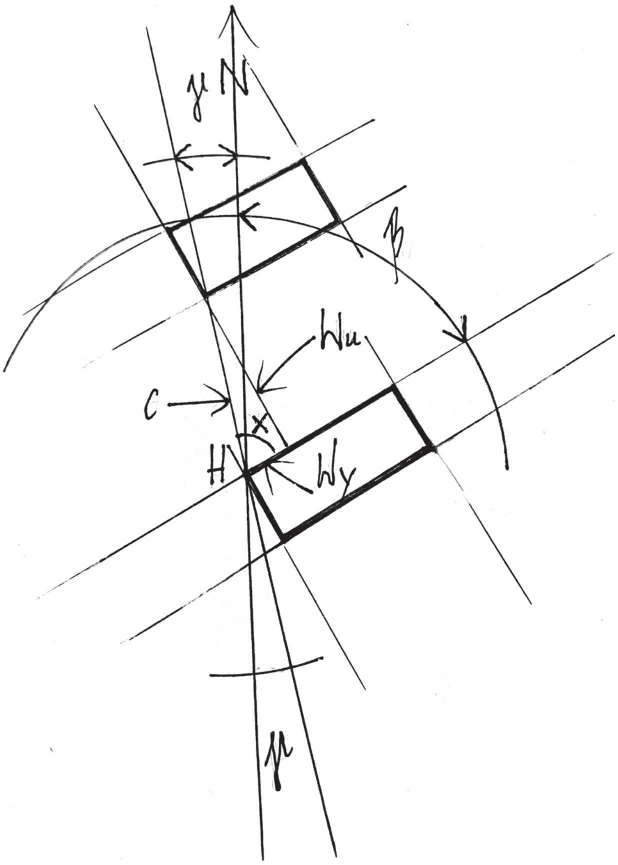

Fig. 1. A diagram of relationships between building orientation, solar azimuth angle, and distance between buildings. Where: β – building's angle in relation to north, γ – solar azimuth angle, H – building height, c – shadow length from height H, W_u – optimal distance between longer sides of buildings, W_y – optimal distance between shorter sides of buildings (elaborated by M. Bartnicka)

Il. 1. Wykres zależności pomiędzy orientacją budynku, wysokością słońca oraz odległościami między budynkami: β – kąt odchylenia budynku od kierunku północy, γ – azymut słońca, H – wysokość budynku, c – długość cienia od wysokości H, W_u – optymalna odległość między wzdłużnymi bokami budynków, W_y – optymalna odległość między krótkimi bokami budynków (oprac. M. Bartnicka)

line to the sun. It is the complement of the *zenith angle*. The solar azimuth angle is the angular displacement from south of the projection of beam radiation on the horizontal plane. Displacements east of south are negative and west of south are positive.

$$\sin\alpha = \cos\delta \cdot \cos\varphi \cdot \cos\omega + \sin\delta \cdot \sin\varphi \qquad (2)$$

$$\cos\gamma = \frac{\cos\delta \cdot \cos\omega - \sin\alpha \cdot \cos\varphi}{\cos\alpha \cdot \sin\varphi} \qquad (3)$$

$$\sin(360 - \gamma) = \frac{\cos\delta \cdot \sin\omega}{\cos\alpha} \qquad (4)$$

where:

α – solar altitude angle = solar elevation angle,
δ – declination of the sun,
φ – local latitude,
ω – hour angle in the local solar time,
γ – solar azimuth angle.

The above formulas show that both values (α) and (γ) depend only on the time in which the test takes place if latitude (φ) and declination (δ) are constant values in the chosen site. Hour angle (ω) is an expression describing the difference between local solar time and solar noon. Individual full hours become a multiple of 15, negative (–) before solar noon and positive (+) after solar noon. The hour angle can also be calculated using the formula (5).

$$\omega = 15°(\tau - 12.00) \qquad (5)$$

where:

τ – the time being checked.

The main issue investigated in this paper is the possibility of calculating the distance between buildings. These calculations are made for a specific day and time. The choice of day depends on the regulations in force in the country. In the overwhelming number of cases, it is the day of the equinox; this applies in Poland, Russia, Slovenia, Sweden, Great Britain and Germany. Other dates are also considered, often additional, e.g. December 21 (USA, South Korea), January 17 (Germany), February 19–October 21 (Netherlands), March 1 (Czech Republic), March 1–October 13 (Slovakia) and April 22 (Estonia).

Regardless of the day on which we consider the optimal distance between buildings, the following reasoning presented below could be adopted as seen in Figure 1.

Figure 1 shows two buildings. The first is the building being obscured and the second, located below, is the "obscuring" building. They are divided by the W_u distance defined as the optimal distance between the longitudinal sides of the buildings (the W_y distance is the optimal distance between the leading edges of the building). The height of the obscuring building (H) used for the calculation casts a shadow on a plane of length (c), such as not to obscure the other building. Between the directions W_u, c and the longitudinal edge of the obscuring building, a triangle is formed, in which at the corner H we have angle x. This angle follows the following relationship:

$$\sin x = \frac{W_u}{c} \Rightarrow W_u = c \cdot \sin x$$

$$\cos x = \frac{W_y}{c} \Rightarrow W_y = c \cdot \cos x$$

Due to the fact that the value of angle x depends on the azimuth of the sun, it can be read from Figure 1 that x is the sum of two angles: the deviation of the obscuring building from the north (β) and the azimuth of the sun (γ): $x = \gamma + \beta$

Knowing that the relationship between the length of the shadow of building c depends on its height (H) and the height of the sun (α), it can be represented as: $c = H \cdot \cot\alpha$

Assuming all of the above inter-dependencies, we can see that:

$$W_u = c \cdot \sin\ (\gamma + \beta) = H \cdot \cot\alpha \cdot \sin\ (\gamma + \beta) \qquad (6)$$

$$W_y = H \cdot \cot\alpha \cdot\ \cos\ (\gamma + \beta) \qquad (7)$$

Finally, assuming that we are looking for a relationship *R* (cf. [23]) between the height of the building *H* and the optimal distance W_u (or W_y), at a specific time, the following general formula should be used (8). With this assumption, the result from the calculations shows the distance W_u as a specific multiple of height *H*.

$$R = \frac{W_u}{\not{\omega}} = \not{\omega} \cdot \cot\alpha \cdot \sin\ (\gamma + \beta) \qquad (8)$$

The above formula is true for the spatial arrangement proposed in Figure 1, when the azimuth *γ* reflects the angle corresponding to (visible at) approximately 11.00 a.m. Buildings can be situated relatively to each other in different directions. The analysis of individual spatial systems showed that the final formula depends on the time at which this distance is checked. Regardless of the spatial arrangement of the object, i.e. the value of *β*, which is the angle of building deviation from the north, the following two sets of formulas will be valid:

– distance between buildings calculated in the morning (before solar noon):

$$R_{Wu} = \cot\alpha \cdot \sin\ (\gamma + \beta) \qquad (9)$$

$$R_{Wy} = \cot\alpha \cdot |\cos\ (\gamma + \beta)| \qquad (10)$$

– distances between buildings calculated in the afternoon (after solar noon):

$$R_{Wu} = \cot\alpha \cdot |\sin\ (\beta - \gamma)| \qquad (11)$$

$$R_{Wy} = \cot\alpha \cdot |\cos\ (\beta - \gamma)| \qquad (12)$$

The obtained result will reflect the proportion between the distance and the height of the building ($W = xH$) at a specific time for the selected latitude.

Practical application of the proposed formulas

If a new building is to be built near an existing one, one can specify at what distance it should be built. To limit the number of calculations, a set of specific data for a given latitude should be prepared. Table 2, for example, contains data for latitude 53°07′59″.

With this proposed table, the calculation of the inter-dependencies between buildings becomes much simpler. If you want to check at what distance buildings located at an angle of 15° ($\beta = 15°$) relative to the north should be placed, assuming that we check this at various hours during the equinox period, use the formula (9), starting from 7.00.

$$R_7 = \frac{\cos\alpha}{\sin\alpha} \cdot \sin\ (\gamma + \beta) = \frac{0.9877}{0.1553} \cdot \sin\ (77.9 + 15) =$$

$$= 6.3599 \cdot 0.9987 = 6.35$$

and, respectively:

$$R_8 = 3.13,\ R_9 = 1.9,\ R_{10} = 1.27,\ R_{11} = 0.77,\ R_{12} = 0.34$$

These calculations show that the optimal distance on the day of the equinox at certain hours is: $W_7 = 6.35H$; $W_8 = 3.13H$; $W_9 = 1.9H$; $W_{10} = 1.27H$; $W_{11} = 0.77H$; $W_{12} = 0.34H$.

Discussion and conclusions

Virtually all current research related to lighting seems to be based on CAD software, which, to varying degrees of accuracy, allows one to create realistic lighting simulations. The results are usually depicted in a visual way, showing the extent of shading or the intensity of sunlight.

Table 2. Set of data necessary to calculate the optimal distance between buildings.
The data correspond to the day of the equinox (δ = 0), for latitude 53°07′59″ (53.1331)
(elaborated by M. Bartnicka)
Tabela 2. Zestaw danych niezbędnych do wyliczania optymalnej odległości między budynkami.
Dane odpowiadają dniu równonocy (δ = 0), dla szerokości geograficznej 53°07′59″
(oprac. M. Bartnicka)

	Time					
Data	7.00	8.00	9.00	10.00	11.00	12.00
ω	–75	–60	–45	–30	–15	0
cos *ω*	0.2588	0.5	0.7071	0.8660	0.9659	1
sin *ω*	–0.9659	–0.8660	–0.7071	–0.5	–0.2588	0
cos *φ*	0.6					
sin *φ*	0.8					
sin *α* (formula (2))	0.1553	0.3	0.4243	0.5196	0.5795	0.6
cos *α*	0.9877	0.9539	0.9052	0.8544	0.8149	0.8
cos *γ* (formula (3))	0.2096	0.4193	0.6249	0.8109	0.9483	1
sin *γ*	0.9778	0.9078	0.7807	0.5852	0.3174	0
γ	77.90°	65.20°	51.32°	35.82°	18.51°	0°

The proposed method gives the possibility of establishing the optimal distances between buildings that provide and facilitate better interior lighting. This relationship is expressed by the R_{Wu} or R_{Wy} values specifying the distance between the buildings as a multiple of the height of the obscuring building H.

The scope of interior lighting depends on several parameters, including the location of the building relatively to the north, the size of the opening, or wall thickness. The subject of the optimal positioning of the buildings has been researched for centuries. Socrates was looking for the optimal orientation of a house that would be warm in winter and cool in summer. Vitruvius paid attention to the overheating of the southern side of the building and suggested positioning streets (and therefore buildings) in accordance with the diagonal of the octagon (i.e. at an angle of 22.5° from the N–S direction). At the beginning of the 20^{th} century, the slogans of hygienists and modernist architects demanded access to light, air and sun. Research at the time led to the conclusion that the best lighting conditions are provided in buildings located in the north-south direction, which enabled lighting of flats from the east and west. It is worth investigating what lighting and spatial conditions are being created by individual building positioning.

According to the data from Table 3, if lighting is assessed in the morning (and respectively in the evening), due to the low solar altitude angle largest possible distances between buildings are required. Interesting results are noted in case of the data obtained when the buildings are aligned with the longitudinal axis in the east-west direction, i.e. the preferred arrangement due to the energy-saving qualities – in this case, one of the façades faces south and the opposite façade faces north. Importantly, the required distance between buildings is constant in this case; in this example it is $W = 1.33H$, but in any other example it would be possible to quickly determine it on the basis of local latitude (φ), because this value, on the day of equinox, is cot $(90° – \varphi)$, i.e. tg φ.

In line with the title of the article, the author presented ways of determining the optimal distance between buildings using the formulas she had investigated and proposed. Moreover, the table can also be used to estimate the recommended building height at a known distance. Usually, the minimum distance between buildings is determined by building codes. In Poland, this value is a minimum of 4 m from the border of the plot and maintaining the distance relationship between buildings $W \geq H$. If one of the buildings exceeds the height of 8 m (2 × 4 m from the border of the plot), the distance should be increased accordingly to maintain the dependence $W \geq H$. According to the regulations, this applies to buildings that are up to 35 m high, with buildings higher than 35 m the distance between them becomes the maximum value. Tables obtained from calculations show the relationship of distance and height as the equation $W = xH$. Based on this, building height can be estimated with the simple formula $H = (1/x)W$.

Many more countries defined their regulations based on the date of the equinox, which somehow divides the conditions of sunlight into two six-month periods, the first one in which light access is much easier for half a year and the second one in which there is much less light for the other half. As can be seen from Table 3, this seemingly most "reasonable" date also places restrictions as to the distance between buildings at high latitudes. That is why many mitigating provisions have been added to the regulations (e.g. in Poland). The main regulation ("Technical conditions to be met by buildings and their location" §60.1 [24]) requires three hours of sunshine in the time slot from 7^{00} a.m. to 17^{00} p.m. At the same time, it is not specified whether the sunshine duration should be a continuous process or the sum of "light episodes".

Another factor reducing the amount of light in the apartment is the limitation of the above-mentioned provision to one room in the apartment, without specifying which room the regulation applies to. Additionally, a provision was granted that allows for the lack of any natural light regulations for one-bedroom apartments (the so-called studio apartments consisting of one room and a kitchen or a kitchenette). However, according to the same regulations, in the space defined as "downtown" it was allowed to reduce by half the sun exposure so that the W/H dependency could be $W \geq 0.5H$, which allowed for the density of urban development to increase to the levels prevailing at the end of the 19^{th} century [25]. These types of allowances can be seen not only in the examples from Poland. This much more global problem results from long-term housing shortages. Housing estates from

Table 3. Optimal distance between buildings (on the day of equinox) facilitating lighting for the façade of the obstructed building depending on the spatial orientation of the obstructing building (β) (elaborated by M. Bartnicka)
Tabela 3. Optymalna odległość między budynkami (w dniu równonocy) zapewniająca doświetlenie elewacji budynku przesłanianego w zależności od orientacji przestrzennej budynku przesłaniającego (β) (oprac. M. Bartnicka)

Spatial orientation of the obscuring building	Optimal distance between buildings expressed as a multiple of the height of the obstructing building (xH) depending on the time of day (sun time)					
	7.00	8.00	9.00	10.00	11.00	12.00
$\beta = 0°$ orientation N–S	6.22H	2.88H	1.66H	0.96H	0.44H	0H
$\beta = 22.5°$	6.25H	3.17H	2.05H	1.40H	0.91H	0.51H
$\beta = 45°$	5.33H	2.98H	2.12H	1.62H	1.25H	0.94H
$\beta = 90°$ orientation E–W	1.33H	1.33H	1.33H	1.33H	1.33H	1.33H

the times of the Polish People's Republic (and during the subsequent years) were characterized by an urban concept on the scale of the entire housing estate, quarter, district, in accordance with the regulations, including maintaining appropriate distances and providing recreational and green spaces. Unfortunately, current housing developments are focused mainly on profit and not on creating suitable and comfortable, also in terms of light, residential spaces. This leads to further densification of urban spaces and the loss of the intellectual achievements of modernism. Gradual abandonment of the requirements for sunlight access to residential interiors will have its consequences.

Phil Leather's team in his studies on stress *Windows in the Workplace: Sunlight, View, and Occupational Stress* [26] points out that the most significant impact on job satisfaction and comfort of using a particular space is the presence of direct solar light penetrating the interior. Allowing the gradual reduction of sunlight into the interior will lead to an excessive density of residential areas. This phenomenon is one of the so-called stressors of space. The psychological reaction of users of spaces lacking in sunlight is stress. This stress is caused by an internal sense of disruption of balance and a lack of influence on the following emerging factors [27]: urban over density, including the scale of buildings, the short distances between the windows of opposite apartments, or simply the loss of views from the windows. Lack of distance between private spaces causes sensory overload and, as a result, difficulties in the use of spaces and the risk of creating oppressive spaces [28].

Undoubtedly, the issues of daylight, its access to interior spaces and its regulation are in the interest of designers, albeit to a much lesser extent, of developers and people involved in real estate. Surely, access to daylight and decent views should become an asset of high-quality buildings and good architecture, after all, slogans about *daylight design* have been increasingly appearing. Determining optimal distances and spatial orientation of buildings is, without doubt, an essential part of good design. Authorities checking compliance with regulations, including access to daylight, are also those who issue building permits. Their control is often based on checking that the design documentation includes drawings indicating the absence of shading; however, they do not perform any adequate verification. The algebraic method presented in the article could easily become a useful control tool not only for the designers and architects, but also for the building control officials.

Translated by
Ewa Youngman

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Abstract

Determining the optimal distance between buildings based on the solar altitude angle to facilitate appropriate illumination in residential interiors in accordance with current legislation

The article touches upon the subject of the availability of sunlight in residential interiors. The distance between buildings is one of the crucial factors responsible for the penetration of sunlight into interiors. The optimal distance can be calculated algebraically and to determine the output data it is sufficient to know the location of the obscuring building in relation to the north.

The aim of the article is to propose an alternative way to check the access of sunlight without the need to create a 3D model and computer simulation. Using the presented method, it is possible to determine the optimal distance between buildings, which will guarantee no shading to the existing building.

The proposed solution derives from the graphic approach to this subject presented in Mieczysław Twarowski's book *Słońce w architekturze* [The Sun in Architecture], i.e. to the so-called sun ruler. The author proposes to change the graphic plotting of the shadow into an algebraic conversion of the distance between buildings. For the calculations, known formulas for the height of the sun (α) and for the azimuth of the sun (γ) were used. As a result of the analysis of spatial layouts of buildings and the possibility of shading, original formulas for calculating the distance between buildings were derived. The obtained result reflects the proportion between the distance and height of the building ($W = xH$) at a specific time for the selected latitude.

The publication proves that it is possible to determine the optimal distances between buildings in an algebraic way without the need for CAD programs. The presented formulas may be used as an instrument for checking the correctness of the non-shading charts presented by investors in multi-family housing projects. At the same time, these formulas can be used to calculate the approximate height of the proposed building depending on the expected distance between that building and existing buildings.

Key words: distance between buildings, N–S orientation of the building, solar altitude angle, *H*/*W* ratio, access of sunlight

Streszczenie

Wyznaczanie optymalnej odległości między budynkami i dopuszczalnej wysokości projektowanego budynku na podstawie wysokości słońca

W artykule poruszono tematykę dostępności światła słonecznego do wnętrz mieszkalnych. Jednym z niezwykle istotnych czynników odpowiadających za przenikanie światła słonecznego do wnętrz jest odpowiednia odległość pomiędzy budynkami. Optymalną odległość można wyliczyć algebraicznie, a do ustalenia danych wyjściowych wystarczy informacja, jakie jest usytuowanie budynku przesłaniającego względem kierunku północy.

Celem artykułu jest zaproponowanie alternatywnego sposobu sprawdzania dostępu promieni słonecznych bez konieczności tworzenia modelu 3D oraz symulacji komputerowej. Za pomocą przedstawionej metody można określić optymalną odległość pomiędzy budynkami, przy której zachowaniu nie nastąpi zacienianie budynku istniejącego.

Proponowane rozwiązanie wywodzi się z graficznego podejścia do tej tematyki prezentowanego w książce Mieczysława Twarowskiego *Słońce w architekturze*, czyli do tzw. linijki słońca. Autorka proponuje przemianę graficznego wykreślania cienia na algebraiczne przeliczanie odległości między budynkami. Do przeliczeń wykorzystane zostały znane wzory na wysokość słońca (α) i na azymut słońca (γ). W wyniku analiz układów przestrzennych budynków i możliwości zacieniania wywiedzione zostały autorskie wzory służące do przeliczania odległości między budynkami. Uzyskany wynik odzwierciedla proporcję między odległością a wysokością budynku ($W = xH$) w konkretnej godzinie dla wybranej szerokości geograficznej.

W publikacji ukazano, że istnieje możliwość ustalenia optymalnych odległości pomiędzy budynkami w sposób algebraiczny, bez konieczności wykorzystywania programów CAD. Przedstawione wzory mogą stać się instrumentem sprawdzania poprawności wykresów braku zacieniania przedstawianych przez inwestorów w projektach zabudowy wielorodzinnej. Jednocześnie wzory te można wykorzystywać do wyliczania orientacyjnej wysokości budynku projektowanego w zależności od przewidywanej odległości pomiędzy nim a budynkami istniejącymi.

Słowa kluczowe: odległość między budynkami, orientacja N–S budynku, wysokość słońca, proporcja *H*/*W*, dostęp światła słonecznego