Assessment of Light Transmission for Comfort and Energy Efficient Insolation by "Green Structures"

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Abstract. Insolation is one of the most important factors of human comfort and health in premises. Nevertheless, in a cooling period, the solar radiation brings additional heat gains decreasing the energy efficiency of buildings. The best practice is to allow the maximum solar radiation in heating and transition periods, and to limit it to the minimum permissible level during a cooling period. Usually, the problem is solved by technical measures, such as automated sun-blind-transformers, automatic jalousie or south orientation of glazing, equipped by a non-transformed canopy. In a previous work of the authors, a solution using "green structures" with deciduous plants was proposed. It avoids automation, allows using the most of orientations for glazing, does not decline the view, provides emotional comfort by the most natural appearance, and also improves the sanitary conditions by phytoncides. The goal of the work is the provision of minimum normative insolation in a cooling period by the design of a "green structure". A geometric model is used for the sunrays, which passed through the planting. The model considers the shape of plant crowns and light transmission through them avoiding direct simulation of the shape of each leaf. An approach for the simple determination of the light transmission through different plants without special apparatus is proposed. The light transmission through different plant crowns was determined for different plants, which can be used in "green structures". The best practice is a combination of plants with dense and openwork crowns.

Keywords: Green Construction, Green Structures, Sun Protection, Natural Illumination, Insolation, Crown Shape.

1 Introduction

Insolation is one of the most important factors of human comfort in premises. The ultraviolet solar light has bactericide action and activates the production of cholecalciferol (vitamin D) in the skin, which raises human health. The sunlight spectrum is the most natural and causes the production of vitamin D, stabilizes circadian biorhythm, improves the emotional conditions. In a heating period, solar radiation acts as passive heating. Nevertheless, in a cooling period, the solar radiation brings additional heat gains decreasing the energy efficiency of buildings. The best practice is to allow the maximum solar radiation in heating and transition periods, and to limit it to the minimum permissible level during a cooling period. Usually, the problem is solved by technical measures, such as automated sunblind-transformers, automatic jalousie or south orientation of glazing, equipped by a non-transformed canopy. Most of the solutions decline view from the window or fully covers it, which causes additional discomfort.

In previous work [1], the authors proposed a solution using "green structures" with deciduous plants. It avoids automation, allows using the most of orientations for glazing, does not decline the view, provides emotional comfort by the most natural appearance, and also improves the sanitary conditions by phytoncides. An algorithm was developed for building a geometrical figure that should be filled by plants. However, the task of the design inside the figure was not solved.

The goal of the present work is the provision of minimum normative insolation in a cooling period by the design of a "green structure" using a geometric model of sunrays, which passed through planting taking into account the shape of plant crowns and light transmission through them.

2 Literature analysis

In ancient times, some green structures were used for sun protection. For example, the Palace of the Shirvanshahs (XV century) in Baku has a green canopy (Fig. 1), which is a characteristic construction in the region today (Fig. 2). The ancient astronomers had enough knowledge to design such kind of sun-shading. The design was oriented for thermal comfort only. Today, humanity uses the bactericidal and antiviral properties of sunrays in buildings. Therefore, the norms of minimal insolation are accepted in most of the countries [2]. Buildings Performance Institute Europe in 2015 reviewed norms of daylight in different countries [2]. It is shown that there is no unity of opinion for the approaches of standardization. In countries with cold climate, over-insolation in heating period provides passive heating and saves the energy from non-renewable sources, but can decrease the comfort of working with monitors. Denmark is the only European Union country, which norms minimum solar gains in heating period. Some other countries, including Denmark, Germany and Italy, used the daylight factor. In the countries above, it should be not less than 2 % in half of a room.

Fig. 1. Green Canopy in Palace of the Shirvanshahs (author's picture)

Fig. 2. Green Canopy of a cafe, Baku (author's picture)

In Poland and Ukraine, the time of insolation is normed. The norms reflect different architectural traditions, daylight gains and sunlight directions. Some peoples like green cities, others live in cities without plants.

In many towns and cities including Ukrainian ones, very often trees can be planted very close to buildings. If the windows are oriented to south-east, south or south-west, this makes rooms on the lower floors cooler due to reflection of sunrays and transpiration cooling due to evapotranspiration – evaporation from soil and transpiration from leaves. For the northern or east orientation, it causes a very dark environment. Thus, by the complaints of habitats, such trees are felled and replaced by small shrubs. In some countries and regions, any obstacles around windows are prohibited [2] which disallows this solution. In Brussels, the distance should be not less than 3 m.

At a cooling period, the insolation brings additional heat gains, which causes unnecessary energy consumption by air conditioning or cooling. In this case, the windows are shaded by jalousies during all the period violating the prohibition above. Thus, for the balanced energy consumption of buildings and healthy environment, it is required to provide the insolation close to the minimum permitted at cooling periods and as much as possible at heating and transition periods.

The task can be solved on different floors by modern "green structures". They are very improved comparably to the ancient [1, 3] analogues – Scandinavian and Iceland roofs, covered by grass; Hanging Gardens of Babylon and others. The improving process for aesthetic purposes was started at the end of XIX – beginning of XX centuries thanks to Charles Rabitz, Le Corbusier, brothers Perret, Walter Gropius, Frank Lloyd Wright, Friedrich Hundertwasser, Walter Zinc and others [1, 3].

Now the design is focused on energy-efficiency problems. There are useful properties of the structures: "cooling effect" by evapotranspiration, a reflection of sunrays, additional thermal insulation and reduction of city drains [4]. The improvement of energy efficiency is comparable with measures in HVAC systems such as proper inlet air distribution [5, 6].

The sun protection of glazing is one of the effective features of "green structures" [1]. Primitive vertical greening of windows by ampel plants is not the best solution. It spoils the view and causes visual discomfort. Today knowledge of astronomy [7, 8], geometry and biology give a wide range of possibilities to design modern "green structures" for sun-shading, which provide more visual comfort than traditional jalousies and external artificial lifeless sun protection.

In a previous work [1], the authors propose using terrace and roof greening for shading the windows and clerestories on roofs. Using the deciduous plants provides enough natural automation avoiding complex mechatronic systems with expensive controllers. The assortment of plants and the algorithm of building the figure, which should be covered by plants, were proposed.

This work is focused on the design of the plants inside the figure to ensure the normative level of insolation using geometry and image processing.

3 Optical transmission of crones

One of the most important input data for "green sun-shading" design is the possibility of crones to transmit light. The classification of crone density is more qualitative than quantitative, for example, dense, sparse or openwork. The estimation of crowns can be performed by Crown Density-Foliage Transparency Card [9], produced by the United States Forest Service of The United States Department of Agriculture. The measurement should be performed "by eye" using a comparison of the crown appearance with the patterns of the card. This method is enough for estimation of live crown ratio for forestry. Nevertheless, it is very rough and too affected by the human factor. Therefore, it is not applicable for engineering needs.

The most precise method to measure the optical transmission is actinometry. An actinometer should be directed to the sky through a crown in multiple points and directly close to the tree at the same angle. The relation between the measured values should show the optical transmission. Nevertheless, with some assumptions, it is possible to use a simpler method, which requires more available and cheap equipment: a camera and a computer. The main idea is using simple image processing methods.

The foliage of some trees is semi-transparent. However, the light passed through a leaf loses the most biologically active spectrum, which is accumulated for photosynthesis. The rest of the spectrum is neither bactericidal nor stimulative for circadian rhythm. It has very little energy. It is possible to neglect them. Thus, the share of visible background through a crone can estimate the optical transmission with enough precision.

The same problem may occur with the reflected radiation from different objects. It may or may not contain biologically active spectrum dependent on the reflective properties of surrounding objects. If the objects have a yellow colour, the radiation cannot activate circadian rhythm receptors at daytime. If they absorb ultraviolet rays, there is no bactericidal effect. The difference is that the radiation can bring significant and useless heat gains at cooling period. Therefore, it is not so easy to take into account the reflected radiation in total insolation of premises. To increase energy efficiency, a good idea is shading by special flat grids with ampel deciduous plants around the vertical glazing. The reflected radiation is not considered in this work.

The following algorithm can estimate the optical transmission:

1. Take a shot(s), preferably in a lossless format such as PNG or RAW, of the crown of the required plant in the possible directions or the average direction of sunrays. The background should be selected for easy separation by colour or brightness. If the plant is on a “green construction” in the necessary region, the results will be more adequate. Strong sun illumination can give very light and very dark leaves, which make the separation more difficult;
2. Process the shots to decompose it by the crown and the background and figuratively crop the picture by the crown excluding very light-transmissive peripheral part (including random branches and leaves);
3. Count the number of pixels in the crown C and the background B;
4. Estimate the optical transmission

$$T = \frac{B}{B+C}. \tag{1}$$

For example, let us use the “green roof” on the apartment complex “Port Baku Residence” (Fig. 3) in Baku. A large dense tree (Fig. 4) on it is a maple (*Acer platanoides*). The task is the estimation of its optical transmission.

1. A shot (Fig. 4) of the maple has been taken 23 may 2018 12:06 PM by Canon EOS 60 D camera and Samyang 10 mm f/2,8 ED AS NCS CS lens in RW2 format with the best quality – 5194×3457 pixels. The shot was taken not for this task. It has a problem because of strong sun illumination causing very bright and very dark leaves;
2. After exposition correction for easier background detection, it was exported to png format using open-source software RawTherapee 5.8 (Fig. 5 a). The following process was performed by open-source software GIMP 2.10.18. For old operating systems, GIMP 2.8 should be used. First, the image was cropped on the tree excluding the area of overlapping with background trees (Fig. 5 b). Then, the presence of α-channel was checked and added, if not. Because of the strong contrast between the leaves, the easier way to eliminate the background is to detect it inside the foliage, select its parts by “Select by colour” tool and delete it to transparency (Fig. 5 c). The tool should be configured to switch off antialiasing. The appropriate threshold should be set for effective selection without affecting the foliage. Then, the crown should be isolated. It was roughly selected by the “Lasso” tool eliminating the random protruding branches and very lacy peripheral. The selection was inverted, and the area was deleted (Fig. 5 d) to transparency without removing the selection. After that, the crown was discolourated to totally black (Fig. 5 e). There are many different possibilities. “Monomixer” was used with zero value of all channels. Finally, the picture was decomposed by colour channels (Fig. 5 f): for the red unnecessary areas, a clear red colour was set, the selection was inverted and filled by “bucket” tool (“Fill whole selection” option is recommended); for the green crown, a clear green colour was set, the black areas was “Selected by colour” and filled by “bucket” with “Fill whole selection” option; finally, clear blue background colour was set and the image was “flattened”.

Fig. 3. Model of Port Baku Residence in Heydar Aliyev Centre, Baku, Azerbaijan (author's picture).

Fig. 4. A maple on the large "green roof" of Port Baku Residence, Baku, Azerbaijan (author's picture).

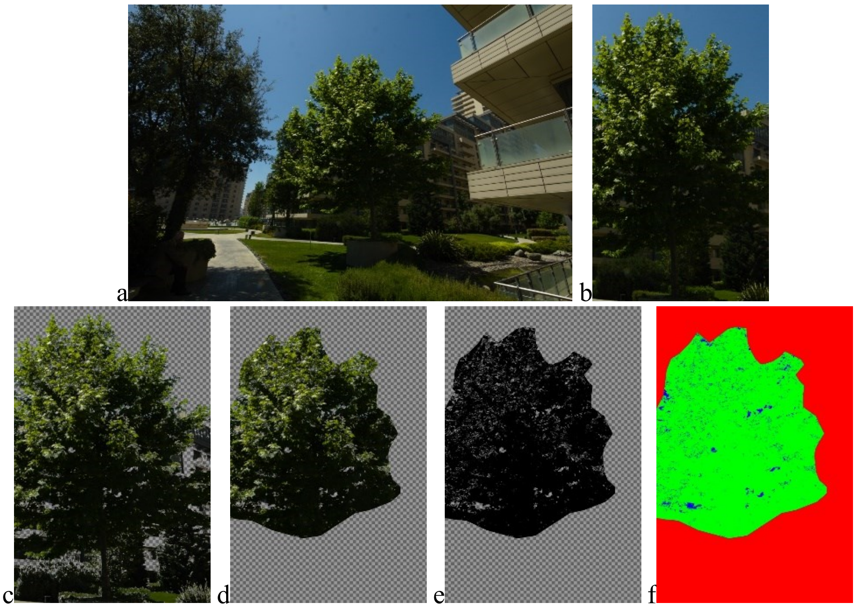

Fig. 5. Decomposition of the maple on Fig. 4: a – correction of exposition; b – cropping; c – removing the background; d – isolating the crown; e – discolourating; f – decomposition by RGB channels: chessboard pattern – transparency.

3. To calculate the pixels, the "Histogram" panel was used. In the green channel, the range 1...1 was set. The "count" field showed $C = 1506670$. For the blue channel, the "count" was $B = 62476$. Therefore, the optical transmission by Eq. (1) is $T = 62476 / (62476 + 1506670) = 4$ %.

Another example is the honour of the green roof – a poplar (*Populus nigra f. pyramidális*) with a height of more than 6 m. The picture (Fig. 6) has only the sky at the background and very small overlap at the bottom. It is very simple to decompose it by the same process as for the maple except for the correction of exposition, which is unnecessary. The results are $C = 475161$; $B = 61937$; $T = 61937 / (61937 + 475161) = 11.5$ %.

4 Design of sun protection

It is necessary to build the figure of sunrays around the glazing [1]. The first stage of greening should be built in a 3D model as it is described in [1]. 3D software can simulate semi-transparent bodies. However, there is a problem to set transparency properties. Standard figures – a sphere, a cone, a cylinder – absorb a lot of light at the centre or the axis and gradually absorb less the further one gets from it. Standard surfaces – spherical, conical, and cylindrical – absorb the same light except the peripheral, where it absorbs more light due to the high thickness of the material. If the software simulates refraction, the result will not be adequate.

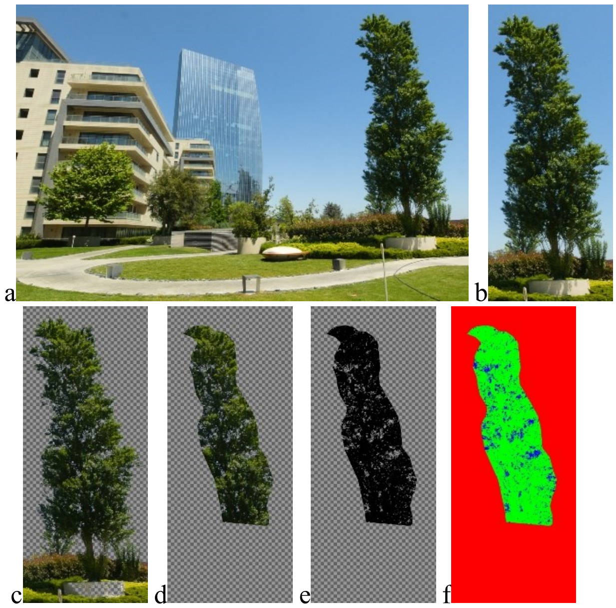

Fig. 6. Decomposition of the maple on Fig. 4: a – original picture; b – cropping; c – removing the background; d – isolating the crown; e – discolourating; f – decomposition by RGB channels: chessboard pattern – transparency.

The crown on Fig. 5 f has a different absorption law. The axis with the trunk absorbs 100 % of light. Around it, big steins of background are distributed uniformly. Small steins are also distributed uniformly except some large gaps more in the right part due to unevenness of solar illumination. The peripheral is formed of the random branches and its absorption can be neglected. The crown on Fig. 6 f also has a different distribution of absorption. Small steins are distributed uniformly. Large gaps are distributed uniformly in the middle of the crown. At the top, they are absent. At the bottom, there is a small amount of them. This evenness is due to the tendency of growth of only those leaves, which can take enough light for photosynthesis. The different crown shape has a different distribution of foliage inside it to keep the uniformity.

The most precise method of design is the simulation of 3D model leaf-by-leaf. It requires:

- a large library of leaf-by-leaf models of different plants in different conditions;
- a lot of computation resources;
- inadequate processor time.

A simplified approach for the design of the “green sun protection” is proposed. Let us assume the uniform optical transmission of crowns. The following algorithm should perform the calculations:

1. Accept the concept of phytodesign of the terrace, roof etc. around the glazing taking into account the figure **F** that should be filled by plants [1];

2. Build a 3D model of the concept, taking the optical transmission of each (i-th) plant T_i in per cent;
3. Take a time grid τ_j [h] with step $\Delta\tau$ [h] and nodes numbered j for calculation dates;
4. Reset the accumulators for insolation parameters for averaged optical transmission and bulk averaged one:

$$I_{tot} := 0\ ,\ \ I_{tot}^{B} := 0\ ; \tag{2}$$

5. For each node of the grid τ_j [h]
   5.1. Find the characteristic angles for the position of the sun [1] without applying daylight saving time;
   5.2. Build the shadow of each crown inside the figure **F** on the glazing obtaining flat figures $\mathbf{P}_{ij}$: the contours are dividing the area of the glazing taking non-overlapping figures $\mathbf{Q}_{kj}$: max(k) ≥ max(i);
   5.3. If it is possible to use bulk averaged optical transmission, take the solar energy for the appropriate, usually, daylight saving time J_i [W/m^2]. The solar energy on a vertical surface can be used in the corresponding orientation or normal to the sun-rays or, as a last resort, on a horizontal surface, assuming the proportionality, dependent on the data provided in norms of the corresponding country;
   5.4. Measure areas of the figures $\mathbf{Q}_{kj}\, A_{kj}$ [m^2];
   5.5. The averaged optical transmission, %:

$$T_j = 100\frac{\sum_k A_{kj}\prod_{o_{kj}}\frac{T_{o_{kj}}}{100}}{\sum_k A_{kj}} = 100\frac{\sum_k A_{kj}\prod_{o_{kj}}\frac{T_{o_{kj}}}{100}}{A}\ , \tag{3}$$

   where A – the area of glazing; o_{kj} – a number of a plant, which projection contains the figure Q_{kj}; a product of zero elements should be accepted as one: no shadow – no absorption;
   5.6. The parameters at the time node for the averaged optical transmission [10^{-2}·h/m^2] and bulk averaged one [10^{-2}·W·h], corresponding,

$$I_j = \Delta\tau T_j\ ,\ \ I_j^B = J_j \Delta\tau T_j = J_j I_j\ ; \tag{4}$$

   5.7. Accumulate the total [10^2·h/m^2] and bulk total insolation [10^2·W· h]:

$$I_{tot} := I_{tot} + I_j\ ;\ \ I_{tot}^B := I_{tot}^B + I_j^B\ ; \tag{5}$$

6. Calculate averaged and bulk average optical transmission [%]:

$$T_{tot} = \frac{I_{tot}}{\tau}\ ;\ \ T_{tot}^B = \frac{I_{tot}^B}{\sum_i J_i \Delta\tau_i}\ , \tag{6}$$

where $\tau = \Sigma\Delta\tau_i$ – the time of significant solar radiation [h];

7. The total insolation, if necessary, should be calculated using the averaged direct plus diffusive or direct solar radiation or per day multiplied per the averaged optical transmission (bulk is recommended) by one of the equations (6). In the last case, diffusive solar radiation can be calculated only from the visible sky area from the glazing or using optical transmission by steps 4-5 for "the average sky ray" ($\pi/4$ elevation in a vertical plane normal to the glazing);
8. The daylight factor should be estimated, if necessary, using the results of step 7 or the equation (6);
9. If the total insolation or daylight factor corresponds to desired, accept the green design, stop the process and use the total insolation for the cooling load;
10. If the total insolation is greater than the normative, decide to use plants with a denser crown or greater size or to add some plants;
11. If the total insolation is less than the normative, decide to use plants with less density or size or to remove some plants;
12. Repeat the process from stage 2.

Let us show an example of a window in Kyiv: longitude 0.5327326 rad east and latitude 0.8805186 rad north. Azimuths for the window 2.7509856 and 5.1029960 rad, oriented on south-west [1]. In [1] there was a misprint – the longitude and latitude are interchanged in the text, – but calculation results are OK. Let us show only one time-step to describe the main principles of the 3D model.

1. For this example, a very simple design of a "green terrace" has been accepted by four poplars (*Populus nigra f. pyramidális*). Figure **F** was built in [1];
2. 3D model of the design is on Fig. 7 a. The optical transmission of the plants is accepted by decomposition of picture (Fig. 6) of Port Baku Residence – $T = 11.5$ %;
3. A time grid τ_j [h] is accepted in 15th July with equal step $\Delta\tau = 1$ h;
4. The accumulators are reset by the equation (2);
5. In the example, let us show the node $\tau_j = 13.5$ h 15th July because the required data is provided in [10]. With daylight saving time, the actual time is 2:30 PM:
   5.1. The characteristic angles were found for position of the sun [1]: azimuth 4.6832655 rad, elevation 0.9520167 rad;
   5.2. The shadows in the direction are built using the known geometrical principles (Fig. 7 b);
   5.3. For vertical surface oriented at south-west between 2:00 PM and 3:00 PM [10] $J_i = 476$ W/m^2, and this is maximum during the day;
   5.4. Area of the shadow parts on Fig. 8 are measured using the 3D software (Table 1)
   5.5. The calculations of the time node are performed in an electronic table (Table 1);
   5.6. The parameters at the time node for the averaged optical transmission and bulk averaged one, by equations (4);

$$I_j = 1 \cdot 13.10 = 13.10 \text{ h/m}^2 \cdot 10^{-2}, \quad I_j^B = 13.10 \cdot 476 = 6236 \text{ W} \cdot \text{h} \cdot 10^{-2}.$$

The formal process of accumulating the average values is not shown.

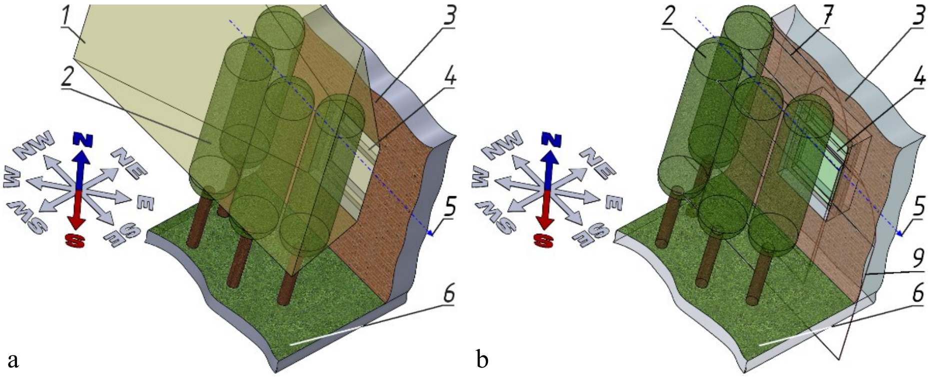

Fig. 7. 3D design of a “green terrace”: a – general view; b – building the shadows: 1 – figure **F**; 2 – plants; 3 – wall; 4 – window; 5 – sun-rays direction; 6 – “green terrace”; 7 – lines of construction the shadow; 8 – contours of the shadow: pos. 7 can be absent if shadow modelling is performed by a software

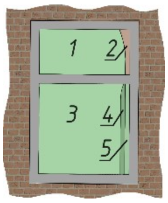

Fig. 7. Shadow on the window: numbers of parts – figures $\mathbf{Q}_{kj}$ – see Table 1

Table 1. Electronic table for calculation steps 5.4-5.5.

Number k of figure $\mathbf{Q}_{kj}$	Plant(s)	Area A_{kj} [m^2]	Optical transmission T_{ij}, %, of plant 1	2	$A_{kj}\prod_{o_{kj}}\frac{T_{o_{kj}}}{100}$ [10^2 m^2]
			Upper window-pane		
1	1	0.4675	11.5	—	0.05376
2	—	0.0325	—	—	0.03253
			Window-frame		
3	1	0.9031	11.5	—	0.10386
4	1, 2	0.0469	11.5	11.5	0.00062
5	2	0.0500	—	11.5	0.00575
Total		1.5000	—	—	0.1965

$T_j = 13{,}10$ %

During operation, some deviations can be observed, which cause over- or under-insolation. The correction can be applied by fertilization of the substratum: some lack of fertilization make crowns more sparse.

5 Conclusions

"Green structures" with deciduous plants are recommended for automated insolation control in rooms. They provide limitation of heat gains by solar radiation in cooling period according to the minimum insolation level and maximum gains in heating period in the most natural and visual-comfort way. They do not require controllers and actuators. The proposed simple approach to the design of a green terrace for sun protection allows obtaining the required level of insolation of rooms without unnecessary heat gains of solar radiation. Optical transmission of plants can be estimated without special equipment and measuring devices using simple image processing technic. Different examples show the possibility and minimum human factor influence on the results. The methods are recommended for engineering practice because they can give minimum normative insolation in a cooling period using the simplified geometric model of the sunrays without difficult ray-tracing taking into account the shape of plant crowns and light transmission through them.

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