Optimization of the Building in Relation to the Insolation Conditions of Premises in Adjacent Buildings

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When designing buildings in dense city centers, a very important step is to study the nearest surroundings of the plot, in order to enable the best possible placement of the building. Many aspects must be taken into account including urban, legislative, environmental and aesthetic factors. These factors, in particular the legislative ones, depend on local conditions. This article describes a methodology for the analysis of insolation of surrounding buildings in the context of local building regulations. A procedure is described that significantly accelerates this phase of the design process and permits integrating it with an optimization process concerning the location of the building on the plot. Examples of application of that procedure are presented and their limitations and capabilities are discussed.

Keywords: optimization, genetic algorithm, insolation, raytracing, sunlight analysis

INTRODUCTION

During the design process of buildings in dense city centers, a very important step is to study the nearest surroundings of the plot to permit the best integration of the building into its location. There are many aspects of the context that need to be taken into account and carefully analyzed, such as urban, legislative, environmental and aesthetic factors. These factors, in particular the legislative ones, depend strongly on local conditions and specific regulations.

The following study was carried out in the downtown of Warsaw, near the central station. In this area of the city there are buildings diversified in terms of height and function, there is a lot of high-rise office buildings, as well as tenement houses or apartment buildings. Discussed plot is not covered by any local spatial development plan, therefore the form of its development will depend on the received building conditions. This document is issued on request for the specific plot on the basis of an attached design proposal together with a description of its characteristics, such as the supply of utilities, the size and use of the buildings and plot development specificity.

The subjected plot of land has an area of 11,000 square meters and has been intended for office development. Because of its large surface area and diverse architectural and urban context, the manner of its development may differ greatly, depending on the vision of the architect and specific conditions resulting from the analysis of the context. One of the regulations that may significantly affect the possibility of
the plot development in dense city centers is the provision on the insolation of apartments. The planned investment cannot significantly reduce the quality of life of other users of the city. The analysis of the impact of the planned investment on the environment is an important step of its planning process.

**Local Building Regulations: Insolation**

According to the Minister of Infrastructure Regulation on the technical conditions to be met by buildings and their location guidelines on lighting, insolation and occlusion of windows are specified. In this article only aspects related to insolation of premises are discussed and the process of their analysis is developed in detail.

In the above-mentioned provisions, the issue of insolation of premises is expressed in the number of hours for which each window should be illuminated. Those provisions concern only apartment buildings, schools, kindergartens and nurseries. The insolation time shall not be less than 3 hours, measured on the spring and autumn equinoxes, between 8 am and 4 pm for buildings of educational and care functions and between 7 am and 5 pm for apartment buildings.

In a multi-room apartment it is allowed to limit the requirements, referred to above, to at least one room. In complementary buildings located in downtown areas it is permitted to limit the time of required insolation to 1.5 hours, and with regard to the one-room apartments in such location the required insolation time is not specified.

Described regulations should be met for all windows, which insolation conditions are subject to change after construction of a new building. Depending on the scale of the planned investment, the scope of insolation analyzes can vary greatly and the number of windows requiring analysis can reach hundreds.

**Sundial Method**

Currently, the method most commonly used in Poland for insolation analysis of windows was proposed and disseminated by Mieczyslaw Twarowski (1996). This method involves using a kind of horizontal sundial designated for the moment of equinox. It illustrates the lengths and angles of the shadow cast on the full hours of local solar time by a bar with a nominal height and its multiples. This tool, printed on tracing paper, as it was inserted in the book "Sun in Architecture", is used by superimposing it on the analyzed building plan with the surrounding buildings drawn to scale.

The sundial can be determined for certain location, but usually it was drawn for each city only once and it was not taking into account differences in locations within the whole area of the city (Figure 1). The resulted in the need for some amendments for each analyzed location or taking large safety margins (Lose 2015). In densely built-up locations it is not always possible to accept ranges of safety beyond the minimum required insolation duration, specified in regulations. For this reason it is necessary to apply tools that enable to conduct precise insolation analysis through the use of computer models.

**Digital Insolation Analysis Methods**

On the market there is a number of software for automated analysis of lighting conditions. These programs include Google SketchUp with a Shadow Analysis plugin, Autodesk Revit, Rhinoceros 3d with its graphical algorithm editor Grasshopper and additional plugins for weather and energy analysis, such as Ladybug and Honeybee that connects it with Ener-
gyPlus, Radiance, Daysim and OpenStudio software. Listed computer programs enable precise determination of sunlight vectors on a given date and time, but does not give the possibility to check whether a particular window or apartment meets the conditions described in the building regulations, mentioned above. In order to verify whether a window is provided with the right amount of light, a method for counting the time in which this window is illuminated needs to be established.

There is also a software dedicated to this type of analysis of local lighting regulations. PRC Analysis created by Jacek Markusiewicz (2014) enables the analysis of windows and whole apartments for compliance with the local laws of insolation and occlusion. After a preliminary analysis it allows to trim the initial body of the building so that all of the windows comply with the regulations. It allows to determine a Maximum Building Volume (MBV), but the calculation that includes all of the potentially affected windows is very time consuming and involves preliminary windows selection in order to permit the software to determine the solution (Figure 2). Because of this it is necessary to conduct a series of preliminary analysis using other software (Kwiecinski and Pasternak 2016).

Repeated changing of software during the design process is cumbersome (Pasternak and Kwiecinski 2015), therefore a new analysis procedure was created in the software that was used for the initial analysis and determination of the MBV in the PRC Analysis. It allows to reduce the need to move from one program to another and at the same time overcome its the limitations in terms of possible amount of analyzed windows.

The creation of this procedure in a parametric environment allows also to create a wide variety of detailed optimization procedures depending on the needs of particular location and the configuration of analyzed windows. For example, for a small plot with a permitted high allowable building area, it may be justified to create a single maximum building volume. For a large plot, which enables typologically diverse development, the optimized form will look differently, depending on the input form and selected typology.

**METHODOLOGY**
Within the framework of the developed method of insolation analysis of premises in adjacent buildings, three stages can be distinguished:

- Initial analysis of insolation of windows in the existing state;
- Analysis of the impact of the proposed form on the surrounding buildings;
- Determination of a Maximum Building Volume or conduct of a custom optimization procedure.

**Insolation analysis**
The first step of this process is to prepare a three-dimensional model of the building surrounding, which includes the whole impact area of the proposed building form. The upper dimensions of the building should be established in order to check how far the shadow of the building during the spring and autumn equinoxes reach (Figure 3), because it will...
determine the windows which insolation conditions are potentially a subject to change.

The next step is to determine which windows belong to apartments or care and education institutions, because their lighting conditions are particularly described in local building regulations. Other windows are not evaluated in this procedure. It is only necessary to model the surrounding buildings to take into account their impact on the lighting conditions that are subject to evaluation (Figure 4).

To satisfy the requirements of building regulations sufficiently, but not restrict the building capabilities of the plot too much, it is necessary to precisely establish the analysis outlines. Since the building regulations specify that the insolation requirements depend on the size of the apartment, it is necessary to discernment which windows belong to which apartment and group them accordingly. In multi-room apartments it is sufficient to meet the requirements for only one room and one-room apartments do not have to meet them at all. For this reason, it is necessary to determine an internal functional arrangement of residential buildings located within the building’s impact zone.

Because the regulations do not clarify to which extent the windows should be illuminated, there is a large scope for interpretation of these provisions. It can be assumed that illumination should be provided on the entire plane of the window or only on its selected points or edges. Depending upon which interpretation is accepted, it is possible to get completely different boundary conditions for the process of optimization and hence, obtain different results of possible spatial building form.

The procedure was created in a parametric environment. Energy Plus weather data file is used to determine the direction of sun rays for the analyzed time periods. The intersections of sun rays with building blocks are checked. Rays illuminating the window are grouped into two to create time intervals. Depending the adopted accuracy of the calculations, they can amount to a minute or more. The number of intervals is counted and compared with the value of the required insolation time specified in the regulation.

At first the number of intervals are calculated for the current state, having regard to the existing buildings, but without taking into consideration the planned building. This allows to determine whether the windows are properly illuminated, before it is checked how the new building is affecting their conditions. If the windows are not correctly exposed they cannot be shaded any more. These windows designate certain surfaces, which the new building cannot exceed in no case.

In the second step, the same windows are checked again, but this time taking into account the proposed building. The intersections of rays, that until now were not obstructed by any building, are checked if they intersect with the new building volume. The windows, that were previously correctly illuminated are checked whether their sun exposure is not deteriorated to an incorrect level. If it is true, they will be included in the optimization procedure as boundary conditions.

The procedure allows to increase the accuracy of window analysis by adding more control points to the line located on the sill level on the inner face of the wall. Depending on the computational capabilities, it is possible to analyze only the center point of each line or include additional points such as end points and additional points between these.

The result of the insolation analysis process is the division of windows into three groups:

- Group 1 - windows that have correct insolation level and are not influenced by the designed building;
- Group 2 - windows that are insufficiently illuminated in the current state, without taking into account the designed building. There shall be no sun rays obscured by its volume. These windows define surfaces that shall to be exceeded by the designed building;
- Group 3 - windows that were correctly illuminated in the current state and the designed building affects their level of insolation. Sun rays obscured by the new buildings are involved in the optimization procedure.

**Maximum Building Volume**

The procedure allows the determination of a Maximum Building Volume. The outline of the plot extruded to a maximum height is trimmed so as to meet the insolation regulations of premises in adjacent buildings. This procedure takes place in two stages. For windows belonging to Group 2, all of the extruded sun rays blocked by the new building are subtracted from the volume (Figure 5).

In the next step sun rays, which are needed for a minimum illumination of the windows from the Group 3, are selected in such a way that the volume subtracted from the input form is minimized (Figure 6).

This procedure for determining the MBV is deterministic, because its objective is to obtain the largest possible volume. From the initial form the smallest total volume designated by extruded sun rays is subtracted. It does not allow, however, to control which parts of the form are more valuable then other and protect them from being deleted. For the designer it is crucial to be able to control the shape and location of the building at every stage of the design process and at the same time meet all the requirements arising from the context and regulations. The ability to use the described analytical method as part of the form finding process with the use of the optimization procedure gives the designer more freedom to shape the form and still meet the legal requirements.

**Optimization procedures**

Another possibility is to develop a bottom up approach, which will aim at finding the right configuration of building volumes and their locations as a result of an optimization process. The objective is that the proposed forms are not worsening the insolation conditions of any windows below the legally acceptable level. The final form depends on the configuration of input parameters and their ranges. Optimization procedures are prepared with the use of genetic algorithms.

**RESULTS**

As an example of the principles of the proposed method, a plot located in the center of Warsaw was selected. In the impact area of the designed building there are located eighteen residential buildings with the total number of windows of 1587. These windows belong to all types of apartments and communication spaces. One-room apartments should be omitted and from multi-room apartments only one room, which is to meet the conditions set out in the regulations, should be selected.

The optimization procedure is designed in such a way that in order to illuminate a particular window in the corresponding period of time, the entire obscuring volume is cut above the plane of the sun ray incident on the windowsill of analyzed window. Therefore it is only necessary to analyze the windows located at the lower floors of the buildings, assuming that the functional layout is the same on each floor. If some floor has a different functional arrangement or other internal division of apartments, then these windows should also be included in the analysis.

After removal of the windows that are not re-
quired in the analysis, the remaining 107 windows, were analyzed in detail in terms of meeting the insolation conditions. For parcels located in downtown areas required insolation time amounts to 1.5 hours.

The insolation analysis shows that there are 53 windows that are properly illuminated in the present state and after the construction of a new building located anywhere on the plot (windows belonging to the Group 1). Their insolation level does not fall below the required minimum specified in the regulation for any newly designed form.

There are 27 windows belonging to Group 2. These are the windows which level of insolation is not currently in compliance with regulations, therefore, the designed building cannot worsen their lighting conditions any more. These windows define the volumes which are entirely subtracted from the initial building form. Subtracted volumes are created by extruding a surface defined by the two adjacent rays incident on one of the control points located on the sill line.

Remaining windows, and there are 27 of them, belong to Group 3. These windows were properly illuminated and this condition worsened after the introduction of the newly designed volume. After verifying how many minutes of the illumination every window is missing and how many minutes of illumination is obscured by the designed building, vectors that are to take part in the optimization process are determined (Figure 7). Depending on how much insolation time is missing, from the set of vectors those that reduce the Maximum Building Volume as little as possible are selected.

Addressed procedure allows to add additional control points located on the line of each windowsill. The above-described results were based on analysis of two control points located on the end points of the line. Analysis of three or more control points, of which at least two are located at the ends of the line gives the same results. This means that using these 2 points is the most optimal and gives reliable results. Perhaps in a more complex spatial arrangement the ability to add more control points would be more useful, because it would give the opportunity to catch the sun’s rays from among closely located buildings. If, however, the analysis will take into account only the midpoint of a line, then less favorable results will be obtained: Group 1 includes then 34 windows, Group 2 - 47 and Group 3 - 26. We can see that the number of windows, which satisfy the provisions significantly reduced, from 53, this number dropped to 34. For 3 control points placed in 0.25, 0.5 and 0.75 length of the line number of windows that meet the regulations equals 49.

The described results were calculated with an accuracy of 5 minutes. If the accuracy of the cal-
Calculations is reduced to 10 minutes, the number of windows that meet the requirements decreases to 49, and the number of underexposed windows increases to 33. This is due to adopted rounding of values. If a calculation is conducted with an accuracy of one minute, the results will be the most reliable, but the time of calculations will increase significantly. For such precision of calculations the number of windows illuminated properly equals to 56, the number of underexposed windows - 25 and windows demanding optimization - 26.

The end result of this procedure is the determination of the Maximum Building Volume, which is represented by the impassable building envelope, set within the framework of building regulations concerning insolation of premises in adjacent buildings (Figure 8). In order for this volume to treated as final, other legal conditions and the ones resulting from the architectural and urban context should be also taken into account.

The resulting Maximum Building Volume is heavily cut, despite the fact that in the process of creating its goal was to reduce the volume as little as possible. The time intervals, which influence on the initial building volume was the smallest, were selected to be subtracted from it. However, that this not the only possible configuration of sun rays needed to illuminate the windows. It is possible to designate a number of other configurations that also comply with the regulations, but their arrangement will allow the location of other volumes on the site, that does not fall within the designated maximum volume. Placing the building on the entire surface of the plot is not permitted in the building regulations, therefore the Maximum Building Volume that is not taking into account other provisions and local factors is useful in the design process but not categorically conclusive. It is possible to locate other forms, beyond the MBV outline determined with the use of individual optimization procedures based on the results of insolation analyzes.

One of the possibilities of implementation of the optimization procedure is the search for such an arrangement size and location of a rectangular prism on the plot in order to maximize its cubic capacity, when there are no underexposed windows (Figure 9). The number of sun rays obscured by the body of the building falling on initially underexposed windows plus the amount of time needed to illuminate the initially correctly isolated windows to the minimum required level after adding the designed building are minimized. This procedure may also involve more than one a rectangular prism or address an arrangement of any other geometric shapes or search for proper parameters of an arbitrary building shape. The initial shape of the building is the entire surface area of the plot extruded to a height of 82 meters. The result of this optimization process is the body of the building, which is 30 percent of the input volume and all of the analyzed windows comply with the building regulations.

Taking into account a greater number of building volumes and maximizing the accumulated cubic capacity it is possible to approximate the Maximum Building Volume. Studying typologically different geometries can lead to obtaining forms well fitted to the context and fulfilling building rules.

CONCLUSIONS
The paper presents a method for finding an optimal building volume and its location on the plot in relation to the insolation conditions of buildings which are located in the impact area of the designed building. The proposed method refers to the national rules governing the conditions of insolation of rooms and apartments in adjacent buildings. These regulations
define precisely how many hours of insolation time should each window that belong to an apartment, school, kindergarten or a nursery have during the autumn and spring equinoxes between certain hours. Depending on how tall the building is planned to be and in how densely built-up location, the number of windows that should be analyzed in terms of their potentially affected insolation conditions can be very large. The proposed method allows simultaneous analysis of a large amount of windows and optimization of the building volume under the given boundary conditions. The first part of the process is based on a parametric model, which analyzes data from the Energy Plus weather data file, in the second section the Maximum Building Volume is determined or optimization procedures based on genetic algorithm are conducted.

Various optimization procedures were tested with typologically different input forms. Depending on the parameter settings, the optimization procedure always resulted in an optimized and well fitted to the requirements of insolation building volume. The fitness function of the genetic algorithm minimized the number of underexposed windows and maximized the volume of the building.

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