Optimization of Atrium Geometry in an Office Building in Terms of Daylighting - a Case Study

Agnes Iringova

Faculty of Civil Engineering, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovakia.

agnes.iringova@fstav.uniza.sk

Abstract. The importance of daylighting in the design of microclimate for work and living spaces. Legislation and legislative requirements for daylighting and combined lighting of workspaces in Slovakia. Theoretical analysis of physical determinants affecting the function, geometrical design, and location of atria in buildings in terms of optimizing the light comfort in work and relax spaces. Exterior atria and their dimensions considering the boundary conditions of the site. Optimizing atria geometry depending on its function and location in terms of daylight distribution. Influence of the atrium height and self-shading on the daylight distribution in workspaces. Daylight intensity and evenness in the offices with windows facing exterior atria - model solutions. Designing atrium geometry for an office building considering microclimate optimization and light comfort in spaces for work and relax in terms of safety and energy efficiency - a solution example.

1. Introduction

Sufficient daylighting of workspaces is one of the basic parameters creating an optimal microclimate. It affects not only visual comfort associated with a work task, but also the space perception in terms of safety. The intensity and even distribution of daylight has a major impact on the work comfort. Daylight is important for human health; it regulates the body's biorhythms, improves the immune system and supports function of internal organs.

The perception of colours and space in people working in spaces illuminated by daylight is not distorted. If workspaces have an optimal diffuse daylight, workers are more creative and less tired, compared to those working in spaces with low daylight intensity. The sufficient daylight distribution is also important from economic point of view. Optimally designed daylighting of workspaces can significantly reduce the cost of artificial lighting installed as an addition to daylighting. It is good to ensure the diffuse daylight distribution in public, circulating, and relax spaces in terms of movement safety and optimal energy performance of a building.

The possibility to ensure the daylight distribution in workspaces situated in densely built-up urban zones is to design buildings containing exterior or interior atria. Their geometry is primarily dependent on the boundary conditions of the site, volume solution of planned buildings as well as functional use of illuminated spaces. The proper geometry and position of atria help optimize daylighting of workspaces. Incorporating the internal atria into the building's plan can optimize the diffuse daylight distribution in circulating or relax spaces, meeting rooms, and even in offices with glazed walls facing an atrium. The design and location of internal atria is generally optimized to increase the safety of workers in circulated spaces and to reduce the economic cost of artificial lighting.
The paper analyses the architectural solution of the atrium geometry in dependence on the boundary conditions and its primary function related to the use of designed spaces in terms of natural light distribution in model solutions.

2. Legislation and requirements for daylighting and combined lighting of workspaces in Slovakia

Daylighting in buildings is commonly designed and evaluated using the daylight factor criterion that is also required by Slovak Standard STN 73 0580.

According to Act No. 355/2007 Coll., the employer is obliged to provide sufficient illumination of permanent workplaces. The workspaces that require combined lighting, or those without daylighting may operate only if daylighting cannot be provided due to the technical, safety or operational reasons. In such spaces, the employer is obliged to ensure the protection of employees’ health by the alternative measures specified in regulation of Act 355/2007. According to STN EN 12464-1 Light and Lighting: Lighting of workplaces: Part 1: Indoor workplaces: daylighting of the space or its defined parts with people’s stay is to be provided in the network of points on a given plane.

Computational models use overcast sky (CIE 1:3) condition to verify the sufficient amount of daylight on a given plane. It is an ideal model for project practice in terms of dimensioning room geometry and window size. The brightness level of such sky does not depend on the azimuthal direction; it rises evenly from horizon to zenith. [6]

If designing window sizes, it does not matter their orientation to the cardinal points. The conditions for visual comfort must be maintained under the all conditions of the light climate. [4] The solution uses the minimum principle and the following prediction is considered: if the the room meets required hygiene minimum, it also meets all other boundary conditions for illumination during the year.

Daylighting is evaluated from the view of:

- daylighting level, using daylight factor $D$
- illumination evenness,
- luminous flux distribution
- dazzling.

The design value of daylight factor $D$ for a particular visual activity in the room with side illumination must be higher than the minimal $D$ value required $D \geq D_{\text{min}}$ or, the average $D$ value in the room with above illumination must be higher than it is required in the standard $D \geq D_{\text{m}}$.

In accordance with the criteria given in Appendix 1, Directive No.541/2007 Coll. and its amendments 206/2011, the minimum allowable $D$ values required for indoor workplaces or their defined parts with long-term stay of employees are as follows:

a/ with side illumination, $D_{\text{min}} = 1.5\%$;
b/ with above and combined illumination, $D_{\text{min}} = 1.5\%$ and $D_{\text{m}} = 3\%$;

where:
- $D_{\text{min}}$ - the minimal $D$ value on the given plane [%],
- $D_{\text{m}}$ - the mean $D$ value on the given plane [%]. [3]

If this requirement is met, it is assumed that the space is illuminated enough to have a positive effect on employees as well as on their visual contact with the outdoor environment. If the workplaces need to be illuminated better due to distinguishing details, artificial lighting is added, but it is not considered as combined lighting. The detailed solution (illumination evenness, protection against insolation, etc.), is specified in STN 73 0580-1 Daylighting in Buildings, making this standard mandatory. [4]

If the amount of external shading by existing buildings is high, it is not always possible to enlarge the window area in newly designed or renovated buildings in such a way that they would meet the criteria for sufficient daylighting in planned workspaces. In these cases, combined lighting can be
installed and used in interiors or in their defined parts that have $D$ values lower than required and at the same time reach at least 1/3 of these values. The mean $D$ value in spaces with permanent stay of people must be at least 1% and the minimum $D$ value must be 0.5%, if higher $D$ values are not required. The mean $D$ value of 1% must be met in the spaces with side illumination. The minimum value of the artificial component intensity in combined lighting is dependent on the visual activity class and its value is 500 Lx. Combined lighting of a workplace is designed so that the brightness ratio in the visual field would not be exceeded, as given in Table 1. [2]

| Visual activity class | Brightness ratio of the observed object to the lighting hole |
|-----------------------|-------------------------------------------------------------|
| I, II, III            | 1 : 40                                                      |
| IV                    | 1 : 100                                                     |
| V, VI, VII            | not defined                                                 |

Table 1. The maximum allowable brightness ratio of the observed object to the lighting hole located up to 60° away from the common view direction.

If the brightness of the lighting holes up to 60° away from the common view direction is higher than 4000 cd.m-2, it is limited by a suitable control device (e.g., blinds, rollers shutters, curtains). Combined lighting of a workplace is designed as unified system taking into account direction, shading, dazzling protection, brightness contrasts in the visual field and other requirements specified in technical standards: STN 73 0580-1 Daylighting in Buildings, Part 1: Essential requirements; STN EN 12464-1 Light and Lighting, Lighting of workplace : Part 1: Indoor workplaces. [2] If the mean or minimum $D$ does not reach the set values, the room or its part is classified as space without daylighting and artificial lighting is added. Permanent workplaces must not be located in such spaces.

3. Theoretical analysis of physical determinants for the volume design and ground plan of the building in confined urban spaces

The geometry design of the building’s ground plan is based on a typological solution depending on the function required for the operations, boundary conditions on the site, and specific investor’s requirements. The main limit in designing building’s volume and geometry is often the high amount of shading by surrounding building. The position of open-air atriums on the facade or inside the building is affected by the area and location in existing urbanism. There is a tendency to utilize the area as maximally as possible, especially in confined spaces or on expensive sites in central urban zones, see the model solution.

The evaluation criterion is the daylight factor $D$ [%] expressing the ratio of interior illumination $E$ in a given point on a given plane (usually the workplane) 0.85 m above the floor to the exterior illumination $Eh$ under the same sky conditions:

$$D = \frac{E}{Eh} \% \ [2]$$

where:

- $E$ - interior illumination of a given point on a given plane,
- $Eh$ - exterior illumination of a similar given point on an unshaded given plane.

The possibility to eliminate the unfavourable urban condition in the building design is to incorporate an atrium into the ground plan. This will enlarge the area of a building envelope and ensure the daylight illumination availability through the windows. Atria can be classified as exterior or interior, depending on their position in a building. If a building is situated in confined urban spaces, combined atria are often used in the design, see Figure. 2.
Exterior atria are situated in front of the building facade considering the ground plan geometry. Atria can be built in different sizes and shapes, from regular rectangles to polygons. They can be open-air, partly enclosed, or completely enclosed with glazed wall and glazed roof. The shapes and variants are conditioned by their primary function.

Exterior open-air atria situated in front of the facade (Figure 1a) enlarge the facade area and distribute daylight to the planned spaces. In case of multifunctional buildings, containing flats and requiring the minimum insolation time in living spaces, the diffuse daylight and direct sunlight availability can be provided by the rotation of atrium side wings.

Exterior partly enclosed atria containing only the vertical glass wall (Figure 1b) are built in the areas with high noise emission in front of the facade. They act as acoustic barrier creating airy, naturally ventilated interspace without increasing the need for acoustic window insulation. Designing such atria in buildings can optimize investments, operational costs and eliminate noise in workspaces.

If facade atria are completely enclosed by transparent panels, they create a space absorbing noise and optimize the building’s thermal protection and energy efficiency. The solution example of the external atrium geometry in the built-up area in terms of building’s thermal protection optimization is shown in Figure 1c.

![Figure 1](image)

**Figure 1.** Geometry optimization of exterior atria in the built-up area in terms of:

a - daylight distribution and insolation of the planned spaces; b - noise elimination; c - thermal loss elimination and energy balance optimization.

The possibility to provide daylight distribution in spaces without side illumination is to incorporate the internal atrium into the building’s ground plan. In such cases, the daylight distribution in adjacent atrium spaces is ensured through the atrium roof by secondary reflections from surfaces in the light propagation path. The atrium can be illuminated from above using a large-area skylight, or a set of light guides. The internal atria are situated inside the layout and their primary function is to supply daylight to the unlighted spaces. Atria can be regular, irregular, circular, elliptical, etc. Their geometric shape is directly dependent on the illuminated space and its function. They have usually transparent roofing.

### 4. Impact of the atrium height and self-shading on the daylight distribution in workspaces

The efficiency of atria in terms of daylight distribution is directly dependent on their height, roof glazing area and its optical quality. This upper lighting system usually ensures sufficient daylight transfer to the spaces below and partly to the spaces linking-up the glazed or open-air atrium part.

Their geometry depends on functional requirements; whether they will provide illumination of permanent workplaces or circulating spaces without permanent stay of people. The area and height requirements for the former one are conditioned by workspace positions; the latter one can be smaller and has the light guide features.

The distance of the adjacent spaces with the daylight intensity required for permanent stay of people depends on the number of floors the atrium is passing through. It is important for permanent workplaces to contain glazed walls linking-up the glazed roof of an atrium. Their daylight distribution efficiency is very low in terms of self-shading by the building’s geometry.
Interior atria are the ideal solution to eliminate using artificial lighting in circulating spaces such as corridors, galleries, back porches, restaurants, relax spaces in winter gardens, meeting rooms and other service spaces that do not contain permanent workplaces. In addition to the architectural and artistic effect, they have a major impact on the lighting of adjacent spaces and the energy efficiency of the building. Designed schemes contain atria 21m high, i.e. all interior atria are situated into the space considering this fact. If designed optimally, they can significantly reduce energy costs of artificial lighting in the circulating spaces.

5. Model solution

The solution is focused on optimization the geometry design of the office building in terms of maximal usability of the useful area suitably illuminated by daylight. It uses exterior facade atria for the model solution of a building situated in the medium shaded area.

The first step optimizes the building’s volume and shape in relation to the surrounding buildings. The analysis compares three versions of a ground plan for a building having the same roof attic height. Their geometry is optimized considering daylighting in the planned workspaces.

The daylighting intensity on the comparative plane for particular boundary conditions is defined using simulations in WLDS 5.0 computer programme; see Figs 4 and 5 showing the schematic ground plans. The solutions are then compared in terms of operational and economic efficiency in relation to daylight illumination availability in the workplaces.

The calculation considered 6 m deep offices with a clear height of 2.7 m. Daylighting in the building is ensured through the side windows 1.8 m high with a 0.9 m windowsill. The average surface factor of the offices was considered 0.5. The resulting light transmittance coefficient through the windows is considered 0.5.

The model solution focuses on setting the building in a gap site. The site is triangular with one side parallel to a high-frequency road. The area has a medium amount of external shading and high noise emission. The site is currently used for parking; see Figure 3.
6. Building’s shape and exterior atria design in terms of daylighting optimization in offices
The site shape and given boundary conditions essentially determine the building’s geometry, see Figs. 2-4. The ground plans of model buildings are adapted to the shape of the site.

- **Version 1** works with the T-shaped building’s ground plan containing the interior atrium with transparent roofing.

- **Version 2** works with the E-shaped building’s ground plan whose side wings are positioned to shade each other minimally. The facade contains two open-air atriums facing the street; as the calculation of daylighting considers.

- **Version 3** works with the V-shaped building’s ground plan whose side wings are positioned to shade each other minimally. The facade contains an open-air atrium facing the street.

7. Daylight intensity and evenness in offices with windows facing exterior atria - model solutions
7.1 Version 1 The building’s ground plan is designed as an irregular rectangle inserted into the triangle of the site. It contains an interior atrium with vertical circulating spaces. The atrium is a rectangle of 25m x 14m. Suitable daylight illumination availability is ensured through the transparent atrium’s roofing and combined illumination of workplaces on the last two floors, see Figure. 4. The analysis considers continuous strip windows 1.8 m high with 0.9 m windowsill. The clear height of offices is 2.7m. The resulting light transmittance coefficient through the window is considered 0.55%, the average light reflectance factor of the office surfaces is considered 0.475.

7.1.1 Daylight illumination availability on the 1st floor Only the perimeter offices 2.9 - 5m deep have the satisfactory daylight illumination factor D [%]; its value depends on the external shading. In
principle, all offices meet the criteria for installation of combined lighting; the rest of the space has $D$ lower than 1.5%, see Figure 5.

The daylighting simulation in version 1 containing glazed walls facing only the interior open-air atrium indicates that the minimum $D$ value in adjacent offices meets the requirements for situating permanent workplaces in the visual activity class IV about 1.5m away from the window wall. The zone suitable for using combined lighting in these offices is up to 2.2 m deep.

![Figure 5. Version 1 - Daylighting intensity in the 1st floor schematic ground plan. [7]](image)

### 7.2 Version 2

The building’s ground plan is designed as the E-shaped irregular polygon inserted into the triangle of the site. It is optimized to create the largest possible facade area so that windows could be situated around the perimeter. The building’s side wings are positioned at 37° angle from a building line. The inner wing is positioned at 74° angle from the building line. The declination is optimized to minimize the self-shading of the office by side wings. The spaces between the side wings create open-air interior atria; see Figure 6. The analysis considers continuous strip windows 1.8 m high with 0.9 m windowsill. The clear height of offices is 2.7m. The resulting light transmittance coefficient through the window is considered 0.55%; the average light reflectance factor of the office surfaces is considered 0.475.

![Figure 6. Version 2 - The building’s position in relation to surrounding buildings](image)

### 7.2.1 Daylight illumination availability on the 1st floor

The perimeter offices that are not self-shaded have the satisfactory daylight illumination factor $D$ [%]. The offices facing the street that are partly self-shaded have the sufficiently daylight illuminated zone 3.0 - 4.5m deep; the $D$ value depends on the external shading. In principle, all offices meet the criteria for installation of combined lighting; the rest of the space has $D$ lower than 1.5%, see Fig. 7.
Figure 7. Version 2 - Daylighting intensity in the 1st floor schematic ground plan [7]

7.3 Version 3
The building has the V-shaped ground plan inserted into the triangle of the site. It is designed to create the largest possible facade area so that perimeter offices could be illuminated by direct daylight. The building’s left side wing is positioned at 36° angle from a building line. The wing declination is optimized to minimize the self-shading of the offices. The space between the side wings creates an open-air exterior atrium, see Fig. 8. The analysis considers continuous strip windows 1.8 m high with 0.9 m windowsill. The clear height of offices is 2.7m. The resulting light transmittance coefficient through the window is considered 0.55%, the average light reflectance factor of the office surfaces is considered 0.475.

Figure 8. Version 3 - The building’s position in relation to surrounding buildings

7.3.1 Daylight illumination availability on the 1st floor
Only the perimeter offices 3.6 - 5m deep have the satisfactory daylight illumination factor $D$ [%]; its value depends on the external shading. In principle, all offices meet the criteria for installation of combined lighting; the rest of the space has $D$ lower than 1.5%, see Figure 9.
8. Comparison of designed ground plan versions in terms of the office areas suitably illuminated by daylight

The design of ground plans in particular versions was focused on creating the most usable area for situating workplaces with sufficient daylighting or combined lighting. The utilization parameters are given in Table 2.

Table 2. Comparison of building’s geometry considering the usability of area suitably illuminated by daylight.

| Version | Built-up area (BA) [m²] | Useful area on the 1st floor with sufficient daylighting or combined lighting (UA) [m²] | Window wall perimeter [m²] | Ratio BA/UA |
|---------|-------------------------|--------------------------------------------------------------------------------|---------------------------|------------|
| 1       | 2480                    | 8502                                                                              | 311                       | 3.4        |
| 2       | 2446                    | 10773                                                                             | 303                       | 4.4        |
| 3       | 2877                    | 12404                                                                             | 324                       | 4.3        |

9. Conclusion

As shown in version 1 of the model building’s solution, the area of spatial usability in terms of situating workplaces sufficiently illuminated by daylight is the smallest. The efficiency of the interior atrium is limited in terms of daylight illumination availability in its perimeter inner spaces. Only about 1/3 of the office depth can be used for situating permanent workplaces. The efficiency of atrium in terms of daylight distribution is limited by the position of the illumination vertical system adjacent to the atrium glazing and by the optical quality of glazing. This case considered the open-air atrium without roofing. If the glazed office wall is more than 2.5 - 3m away from the glazed roof edge, only public circulating space is sufficiently illuminated by daylight. The corridors more than 4m deep meet the required D value for visual activity class V and VI (handling objects, eating food, waiting room, walking in unknown space).

In addition to light comfort, the light distribution through the atrium is important in terms of safe movement of people in circulating spaces. It offers the possibility to make the space more pleasant by greeneries. The given solution is budged wise in terms of building’s energy efficiency, operational cost of artificial lighting, and optimizing the thermo-insulated roof glazing. Versions 2 and 3 offer optimum solutions in terms of area utilization for situating workplaces. More than 70% of the area is sufficiently illuminated by daylight; the rest meets the criteria for installation of combined lighting. It follows that the optimum building's ground plan geometry can ensure a high-quality work environment even in more shaded urban zones.
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