A parametric tool for outdoor shade design: harnessing quantitative indices and visual feedback for effective and efficient climatic design of streets

Abstract. To date, there is a lack of an orderly and data-based method for quantifying, evaluating, and benchmarking street-level outdoor shade in streets and urban public spaces. The lack of such a method impedes the effective design of walkable and liveable outdoors in locations where shading is essential for significantly mitigating outdoor heat stress. To address this shortcoming, we have developed **Kikayon**, a relatively simple parametric tool that allows planners and designers to easily compare the effect of design alternatives on outdoor shade provision based on building geometry and tree canopy morphologies while taking into account the variance of exposure to solar radiation at different times. The tool calculates several shade and tree indices, some we have originally developed, for each street design, giving users quick and straightforward feedback and enabling them to quantitatively compare design alternatives. Our tool is implemented as a **Grasshopper** code that harnesses several components of the **Ladybug Tools** suite.

Keywords: Urban Microclimate, Shade Maps, Parametric Urban Design, Heat Stress, Outdoor Shade.

1 Introduction

The most common indicator of urban overheating is higher air temperatures, usually recorded at street level. An increase in air temperatures can have diverse negative effects, including exacerbated outdoor heat stress (during daytime and nighttime alike), deteriorated air quality, and even increase in mortality rates [1–5]. However, previous research has consistently demonstrated that during the hot season, direct and diffuse solar radiation play a significant role in the generation of excessive daytime heat stress in multiple geographic locations, while outdoor shade provision has shown to be able to significantly mitigate it [6–13]. Shade also reduces health risks caused by exposure to UV radiation [14] while also having the potential to reduce street-level air temperatures and cooling loads in buildings because it decreases the insolation, and thereby the heat absorption, of man-made surfaces in our cities [15].

The potential of shade provision to substantially reduce heat stress is implicit in the most widely used outdoor thermal comfort models, such as, for example, the Physiologically Equivalent Temperature (PET), the Universal Thermal Climate Index (UTCI), and the Index of Thermal Stress (ITS)[16–20]. Such models consider the effect of exposure to shortwave and longwave radiation through inputs like the mean radiant flux intensity or its derivative, mean radiant temperature (MRT)[15]. Exposure to direct and diffuse solar radiation has a decisive effect on increase in MRT values and thus also on the perceived heat stress according to each of these models. In practice, the capacity of urban design to control other factors considered by common comfort models, such as air temperature, relative humidity, and wind speed, is rather limited [21]. Shade, on the other hand, is almost entirely determined by how urban streets and open spaces are designed and maintained, even at a rather local level. Therefore, in many locations, one can argue that tackling inadequate outdoor shading may be the single most important climatic task an urban planner can engage in for reducing urban heat stress.

Cities that already promote climatic urban planning and design policies are usually faced with difficulties in translating them into evidence-based concrete actions [22–24]. This applies also to outdoor shade: while the target of intensifying outdoor shade is widely recognized in climatic action plans around the world [25–30], the detailed planning of its implementation does not yet follow clear, systematic, and replicable methodologies. Besides a handful of initial attempts to suggest quantitative criteria for street shade evaluation [31, 32], the design of outdoor shade almost always relies on basic rules of thumb that at times can be misleading or result in inefficient allocation of resources (for example, in excessive street tree planting in streets that are well shaded as a result of street and building geometries and street orientation). Moreover, assuming that quantitative standards for outdoor shade provisions can be developed and adopted by planning authorities, designers must be provided with simple and design-oriented tools that can enable them to quickly create, evaluate, and improve design alternatives in light of their effect on outdoor shade and the investments required to provide it. This article describes such an attempt that combines quantitative indices for outdoor shade evaluation previously developed by the first author [32, 33] with the development of a parametric tool that applies these indices to assist designers in evaluating shading strategies for streets.

2 Scientific background

The design tool we have developed enables users to evaluate how effective their street designs are in terms of outdoor shade provision by calculating two indices developed by the first author: a Shade Index and a Shade Availability Index. In addition, and since trees are considered to be one of the most effective street elements for enhancing outdoor shade, the tool also implements a commonly used Tree Canopy Cover Index for quantitatively evaluating the cover provided by tree canopies in a street, which may be indicative to their contribution to street-level shade. One advantage of these indices lies in the way they describe the quality of outdoor shade provision using a unitless scale, thus making them ideal for straightforward evaluation of certain aspects of climatic design even by designers with little knowledge in urban climatology and its complex measurement methodologies. The following sections describe these indices in detail.

2.1 Street Shade Index

A street Shade Index (SI) describes on a scale of 0 to 1 the ratio between the blocked insolation at ground level at a certain location and the maximum insolation of an unobstructed horizontal surface at the same time and location. The higher the value, the higher the shading. This indicator considers shade produced by all elements in an urban environment: buildings, trees, and other shade-giving elements. It can be formulated as follows:

$$SI_p = 1 - \left(\frac{Insolation_p}{Insolation_r}\right) \quad (1)$$

where SI_p is the SI at a certain point, $Insolation_p$ is the insolation at that point, and $Insolation_r$ is the insolation at an unobstructed reference point during the same period. When applied to a street segment or a specific part of a street, SI is calculated as an average of all sampled point SI values contained in that area (the sampling density depends on user preference, though a sampling rate higher than 1 m may overlook fine differences in spatial shade distribution). The SI depends on the date and time of calculation: different dates and times will produce different SI values for the same location and urban morphology. While it is more effective to calculate SI values for mid-summer, when daytime air temperatures are at their peak and heat stress is at its highest level, it is possible to use other dates as reference dates for shade evaluation (for example, during spring and autumn). To evaluate the overall shading effect of street and building geometry during daytime hours, it is better to use the cumulative exposure of ground level during a time range that represents all or most of daytime hours. Nevertheless, it is also possible to calculate SI values for a certain hour, or for a short time range of a couple of hours.

2.2 Sidewalk Shade Availability Index

While SI provides an accurate description of the amount of blocked global radiation at street level, it may not reflect well the spatial distribution of shade in the available space for pedestrian traffic. Here, a different index is suggested to quantify the spatial distribution of shade on sidewalks. The Shade Availability Index (SAI) describes on a scale of 0 to 1 the ratio of daytime hours during a specific time range in which at least 50% of a sidewalk area is shaded (kept unexposed from direct shortwave radiation). The calculation of the SAI is therefore time-dependent: as with the SI, the same street configuration can result in different SAI values not only on different dates, but also when calculating shade availability in different periods. It is advisable to calculate the SAI for the same date and time as the SI, as a complementary index that focuses not on the degree of heat stress caused by exposure to global radiation but rather on the existence of a viable choice for a pedestrian to continuously walk in the shade along a sidewalk.

2.3 Street Tree Canopy Cover

The third index calculated by the tool is that of a Street Tree Canopy Cover (TCC). It describes, on a scale of 0 to 1, the ratio between the projection area on a horizontal surface of all tree canopies located within a street and the total area of the same street. The higher the street TCC value, the higher the tree canopy cover of the street. TCC values can indicate the likelihood of a street to enjoy high levels of street-level shading cast by wide-canopied trees. Nevertheless, since street-level shade depends also on the shade cast by buildings and other physical objects, TCC alone may not describe well the overall shade conditions in a certain street segment, especially where TCC values are low. Therefore, while street TCC can provide complementary information on the dependence of certain street configurations on trees for street-level shade provision, evaluation of shade provision should be done based on the SI and SAI described above.

3 Kikayon: tool description

The tool we have developed, named **Kikayon**, is a parametric tool implemented as a **Grasshopper** code while harnessing several components of the **Ladybug Tools** suite [34] to calculate SI and SAI values. It allows planners and designers to easily compare the effect of design alternatives of a street configuration on outdoor shade provision based on building geometry and tree canopy morphologies while taking into account the variance of exposure to solar radiation at different times. Based on this geometry, the tool automatically computes the indices described in Section 2 for each sidewalk or the entire street. In addition, the tool provides visual feedback, presenting the typical pattern of shade distribution across the street, which helps to interactively tweak the design based on the quantity and quality of shade provision. Designers are expected to use the tool by following an ordered sequence of actions described below.

3.1 Inputs

User inputs are separated into several input types: street geometry, number and types of shading elements, calculation setup variables, and different display options. Street geometry assumes a street which consists of a road for vehicular traffic and a sidewalk flanking each of its sides. **Street geometry** is thus parametrically created by defining numerical values for the following elements:

1. **Length and orientation** of the modelled street section.
2. Width of each of the **sidewalks**, calculated as the cumulative width of the following street elements: walking strip, street furniture strip, bicycle lane, and a planting strip. Providing width for the walking strip is mandatory while all other components are optional.
3. **Road** width, calculated as the cumulative width of a traffic strip and an optional parking strip (next to one of the two sidewalks or next to both).
4. The width of an optional central **walking boulevard**.
5. **Building** geometry for each of the street sides separately, created by defining the following components: number of buildings, building depth, front and lateral building line, entrance level height, number of typical floors above entrance level, height of a typical floor, front and lateral setbacks of a typical floor (optional), roof level height, and front and lateral setbacks of the roof level (optional). While building design on each of the street sides is determined independently (which means also that one side of the street can have no buildings at all), the current version of the tool assumes all buildings along a sidewalk are similar and evenly distributed along the sidewalk.

We recommend that the initial calculation of SI and SAI values will be performed without the inclusion of additional shading elements, to evaluate outdoor shade levels resulting from the basic elements of the street: its height-to-width ratio, its building geometry, and its orientation. After performing such an initial calculation, it is easier to consider and explore different shading strategies by adding the three types of shading elements included in the tool: trees, awnings protruding from building facades, and colonnades. It is possible to use each of the three shading element types separately or simultaneously.

The inclusion of trees in the model is done by choosing from a predefined list of tree types representing different tree geometries or by creating custom tree types. **Tree type** geometry is determined by providing numerical values for the following variables: tree trunk radius, tree trunk height, tree canopy radius, and tree canopy height. It is assumed that trees will be planted on one or two rows in each of the sidewalks and the optional central walking boulevard. The type and number of trees in each of these rows, as well as their distance from the curbs, are separately controlled. Users can therefore create an intricate design of tree planting, combining different tree geometries and positions in different planting rows. It is important to note that for keeping radiation calculation times low, tree canopies are represented in the model as uniformly enclosed geometric volumes. This means that unlike real tree canopies, through which some solar radiation is transmitted (usually between 10% to 15% of incident radiation), the modelled canopies do not transmit radiation.

The two other external shading elements are dependent on the predefined building geometries of each of the street sides. Users can set the depth of a **protruding awning** and its height above ground level or the depth of a **colonnade** running along the front façade of each building (a colonnade's height is identical to the height of the ground floor). As with trees, the inclusion of each of these elements is optional.

Before initializing the calculation procedure of the output indices, users are required to define some of the calculation settings. First, to ensure correct calculation of street-level exposure to incoming shortwave radiation, users need to select a standardized weather file reflecting the geographic location of the modelled street from the online EPW repository at climate.onebuilding.org. Next, users can define the date and hours of calculation, although it is recommended to use the default values, which are 6 August between 07:00 and 16:00 (standard time, totalling 10 hours). These default values represent the height of summer and therefore also the height of outdoor heat stress, during which shade is most needed. Other variables that can be defined by the users include some display and results-saving options since results for each run are displayed as a combination of visual and textual outputs (see below).

3.2 Calculation and outputs

Using the input geometry and weather data, the tool applies the Incident Radiation component of the **Ladybug Tools** suit to calculate the cumulative incidence of global solar radiation (direct and diffuse) on all ground surfaces in the street model. For calculating SI values, additional calculation of the solar incidence on an unshaded horizontal reference cell outside the modelled street is simultaneously executed. The **Ladybug** component performs separate calculation for each grid cell of the radiation-receiving surface. Calculation grid size can be controlled by the user: we recommend starting preliminary calculations at a cell size of 4 m but performing detailed calculations at a cell size of 1 m or less. Calculation time of a 200 m long street with a cell size of 1 m may take about 45 seconds.

To determine the SI and SAI values, the raw output of the Incident Radiation calculation is further analysed by the tool based on additional code. Output SI values are calculated for each sidewalk separately, for the central boulevard (if existing), for the road, and for the entire right of way (sidewalks, boulevard, and road) of the street. Output SAI values are calculated for each sidewalk and for the central boulevard (if existing) separately.

Calculation of TCC values for the entire area of the street is based on the geometric properties of the trees and the street. Other calculated outputs relating to trees are the number of trees used in the entire model, and the number of trees per area unit (in our case, a dunam, which equals 1000 sqm) in the entire model, which represents the tree density of the street. When evaluated with respect to the SI and SAI values, these three quantitative outputs can give indications of the added value of increased number of trees in terms of their effect on outdoor shade.

4 Use scenario example

4.1 Baseline geometry

The developed tool is designed to provide relatively quick and straightforward feedback on employing different design strategies for outdoor shade provision in a way that can easily support design decisions based on quantitative outputs. In the following example, set in the Mediterranean city of Tel Aviv-Yafo, we begin with a predefined 200 m long street with a central pedestrian boulevard 15 m wide flanked by two roads 7.5 m wide and two sidewalks 8 m wide (totalling in a right of way 46 m wide). The street is positioned on a north-south axis so that the main building facades on both sides of the streets face east and west respectively. The buildings on each of the street sides have different geometric features, as described in **Table 1**. A 3D rendering of the baseline street geometry, as it is presented to the users, appears in **Fig. 1**.

Shade values for this street design were calculated for 6 August between 07:00 and 16:00 (default calculation time). The results screenshot (**Fig. 2**) details the resulting SI and SAI values, as well as a top-view representation of the radiation exposure levels in kwh per sqm across the entire area of the street, a compass symbol showing the street's orientation, a circle representing the corresponding sky dome indicating the incoming radiation during the calculated hours, and details on the calculated period, location, and source weather file.

While the results of the baseline calculation show relatively low SI values in both sidewalks (0.27), they also indicate that for several hours during that day each of the sidewalks provide good shading conditions (represented by an SAI value of 0.4). This is a result of the combined effect of street orientation and building geometries. While the central boulevard also benefits from some shade cast by the buildings, its SI and SAI values are lower than the corresponding values of each of the sidewalks, because of the relative openness of the central section of the street to the sky.

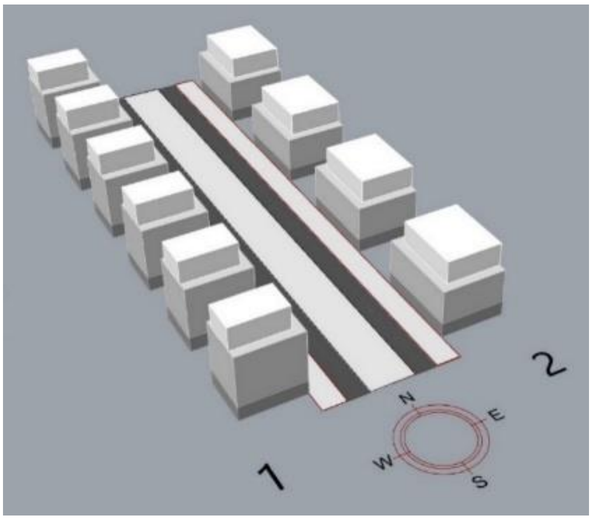


Fig. 1. A 3D representation of the baseline model, before adding shading elements.

Table 1. Street geometry properties of the design example.

Street side	Western (side 1)	Eastern (side 2)
Number of buildings	6	4
Building frontage width [m]	17.3	30
Front building line [m]	0	0
Lateral building line [m]	8	10
Building depth [m]	22	22
Entrance level height [m]	5	5
Number of typical floors	6	4
Typical floor height [m]	3	3
Front setback of a typical floor [m]	0	0
Lateral setback of a typical floor [m]	0	0
Roof level height [m]	8	8
Front setback of a typical floor [m]	3	3
Lateral setback of a typical floor [m]	3	3

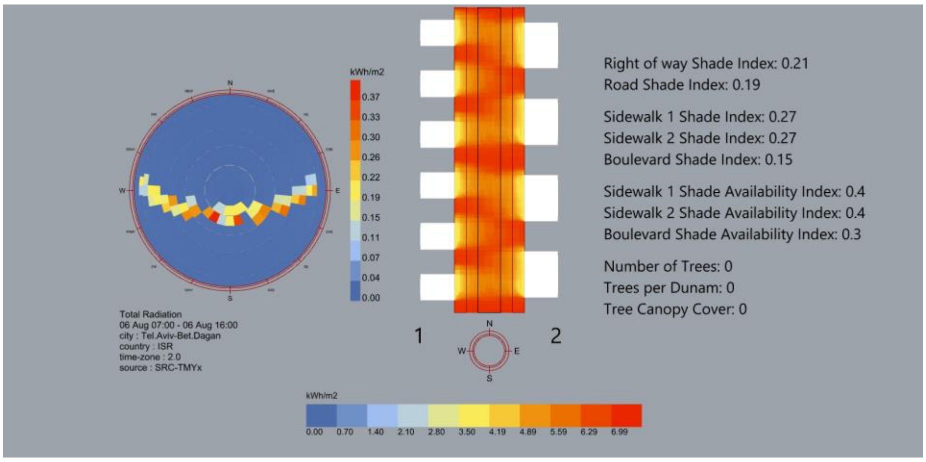


Fig. 2. Results screen of the baseline model.

4.2 Design scenarios for increased shade

Assuming that street and building geometries must be kept unchanged, the baseline results mean that improvement of the shade conditions in the sidewalks and the boulevard has to rely on additional shading elements. The following design steps thus explored several shading strategies: adding one row of trees to the sidewalks or two rows of trees to the boulevard and redesigning the buildings to include a colonnade on each of the street sides (without changing their number, width, or height). Details on the additional shading element in each of the design scenarios (six in total) appear in **Table 2**, while 3D renderings of each design scenario appear in **Fig. 3**.

4.3 Results

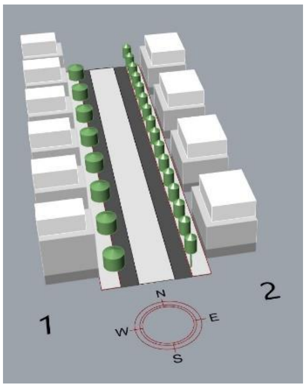
Comparison of the calculation results of the design scenarios and the baseline case (**Table 3**) can assist in understanding the contribution, as well as the limits, of applying different shading strategies. While it is always possible to integrate numerous street trees with wide and lush canopies in a street design to secure high levels of outdoor shade, realistic and effective shade tree planting must recognize the inherent difficulties of providing adequate underground space for achieving a developed tree-root system without which canopies will remain undeveloped and ineffective in terms of shading. This means that when wide canopied trees are part of the design, this must go hand in hand with careful planning of underground technical infrastructures in the trees' vicinity. The bigger the tree canopy, the larger the underground soil volume it requires [35]. The different design scenarios reflect this limitation: they try to balance between the inclusion of a reasonable number of wide-canopied trees and other shading strategies that do not rely on trees.

Table 2. Shading elements description for each design scenario.

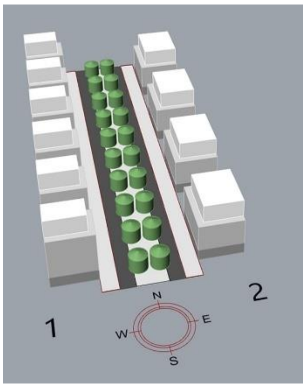
	Design Scenario	A	B	C	D	E	F
Western sidewalk (one row of identical trees)	Number of trees	8	0	0	0	0	0
	Distance between tree trunks [m]	25	-	-	-	-	-
	Tree canopy height [m]	6.4	-	-	-	-	-
	Tree canopy radius [m]	4.5	-	-	-	-	-
	Tree trunk height [m]	1.9	-	-	-	-	-
	Tree trunk radius [m]	0.3	-	-	-	-	-
	Colonnade depth [m]	-	-	-	5	5	5
Eastern sidewalk (one row of identical trees)	Number of trees	16	0	0	0	0	0
	Distance between tree trunks [m]	12.5	-	-	-	-	-
	Tree canopy height [m]	6.8	-	-	-	-	-
	Tree canopy radius [m]	2.5	-	-	-	-	-
	Tree trunk height [m]	9	-	-	-	-	-
	Tree trunk radius [m]	0.3	-	-	-	-	-
	Colonnade depth [m]	-	-	-	5	5	5
Boulevard (two rows of identical trees)	Number of trees	0	10	15	15	15	12
	Distance between tree trunks [m]	-	20	13.3	13.3	13.3	16.6
	Tree canopy height [m]	-	6.4	6.4	6.4	4.0	6.4
	Tree canopy radius [m]	-	4.5	4.5	4.5	2.5	4.5
	Tree trunk height [m]	-	1.9	1.9	1.9	3.0	1.9
	Tree trunk radius [m]	-	0.3	0.3	0.3	0.3	0.3

Table 3. Calculation results for all design scenarios.

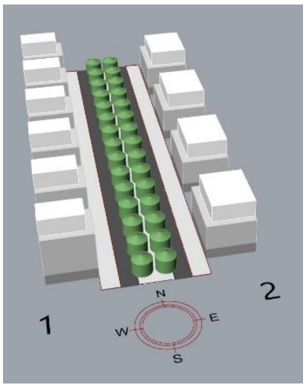
Design Scenario	Baseline	A	B	C	D	E	F
Right of way Shade Index	0.21	0.32	0.39	0.48	0.56	0.39	0.51
Road Shade Index	0.19	0.30	0.36	0.44	0.50	0.34	0.45
Western sidewalk Shade Index	0.27	0.49	0.30	0.31	0.46	0.43	0.46
Eastern sidewalk Shade Index	0.27	0.40	0.30	0.31	0.48	0.45	0.47
Boulevard Shade Index	0.15	0.20	0.53	0.71	0.73	0.40	0.63
Western sidewalk Shade Availability Index	0.40	0.60	0.50	0.50	0.60	0.60	0.60
Eastern sidewalk Shade Availability Index	0.40	0.40	0.40	0.40	0.70	0.60	0.70
Boulevard Shade Availability Index	0.30	0.30	0.50	1.00	1.00	0.50	1.00
Number of trees	0	24	20	30	30	30	24
Trees per dunam [1000 sqm]	0	2.61	2.17	3.26	3.26	3.26	2.61
Street Tree Canopy Cover	0	0.09	0.14	0.21	0.21	0.06	0.17



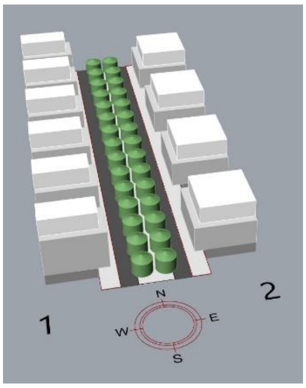
Scenario A



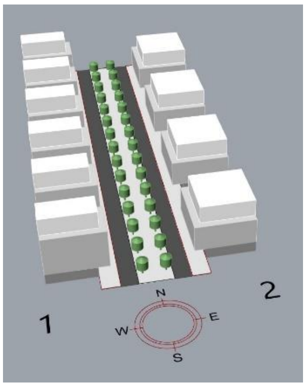
Scenario B



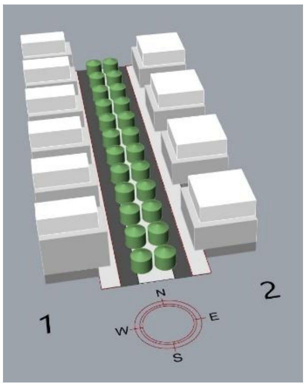
Scenario C



Scenario D



Scenario E



Scenario F

Fig. 3. 3D representations of the different design scenarios of adding different shading elements.

The first design scenario (scenario A) used two different tree types planted along each of the sidewalks (12 trees in each row). Wide-canopied trees were positioned on the western sidewalk, and trees of narrow and high tree canopies (which require less underground soil volume) were positioned on the eastern sidewalk. This difference was reflected in the resulting SI and SAI values of each of the sidewalks, although the eastern sidewalk's SAI remained the same as in the baseline design, marking lower shading efficacy of the narrow-canopied trees used in that sidewalk. Adding two rows of wide-canopied trees to the central boulevard (scenario B) instead of the sidewalk trees significantly improved the boulevard's SI and SAI values, but at the same time had only a small contributing effect to the shading of the western and eastern sidewalks.

Increasing the number of boulevard trees by 50% (from 20 to 30, scenario C) had a significant effect on shade quality in the boulevard (increasing SI values from 0.53 to 0.71 and SAI values from 0.50 to 1.00) but will probably require much higher initial investment because of the doubling of wide-canopied trees. Changing the tree types of the boulevard trees to smaller, and thus less expensive, trees (scenario E) significantly reduced their effectiveness in providing more than reasonable shade in the boulevard. An effective compromise between the number of trees and their shading effect in the boulevard was reflected in scenario F, which was based on slightly reducing the number of boulevard trees from 30 to 24 while still using the wide-canopied trees.

As for the shading of the sidewalks, scenarios D, E, and F integrated colonnades into the building design on both sidewalks instead of the trees. The colonnades provided slightly better SI and SAI values in both sidewalks, making them an effective alternative to tree planting with all its inherent limitations and difficulties. Scenario F (**Fig. 4**) thus reflected a combined shading strategy that while using the same number of trees as in scenario A, significantly increased the shading conditions in all parts of the street.

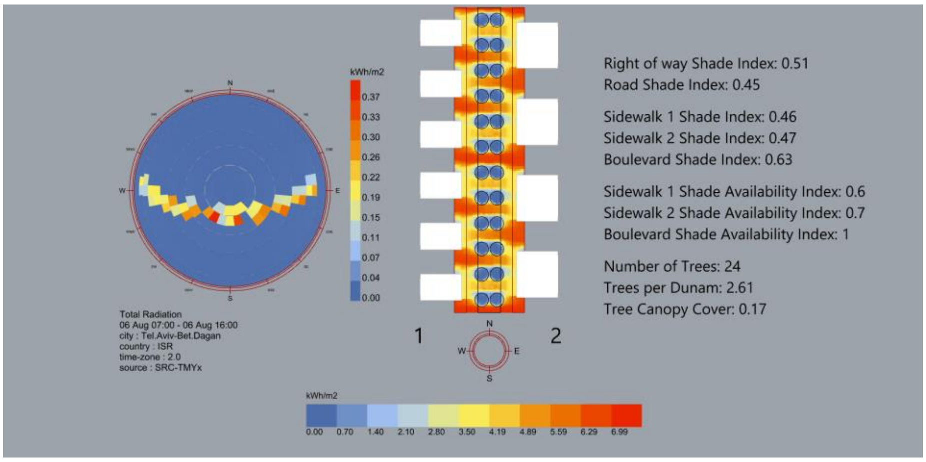


Fig. 4. Results screen of Scenario F model.

5 Discussion and conclusion

The above use example demonstrates the flexibility of the developed tool in analysing outdoor shading conditions under a variety of street and building geometries, as well as the employment of different shading strategies. By providing quantitative and relatively quick feedback on the shading qualities of different design combinations, the tool is expected to enhance user engagement with climatic design and improve the shading efficacy of a variety of design options. While the tool can be used for design optimization, it is more important to use it for considering the advantages and disadvantages of a wide variety of shading alternatives.

Since shade trees are expensive elements to implement and maintain, the tool can help in achieving a reasonable balance of increasing shading conditions while keeping shading costs low. Future versions may also include components that would quantify the financial cost of tree planting based on required tree canopy dimensions and the resulting underground soil volume for the tree's root system. At the same time, the tool also enables the users to quickly understand to what extent the avoidance of tree planting, which is currently perceived as one of the most effective urban design tools for urban cooling [36], may become detrimental to summer thermal comfort of pedestrians and other road users. The visual presentation of street-level shade distribution assists in figuring out better shading options and their possible effectiveness.

While the current level of scientific knowledge in urban climatology can support effective climatic urban design, the implementation of proactive climatic urban design is still generally limited [22, 23]. Arguably, this can be attributed to professional hurdles restricting the ability of design professionals to thoroughly understand and implement the products of scientific research in routine design tasks. The developed tool attempts to streamline the integration of climatic considerations in urban design while bridging the gap between scientific knowledge and design considerations. Users of **Kikayon** do not need to fully understand the intricate and complex nature of microclimatic phenomena in cities. Instead, they can rely on several simple indices that reflect the effect of their design on pedestrian heat stress while concentrating on familiar design tasks as giving shape to a street, its buildings, and its vegetation.

Kikayon is designed as a design-assisting tool and therefore prefers the ease and speed of use over the creation of complex street and building geometries. It substantially differs from common computational tools for urban climate simulation and evaluation of urban morphologies, as, for example, ENVI-met [37] and the UMEP plugin for QGIS [38], in the relative speed of model creation, ease and speed of calculation, and the presentation of the climatic effect of design through several unitless indices that can be easily communicated to professionals with little knowledge in urban climatic processes. This, however, comes with a price, not only because the tool limits itself to shade quantification alone, but also because the street geometries that can be calculated by the tool have to conform to certain design conventions and assumptions. The latter limitation can be addressed in future versions of the tool, which may enable users to perform calculations on street and building geometries that cannot be properly represented using the existing version of the tool. However, user control of a wide range of design features in the current version means that the tool is already useful for analysing numerous instances of real-life urban design scenarios.

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