Methodology for Comparison of Building Daylighting Systems

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Abstract. The energy balance of buildings depends greatly on the type of external fencing, including translucent. The article presents a brief description of different types of daylighting systems that have different optical, geometric and thermal characteristics. The change in these characteristics affects the quality of lighting in the room, as well as determines the operating costs associated with losses and heat flows into the building through translucent fences. The task of comparing and choosing the optimal daylighting system should take into account all of the above factors. The authors propose a complex comparison criterion that takes into account thermal, optical, operational properties and capital costs. The structure of the proposed criterion allows you to add new indicators or remove irrelevant for a particular consumer comparison parameters. The method is composed and the calculated dependences for determining the numerical value of individual indicators included in the complex criterion are given. All parameters included in the proposed criterion have no dimension. This makes it possible to reduce the dependence of the calculations on changes in current energy prices.

1. Introduction

Daylight has an important hygienic significance for human life and activity [1]. The research results show that correctly organized lighting affects not only the productivity of labor, but also determines the psychological comfort of a person in the room [2].

There are many daylighting systems (DLS) that differ in its constructive, functional and energy parameters. In addition to traditional windows in buildings, top lighting systems in the form of light lanterns can be used; they can increase the uniformity of daylight and reduce energy consumption [3]. The group of reflecting devices in the form of light shelves has good heat-shielding and optical properties [4], but they require exact correspondence of the arrangement of the reflecting elements and the planning structure of the room.

Separately, a relatively new group of daylighting systems should be distinguished, namely, hollow tubular light guides, which allow the transmission of light over a distance of several floors [5, 6].

Each of the listed daylighting systems has its own advantages, disadvantages, and limitations on the possibility of their application in buildings of different purposes [7]. The great difference in the optical, operational and heat-shielding properties of existing daylighting systems explains the urgency of the problem of choosing its optimal design for a specific building [8-11].

A lot of research is devoted to assessing the economic efficiency of daylight applications, but at the same time energy characteristics are taken into account most often; they are associated with the use of cooling systems or artificial lighting of the building [12-18].

Some authors compare different daylighting systems with each other [19-21], but the results they
obtained represent particular cases of solving the problem of choosing the optimal design of the DLSs.

As a result of the review of scientific publications, it was revealed that there is no method for comparing different DLSs, taking into account its diverse characteristics (optical, heat-shielding, operational).

2. Description of the proposed criterion
The authors propose a complex criterion $\eta$ for comparing different daylighting systems, represented by the multiplication:

$$\eta = \eta_1 \eta_2 \eta_3 \eta_4,$$

where $\eta_1$ is the index of optical characteristics; $\eta_2$ is the index of heat-shielding characteristics; $\eta_3$ is the index of operational characteristics; $\eta_4$ is the index of capital costs.

One of the main characteristics is the ability of the DLS to transfer the daylight into the room. This ability depends on the material, location and design features of the DLS.

The index of optical characteristics is proposed to be determined from the dependence

$$\eta_1 = \eta_{1.1} \eta_{1.2},$$

where $\eta_{1.1}$ is the index of the light transmittance of transparent material; $\eta_{1.2}$ is the index of the light transfer in the distance;

The index of the light transmittance of transparent material $\eta_{1.1}$ depends on the type of glasses, their thickness, quantity, and the nature of the surface (roughness, regularity, contamination). The values of the index $\eta_{1.1}$ can be determined from the reference or normative literature, where it is called the light transmission coefficient.

The index of the light transfer in the distance $\eta_{1.2}$ is proposed to be determined from the dependence

$$\eta_{1.2} = \frac{E_{\text{int}}}{E_{\text{ext}}},$$

where $E_{\text{int}}$ is natural illumination inside the room at the output from the light-transmitting device, lx; $E_{\text{ext}}$ is natural illumination outside before the center of the light-transmitting fence, lx.

The index of the light transfer in the distance is an analog of the coefficient of daylight, differing from it by the locations of the points at which the illumination is determined. Because the design of DLSs is quite diverse, it is proposed to determine the stationary locations of the measuring points in accordance with the diagrams shown in figure 1. Numerical values of illumination $E_{\text{int}}$ and $E_{\text{ext}}$ can be determined by modeling or experimental evaluation of daylighting systems [8].

The index of heat-shielding characteristics $\eta_2$ is proposed to be determined from the dependence

$$\eta_2 = \eta_{2.1} \eta_{2.2},$$

where $\eta_{2.1}$ - the index of the heat entry through the DLS in summer; $\eta_{2.2}$ - the index of the heat loss through the DLS in winter;

Given the variety of existing DLSs that have different characteristics and sizes, it is proposed to use the algorithm shown in figure 2 to determine the coefficients $\eta_{2.1}$ and $\eta_{2.2}$. For each of the DLSs being compared, heat losses in the warm period of the year $q_{\text{WPY},i}$, W/m², and heat losses during the cold period of the year $q_{\text{CPY},i}$, W/m², are calculated. At the current stage of calculations it is proposed to use the existing calculation methods that take into account the design features of the translucent fence and the climatological characteristics of the terrain for which the calculation is carried out [20-22].

From the calculated values $q_{\text{WPY},i}$ (see figure 2, a) and $q_{\text{CPY},i}$ (see figure 2, b), the minimum values are chosen, which are subsequently used to obtain the dimensionless coefficients $\eta_{2.1}$ and $\eta_{2.2}$. The coefficient $\eta_{2.1}$, taking into account the amount of heat input from solar radiation, is found by the formula

$$\eta_{2.1} = \frac{q_{\text{WPY},i}^{\text{min}}}{q_{\text{WPY},i}},$$

where $q_{\text{WPY},i}$ is the unit value of heat entering through the DLS under consideration from solar radiation, W/m²; $q_{\text{WPY},i}^{\text{min}}$ is the minimum of the comparative unit values of heat entering through the DLS from solar radiation, W/m².
Figure 1. Schemes of location of the measurement points $E_{\text{int}}$ and $E_{\text{ext}}$: a – for the window; b – for the clerestory; c – for the hollow tubular light guides; d – for the lantern-superstructure ($E_{\text{ext}}$ is calculated as the arithmetic average $E'_{\text{ext}}$ and $E''_{\text{ext}}$); e – for the shed-light.

Figure 2. The algorithm for determining the coefficient $\eta_{2.1}$ that takes into account the heat entry through the DLS (a) and the coefficient $\eta_{2.2}$ that takes into account the heat loss through the DLS (b).

Accordingly, the coefficient $\eta_{2.2}$, taking into account heat losses through the enclosing structures, is found by the formula

$$\eta_{2.2} = \frac{q_{\text{CPY},j}}{q_{\text{CPY},i}}$$

where $q_{\text{CPY},i}$ is the unit value of heat losses through the enclosing structures of the considered DLS,
W/m²; \( q_{CPY,i}^{\text{min}} \) – is the minimum of the comparative unit values of heat losses through the enclosing structures, W/m².

The main function of the DLSs being compared is their ability to create a sufficient level of illumination. In the considered complex criterion, this function is proposed to be taken into account by the performance indicator \( \eta_3 \), determined by the formula

\[
\eta_3 = \eta_{3.1} \eta_{3.2},
\]

where \( \eta_{3.1} \) is an indicator that takes into account the decrease in the coefficient of daylight (CDL) during operation; \( \eta_{3.2} \) is an indicator of uniformity of illumination.

The parameter \( \eta_{3.1} \), which takes into account the decrease in the CDL during operation, is found from the dependence:

\[
\eta_{3.1} = \frac{1}{K_s},
\]

where \( K_s \) is the safety factor, which takes into account the decrease in illumination due to pollution and aging of translucent fillings in the light apertures, as well as a decrease in the reflecting properties of the surfaces of the room; accepted by SP 52.13330.2011 "Daylighting and artificial lighting", table 3.

The indicator of uniformity of illumination \( \eta_{3.2} \) is proposed to be calculated by the formula

\[
\eta_{3.2} = \frac{E_{\text{min}}}{E_{\text{max}}},
\]

where \( E_{\text{min}} \) is the lowest illumination on the working plane of the room, lx; \( E_{\text{max}} \) is the greatest illumination on the working plane of the room, lx.

An important factor in choosing the DLS is the cost of their device. To determine the index of capital costs \( \eta_4 \), it is proposed to use an algorithm similar to that shown in Figure 3.

First, for the compared daylighting systems, the unit costs \( K_{\text{un},i} \), rub./un.CDL, per unit of the coefficient of daylight, are calculated according to the formula.

\[
K_{\text{un}} = K_i / e_{pd},
\]

where \( K_i \) is the capital costs for the installation of daylighting system, rub.; \( e_{pd} \) is the calculated value of the coefficient of daylight.

From the calculated values of \( K_{\text{un}} \) the minimum value is chosen, with the use of which the index of capital costs \( \eta_4 \) is calculated by the formula

\[
\eta_4 = \frac{K_{\text{un}}^{\text{min}}}{K_{\text{un},i}},
\]

where \( K_{\text{un},i} \) is the unit costs for the device of the DLS under consideration, rub./un.CDL; \( K_{\text{un}}^{\text{min}} \) is the minimum of the compared unit costs for increasing the natural illumination of the room, rub./un.CDL.

It should be noted that all the indexes that make up the complex criterion (formula (1)) are dimensionless; their value does not exceed one. This structure of the criterion allows you to remove insignificant for a particular building indicators or add new ones, in accordance with the requirements of the customer.

3. The algorithm of application of the complex criterion

The proposed complex criterion can be used when choosing daylighting systems for both new design and reconstruction in order to increase the illumination of the room. The practical application of a complex criterion can be realized on the basis of the algorithm shown in figure 3.

At the initial stage, the initial data necessary for the development of design solutions for daylighting systems should be formed: the geometric dimensions and purpose of the room, the geographical coordinates of the construction area.

When forming the compared options, an important condition is the possibility of integrating the DS into the volumetric and planning structure of the building, and also the structural features of the outer fences should be taken into account. As a result of the formation of possible versions of the DSs, their geometric and structural characteristics and materials should be determined.
Next, the coefficient of daylight is calculated for the compared options in accordance with the approved methods of the set of rules SP 52.13330.2011 «Daylighting and artificial lighting» or other author's methodologies [5, 21, 23]. For further comparison, we choose such designs of daylighting systems that provide natural illumination of not less than the standardized value. In case, if there were no such variants, then it is necessary to adjust the sizes of the developed DSs or to consider other options.

Next, the complex criterion is calculated using formulas (1) - (11) and based on a comparison of the values obtained, the design of the daylighting system is selected.

4. Conclusion
The proposed complex criterion makes it possible to take into account the different characteristics of the comparable daylighting systems. The dimensionless form of the criterion allows you to add or remove some of the indexes. For example, instead of an index that takes into account capital costs, you can enter an index that takes into account the resulted costs. It is advisable in the case when a significant difference in the costs of maintenance of the compared versions of daylighting systems is assumed.

The advantage of the proposed complex criterion is the possibility of using various calculation methods that take into account the design features of light transmitting devices. It is also possible to use the results of calculations of individual characteristics obtained by other authors.

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