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The practical implications of the EN 17037 minimum target daylight factor for building design and urban daylight in several European countries

Jozef Hraška, Jakub Čurpek [*]

Faculty of Civil Engineering, Slovak University of Technology, Bratislava 810 05, Slovakia

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A B S T R A C T

Sufficient daylight in the indoor environment of buildings is important not only for vision and well-being as daylight also has significant non-visual effects on the human organism. The provision of daylight in the interiors of buildings significantly affects the architectural and urban parameters of the building environment. Harmonized EN 17037 introduced a number of changes and ambiguities to the relatively established principles of incorporating daylight in buildings in several European countries; these were significant for both architects and other stakeholders. This paper compares the long-standing practice and historical context of daylight provision according to the criteria of national standards in selected European countries (Germany, Czech Republic, Slovak republic, Sweden) with the minimum target daylight factor according to the harmonized EN 17037. The consequences of the methodological differences and design criteria of daylight provision are presented in case studies of the assessment of the daylight in residential rooms and typical school classrooms. Daylight factor and lighting distribution are analyzed for different room scenarios, different window configurations and obstruction angles according to local standards in the mentioned European countries versus EN 17037. The paper also highlights the practical impact of the EN 17037 criteria on building design and the extent of façade obstruction.

1. Introduction

Solar radiation has a dominant effect on practically the entire natural world. Daylight, the most important part of sunlight for people's lives, has been respected in the creation of the building environment for millennia. The history of architecture documents that the provision of daylight in the indoor environment of buildings is determined by climatic conditions, type of buildings, material conditions, people's way of life and cultural influences [1–3]. The use of diffuse and direct sunlight both in the past and today strongly influenced architecture and urban planning. Daylight is a freely available natural resource that is healthy, ecological and fully in line with the societal goals of sustainable development [4].

The natural alternation of day and night creates circadian oscillations in living organisms, which directly and indirectly affect a number of physiological and psychological processes in human organisms [5,6,7]. Chronobiological and medical research provides ample evidence of how important daylight is not only for health, but also for physical and psychological productivity throughout human life [8–10]. Throughout the 20th century, systems were created for the evaluation of daylight, with the system based on the

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[*] Corresponding author.
E-mail address: jakub.curpek@stuba.sk (J. Čurpek).

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daylight factor (DF) being the most widespread. The DF is the ratio of daylight illuminance in a certain place of the indoor space to the exterior illuminance of an unshaded horizontal plane under the standard CIE (Commission Internationale de l'Éclairage) overcast sky [11].

$$DF = \frac{E_i}{E_e} \times 100\ [\%] \tag{1}$$

In many countries, minimum DF criteria were standardized during the second half of the 20th century, and in some countries, they have been incorporated into legislation. These standards and regulations specified the geometry and size of daylight apertures in habitable rooms, including the distances and heights of external obstructions. The DF levels and the places in the interiors where it was necessary to reach them were differentiated according to the purposes of the interior spaces and the visual tasks of the activities that were mainly carried out in them. In residential rooms in several European countries (for example, Germany, Czech Republic, Sweden, Slovakia), the daylight factor is evaluated at the half-depth of the room, see Fig. 8 on the left.

At the beginning of the 21st century, some researchers recommended the introduction of year-round climate-based daylight modelling (Climate-Based Daylight Modeling - CBDM) [12–15]. It was pointed out that the DF method was static, outdated and came from the pre-computer age. The high performance of computer technology and its wide application in building design as well as the development of building simulations created the prerequisites for the gradual introduction of CBDM into project practice. When designing and evaluating daylight according to the CBDM, it is usually based on what time of the year daylight is able to provide the level of illumination required by the standards for artificial lighting. Harmonized EN 17037 (2018) [16] is based on the CBDM philosophy and offers two methods for designing and evaluating daylight in buildings.

One of these methods is a target daylight factor based on the median exterior diffuse horizontal illuminance from the sky that is available at the site under consideration. In this way, the authors of the standard tried to preserve the established tradition of evaluating daylight in buildings using the DF method, which was used in many European countries. This metric, in accordance with the additional requirements and criteria of EN 17037 on daylight provision in buildings, is compared in this paper with the "classic" DF method. The second EN 17037 calculation method calculates absolute illuminance levels based on the local light climate defined by reference climate years, including direct sunlight. This "more flexible" method is not discussed in this paper because it is not comparable to the DF method.

1.1. *Aims and scope*

EN 17037 proposed that an illuminance level at least 300 lx over 50 % of the reference plane and at the same time a minimum threshold illuminance of 100 lx across 95 % of the space in all regularly occupied indoor spaces for more than half of daylight hours should be achieved. EN 17037 also introduces illuminance levels 500 and 750 lx that correspond to an 'average', and a 'high' daylight performance. These criteria are set for all spaces that could be regularly occupied regardless of their specific purpose. This methodical approach is quite contrary to the way of providing daylight in buildings, which has become established in several European countries. For example, in Germany, the Czech Republic and Slovakia, the level of daylight availability is differentiated according to the purpose of the interior space and the type of visual work mainly performed in it.

The main objectives of this paper are.

- Chronologically analyze the development of the principles, methods and criteria for daylight evaluation in buildings.
- To conduct case studies that highlight the challenges of meeting the minimum target daylight factor criteria in residential rooms, and document the significant differences between the daylight requirements for school classrooms that have been applied in many European countries for many decades and the criteria required in EN 17037.
- To analyze the practical consequences of the criteria of daylight in buildings specified in EN 17037 on architecture and urban daylight mainly in Central European climatic and cultural conditions.

2. A brief history of the criteria and methods for designing and evaluating daylight in buildings

Marcus Vitruvius Pollio, an ancient Roman military engineer and architect, in his expansive work "Ten Books on Architecture" [1] states that in those parts of the interior of buildings from which the sky can be seen, sufficient daylight is felt subjectively. At the end of the 19th century, several researchers began to quantify this empirical knowledge using geometric methods [17]. Although the first measurements of daylight were carried out in the early years of the 20th century [18,19], their results were not translated into methods for designing and evaluating daylight in buildings. In the first decades of the 20th century, during the practical design of buildings, only the sky's illuminance of the interior (Sky Factor – SF) from the daylight openings in the envelope (without glazing, type of windows or skylight structure, etc.) was considered. Several graphic tools were proposed for determining the sky's illumination of the interior [20–22], which actually graphically quantified and generalized the ancient observations of Vitruvius. The question was, how much of the sky should be seen and from which part of the room, so that on cloudy days people have the feeling of enough daylight in the room.

In residential rooms (initially also in offices), SF was usually calculated in their center at the height of a work table (0.85 m above the floor). Waldram and Waldram [20] suggested that in places where the SF is above 0.2 %, daylight can be considered sufficient even for carrying out administrative work. With an external sky horizontal illuminance of 5000 lx, this is only 10 lx. However, it should be noted that if the value of an SF is 0.2 % in the center of the room, a value about 0.6 % of the subsequent daylight factor is expected in the same place due to the influence of reflected light from the terrain and bright internal surfaces assuming a typical window frame and clean clear glass. The "grumble line" set by Waldram with a value of 0.2 % was later challenged as the boundary between a satisfactorily and unsatisfactorily lit part of the room. In fact, SF = 0.2 % could be considered as an indirect indication of the subjective perception of sufficient daylight in the room under cloudy conditions.

Building regulations in several European countries generally required that the height of street facades be no higher than the width of the street (45° angle). In Central European countries, the minimum window area of living rooms was usually suggested to be 1/8 to 1/10 of the floor area of the room. Such rules are still used in several countries as a legislatively binding requirement that guarantees a certain level of daylight in living rooms, even though its value is generally significantly lower compared to the requirements of national daylight standards. Such a practice suits the work of architects and urban planners, who need a quick and relatively reliable estimate of the size of buildings and their windows at the initial stages of design. The annual average occurrence of cloud cover in Central Europe is higher than 50 %, while its occurrence dominates in the winter period. With some simplification, it can be stated that in the first half of the 20th century, the architect's work, which is directly connected to geometry, was accompanied by geometric criteria for the design of lighting openings and geometric calculation tools. Designing daylight into buildings was under the full control of the architect.

The first models of both cloudy and completely clear skies, based on sky brightness measurements, were created in the 1920s; these are well documented in Ref. [23]. The luminance distribution model in an overcast sky as a basic for the design and evaluation of daylight in buildings was established by Ref. [24]. This model was adopted by the International Commission on Illumination (CIE) as the standard lighting model of the sky [11]. Calculation methods, standards and criteria for daylight in buildings in several European countries were based on luminance patterns under heavily overcast skies. The sky factor criterion was replaced by the daylight factor determined under the conditions of a standard overcast sky.

In addition to direct light from the sky, the DF method also takes into account reflected diffuse light from a range of internal and external surfaces, as well as the loss of light when it passes through windows, skylights or other translucent parts of a building envelope. Later, standards for measuring the DF were created (e.g. BS CP 3, 1964, ČSN 36 0014, 1967) [25,26] and increased the number of artificial skies in the world, which were mostly based on the standard overcast sky model. Simple but labor-intensive geometric tools and semi-empirical calculation methods for determining the interreflection of daylight [27] were only able to provide approximate values of the DF, even in relatively simple geometries. In former Central European socialist countries, daylight in buildings was part of legal requirements to protect public health. The daylight criteria had to be simple and verifiable due to their legality, as they were strictly controlled by the state hygiene service. Also for this reason, the CIE overcast sky model was considered a suitable basis for calculation methods of daylight provision in buildings and a basis for experimental verification of the fulfilment of the "in situ" criteria.

DF values at certain points in the interior consist mostly or entirely of reflected light. The calculation of the DF at many points was considered laborious, inefficient and in "common cases" replaceable by the Average Daylight Factor (ADF) method [28–30]. Practical architects, building designers and stakeholders in many countries welcomed such a step. The very simple calculation and especially the relatively free interpretation of the ADF criteria have become popular in several countries (for example, in Italy, China, UK, Ireland). The ADF method has a number of shortcomings. However, its popularity may be due to the fact that in cases of relatively standardized typological building solutions (e.g. residential buildings) detailed calculations of daylight are not necessary. The ADF method was adopted by the BREEAM sustainable building assessment certification system (BREEAM, 2021) [31].

A lot of work was done on the design of models of luminance distribution of various reference skies during the last decades of the 20th century [32–34]. The efforts of many researchers resulted in the publication of the CIE Standard General Sky [35]. The method of Daylight Coefficients [36] opened up the space for relatively effective year-round simulations of interior daylight with any sun position and a range of brightness distributions in the sky. Developments in the field of simulations of the lighting environment in buildings and the possibility of relatively realistic analyses of daylight in buildings throughout the year caused some specialists in building daylight to sharply criticize the DF method at the beginning of the 21st century as being outdated and generally unfit for purpose [13,37,38].

The spatial daylight autonomy (sDA) method, proposed by the Swiss Electricians' Association in 1989 [39], came into common use in the new millennium. The sDA method was developed by lighting environment simulation specialists [15,40,41]. The certification system of "green" buildings LEED v4 [42], which adapted the CBDM method according to the requirements and criteria IES [41], significantly contributed to its almost worldwide adoption. LEED adopted the same criterion requirements for daylight illumination in all types of indoor spaces, regardless of the region of the Earth in which the building was located. Currently, emerging ideas about automated daylighting design [43] fit into the context of previous trends.

Long-term empirically verified European national standards based on the DF, which supported international directives and were part of building laws in several countries, must be aligned with the EN 17037 standard [16], which is based on the CBDM philosophy. The standardization of sky luminance distribution models and significant progress in the automation of calculations of the illumination of the interior spaces of buildings do not provide a direct answer to how much daylight there should be in the interiors of buildings. Daylight in the CBDM is understood to a large extent as a part, partial replacement for, or supplement to artificial lighting. Daylight autonomy is usually expected in the range of 40 %–60 %, typically 50 %. In the past, in Central Europe, daylight in buildings was fundamentally designed as primary lighting, which was supposed to provide enough daylight to carry out predominantly visual activities in a specific interior space for 80 % of the day on average. The stated percentages cannot be directly compared, because their starting points and determination methodologies differ significantly. In the CBDM method, it is assumed that artificial lighting is switched on when the level of daylight falls below the standard value of artificial light illumination. Significant differences between the perception of daylight and artificial light in indoor spaces are thus ignored. Several studies [44,45] show that building occupants switch on artificial lighting at significantly lower daylight levels than predicted by CBDM.

3. Methodology

In this paper, the requirements for daylight in buildings and the relevant criteria of EN 17037 are compared with the analogous requirements of the national standards on daylight in buildings in Germany, Czech Republic, Slovak Republic and Sweden. The methodology and criteria for evaluating the daylighting of apartments is very similar in the mentioned countries. That is why, as a representative of the assessment of the daylighting of residential rooms, we have chosen the system that is used in the Slovak Republic.

3.1. The principles and problematic aspects of daylight assessment in buildings according to EN 17037

EN 17037 uses methods to assess daylight in buildings that include the local light climate. The standard requires a minimum daylighting provision of 300 lx of natural light illuminance over 50 % of the space and 100 lx minimum over 95 % of the space, both for more than half of the daylight hours in the year (2190 h). The daylighting provision can be calculated by two different calculation method, and it is expected that a proven software will be used for the calculation. One calculation procedure is linked in EN 17037 to the median availability of diffused skylight in the local natural lighting environment. The second EN 17037 calculation method calculates the absolute levels of daylight in lux, while also including direct sunlight. The standard does not comment in any way on the fact that the results of daylight illuminance calculations using each standard method differ significantly. Substantial differences in either set of calculations, however, have a significant impact on urban planning and the architectural design of buildings.

The requirements for daylight in Germany are specified in DIN 5034–1:2021 [46], in the Czech Republic in ČSN 73 0580-1 [47], in Slovakia in STN 73 0580-1, 2 [48,49] and in Sweden in SS 91 42 01:1988 [50]. In the Czech Republic, Slovakia and Sweden, the aforementioned standards are used as a reference/legislative concept and criteria for daylight in all rooms where people stay for an extended period of time. The standard requirements for daylight in buildings in Germany are not directly incorporated into the generally binding building regulations. The requirements for daylight in residential rooms are only slightly different in the aforementioned countries. For this reason, we have chosen the method of daylight assessment used in Slovakia as a representative for the evaluation.

The EN 17037 standard states the values of the median diffuse sky horizontal illuminance for the capitals of European states, see Table 1. If in a country, on the reference plane or on its part, a target illuminance of $E_T = 300$ lx is required, then the target daylight factor D_T is calculated.

$$D_T = \frac{300\ lx}{E_{v,d,med}} \times 100\ [\%] \tag{2}$$

The approval of EN 17037 was met with mixed reactions from experts. Some experts welcomed it with enthusiasm, while others accepted it with embarrassment [51–56]. The "realistic" year-round evaluation of daylight in practically every interior space and in any urban environment using numerical simulations is considered to be a positive aspect of the standard. Despite the considerable maturity of programs simulating the propagation of light in the interior spaces of buildings, there are still differences between them in the results of calculations. In geometrically and materially more complex cases, the differences in results between simulation programs can reach several tens of percent in specific places [57,58]. Several practical architects and daylighting specialists consider the use of complex methodologies in EN 17037 to be unjustified in the vast majority of cases. These methodologies generally have little added value in terms of designing lighting openings in climatic regions with a predominant occurrence of cloudy days.

EN 17037 opened up a very wide area for the "playing game" in the design of daylight in buildings. Different scenarios in the use of shading devices on glazed openings in a building's envelope, different scenarios in the time of use of indoor spaces in buildings and assumptions of occupant behavior cause the results of computer simulations to be highly dependent on the chosen assumptions.

The EN 17037 criteria and their evaluation by method 2 (year-round simulation using data for the given site) prefer the summer half of the year, in which the days are longer and in Central Europe there is also a higher incidence of direct sunlight. For example, in Bratislava, Slovakia the days are on average 1.5 times longer in the summer half-year than in the winter half-year and the average hourly duration of sunshine in December is 52 h and in July 298 h. Cumulative assessment of daylight puts the wintertime at a disadvantage, when the availability of daylight in buildings is most welcome.

Fig. 1 shows the long-term averages of the occurrence of overcast days, partly cloudy days and mostly clear sunny days (days in which less than 20 % of the sky is covered by clouds) in Bratislava, Slovakia (from meteoblue) [59]. The average annual occurrence of relative sunshine duration in Bratislava is approximately 50 %, while it dominates in the summer half-year. The absolute levels of daylight required in EN 17037 can be achieved in Bratislava only when there is direct sunlight and that with relatively small lighting

Table 1
Requirements for daylight in residential rooms and classrooms in selected European countries.

Country	Germany	Czech Republic	Slovakia	Sweden
$E_{v,d,med}$ according EN 17037 (lx)	13 900	14 900	16 300	12 100
Minimum target daylight factor D_T (%)	2.2	2.0	1.8	2.5
Min. point DF at the half-depth of residential rooms (%)	0.9	0.9	0.9	1.0
Min. point DF in classrooms (%)	2.0 On the whole reference plane.	1.5 On the whole reference plane.	1.5 On the whole reference plane.	1.0 At the half-depth of the room.

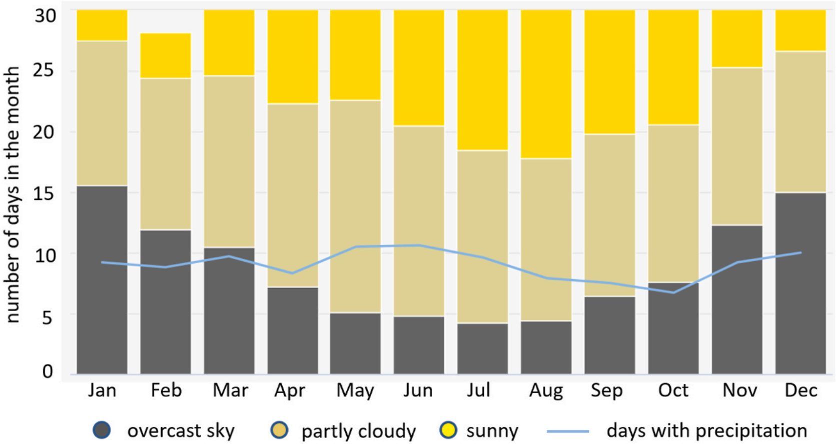

Fig. 1. Average occurrence of overcast, partly cloudy and sunny days and days with precipitation in Bratislava (Slovakia) [59].

openings. If the window sizes are designed according to the method referred to in EN 17037 as method 2, there will be a significant lack of daylight in the interior spaces during cloudy winter days. The key shortcoming of EN 17037 is that the standard sets the same requirements for daylighting "to all spaces that may be regularly occupied by people for extended periods" without specifying the purpose of the space. This fact has already been analyzed by several authors [51–54]. In particular, this study deals with this issue. Only the requirements and criteria of EN 17037 for ensuring daylight in side-lit spaces using the median daylight factor method are considered in this study.

3.2. Principles of assessment of daylighting in buildings in the several European countries

In the former Czechoslovakia, there were state-controlled legislative requirements and criteria for the design of daylight in buildings (a right to light) for many decades [60–63]. There were special (lower) requirements for residential buildings and other (more demanding) requirements for workplaces. Workspaces were divided into those in which the requirements for daylight had to be met in full (e.g. classrooms) and those in which combined lighting with a certain proportion of daylight could be used (e.g. offices). In apartments and in some other types of indoor spaces, a minimum time of direct solar exposure was required. In existing apartments, direct solar exposure could not be reduced below the specified minimum time due to new construction in their vicinity.

After the dissolution of Czechoslovakia, this practice continued with minor modifications in the Czech Republic and the Slovak Republic. The daylight criteria were based on medical knowledge, requirements for the predominant type of visual work performed in the relevant space, and also with the aim of preventing injuries that could be caused by reduced visibility. The criteria indirectly took into account climatic conditions and socio-cultural contexts. In the Central European region there are significant seasonal and daily daylight fluctuations. Direct solar exposure in dwellings is required only in the summer half of the year. The requirements for daylight are based on the climatic conditions in the winter half of the year, when the occurrence of densely cloudy days prevails. The fulfillment of these requirements was checked by state institutions in the initial stages of building design, when fundamental architectural and urban planning parameters are set.

In the former Czechoslovakia and later in Slovakia the criteria for daylight in living rooms in apartments (STN 73 0580-2) [48] were inspired by the German standard (DIN 5034) [64], which were mainly based on research of Seidl et al. [65,66,]. The standard criteria are based on experiments that measured people's satisfaction with the lighting environment of side-lit residential rooms under cloudy skies, as indicated by their willingness to turn on artificial lighting. At two points in the half-depth of the living room at a height of 0.85 m above the floor and at a distance of 1 m from the side walls, an average value of the DF of 0.9 % is required for one-sided lateral daylighting of an empty room is considered. In Sweden, the point daylight factor criterion of 1.0 % at half the depth of the residential room is fully consistent with the DF values of 0.9 % at a distance of 1 m from the side walls.

At the same time, the minimum value of the DF in one of the points must not fall below 0.75 %. If the residential room is deeper than 6 m, points that are 3 m away from the inner surface of the window wall are assessed in Slovakia. This is a response to the tendency to create deep residential rooms connected to the kitchen, the depth of which usually reaches around 7.5 m and is thus greater than the limit depth of a living room of 6.0 m, which in the past was prescribed in several European countries. In order to reach a value of the daylight factor of at least 0.90 % on the horizontal plane in the center of the room at a height of 0.85 m above the floor, at least part of the sky must be visible from this place through the lighting opening. The criterion of the DF in the value of 0.90 % thus indirectly guarantees a high-quality view from the dwelling room as well as the urban density. The urban density in terms of the availability of daylight is regulated in Slovakia by the criterion of the equivalent shading angle of the windows (STN 73 0580-1:Z2) [49] and in the Czech Republic by the vertical DF of control points on the building facade. Both criteria are determined under standard overcast sky conditions.

The real practice responded to the fact that rooms oriented to different cardinal points receive different amounts of daylight and solar radiation throughout the year with a range of guidelines for architects in terms of the layout of apartments and the provision of shading and other similar devices. The combination of guidelines for ensuring daylight and sunlight in apartments and other types of interior spaces and their projection into urbanism and architecture provides an indirect but effective solution to the dynamic nature of the local light climate. The guidelines are based on long-term empirical experience.

In Slovakia and Czech Republic, a suitably lit workplace (school classrooms are also included) with lateral daylighting is generally considered to be one that meets the hygiene requirements, which means that the point daylight factor (DF) at a height of 0.85 m above the floor must be at least 1.5 % [61–63]. In the case of top daylight an average DF of at least 3.0 % is required. Where there is combined lighting, a level of at least a third of the above-mentioned values of DF is required. If a third of the required value of the DF is not achieved in a workspace, it is considered to be without daylight and specific hygiene requirements are applied. In Germany, workplaces with roof skylights must have an average daylight factor of at least 4 % on the reference plane, and the minimum daylight factor must be at least 2 %[49]. In Sweden, the requirements for daylighting in classrooms are analogous to the requirements for daylighting in residential rooms.

It is therefore obvious that in Slovakia there is a significant difference between the requirements for a well-lit residential room and a sufficiently lit workspace. Similar differences also apply in Slovakia in the requirements for artificial lighting in apartments and workplaces. While, for example, artificial lighting of 150–200 lx is recommended in living rooms, only 100 lx is recommended in bedrooms. An intensity of artificial lighting in the range of 300–500 lx is required in offices [67]. Similar requirements for artificial lighting in apartments exist, for example, in Russia [68], in Thailand [69] and in many other countries.

3.3. Models setting

The one-zone simulation models of a residential room were created in a building energy simulation software DesignBuilder [70]. Daylight illuminance distribution was calculated by the Radiance ray-tracing simulation engine under standard overcast sky with reports an average DF on the reference plane 0.85 m above the floor.

3.3.1. Case study A: residential room

A 3-D geometrical model represents a room, which is most common in dwellings in European countries. The model geometry was steeply (0.5 m) modified with various depth from 3.0 to 6.0 m. Dimensions and photometric parameters of the reference residential rooms are summarized in Table 2.

The margin around the reference plane was set to 1.0 m, it is an area where illuminance data were not included in results according to the requirements of STN 73 0580-2. The requirement that a 1 m wide strip around the perimeter of the room should not be included in the calculation area was applied in national deviation due to regulations in Slovakia in EN 17037. The height of the window was 1.5 m, and its width was adjusted according to both standard requirements (STN 73 0580-2 and EN 17037) [16,51]. Moreover, the

Table 2
Dimensions and photometric parameters of the reference residential rooms.

Depth of the room (m)	from 3.0 to 6.0
Width of the room (m)	from 3.0 to 6.0
Clear height of the room (m)	2.6
Height of the window (m)	1.5
Width of the window (m)	according to EN/STN requirements
External obstruction angles (degree)	from 0 to 45
Floor light reflectance (–)	0.25
Walls light reflectance (–)	0.50
Ceiling light reflectance (–)	0.70
Light transmittance of triple glazing (–)	0.70
Glazing ration (–)	0.70
Maintenance factor (–)	1.0

Table 3
Parameters of the calculation program.

Working plane height (m)	0.85
Margin (m)	1.00
Ground plane extension (m)	20.00
Sky method	Standard sky
Sky model	CIE overcast day
Minimum grid size (m)	0.05
Maximum grid size (m)	0.05
Ambient bounces	12
Ambient accuracy	0.22
Ambient resolution	512
Ambient divisions	1024
Ambient super-samples	512

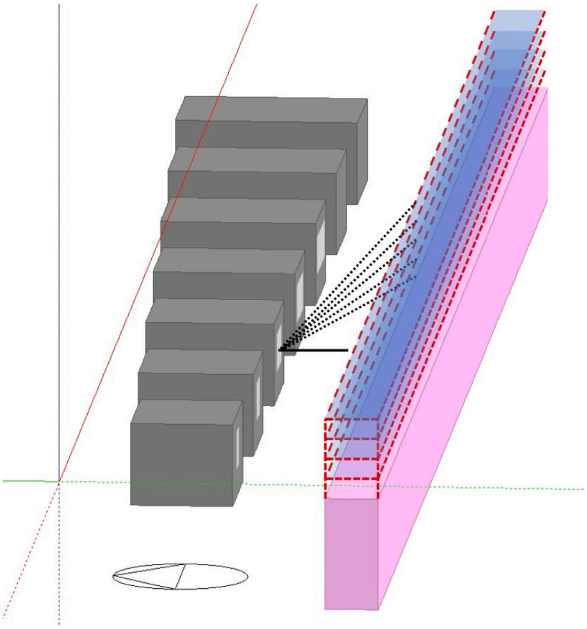

Fig. 2. Simulation models with different heights of external obstacle in DesignBuilder.

influence of external obstruction was investigated in various levels of obstruction angles from 0° to 45°. Other computational parameters of the simulation software are listed in Table 3. The scheme of simulation models with the external obstacle is depicted in Fig. 2.

3.3.2. Case study B: school classroom

A second simulation study focused on the case of a classical classroom, where the difference between the requirements of STN 73 0580-1 and EN 17037 for daylight was investigated. STN 73 0580-1 requires DF values higher than 1.5 % at every point of the reference plane to be achieved. In Slovakia, it is based on the fact that every student's workplace must achieve a hygienic minimum of daylight, which is set by the value DF = 1.5 %. Two simulation models of a typical classroom were created in DesignBuilder (Fig. 3) with the same values of surfaces light reflectance as for the case of dwelling rooms (see above). No shading obstacles were considered. Geometry of the classroom was set with dimensions (6.5 room depth, 9.0 room width, 3.6 room height). Three windows were modelled with width 2.4 m. Dimensions and photometric parameters of the reference school classroom are summarized in Table 4.

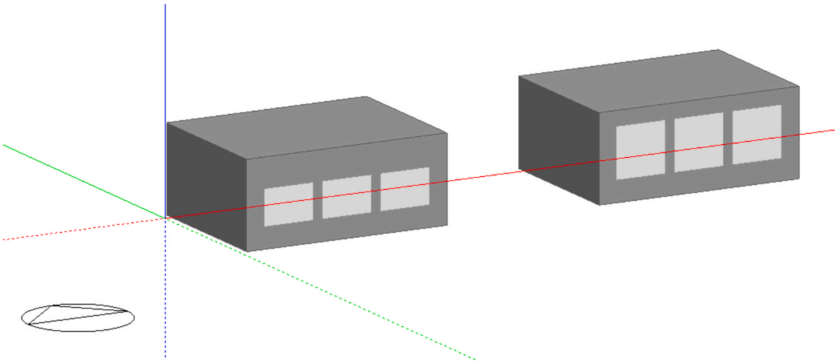

Fig. 3. Simulation models of classroom in DesignBuilder.

Table 4
Dimensions and photometric parameters of the reference school classrooms.

Depth of the room (m)	6.5
Width of the room (m)	9.0
Clear height of the room (m)	3.6
Height of the windows (m)	according to EN/STN requirements
Width of the windows (m)	2.4
External obstruction angles (degree)	no considered
Floor light reflectance (−)	0.25
Walls light reflectance (−)	0.50
Ceiling light reflectance (−)	0.70
Light transmittance of triple glazing (−)	0.70
Glazing ration (−)	0.70
Maintenance factor (−)	1.0

4. Results

4.1. Results for case study A: residential room

Simulation outputs revealed considerable differences between STN 73 0580-2 and EN 17037 in terms of minimum ranges of window width for dwelling rooms according to various obstruction angles (Figs. 4–7). Absolute differences between both requirements lay not only in the different values of DF but also in the various philosophies. In the case of STN 73 0580-2, for lower room depths with low or no obstruction, the minimum values of required window width is determined as 55 % of the width of the room (1.65, 2.20, 2.75, 3.30 m). In small and poorly shaded rooms, it is possible to achieve the DF required in STN 73 0580-2 even with small windows. The requirement of 55 % of the width of the window from the width of the room reduces the brightness contrast between the window and the dark corners of the window wall and at the same time guarantees a good view from the room. However, EN 17037 requirements allow a lower minimum required window width for these situations. In complex boundary conditions (high obstruction angles and deeper room), the effect of different values of DF is significant. This means that the assessment of the room according to EN 17037 does not allow for the creation of deeper rooms with the required window dimensions. On the other hand, STN 73 0580-2 with lower DF requirements allows for the creation of deeper rooms with external shading. Accordingly, EN 17037 provides wider interval of minimum required room window width in dependence of room depth for obstruction angles from 0° to 35°, and 40° for the room width 6 m.

The graphical comparison of modelled zones (in accordance to STN 73 0580-2 and EN 17037) with the position of reference plane and control points is depicted in Fig. 8. According to the requirements of EN 17037, for several cases with obstruction angles, the window height of 1.5 m is unsatisfactory and should be increased. These differences between the criteria lie mainly in the philosophy of the approach to standardization. While the requirements for daylight in apartment rooms in STN 73 0580-2 are based on experimental research and experience, the requirements in EN 17037 are mainly based on the requirements for artificial lighting.

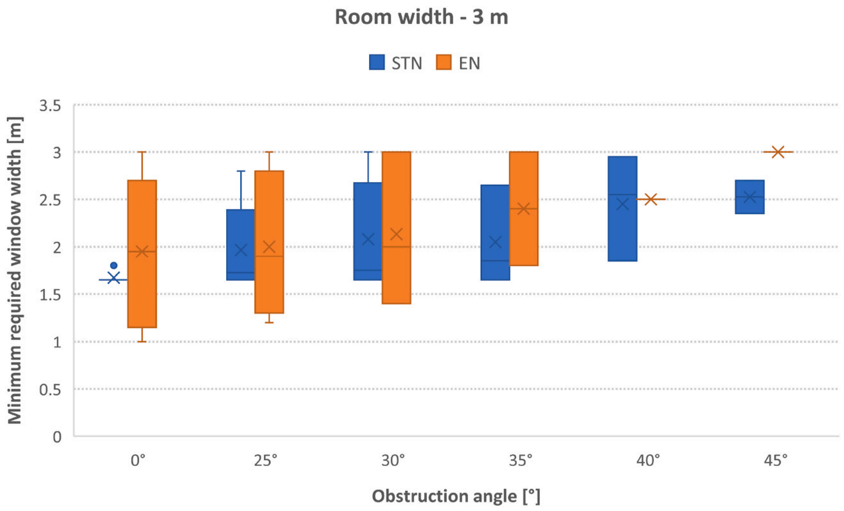

Fig. 4. Daylight simulation results of minimum required window, for room width (3.0 m) with window height (1.5 m).

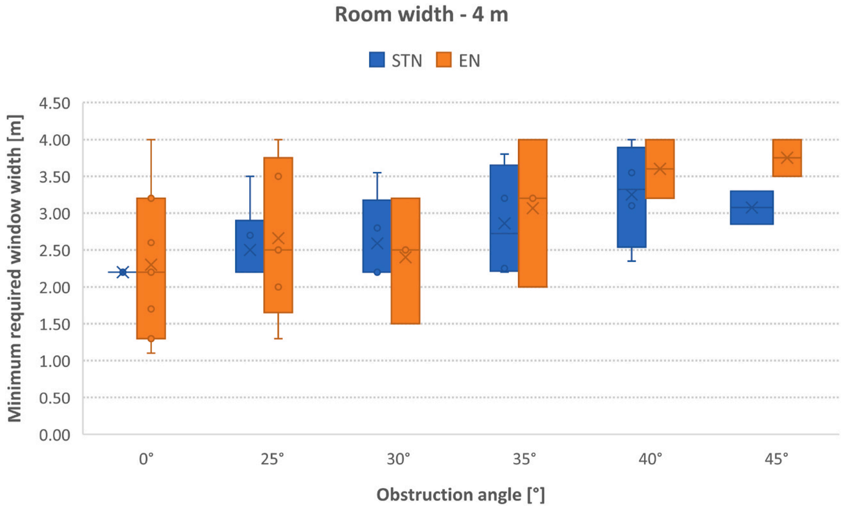

Fig. 5. Daylight simulation results of minimum required window, for room width (4.0 m) with window height (1.5 m).

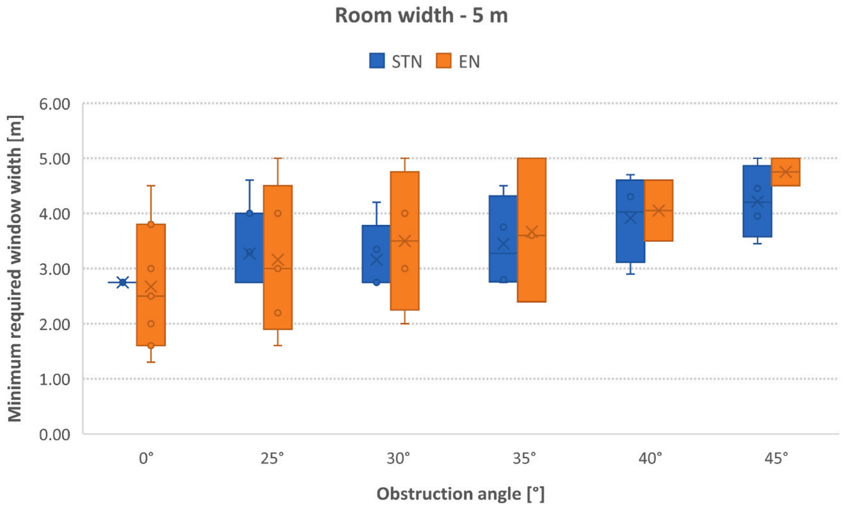

Fig. 6. Daylight simulation results of minimum required window width, for room width (5.0 m) with window height (1.5 m).

Residential rooms with different internal dimensions and various obstruction angles (shading in urban scale) require specific minimum window areas according to standards (EN or STN). The mutual comparison between these two standards (Table 5) reveals that rooms with lower depth could have smaller windows (approximately 10–50 % smaller in comparison with STN requirements) according to EN in situations with a low shading effect (OA $\leq$ 35°). However, in cases of (OA $\geq$ 35°), higher window areas are required (approximately 20–30 % higher in comparison with STN requirements). When the room depth increases, higher window areas are required according to EN in comparison with STN (**OA = 0**°, 6 m $\leq$ RD $\geq$ 4.5 m, up to 81.82 % higher WA; **OA = 25**°, 5 m $\leq$ RD $\geq$ 4 m, up to 66.67 % higher WA; **OA = 30**°, 4.5 m $\leq$ RD $\geq$ 3 m, up to 71.43 % higher WA; **OA = 35**°, 4 m $\leq$ RD $\geq$ 3 m, up to 62.19 % higher WA; **OA = 40**°, 4 m $\leq$ RD $\geq$ 3 m, up to 36.17 % higher WA; **OA = 45**°, 4 m $\leq$ RD $\geq$ 3 m, up to 30.43 % higher WA).

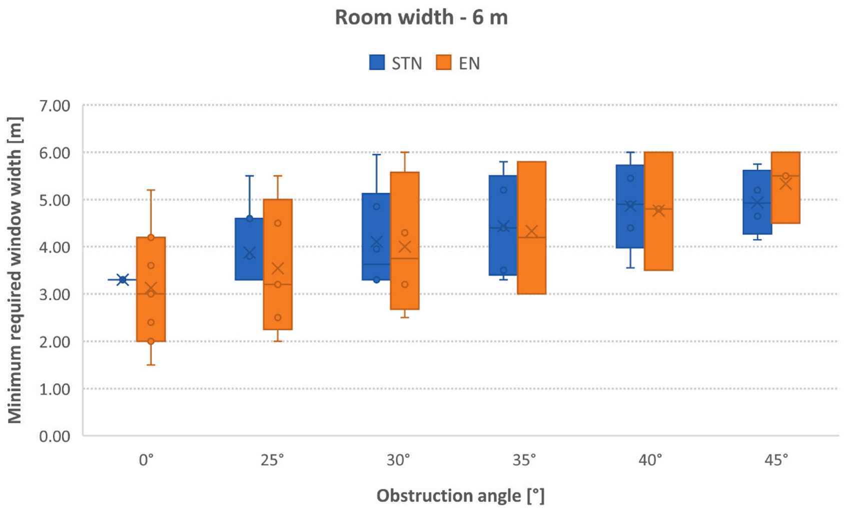

Fig. 7. Daylight simulation results of minimum required window width, for room width (6.0 m) with window height (1.5 m).

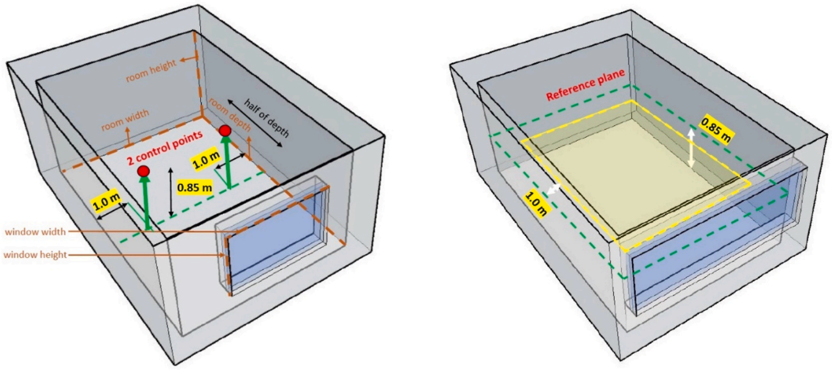

Fig. 8. Comparison of simulation models of living room in accordance with STN 73 0580-2 (left) and EN 17037 (right) requirements.

4.2. *Results for case study B: school classroom*

Simulation results revealed that for STN 73 0580-1 requirements, the height of the windows should be a minimum of 2.4 m, and for EN 17037 1.7 m (Fig. 9). Ferenčíková and Darula [71] stated that exterior diffuse horizontal illuminance $E_{v,d} > 7700$ lx occurs during 80 % of the teaching time in primary and secondary schools in Bratislava (Slovakia). Where DF = 1.5 %, this means an illumination of 115.5 lx, and where DF = 0.61 %, it is only 47 lx. The EN 17037 standard significantly reduces the requirements for daylight in classrooms for a significant number of pupils in the classical classroom compared to the former national standard. According to the requirements of EN 17037, the horizontal illuminance on school desks furthest from the windows on cloudy days at the level of 100 lx is only achieved for about half of the teaching time. The distribution of daylight on the reference plane according to the requirements of both standards is illustrated in Fig. 10.

Table 5

Percentage change of the STN required minimum window area (WA) within the requirements of the EN.

Obstruction angle (OA)	0°							25°						
Room depth (RD)	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**	**5.5 m**	**6 m**	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**	**5.5 m**	**6 m**
Room width (RW)														
3 m	−39.39	−27.27	3.03	33.33	57.58	81.82	*nE*	−27.27	−3.03	33.33	66.67	*nE*	*nE*	*nE/S*
4 m	−50.00	−40.91	−22.73	0.00	18.18	45.45	81.82	−40.91	−9.09	13.64	59.09	48.15	*nE*	*nE/S*
5 m	−52.73	−41.82	−27.27	−9.09	9.09	38.18	63.64	−41.82	−20.00	9.09	45.45	51.52	*nE*	*nE/S*
6 m	−54.55	−39.39	−27.27	−9.09	9.09	27.27	57.58	−39.39	−24.24	−3.03	36.36	44.74	*nE*	*nE*
Obstruction angle (OA)	**30°**							**35°**						
Room depth (RD)	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**	**5.5 m**	**6 m**	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**	**5.5 m**	**6 m**
Room width (RW)														
3 m	−15.15	21.21	71.43	*nE*	*nE*	*nE/S*	*nE/S*	9.09	62.16	*nE*	*nE/S*	*nE/S*	*nE/S*	*nE/S*
4 m	−31.82	13.64	45.45	*nE*	*nE*	*nE/S*	*nE/S*	−9.09	42.22	25.00	*nE*	*nE/S*	*nE/S*	*nE/S*
5 m	−27.27	9.09	45.45	49.25	*nE*	*nE/S*	*nE/S*	−12.73	28.57	33.33	*nE*	*nE/S*	*nE/S*	*nE/S*
6 m	−24.24	−3.03	30.30	51.90	*nE*	*nE*	*nE/S*	−9.09	20.00	31.82	*nE*	*nE*	*nE/S*	*nE/S*
Obstruction angle (OA)	**40°**							**45°**						
Room depth (RD)	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**	**5.5 m**	**6 m**	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**	**5.5 m**	**6 m**
Room width (RW)														
3 m	35.14	*nE*	*nE*	*nE/S*	*nE/S*	*nE/S*	*nE/S*	27.66	*nE*	*nE/S*	*nE/S*	*nE/S*	*nE/S*	*nE/S*
4 m	36.17	29.03	*nE*	*nE*	*nE/S*	*nE/S*	*nE/S*	22.81	21.21	*nE/S*	*nE/S*	*nE/S*	*nE/S*	*nE/S*
5 m	20.69	22.67	*nE*	*nE*	*nE/S*	*nE/S*	*nE/S*	30.43	26.58	*nE*	*nE*	*nE/S*	*nE/S*	*nE/S*
6 m	−1.41	9.09	22.45	*nE*	*nE*	*nE/S*	*nE/S*	8.43	18.28	15.38	*nE*	*nE/S*	*nE/S*	*nE/S*

*nE - not meet the conditions of the EN standard.

*nE/S - not meet the conditions of the EN and STN standard.

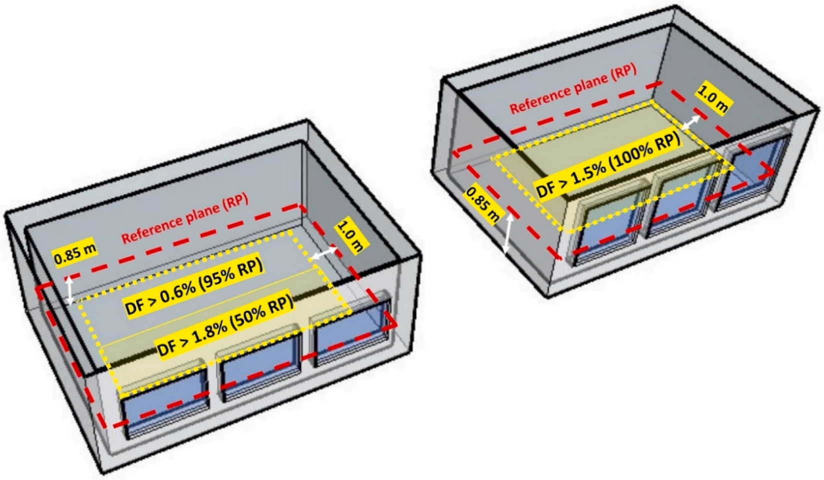

Fig. 9. Comparison of simulation models of school classroom in accordance to EN 17037 (left) and STN 73 0580-1 (right) requirements.

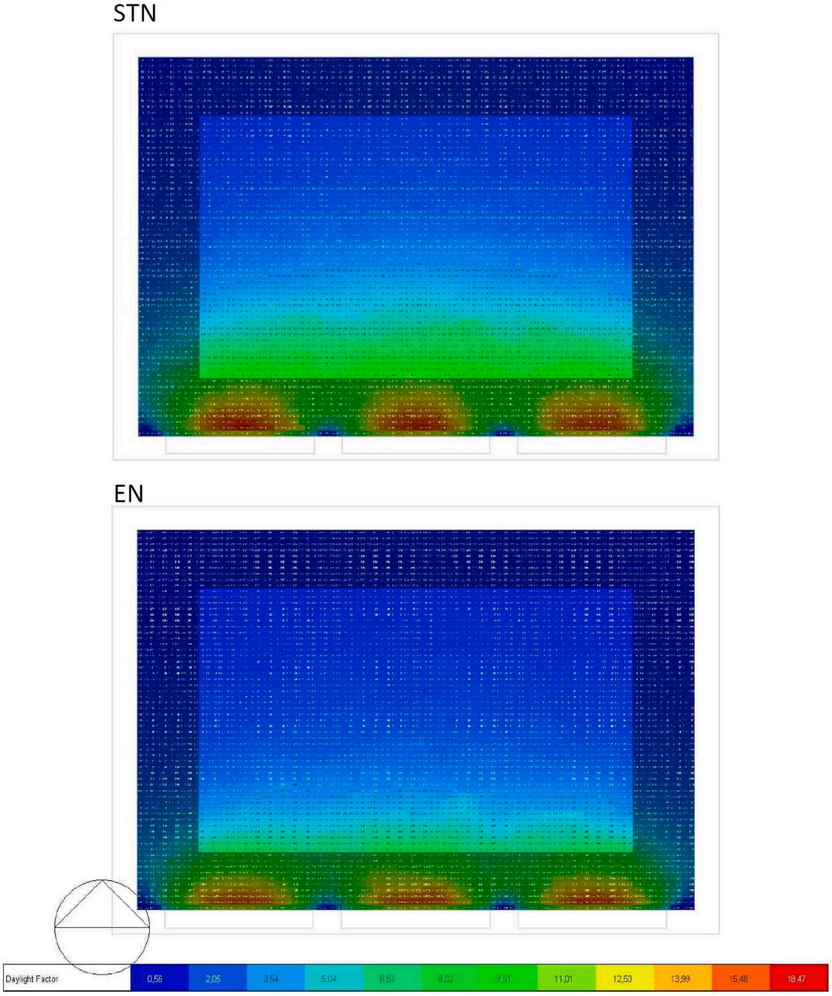

Fig. 10. Daylight distribution on the reference plane for STN 73 0580-2 requirements (up) and EN 17037 requirements (down).

5. Discussion

Year-round dynamic simulations of daylight in buildings can be considered a useful tool in the daylight design process. The introduction of dynamic simulations creates an apparent space to remove several limitations caused by the design of daylight according to the DF method. A specific practical problem is that dynamic simulations also introduce considerable "dynamism" into the way daylight is evaluated. The usability of direct sunlight for indoor lighting in the case of frequent and highly variable cloud cover, such as is typical in the Central European region, is strongly dependent on calculation assumptions, which, as a rule, do not sufficiently reflect the actual behavior of indoor occupants. Experience shows that user behavior causes significant differences between forecasts and the real use of daylight or solar energy in buildings. Despite the fact that current dynamic daylight simulations are more user-friendly, they still require highly qualified operators. It is problematic to integrate year-round simulations of daylight in buildings into the regulations, because they are ambiguous and cannot be readily verified.

The fundamental practical problem of EN 17037 lies in the uniform setting of minimum target daylight factors for all spaces that may be regularly occupied. The problem is that even the minimum daylight targets are set too ambitiously, especially for residential buildings. In the case of residential rooms, the criteria expressed by the target minimum median daylight factor in EN 17037 often cannot be achieved even with extremely large lighting openings. It is logical to ask whether the historical practice of designing the size of windows in dwelling rooms in many European countries, based on the DF method, was wrong and whether it was necessary to replace it with the new and insufficiently justified criteria of EN 17037.

This study has highlighted significant differences between the requirements and criteria of EN 17037 for daylight in apartments and classrooms and the criteria of national standards in several European countries. The acceptance of EN 17037 criteria for daylight in buildings has a significant impact on the design of buildings and the creation of urban structures.

In the case of daylight in apartments, several European countries have adopted DIN 5034 [67] criteria based on experimentally confirmed overall perception of side-lit residential spaces. At the same time, it was assumed that for more visually demanding work, there is enough daylight near the windows even during cloudy days. Darula and Kittler [51] analyzed the criteria of EN 17037 in residential buildings and stated that they cannot be achieved even in „normal“ external shading situations. As one of the possible solutions, the authors suggest "to reduce the reference plane which will be shorter in depth … ". Paradoxically, this "solution" does not contradict EN 17037, because in the standard the reference plane is defined as "a plane in a space on which illuminances and/or daylight factors are calculated, specified or measured". With such a universal "solution" and a suitable choice of the size of the reference plane, almost any proposal for the size of the windows can be brought into compliance with the EN 17037 criterion. However, it is also necessary to point out that EN 17037 also contains recommendations of daylight provision for fractions of a space. It is one of several inconsistencies to be found in the standard.

The compliance of daylight in residential spaces with several criteria was compared with respect to the geometric parameters of the rooms and the urban density [72]. The author notes the incompatibility of the vast majority of evaluated residential rooms in Sweden with the EN 17037 criterion. The conclusions of these studies confirm and support this study’s analyses. In the case of classrooms, the philosophy of Czech and Slovak standards [47,49] was based on hygienic (health) requirements for the availability of sufficient daylight for all students in the classroom. At the same time, it is necessary to meet the requirements for the performance of visual work, which are mainly performed in the relevant indoor environment. In the case of visual tasks associated with writing and reading, the standards for lateral daylighting require a DF value of at least 1.50 % at each workplace, i.e. at the school desks that are furthest from the windows. The EN 17037 standard significantly reduces the requirements for daylighting in classrooms compared to former national standards.

It can be expected that the noncommittal and arbitrarily set requirements of EN 17037 for daylight in buildings will be modified or simply ignored in several European countries. It primarily concerns the criteria for daylight provision in residential spaces. This process is already underway. In the British Standard version of EN 17037 (BS EN 17037, 2018) [73], a National Annex has been applied, in which lower target illuminance values are recommended for dwellings, or median daylight factors compared to the values specified in EN 17037. As part of the harmonization of EN 17037 with national standards on daylight in residential buildings, the unrealistically high requirements of EN 17037 for daylight in dwellings were not accepted in Germany (DIN 5034–1:2021–08) [49].

The primary goal of this study is to contribute to the international discussion on the advantages and disadvantages of EN 17037. We believe that even after the publication of EN 17037, there is still a wide range of opportunities for the development of daylight indicators in the European context, which will take into account current and future challenges. Point daylight factor is a pragmatic criterion for assessing the daylight illumination of buildings, which has been successfully used in many European countries for decades. The selected criteria guaranteed sufficient daylight in buildings even in overcast conditions. However, these criteria could only be met in cases of not very deep rooms and in not dense development. Currently, architecture must take into account increasing requirements for techno-economic utilization of buildings and densification of urban areas. In these conditions, the long-standing daylight factor criteria are often not achievable. The substantial increase in daylight metrics, which EN 17037 brought, is not the answer to the current challenges. In the search for "optimal" daylight metrics, the health benefits of daylight (both diffuse and direct) should be considered first and foremost. Energy, comfort, climate, culture, and other aspects should also be considered. One of the outputs of such research should be simple criteria that can be applied in local regulations.

6. Conclusions

The requirements for daylight provision in buildings should respect, on the one hand, the requirements of inhabitants and institutions concerned with public health and, on the other hand, the expectations of developers, municipalities, building planners, lighting and HVAC experts, and other consultants. The views of the wider building industry in individual countries should also be taken into consideration. Achieving a balance is a complex process, in which it is necessary to respect the uniqueness of individual situations. It is not appropriate to change the design of daylight in buildings by replacing simple evaluation methods and criteria based on empirical experience with optimization methods based on year-round dynamic simulations in a way "yes" to dynamic simulations and "no" to simplified methods. The selection of a design method should be conditioned by whether in a particular case it is sufficient to use a simple/simplified design procedure, or whether a specific solution for optimization is required for which it would be more appropriate to use a dynamic year-round simulation. The DF method makes it possible to determine relatively quickly the minimum requirements for ensuring daylight in a room and it is especially suitable in the early stage of design as it comprehensively takes into account the basic geometric and photometric design characteristics.

From the analysis of the historical development of the criteria and calculation methods for daylight in buildings and from the comparison of the calculation analyzes of several types of indoor spaces evaluated in terms of the DF and the minimum daylight target factor according to EN 17037, this study offers the following conclusions.

- The target median factors of daylight required in EN 17037 significantly change the relatively stable ways of urban and architectural planning of human settlements and various types of buildings and their interior spaces under several European climatic and cultural conditions.
- The minimum daylight target factor according to EN 17037 required for residential rooms is highly excessive (practically double) compared to the long-term historically-proven criteria used in many European countries. EN 17037 criteria can only be achieved for heavily glazed facades, even with little external obstruction and in shallow rooms. It is well known that the significant glazing of facades increases heat consumption for heating and leads to excessive summer overheating. The requirements of the EN 17037 can thus worsen the overall energy performance of buildings.
- The minimum target daylight factor according to EN 17037 for school classrooms is significantly lower compared to the requirements in Germany, Czech Republic and Slovakia and does not ensure enough daylight for all pupils in traditional types of classrooms.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Jozef Hraška: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jakub Čurpek:** Visualization, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

Symbol: Expression Unit

$E_{v,d,med}$	Median diffuse sky horizontal illuminance [lx]
E_T	Target illuminance [lx]
$E_{v,d}$	Exterior diffuse horizontal illuminance [lx]
D_T	Daylight factor [%]
D_{TM}	Minimum target daylight factor of DTM [%]

Abbreviations and subscripts

ADF	Average Daylight Factor
BS CP	British standard, Code of Practice
CBDM	Climate-Based Daylight Modeling
CIE	Commission Internationale de l'Éclairage
ČSN	Československá technická norma (Czechoslovak technical standard) or Česká technická norma (Czech technical standard)
DF	DIN Daylight Factor Deutsches Institut für Normung (German Institute for Standardization)
EN	European Standard (European Norm)

IES	Illuminating Engineering Society
nE	not meet the conditions of the EN standard
nE/S	not meet the conditions of the EN and STN standard
OA	Obstruction angle
RD	Room depth
RW	Room width
sDA	Spatial Daylight Autonomy
SF	Sky Factor
SP	Svod pravil (Code Practice)
WA	Window area

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