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Visualization of Solar Radiation Using Three-Dimensional Computer Graphics Technologies

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Abstract

Currently, the prediction, calculation and rationing of solar radiation is a serious problem that has a wide impact on the spheres of human activity. Creating and maintaining a comfortable living environment, as well as solving the world's energy problems, are the fundamental criteria that determine its relevance. This article discusses the possibility of using three-dimensional graphics technologies to calculate insolation. The paper considers an algorithm for calculating the four main components of the visualization of global solar radiation: direct beam radiation, diffuse radiation, reflected beam radiation and reflected diffuse radiation. The freely distributed open source software Blender 3D is used as a tool for working with computer graphics. In the course of the study, calculations based on the principle of bidirectional path tracing, which is used in the visualization algorithms of the Cycles graphics engine, are presented. The use of the technology of transferring complex data to the raster image format allows you to create a separate texture map for each component of the simulated lighting. Based on the obtained texture maps, it is possible to calculate the global solar radiation for all created or imported 3D models in the three-dimensional space of Blender 3D.

Keywords: insolation, visualization, visual model, solar radiation, three-dimensional graphics, 3D, Blender3D, Cycles, computer graphics.

1. Introduction

Currently, forecasting, calculating and rationing of solar radiation is a serious problem that has a wide impact on various spheres of human activity. The current trend in the economy of many countries is ESG transformation, which includes the environment (E – environment), social factors (S –social) and corporate governance standards (G – governance) with a focus on long-term and sustainable development (SD) of territories. As the urban population increases every year, the SD vector is not infrequently focused on the implementation of policies that contribute to the creation of livable, economically attractive and prosperous cities [1]. The goals of the SD center are aimed at the transition to rational consumption models, including in urban planning and construction, which make it possible to maximize the use of natural potential, while minimizing the negative impact on the environment. Therefore, the study of such an important process as insolation by modern means of mathematical and computer modeling is one of the urgent tasks, the results of which can be applied in the implementation of ESG principles.

Insolation – (INcoming SOLar RadiATION) is a term used to describe the process of irradiating surfaces and objects with a stream of sunlight (solar radiation) [2]. This concept has become widespread in the fields of astronomy, construction, design and architecture, and is also considered in hygiene (as the effect of solar radiation on humans). In accordance with this, there are various computational models for determining insolation, which can be divided into two categories: geometric and energy models.

Geometric methods are also called spatio-temporal. They determine the angle, direction, refraction and area of the light flux to the surface for a given period of time. Energy methods are not used as widely as geometric ones, they consider the solar flux in more detail and use optical units of measurement of radiation energy (for example, the intensity of ultraviolet radiation). The very concept of insolation is connected with geometric methods of calculation. With their help, you can estimate the duration of illumination and shading of the selected spatially distributed territory. Energy methods are derivatives of geometric methods, and cannot become the basis for the design of natural lighting of buildings and territories, since they are not a constant factor. Thus, insolation, based on geometric calculation methods, can be considered as a stream of sunlight affecting a certain surface – a measure of W/m^2 (the average value of solar radiation per unit area per year). Because often the calculation is carried out within a certain period of time (hour, day, month, year), then there is another measurement measure – kWh/m^2 (the average amount of solar energy per unit area for a certain period of time).

In the process of working on residential development projects, specialists are constantly faced with the task of assessing the duration of insolation of residential premises and urban areas. At the same time, not all existing mathematical and computer models for calculating solar radiation, such as ESRI's ArcGIS Solar Analyst model, allow taking into account the vertical surfaces of buildings and structures [3]. Taking this into account, visualization in computer graphics allows you to simultaneously solve the problem of choosing a visual representation of the source information in accordance with the specifics of a given subject area and literally "visualize", i.e., analyze data using the advantages of human visual perception. Therefore, within the framework of this article, one of the methods of insolation modeling based on visualization using three-dimensional computer graphics technologies is considered. In addition to effective visual representation, the chosen level of abstraction is optimal for visualizing vast urban areas. It also helps to increase the accuracy of modeling and visualization results by taking into account vertical surfaces of structures, building facades and complex three-dimensional shapes that are not available when calculating insolation based on two-dimensional spatial data [4]. Next, we will consider the main components of the computational model of insolation, which formed the basis for the visualization of solar radiation.

2. Components of the calculation of global solar radiation

The concept of insolation is based on the concept of solar radiation (radiation), and is often used interchangeably. Nevertheless, there are certain differences between them that are important to take into account for understanding the subject area. To do this, we will determine the main types of solar radiation – full, direct, scattered and reflected radiation.

The total (total) amount of solar radiation (TSI – Total Solar Irradiance) is a measure that determines the total amount of all solar energy from perpendicularly incident sun rays of different lengths that have reached the upper limit of the Earth's atmosphere [5]. The value of this variable varies from year to year, taking into account solar activity and other ongoing physical processes. Figure 1 shows a historical reconstruction of the change in the value of total solar radiation [6].

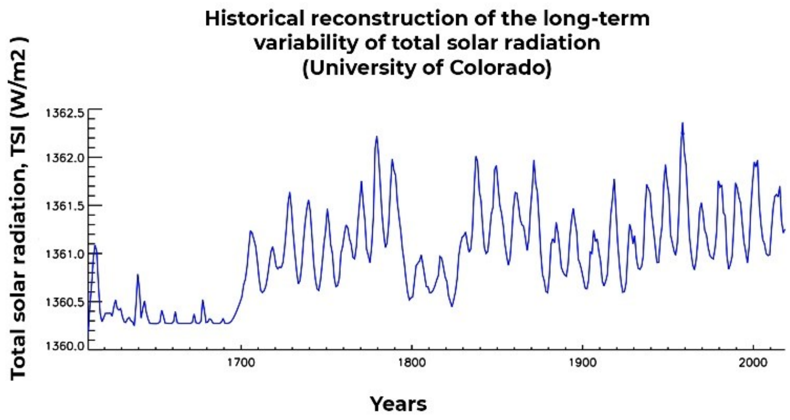

Fig. 1. Long-term variability of total solar radiation (TSI)

The insolation itself or global solar radiation (GHI – Global Horizontal Irradiance) is the total value of several components (depending on the calculation model): direct solar radiation, scattered solar radiation, reflected solar radiation (albedo) [7].

Direct Normal Irradiance (DHI – Direct Normal Irradiance) is the amount of solar radiation falling on the Earth's surface under ideal conditions of atmospheric transparency and cloudless sky, without taking into account scattered radiation. Since the net value of the solar flux varies according to the distance between the Sun and the Earth, as well as solar cycles, the value of direct solar radiation is approximately equal to the net value minus the absorbed or scattered solar flux by the earth's atmosphere [8]. Deductible losses may occur due to various atmospheric factors such as cloud cover, humidity level, pollution level, etc.

Although the upper level of the Earth's atmosphere receives a significant amount of solar energy (approximately 1368 W/m^2) as noted above, not all of the flow reaches the earth's surface. Approximately 30% of the total flow that reaches the Earth will be reflected back into space, absorbed or dispersed in the Earth's atmosphere [9].

Scattered solar radiation (also diffuse radiation of the sky) – to simplify the perception of insolation, this term includes not only scattering, but also absorption of the light flux by particles of solids and molecules of substances. The air mixture of the Earth's atmosphere best scatters short-wave streams of light, which belong to the violet and blue colors of the visible spectrum. With a different composition of the atmosphere, for example, on Mars, the human eye would perceive the sky of the planet in pink tones. Scattering and absorption significantly weaken the intensity of solar radiation reaching the Earth's surface.

Weather and climatic conditions, as well as anthropogenic factors affecting the atmosphere, affect the values of direct and scattered light fluxes. So, on a clear sunny day when the Sun is at the zenith, the scattered solar radiation is at least 20% of the global solar radiation. In the presence of clouds, fog, high humidity, smog, etc. conditions the percentage of scattered radiation is greatly increased [10].

The amount of light reflected from the surface of an object, relative to the amount of light absorbed by that surface, is measured by a physical property called albedo. Albedo is an important parameter in determining how much heat is absorbed by the surfaces of urban buildings and structures, therefore it is used in calculations of insolation in the design of urban space. In [11] some values of the albedo of the natural cover of the earth's surface are given, represented as a reflection coefficient expressed as a percentage.

One of the ways to quantify the solar potential of a particular place is to compile solar maps that contain information about the annual values of solar radiation on a certain territory or the surface of buildings (roofs or/and facades) and are developed by means of geoinformation systems [12]. Solar maps can be used for the design of urban space and the rational use of solar energy within the framework of ESG SD programs. The insolation map of Russia is shown in Fig. 2 [13].

Fig. 2. Solar map of Russia

The values of solar radiation can be obtained by: a) direct measurement of solar radiation at the station; b) measurements of other weather parameters on the basis of which solar radiation can be calculated. If there are a sufficient number of survey points (i.e. measurement points) in the area of interest, then interpolation methods can be used to calculate and visualize the insolation of the territory. In the case when it is necessary to estimate solar radiation in areas where there are no measurement data, it is possible to use models of solar activity, the initial data for which are measured meteorological data (for example, temperature, humidity, precipitation, etc.), as well as spatial data (for example, latitude, longitude, aspect, angle of slope of the surface).

The presented components of the insolation calculation can be described mathematically for further modeling and visualization in computer graphics applications.

3. Visualization of solar radiation based on three-dimensional modeling methods

Various software can be used to simulate insolation. Traditional models of solar radiation in geoinformation systems are mainly designed to obtain spatio-temporal estimates of insolation over vast geographical areas. Nevertheless, the widely used *ESRI ArcGIS Solar Analyst* and *GRASS GIS r.sun* insolation models can only work on two-dimensional maps, taking into account the values of the z surface height [3]. In addition, often the entire complexity of urban development, taking into account complex surfaces and their physical properties (for example, albedo), can be modeled only in three-dimensional space, since 2D maps cannot accurately display complex geometric characteristics that affect the accuracy of the calculation of insolation.

The key concept in computer graphics is the LoD system (LoD, Level of Detail). LoD is used to achieve a balance between the complexity of computer calculations and the accuracy of visualization (or in another way, the degree of abstraction of reality). With the help of a level system, it is possible to determine the difference between the geometry of a real-world object and the geometry of the model of its simplified equivalent, i.e. how accurately the model describes the original.

It is possible to obtain an initial 3D model of the city with the first level of detail for subsequent modifications in a computer graphics application using vector data from publicly available open cartographic web services that contain vector and attribute data about spatially distributed objects. Such a web service, for example, is OpenStreetMap. Methods of creating digital terrain models (DMM) and digital terrain models (DEM), which are used to create a three-dimensional model of territories, differ depending on the type of tasks being solved: landscape design, construction and design of buildings and structures, environmental protection, scientific research, etc. Accordingly, the required accuracy of detail also depends on the chosen method. The use of satellite imagery and radar topographic survey (SRTM - Shuttle radar topographic mission) to build a DEM is less accurate and less labor-intensive method. At the same time, urban infrastructure data can be added both from the aforementioned open spatial data web services (the most abstract levels of detail) and manually from computer-aided design (CAD) programs (the most accurate levels of detail). The most detailed and at the same time the most expensive and resource-intensive is the method of obtaining a cloud of LiDAR points (from the English Light Detection and Ranging - determining the range using light) based on aerial photography.

In computer graphics applications for the formation of the resulting image (visualization), one of the key elements of the calculation is the simulation of natural and artificial lighting. At the same time, advanced visualization algorithms can track millions of individual light rays during rendering (creating a photorealistic image representing the projection of a 3D model) to determine the color of a specific pixel in the final image. In this regard, three–dimensional technologies of computer graphics applications can be used to calculate insolation - using built-in render engines that allow you to create visualization and calculation of how light affects the surface of a building in a certain period of time.

Such a computational problem can be solved by open-source computer graphics applications and capable of processing vector spatial data about the real world, which, through the introduction of custom extension modules developed, open up a number of possibilities for solving non-trivial tasks.

The following software packages can be distinguished for creating a three-dimensional visualization of an urban area for calculating solar radiation:

- Unity/Unreal Engine game engines and ArcGIS GIS application;
- an application for creating three-dimensional computer graphics Blender and QGIS GIS application.

Within the framework of this study, a computational model is considered on the example of the Blender3D software, which has a number of features– these are the work with non-proprietary vector spatial data and remote sensing data, condition of use (free-distributable), availability of physical process simulation tools and optimization models based on the object level of detail system. These factors are fundamental for solving the chosen problem.

4. A model for calculating and visualizing global solar radiation in Blender 3D

Blender 3D is a professional freely distributed open-source software, as well as with integrated rendering engines – Cycles and EEVEE. Blender 3D provides the greatest possibilities in terms of flexibility and ease of creating your own modules and calculation algorithms based on sequentially executed commands, – scripts (from the English script), - the Python programming language. The algorithm for calculating illumination in Cycles is based on the bidirectional path-tracing method. Path tracing is a Monte Carlo method used in computer graphics to create images of three–dimensional spaces in such a way that global illumination corresponds to reality as much as possible. I.e., with a sufficient number of paths released, we get a picture of the distribution of light comparable to the real world.

In addition, there is a function of "baking" texture maps in Blender3D. With its help, various values of the characteristics of the three-dimensional surface of an object in a 3D scene (for example, color, textures, lighting, reflections and shadows) can be pre-calculated by the graphics engine of a three-dimensional application and recorded in the advising texture maps [14]. Then using a set of rules called UV-scanning of a three-dimensional grid (UV-map) each pixel of a two-dimensional "expanded" texture can be correlated to a three-dimensional surface. The process of "baking" texture maps reduces the load on the graphics engine of a three-dimensional application, allowing you to speed up the process of visualizing a 3D scene [15]. When data on solar radiation is recorded in textures, the analysis can be carried out in any resolution without changing the shape of the objects under consideration.

A single pixel of the texture can be used to represent any unit of measurement on the model, such as a meter or a centimeter. Simulation of solar radiation can be performed in Blender3D due to the possibility of calculating and combining direct and diffuse lighting. Thus, global solar radiation can be divided into four separate components in calculations: direct beam radiation; reflected beam radiation; diffuse radiation; and reflected diffuse radiation [16].

In this case, specular and diffuse materials affect the formation of reflected light rays, and transparent materials affect the intensity of the resulting shadows. Combinations of different materials are also possible. For example, you can reproduce a glass surface that reflects a certain amount of light and simultaneously transmits part of the sun's rays, but with less energy. Figure 3 shows the interaction of various lighting sources, surfaces, as well as the materials specified by them. The angle of incidence of the light beam is 45° for both surfaces. The emission material is set on A and B of the vertical surface – it is the only light source. A diffuse material is given to the horizontal surface in part A, and a mirror material in part B. Parts C and D show the difference between full and partial shading. Thus, using materials in Blender3D, you can control the albedo levels for different surfaces. An ideal diffuse black material will completely absorb incoming light, while an ideal specular white material determines a complete, 100% reflection of light [17].

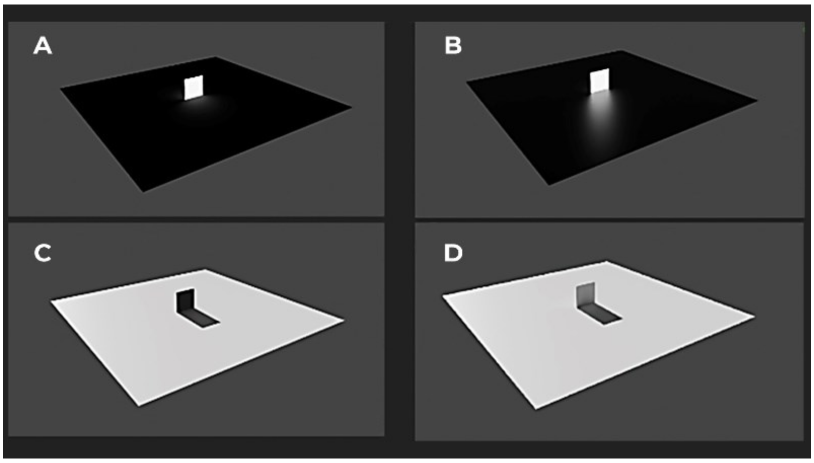

Fig. 3. Visualization of various reflection and shading parameters

When calculating the radiation of a solar ray, it is necessary to take into account its angle of incidence on the analyzed surface, as well as any shading and reflections. The Blender3D "Sun" light source, which simulates the real sun, allows you to identify these elements. Moreover, thanks to the "Sun position" extension module, you can set the coordinates of the center of the scene in decimal degrees, as well as the date and time. This will allow us to calculate the vector necessary to determine the direction of the beam in a virtual 3D environment, since the values of the height and azimuth of the real sun will be known [17].

The angle of incidence of light rays on the surface of the model under study should be calculated using the solar vector. This angle (in equation 1 – Ai) can be characterized as the angle formed by the intersection of the sunbeam and the normal vector of the face, which in Blender3D is used to describe a single surface. The calculation formula for direct beam radiation (*DBI*) is presented in Equation 1.

$$DBI' = DBI * cos\,(90° - Ai) \tag{1}$$

A shadow map (or cube map) is a cube where the light is in the center of that cube. The cube has six faces, and using the Cube Size parameter for each of them, you can set a certain resolution (for example, 1024 by 1024 pixels). When calculating shadows, the search for the nearest occluders (in computer graphics, any object that casts shadows) is performed only at the vertices of the three–dimensional grid, but not between them. Therefore, the higher the Cube Size value, the more smooth and high-quality the edge of the shadow of the object will be, at low values smoothing will not be enough and the shadow will appear rough and pixelated (Fig. 4) [18].

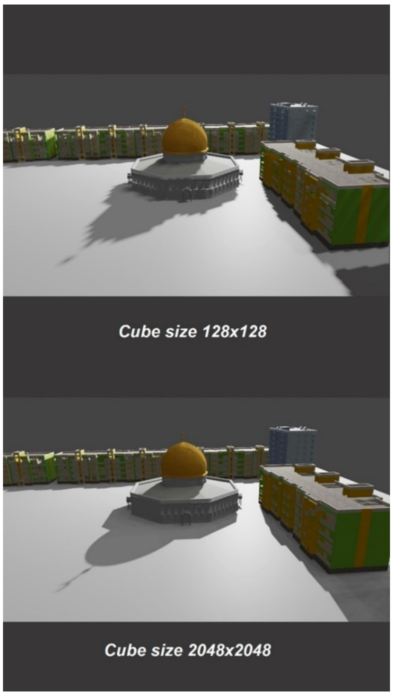

Fig. 4. Visualization of various values of the Cube size parameter

If there are no shadows, the pixels in the texture map created by the Blender3D function have a value of 1, and when there are shadows, they have a value of 0. All intermediate values indicate the passage of light rays through translucent surfaces. We obtain the value corrected by the shading coefficient (equation 2) by multiplying the pixel values of the texture (in equation 2 – x) by the reduced value of the direct beam radiation. The DBI in Equation 2 is calculated using the Hoyt Clark Hottel method [19].

$$Direct\ beam\ irradiance = \mathrm{x} * DBI' \tag{2}$$

Analyzing the reflection indicators of the light beam of the "Sun" object, it was found that the pixel value and the percentage of reflection do not change linearly (the graph of the function is shown in Fig. 5), but they can be described by a polynomial of the third degree. [17] This is due to the properties of the Cycles rendering engine. Using equation 3, where x is the color value of the pixel in question, a texture with pixel values that correspond to the degree of light reflection can be converted to the radiation value of the reflected sunbeam:

$$Reflected\ beam\ irradiance = DBI * (1.03 * \mathrm{x3} + 1.98 * \mathrm{x2} + 0.08 * \mathrm{x}) \tag{3}$$

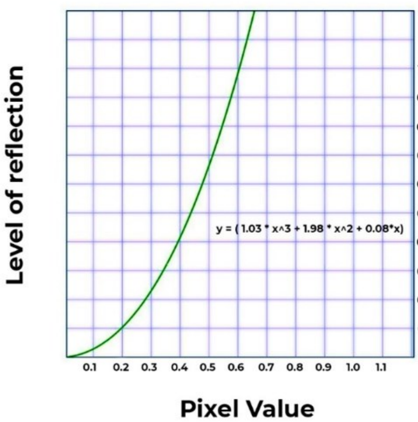

Fig. 5. Graph of the reflected beam emission function

The second component of the calculations of global solar radiation is the calculation of scattered (diffuse) radiation. The global stage lighting system, the so-called "sky maps" in Blender3D allows you to take into account the shading of all objects in the scene, as well as change the angle of inclination and orientation of the surface. The "sky" light source is a virtual sphere simulating a celestial dome. The lower the "visibility" parameter of the sphere, the shading becomes more pronounced. Just as in the calculations of direct beam radiation, both direct and reflected light can be taken into account [20].

At this stage, you need to create a texture map of diffuse lighting. According to measurements, a pixel value of 0.737 represents a full shadow, while a value of 0 represents the full visibility of a clear "sky" [17]. The measurements were carried out using a global light source "sky dome" and an unshaded plane. The value reduced by the amount of energy that reaches the surface under consideration is calculated by multiplying the pixel values by a given diffuse radiation value (DR, represented in Equation 4), where "diff" means diffuse radiation with correction of astronomical refraction, presented in Table 1, and x is the pixel values.

$$DR = diff * \frac{x}{0.737} \tag{4}$$

The calculation of the reflected diffuse radiation was carried out on the basis of the diffuse texture map of indirect lighting created after rendering in Blender. As in the case of direct radiation, a value of 0.737 corresponds to the incidence of reflected light with 100 percent intensity. The value of reflected diffuse radiation is also calculated according to equation 4, only in this case the color of pixels changes linearly depending on the reflection value. The final value of diffuse radiation is the sum of the values of direct and reflected diffuse radiation.

5. Results and their discussion

The algorithm under consideration divides the calculation of global solar radiation into four parts, which are then combined together to obtain the final insolation index and its visualization in 3D. Figure 6 shows the scheme of the algorithm for calculating and visualizing insolation at a certain point in time. To perform calculations, you need to select the appropriate iteration. The iteration can be set with an accuracy of up to one minute, which is the smallest calculation step for the analysis being carried out. In the presented algorithm, a theoretical calculation of the insolation values was used, but they can be replaced by other values, for example, obtained from long-term observations (meteorological year data).

Table 1. Correction of astronomical refraction

Solar flyover	Approximate correction of atmospheric refraction (°)
85°-90°	0
5°-85°	$\frac{1°}{3600''}\left[\frac{58.1''}{\tan(h)} - \frac{0.07''}{tan^3(h)} + \frac{0.000086''}{tan^5(h)}\right]$
-0,575°-5°	$\frac{1°}{3600''}\left(1735'' - 518.2''h + 103.4''^{h^2} - 12.79''h^3 + 0.711''h^4\right)$
< -0.575°	$\frac{1°}{3600''}\left(\frac{-20.774''}{\tan(h)}\right)$

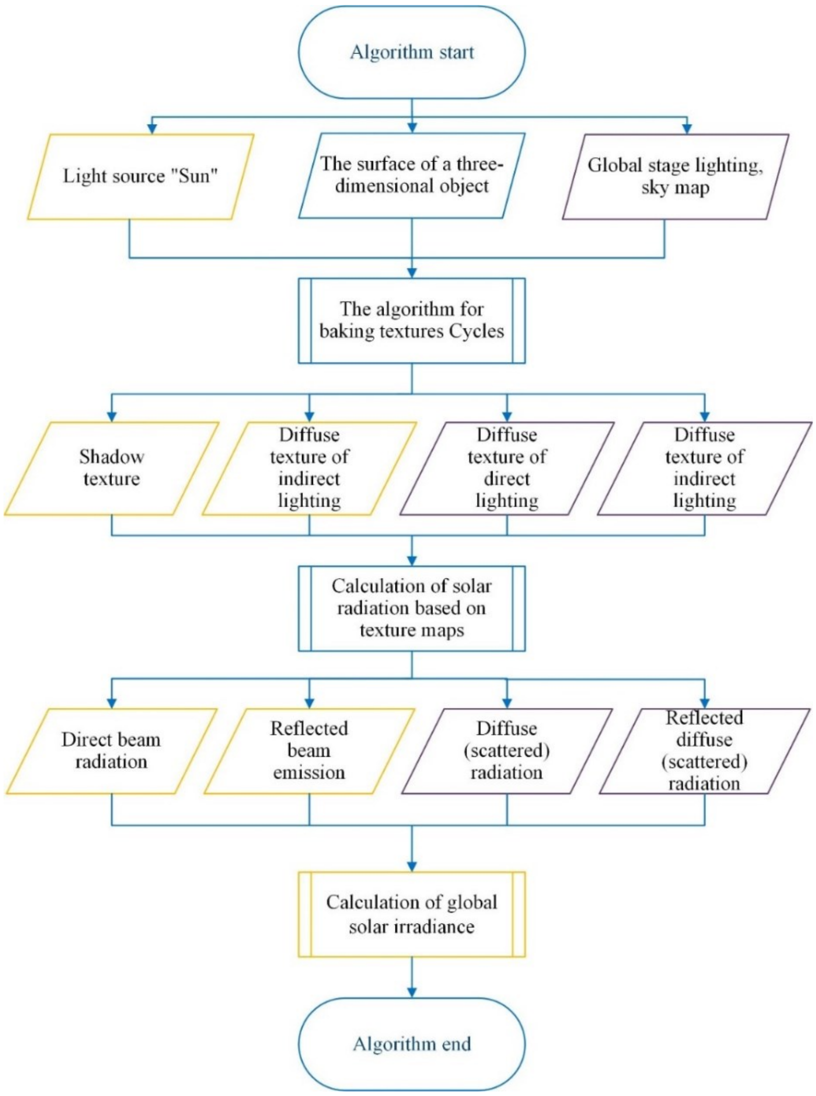

Fig. 6. Scheme of the algorithm for calculating insolation

Conclusion

The main purpose of the article is to create a flexible calculation method, which formed the basis for the application of visualization of insolation in urban areas. The main tasks included providing a simple solution based on open-source applications capable of analyzing solar radiation taking into account the reflection and scattering of light. The developed algorithm for calculating insolation makes it possible to obtain a visual model of global solar radiation and its effect on a certain surface for a given period of time. The accuracy of the analysis performed depends on the resolution of the specified textures. The smallest possible time range of the analysis is one minute. These results are useful for developing solar energy distribution policies, architects, and urban planning.

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