Guidelines for Applying Quantitative Shade Indicators in Urban Planning in Israel

Or Aleksandrowicz, Naama Shapira, Michelle Clark Levenson, Shachar Zur and David Pearlmutter

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The Center For Urban Forestry And Shading

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GUIDELINES FOR APPLYING QUANTITATIVE SHADE INDICATORS IN URBAN PLANNING IN ISRAEL

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SUMMARY

This document presents a comprehensive methodology for promoting strategic planning for urban shading and for providing planning bodies and planners with standards for quantitative and qualitative assessment of existing and projected levels of shading according to different planning scenarios. The document presents a concise overview that identifies the weak points in contemporary methods for quantifying shading in urban areas in Israel (and around the world), followed by a description of a new method for setting targets for shade planning on urban streets. This method, presented here as part of an overall process for formulating a municipal shading strategy, is based on a new quantitative index developed by the authors – **the Shade Availability Index**.

Promoting shading in urban streets by using trees, as a key part of Israel's environmental response to global warming, lies at the center of Government Decision 1022 of 23 January 2022. In a document entitled **The National Strategic Plan for Urban Shading and Cooling Using Trees**, which was published at the end of 2022 by the Ministry of Environmental Protection, the Israeli Green Building Council, the Ministry of Agriculture and Rural Development, and the National Economic Council, it is possible to read an implicit recognition of the methodological difficulties inherent in implementing the government decision. The document acknowledges that there is still a lack of a widely accepted scientific methodology for setting

urban shading and urban forestry targets and for defining the precise mapping needs resulting from these goals. Without such a methodology, all parties involved in advancing the decision will find it difficult to efficiently and effectively realize the planting of shade trees in Israel's cities, to monitor the progress of actions in this area, and to allocate resources to places where they are specifically needed.

Shading in the urban environment depends entirely on the planning and design of the built environment. Therefore, one cannot expect to find well-shaded streets without giving shade a significant place in the planning processes at different levels. In specific geometric configurations, good shading can be achieved by using the buildings next to the sidewalks. However, securing sufficient shading often requires additional three-dimensional components at the street level, **mainly trees** but also pergolas and other means of shading with fabrics. For planning bodies to meet predefined, measurable shading targets and to optimize the allocation of resources to achieve them, a uniform method must be adopted for accurate quantitative assessment of the cumulative effect of shading from buildings, trees, and any other landscaping elements. **The Shade Availability Index**, which emphasizes shading conditions on sidewalks, was developed for this purpose.

Systematically improving the state of shading on streets requires an **urban shading strategy**. We propose three distinct stages in building such a strategy: **mapping, prioritizing actions, and planning intervention**. At the mapping stage, a shade map should be prepared using a method previously developed by the authors. This method, which was first implemented in a project commissioned by the Tel Aviv-Yafo Municipality (2019), has since been applied in more than a dozen other cities in Israel. Such an urban shade map reveals a city's hierarchy of "shade assets," namely, which street segments are well shaded and which are so poorly shaded that walkers would suffer severe exposure to solar radiation during the hot season. Based on such a shade map, a municipality can identify the city's climatic vulnerabilities and prioritize actions to significantly ease the heat stress in its area. Prioritization must stem from a set of municipal considerations that include – alongside the state of shading – economic, social, demographic, and transportation-related considerations.

The detailed shade planning that follows the identification of weak spots and prioritizing shade intensification is intended to ensure that the practical actions taken by a municipality will bring about a significant change in the shading conditions within a reasonable period. By definition, the planning process is expected to involve examining various alternatives, the comparison of which must be based, first and foremost, on meeting measurable shade threshold targets. **The Shade Availability Index** is designed to meet this need.

The Shade Availability Index is calculated for each of the walking strips or sidewalks in a street segment, since our priorities lie in the shading and cooling of urban walking spaces. The index is calculated by measuring the amount of shaded space on each sidewalk at ten hourly intervals between 08:00 and 17:00 on a typical summer day in early August (**the reference**

time for calculating the index), since this is the time when the outdoor heat stress peaks under the prevailing climatic conditions in Israel. At each of these ten times, we examine the ratio between the shaded area of the sidewalk and the total sidewalk area. A point in time when the shaded sidewalk area exceeds 50% of the total sidewalk area is considered to be a point in time when the sidewalk is **sufficiently shaded**.

The **Shade Availability Index** describes, on a scale from 0 to 1, the relative proportion of time a sidewalk or walking strip is **sufficiently shaded** during the reference time. For example, when the shaded sidewalk area is 50% or more at four out of ten time points, the Shade Availability Index is 0.4. The index treats a point in space as a shaded point if it is not hit by direct solar radiation. For simplification, the calculation does not consider the effect of reflected radiation, which may cause slight differences in the intensity of light radiation at the shaded point. The calculation of the Shade Availability Index assumes that buildings and shading devices on the street are more or less distributed along it at regular intervals. In cases where the nature of construction or shading in a particular street segment varies substantially along its length, the Shade Availability Index must be calculated separately for each part of the street segment in which the shading is more or less uniform.

Based on the **Shade Availability Index**, it is also possible to set normative shading targets for shading on sidewalks. We suggest setting the following three levels of shading targets:

Acceptable shading	**Very good shading**	**Excellent shading**
Shade Availability Index value of 0.5 or higher	Shade Availability Index value of 0.7 or higher	Shade Availability Index value of 0.9 or higher

As explained above, this index reflects **a relative length of time** in which sufficient shading conditions are met, with sufficient shading meaning that at least 50% of the pavement area is shaded. Therefore, it can be said that a sidewalk with **acceptable** shading provides sufficient shading conditions during at least half of the relevant daylight hours (08:00-17:00) on a summer day. **Excellent** shading is obtained when these shading conditions are met at least 90% of the time. In contrast, a sidewalk cannot be considered genuinely shaded if the required shading conditions are met for less than 50% of the reference time.

The Shade Availability Index does not assign different weightings to shading at different times, even though the intensity of solar radiation varies throughout the day. This is because, during the reference time (most of the daylight hours on a typical summer day), the need for shading is equally important at almost all times. Without shade, the heat stress is expected to be extreme at almost all times during the day, even if the physical effect of radiation on the perceived heat stress differs slightly. The index does not distinguish between continuous sidewalk shade and alternating light and shade patches along the sidewalk as long as the total shaded area exceeds half of the sidewalk area. The reason for this is that we believe that when half of the area of a sidewalk is in continuous shade, street users can choose equally between moving in the shade or being exposed to solar radiation. When at least 50% of the sidewalk area is in intermittent shade, the sidewalk user will enjoy a sufficiently shaded walking path from one end of the street segment to another, even though the shaded area of the sidewalk also includes intermittent patches of solar exposure.

As part of the process of developing the normative rating of the Shade Availability Index, we also conducted a comprehensive parametric examination of thousands of planning scenarios to examine whether it is possible to meet the three levels of shading described above in the planning of main and side streets, assuming that the height of buildings on the street is four stories or more. The examination revealed that it is indeed possible to reach the upper threshold that we defined (Shade Availability Index of 0.9 or more) in most reasonable planning scenarios on main streets and in any reasonable planning scenario on side streets. However, to reach this state, it will be necessary to plant **shade trees** in many cases. This is true regardless of a street's orientation, although, in certain directions and geometric configurations, the highest shading threshold can be met through buildings alone.

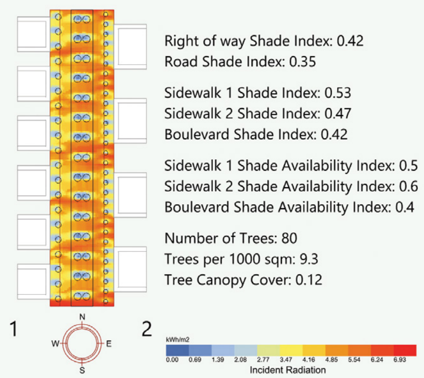
In this context, it is important to emphasize that **shade trees** are trees whose crown (all the branches and leaves) is sufficiently wide and dense to cast a relatively uniform shadow on the ground. Therefore, not every tree planted in built-up areas is a shade tree, even if the tree itself is of a species recommended for street planting. The design assumption should be that a tree defined as a shade tree will be a tree whose growing, pruning, and maintenance conditions during the hot season will allow its crown to block at least 90% of the direct sunlight falling on the top layer of the tree crown and whose shade on the ground is continuous and relatively uniform. The presence of trees in urban spaces may have positive or negative environmental impacts regardless of the shade they cast, and these effects should be considered when designing shading that is at least partially based on the use of shade trees. However, the Shade Availability Index is not intended to examine these effects quantitatively; rather, it is limited to quantifying the effect of shade trees on the state of shading on sidewalks.

Stages in formulating and implementing an urban shading strategy

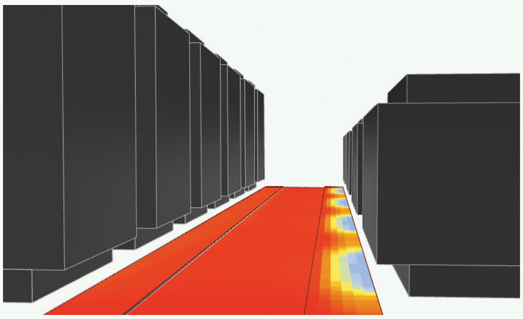
1 | **MAP the urban shade hierarchy by using shade maps**

2 | **PRIORITIZE intervention sites for shade intensification or shade preservation**

3 | **DESIGN shading according to the Shade Availability Index**

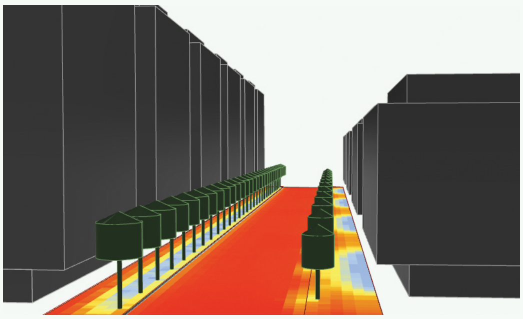


Shading levels rated according to the Shade Availability Index (SAI)



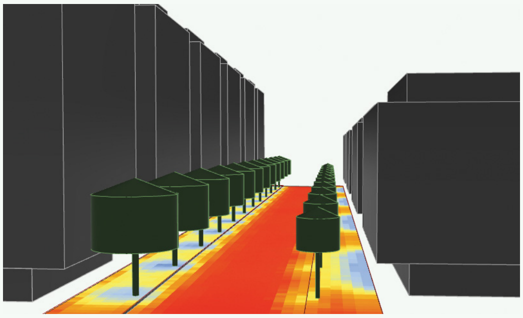
Insufficient shading

SAI < 0.5



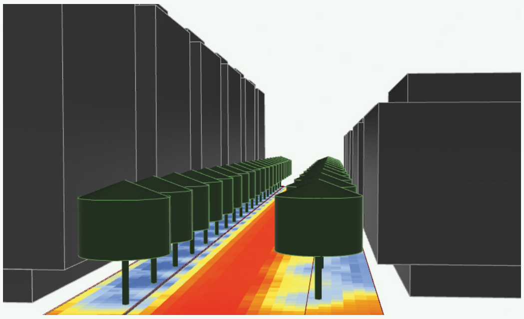
Acceptable shading

SAI ≥ 0.5



Very good shading

SAI ≥ 0.7



Excellent shading

SAI ≥ 0.9

INTRODUCTION | THE CHALLENGE OF QUANTIFYING SHADE IN URBAN ENVIRONMENTS

In Israel, it is expected that during the coming decades there will be a gradual increase in air temperatures during the warmer months alongside an increase in the duration and frequency of heat waves due both to global climate change and to the spatial distribution and densification of urban concentrations, which are exacerbating the urban heat island phenomenon. These changes will lead to a significant increase in the intensity of the heat stress experienced by users of urban spaces unless preliminary actions are taken to alleviate it. Already today, in the climatic conditions prevailing in Israel over many months of the year (at least between May and November), exposure to solar radiation – both direct and indirect – is the main environmental factor causing a substantial increase in the heat stress intensity experienced during the daytime, with an attendant sharp decline in outdoor thermal comfort.[1] In addition, exposure of outdoor spaces to direct sunlight for a significant number of hours each day leads to warming of the entire urban environment in the evening and early hours of the night,

1 Aleksandrowicz, O., & Pearlmutter, D. (2023). The significance of shade provision in reducing street-level summer heat stress in a hot Mediterranean climate. *Landscape and Urban Planning*, 229, 104588.

increasing the intensity of heat stress during these hours both inside and outside buildings and, hence, increasing the energy consumption of air-conditioning systems.

Planning actions can lead to a decline in air temperatures or an increase in wind speeds in urban environments. Still, in the climatic conditions prevalent in Israel, these actions generally have a limited impact on improving thermal comfort. Nonetheless, an aspect of planning that can significantly alleviate heat stress at its current and predicted levels (with the expected increase in air temperatures due to climate change) is to ensure significant and continuous shading along streets and in open public spaces. Importantly, shading in the urban environment has the additional advantages of reducing skin cancer morbidity, moderating the urban heat island phenomenon, reducing energy consumption for cooling indoor spaces, and improving the physical conditions that could increase walkability in urban spaces.[2]

Shading in the urban environment is closely dependent on the planning and design of built-up areas. In specific geometric configurations, good shading can be achieved by benefiting from the shadows cast by buildings next to sidewalks. However, securing sufficient shading often requires additional three-dimensional components at the street level, such as pergolas, shading fabrics and, especially, trees. Trees offer additional advantages beyond shading, namely, reducing the pollution of air and

2 Knesset – Research and Information Center (2022). *Shading policy in public spaces* [in Hebrew]; Ministry of Environmental Protection, Israeli Green Building Council, Ministry of Agriculture, National Economic Council (2022). *A national strategic plan for shading and cooling the urban space using trees* [in Hebrew].

surface water sources, contributing ecologically as a habitat for a variety of animals, improving the esthetic appearance of the built environment and, to a certain extent, regulating surface runoff.[3] Studies from around the world also point to other possible advantages of planting trees along streets, such as increasing business productivity[4] and real estate values.[5] However, shading urban spaces with trees requires financial and other resources to allow for significant soil volume and root growth and ongoing maintenance (pruning, irrigation); without this investment, it is highly likely that a tree crown (all the branches and leaves) will not provide effective shading. Moreover, new plantings of trees usually do not provide an immediate solution to the lack of shade, since a mature shade tree develops a significant shade-providing crown only a decade or more after planting, and even then, only if it has received adequate growing conditions.[6]

Promoting the shading of urban streets using trees, as a key part of Israel's environmental response to global warming, lies at the center of Government Decision 1022 of 23 January 2022.[7] That Decision was based on a report compiled by an inter-ministerial team led by the National Economic Council.[8]

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3 Tyrväinen, L., Pauleit, S., Seeland, K., & de Vries, S. (2005). Benefits and uses of urban forests and trees. In C. Konijnendijk, K. Nilsson, T. Randrup, & J. Schipperijn (Eds.), *Urban Forests and Trees* (pp. 81-114). Springer.

4 Wolf, K. L. (2005). Business district streetscapes, trees, and consumer response. *Journal of Forestry*, 103(8), 396-400.

5 Song, X. P., Tan, P. Y., Edwards, P., & Richards, D. (2018). The economic benefits and costs of trees in urban forest stewardship: A systematic review. *Urban Forestry & Urban Greening*, 29, 162-170.

6 Galon, I., and Heller, A. (2013). *Guide to Street Trees in Israel* [in Hebrew]. The Ministry of Agriculture and Rural Development and the Ministry of Environmental Protection.

7 The Israeli Government Decision No. 1022 of 23 January 2022. *Shading and cooling the urban space using street trees as part of climate change preparedness* [in Hebrew].

8 National Economic Council, Prime Minister's Office (2022). *Promoting street trees in Israel's cities – shading and cooling the urban space using street trees in preparation for climate change* [in Hebrew].

The team was cognizant of the immense benefit of street trees – from the environmental, health, social, and even economic perspectives – and of their importance in the country's preparedness for climate change. Yet, they also concluded that many barriers remain to sustaining and further developing the presence of street trees in Israeli cities, both at the planning stage and at the implementation and maintenance stages, partly due to a lack of the data required for effective planning. In a document entitled **The National Strategic Plan for Urban Shading and Cooling Using Trees**, which was published at the end of 2022 by the Ministry of Environmental Protection, the Israeli Green Building Council, the Ministry of Agriculture and Rural Development, and the National Economic Council, it is possible to read an implicit recognition of the methodological difficulties inherent in implementing the government Decision.[9] The document acknowledged that there is still a lack of a widely accepted scientific methodology for setting urban shading and urban forestry targets and defining the precise mapping needs generated by these targets. Without such a methodology, all parties involved in advancing the Decision will find it difficult to efficiently and effectively realize the planting of shade trees in Israel's cities, to monitor the progress of actions in this area, and to allocate resources to places where they are specifically needed.

Establishing an agreed-upon measurement method of shade in urban spaces is thus critical for regulatory, planning, and design purposes.

9 Ministry of Environmental Protection, Israeli Green Building Council, Ministry of Agriculture and Rural Development, National Economic Council (2022). *A national strategic plan for shading and cooling the urban space using trees* [in Hebrew]. See also a more recent version of the plan: Yelinek, A. & Schvetz, K. (2023). *A national strategic plan for shading and cooling the urban space using trees* [in Hebrew]. Israel Green Building Council.

However, qualitative or quantitative delineation of the required shade levels raises methodological difficulties, which stem first and foremost from the need to define what shade is, how to quantify it spatially, and at what times of the day it is especially important. Another point that requires clarification is the basic spatial unit for measuring shade, since different levels of shading can be calculated for different spatial units, such as a segment of a street that includes the right-of-way as a whole (the entire street area dedicated to public use), an entire sidewalk, or the effective walking area on a sidewalk.

This document describes a comprehensive methodology for answering these questions with the aim to provide planning bodies and urban planners with standards for quantitative and qualitative assessment of existing and projected levels of shading according to different planning scenarios. The document thus presents a concise overview that identifies the weak points in contemporary methods for quantifying shading in urban areas in Israel (and around the world), followed by a presentation of a new method for setting targets for shade planning on urban streets. This method, presented here as part of an overall process of formulating a municipal shading strategy, is based on a new quantitative index, the **Shade Availability Index**, which emphasizes the shading conditions on **sidewalks** in the spirit of Government Decision 1022. In addition to a detailed description of the index and the targets derived from it, this document also includes systematic demonstrations of the application of the index under various planning conditions and an analysis of the feasibility of meeting the normative targets that we set in this work in the practical planning of streets in Israel.

EXISTING METHODS FOR QUANTIFYING SHADE IN URBAN SPACE

Shading in urban environments has received systematic attention in a few places around the world within the framework of various document types- master plans, planning standards and guides, health guidelines, guidelines for coping with heat, and design recommendations. In general, these documents emphasize the health, social, environmental and economic benefits of shade in general and of trees in particular, such as reducing the intensity of the urban heat island, encouraging physical activity, reducing energy consumption, improving air quality, managing surface runoff, supporting biodiversity, and more. However, while some documents include binding standards, others simply treat shading as a general recommendation. It is not always possible to learn from publications that present spatial shading requirements or recommendations to what extent these documents have binding validity, although some of them refer to other official binding instructions.[10]

Policy documents dealing with shading have been published in a relatively limited number of places around the world. Many of them point to the need

10 A comprehensive review of the subject is presented in the preliminary report prepared as part of this project, see: Shapira, N., & Aleksandrowicz, O. (2024). *Review and analysis of methods for evaluating, quantifying and promoting shade in urban spaces* [in Hebrew]. BDAR Lab, Technion, and Samuel Neaman Institute.

to give priority to shading projects so that maximum social and environmental benefit is achieved, subject to the availability of economic means, but this is often done without setting quantitative targets or a method of prioritizing action based on a quantitative scale of the quality of shading in different spaces. For example, some of the documents state that shaded locations should be promoted as part of street design or as an effort to ensure optimal shading, but at the same time do not provide an objective quantitative definition of such a “shaded location” or of what can be regarded as “optimal shading conditions.”

The most detailed and extensive documents identified in our work were published in Abu Dhabi, southeastern Australia, and Arizona (USA), and all offer a quantitative method of measuring shade. The purpose of these documents varies according to the climatic characteristics of the region and the nature of the body that commissioned the publication. In Abu Dhabi, shading guidelines were included in guides for sustainable planning of public spaces. In Australia, shading first appeared in policy documents dealing with skin cancer prevention, although in recent years, it is evident that shading is increasingly being presented there as an important means for mitigating heat stress. In Arizona, emphasis was placed on increasing thermal comfort through shading as a basis for encouraging non-motorized transportation, while recognizing that shading also has a place in reducing the intensity of the urban heat island. Nonetheless, despite their different aims, the way in which these documents approach shade quantification is similar (Table 1): shade is calculated in a simple geometric way, as the ratio between the projection area of the shading devices (including trees) on a shaded horizontal surface and the area of a reference space that these devices are intended to shade. This reference space can be a street segment, a public park, a square, a neighborhood, or even an entire city.

Table 1: Summary of shade indexes in different countries

	Abu Dhabi[11]	Arizona[12]	Australia[13]
Purpose of shading	Improving thermal comfort (sustainable urbanism)	Creating thermal comfort for a safe and healthy future	Urban cooling alongside health aspects
Type of shading	Natural and artificial	Natural and artificial	Mainly natural
Shade calculation method	Geometric (projection of shading devices on a horizontal surface relative to the reference area)	Geometric (projection of shading devices on a horizontal surface relative to the reference area)	Geometric (projection of shading devices on a horizontal surface relative to the reference area)
Minimal shade ratio	Streets 60–75%; open public spaces 60%; seating areas 70%; cycling routes 50%; playgrounds 90%; parking spaces 40%	For a period of 20 minutes (walking or waiting), minimum acceptable shading is 20%; good shading is 30%, and excellent shading is 60%	30% urban tree canopy cover; on paths, a tree every 15 m; parking lots 10%; and specific reference to sensitive facilities (education, health)
Takes tree growth time into account	Yes (measured 5 years after planting and when the tree reaches its full growth potential)	No	No
Reference time	13:00, 21 March and 21 June	12:00-18:00, May to October	09:00-15:00
Definition of a shaded area	1.8 m wide strip along the street's walking area		

11 Abu Dhabi Urban Planning Council (2010). *The Pearl Rating System for Estidama Community Rating System*; Abu Dhabi Urban Planning Council (2016). *The Pearl Rating System for Estidama Public Realm Rating System*.
12 Nature's Cooling Systems Project (2019). *Heat Action Planning Guide, for Neighborhoods of Greater Phoenix*. Creating Urban Heat Solutions in the Valley of the Sun.
13 Stoneham, M., Earl, C., & Baldwin, L. (2007). *Creating shade at public facilities: Policy and guidelines for local government* (second edition). Australian Institute of Environmental Health (AIEH), Australia; Low Carbon Living CRC (2017). *Guide to Urban Cooling Strategies*; Coutts, A., & Tapper. N. (2017). *Trees for a cool city: Guidelines for optimised tree placement*. Melbourne Australia: Cooperative Research Centre for Water Sensitive Cities.

However, several points are not addressed in the above documents, as follows:

- A measurement of 'urban tree canopy cover,' in which a single average value is taken to represent the state of the urban forest throughout a city, is far from a suitable metric for providing a good understanding of possible spatial variations in the distribution of urban tree resources. For example, when the urban boundaries include 'green belts' on the city's outskirts, they positively affect the urban tree canopy cover ratio (the ratio of the total area of vertical projections of tree crowns within a given spatial unit to the total area of the same unit), thereby concealing any lack of canopy cover in certain inner-city neighborhoods.

- Similarly, determining a target tree canopy cover ratio in a given space or a street without addressing either shade continuity in that space or the changing pattern of shading during the daytime and over the different seasons may yield design solutions whose effectiveness is limited.

- When shade is calculated based on the projection area of the shading element on a horizontal surface (such as the tree canopy cover ratio), this representation does not reflect a realistic situation because, in the vast majority of cases, the sun is not located at its zenith (an angle of 90 degrees relative to the ground surface), but at lower angles. This method thus ignores the varying radiation intensity of the sun during the daytime and over the seasons and the changing angles of direct solar radiation, which sometimes causes the shade to fall far from the shading device itself (for example, a tree whose crown casts a shadow on the road beside it rather than on the sidewalk where it is planted). For the same reason, this calculation method ignores the contribution of buildings to street shading, even though this contribution may be significant in some cases.

- Since the spatial coverage of shade varies from hour to hour and season to season, a broad definition of a reference time (e.g., 11:00-15:00 between April and September) does not take into account the significant differences in the sun's position in the sky and in radiation intensity during these months and times. An overly broad definition may lead to the implementation of shading solutions that do not provide an optimal response precisely when heat stress is at its peak.

- The assumption that the various means of shading (trees, fabrics, netting, pergolas, etc.) entirely block direct solar radiation is inaccurate in most cases. The methods for calculating shade coverage usually ignore differences between shading materials and give equal treatment to shading devices that are significantly different in terms of penetration of solar radiation.

In Israel, adequate shading in the public sphere is currently promoted through various policy tools. Mandatory guidelines for shading are mainly dedicated to protecting vulnerable populations in areas with significant sun exposure and only for defined spaces, particularly educational institutions, playgrounds, swimming pools, and beaches. It can be learned from discussions held on the subject that the main motivation for adopting these regulations derives from health and safety considerations (protection against skin cancer and sunburn), with little emphasis on thermal comfort in outdoor urban spaces.[14] However, even the most up-to-date and detailed regulations on the subject, relating to the shading of playgrounds, do not provide a sufficiently clear description of how shading should be implemented in those spaces. Although the regulations do define both a reference time for measuring shade and the quality of shading ("the thermal conditions obtained by a shading solution, including shade density, preservation of shading conditions over time, and thermal comfort"), the regulations stipulate that shading should be planned and implemented by taking these conditions into account, but they do not specify any mandatory quantitative values. Likewise, the definition of what constitutes shade ("an area where the sun's rays do not reach directly") implicitly assumes that any surface used for shading fully absorbs direct sunlight, but this situation rarely exists in reality. Moreover, the regulations relate solely to shading playgrounds' play facilities and do not relate to the shading of adjacent seating and rest areas or to access paths to playgrounds and their facilities. The conclusion that can be drawn from the above review is that, **in practice, there are currently no binding guidelines in Israel for the planning of shading in urban streets, and hence no regulatory devices for improving thermal comfort during the hot season in the public spaces of Israeli cities.**

The gap between the desire to significantly improve the state of shading in urban spaces and the lack of quantitative tools for shade planning has

14 For example, see the Knesset's Special Committee on Children's Rights, meeting on 14 July 2015, on 'shading in playgrounds.' Protocol No. 8.

led, in recent years, to initial attempts to propose a comprehensive method for quantifying shade in different types of urban spaces, particularly urban streets. The **Open Space Shade Policy Planning Guidelines**[15] prepared by Tami Hirsh and Shachar Zur for the Tel Aviv-Yafo Municipality in 2017 is perhaps the first policy document published in Israel on urban shading that includes comprehensive quantitative indexes. The document, which is not binding, deals with artificial and natural shading solutions (including shading from buildings) for shading different spaces in the city, including streets, open spaces, outdoor areas of educational, sports and community buildings, and parking lots. Shading is quantified by a geometric calculation of the area of a horizontal plane's shade coverage relative to that plane's total area. According to these guidelines, the shaded area should cover at least 80% of the reference area in the following locations: places of interest, public gathering areas (playground facilities, seating areas, etc.), passageways, and streets (where 80% continuous coverage is required, but only on one of the two sidewalks). The document sets lower shade levels for school yards and underground parking lots (50%), squares and plazas (40%), and sports centers and green areas, such as parks (20%). The document does not explain why the quantitative shading thresholds were set as they were or the reason for distinguishing between the required shading thresholds for different types of open spaces. In addition, the document does not clearly refer to how the boundaries of the reference area should be calculated in areas whose definition is vague (for example, how the

15 Hirsh, T., & Zur, S. (2017). *Open space shade policy planning guidelines for landscaping and architectural design plans and municipal projects*. City Architect's Office, Tel Aviv-Yafo Municipality.

boundaries of different “places of interest and gathering places” are determined).

The document specifies nine reference times for which the reference space must meet the required shading threshold: three points in time (10:00, 13:00, and 16:00) on each of three reference days (21 June, 21 August, and 21 October). The document does not explain the choice of these dates, but it can be assumed that the intention was to represent the state of shading during daylight hours in the early summer, at the height of summer, and in autumn. The guidelines do not include a clear explanation of the tool by which the shade projection was calculated for the reference area, but it does recommend performing the calculation using 3D modeling software available on the market (such as AutoCAD, Revit, SketchUp, and Rhino).

Alongside the quantitative calculations, the guidelines document presents a method for evaluating shade quality, which includes four aspects of the impact of a shading device on the local climate in its vicinity (in terms of air temperature, humidity, heat emission, and ability to serve as a wind break), two aspects of comfort and health (light transmission and protection from UV radiation), and two aspects of maintenance (lifespan and frequency of maintenance). Each shading medium (natural or artificial) is graded according to each aspect (on a three-level scale: satisfactory, neutral/ medium, and very good). In addition, the document presents four basic conditions for the cultivation of healthy and long-living shade trees in paved areas, defines recommended shade trees, and provides guidelines for shade planning according to the type of open urban space, such as preference for natural shading solutions, selection and cultivation of trees that will ensure quality long-term shading, planning complementary shading solutions for different stages during the tree growth, and minimal spacing between trees. However, the document does not provide a practical tool for comparing planning alternatives or examining the applicability of the shading thresholds it sets in different planning scenarios.

Policies and Guidelines for Shading in Public Urban Spaces were developed in 2017-2019 by a research team led by architect Naomi Angel (the then Tel Aviv District Planner at the Planning Authority), Limor Shashua-Bar, Aviva Peeters, and Smadar Meir. The work, which did not receive a binding status and was not published as an official document of the Planning Authority, focused on shading streets, walking routes, and bicycle paths.[16] The study aimed to establish quantitative and qualitative criteria for planning continuous shade in public urban spaces and to formulate guidelines for optimal shading. The study determined that the purpose of shading is **to completely prevent** heat stress on the human body (complete thermal comfort), and quantitative targets were derived from this goal by using a new index designated the **Open-space Shading Index** (OSI). The index was developed based on a series of sample climate measurements on urban streets and thermal simulations in which various daytime planning scenarios were examined in July on the Israeli Coastal Plain.

16 The work was presented at plenary session 865 of the Tel Aviv District Committee on 3 September 2018. A summary of the work was published in the article: Peeters, A., Shashua-Bar, L., Meir, S., Shmulevich, R. R., Caspi, Y., Weyl, M., Motzafi-Haller, W., & Angel, N. (2020). A decision support tool for calculating effective shading in urban streets. *Urban Climate*, 34, 100672.

The Open-space Shading Index is essentially a geometric index that sets targets according to the ratio between the projection area of the shading devices on a horizontal surface and the reference area (in most cases, the right-of-way area in a street segment). The index distinguishes between the shade quality of different shading devices. It gives different weightings to trees of different foliage densities and artificial shading devices, with dense foliage trees receiving the greatest weight. Thus, for example, it was determined that on a street with trees with dense foliage, canopy cover of at least 60% of the right-of-way area is required, but if shading is achieved by using pergolas alone, a higher percentage of coverage of at least 85% will be required. The study did not examine the ease with which the shading targets could be achieved in different urban morphologies or the extent to which its targets are already being realized in urban spaces in Israel.

The reliance of the Open-space Shading Index on calculating the vertical projection area of shading devices ignores the difference in shade projection patterns in different street directions, for different street canyon configurations, and at different times. While these properties were implicitly taken into consideration, since the index was developed on the basis of thermal simulations for a street with an east-west orientation and for a street height-to-width ratio of 1, this specific scenario represents an extreme lack of shade that is not typical of many planning situations. Hence, the work set sweeping shading targets without distinguishing between different urban morphologies for which it was perhaps possible to secure thermal comfort in the summer even when design thresholds were lower. In addition, the assumption that shading can provide thermal comfort in the Israeli summer (although supported by several sample measurements conducted in the Greater Tel Aviv area) is inconsistent with the findings of our study based on measurements at hundreds of points that we conducted in Tel Aviv and Kfar Saba. Our study showed that, in many cases in the summer, excellent shading is not a guarantee of complete thermal comfort, although it is essential for a significant reduction in daytime heat stress.[17] It follows that in formulating a quantitative index for shading, it makes sense to focus on **the relative contribution** of shade to a significant reduction in heat stress, rather than its **absolute contribution** to full thermal comfort in summer.

17 Aleksandrowicz, O., & Pearlmutter, D. (2023). The significance of shade provision in reducing street-level summer heat stress in a hot Mediterranean climate. *Landscape and Urban Planning*, 229, 104588.

FORMULATION AND IMPLEMENTATION OF A SHADING STRATEGY FOR URBAN AREAS: A PROPOSED METHOD

The method described in this document is intended to provide practical tools for quantitative assessment of existing or projected shading conditions in urban environments at various scales of urban planning. At the national level, the described evaluation method can be used to set realistic national targets for shading, to formulate binding regulations for the integration of shading into master plans, and to set targets in government-supported tenders for the actual implementation of plans for additional shading in urban spaces. At the local level, the method can be used to formulate strategic shading plans, to design basic street segments in new neighborhoods, and to plan the inclusion of additional shading components into existing street segments.

In the method we propose, determining an urban shading strategy is based on a three-stage process (Table 2): mapping the urban shade hierarchy; prioritizing intervention areas for shade intensification; and detailed shade design on the scale of a single street segment. The method we present for mapping urban shade hierarchy has already been described by the authors in a previous publication and has been applied in more than a dozen cities in Israel to date;[18] therefore, we include only a concise description of it here. Prioritizing intervention zones involves local urban considerations that go beyond strict climatic considerations, and, therefore, this stage is only outlined in general. The greater part of the current document is devoted to describing the method for setting normative quantitative shading targets and applying them in detailed plans. This method, presented here for the first time, is based on a new index, the **Shade Availability Index** (SAI), described in detail below. The method is equally suitable for redesigning existing streets and for planning future streets within the framework of urban master plans.

Table 2: Applicability of the proposed work stages to different planning scenarios

	Mapping shade hierarchy	Prioritizing shading actions	Detailed shading design
Setting a national policy	✓	✓	✓
Formulating an urban strategy	✓	✓	✓
Drawing up an urban master plan		✓	✓
Detailed design of a street segment			✓

18 Aleksandrowicz, A., Zur, S., Lebendiger, Y., & Lerman, Y. (2019). *Shade maps and their application for shade conservation and intensification in Tel Aviv-Yafo: Final Report*. Submitted to the Conservation Department, Tel Aviv-Yafo Municipality.

Mapping an urban shade hierarchy: the spatial Shade Index

Urban areas develop over time according to different planning concepts, resulting in significant differences in built-up density and in the presence of shade trees or other means of shading in public spaces. Often, climatic issues, including the shading of public spaces, are not taken into consideration during planning and do not serve as a benchmark for examining planning quality. As a result, many streets in Israel, including main streets that serve a wide public, do not provide even minimal protection against exposure to solar radiation (direct, diffuse, and reflected) during the hot season. In light of this situation, the first step in determining an urban shading strategy is a detailed mapping of the urban shade hierarchy to identify the climatic vulnerabilities in existing urban street networks.

Urban shade maps are maps that visually present shading levels in urban spaces in the high resolution required to understand the specific state of shading at each point in the city from the perspective of non-motorized road users (pedestrians, cyclists, etc.). Such maps must be based on a clear and reproducible quantitative index that will allow a simple comparison between the levels of shading prevailing in different urban public spaces. We propose to prepare urban shade maps according to the spatial **Shade Index** (SI), using a method that we have already applied in more than a dozen cities in Israel.[19] The spatial Shade Index describes, on a simple scale from 0 to 1, the extent to which the cumulative direct effect of solar radiation at ground level is blocked during a typical summer day. The proportion of blocking depends on the position of the sun in the sky at any given hour, the intensity of the sun's radiation at that time, and the three-dimensional characteristics of the urban space (width of the right-of-way, height and density of buildings, tree density, and the height, projection area and density of tree crowns). The state of shading that a shade map reflects may change significantly due to significant changes in the built environment (for example, the demolition of buildings, the extension of existing buildings, or the erection of new structures) and the urban forest (for example, felling or pruning of trees, planting new trees, or the rapid crown growth of young trees). Therefore, it is recommended that urban shade maps be prepared at regular intervals of at least three to five years, a period of time that allows monitoring of substantial changes in buildings and trees and evaluating the benefit derived from targeted projects to improve the state of shading in a city.

A shade map of streets and open public spaces will facilitate the presentation of the shade hierarchy in the main walking spaces in a city. In such a map, an average spatial Shade Index is calculated for each street segment (a part of a street bounded between two road junctions, covering the segment's entire right-of-way) and for every open public space. For

19 Ibid., and also: Aleksandrowicz, O., Zur, S., Lebendiger, Y., & Lerman, Y. (2020). Shade maps for prioritizing municipal microclimatic action in hot climates: Learning from Tel Aviv-Yafo. *Sustainable Cities and Society*, 53, 101931; Aleksandrowicz, O. (2022). Mapping and management of urban shade assets: a novel approach for promoting climatic urban action. In A. Khan, H. Akbari, F. Fiorito, S. Mithun, & D. Niyogi (Eds.), *Global Urban Heat Island Mitigation* (pp. 1–27). Elsevier.

example, a shade map of the streets and open public spaces of the city of Holon (Figure 1) shows a wide range of shading levels, from a Shade Index of 0.0 (i.e., no shading at all) to 0.75 (i.e., three-quarters of the cumulative global solar radiation on a summer day is blocked before reaching the ground surface). However, a statistical analysis shows that the Shade Index in most street segments in the city ranges from 0.10 to 0.30, i.e., between very low and moderately low levels of shading. Based on this map, it is, therefore, possible to easily identify segments of streets and open spaces where shading conditions are extremely low, to distinguish between places where shading conditions are relatively high, and based on this hierarchy to prioritize, in combination with other planning considerations, concrete and focused actions to improve the state of shading.

The spatial Shade Index also makes it possible to calculate average shading levels in neighborhoods or urban areas with predefined boundaries (such as districts, planning zones, and statistical zones). For example, a **zonal shade map** showing the average shading situation in urban zones of the city of Holon (Figure 2) reveals significant differences in shading between the city's older neighborhoods (mainly in the north of the city) and the large industrial zone in the eastern part of the city. It can also be seen that in an area in the heart of the city, where some of the museums and main public buildings are concentrated, the general level of shading is relatively low compared to that in the residential neighborhoods around it. Such an analysis, combined with additional data associated with the same zones or neighborhoods, will allow planners to focus on defined areas where shading conditions are significantly lower on average than in other areas of the city, even if the target areas contain street segments where shading conditions are good. A combination of the two maps – a street shade map and a zonal shade map (Figure 3) – will also enable planners to easily pinpoint streets suffering from a significant lack of shading in areas with relatively good average shading and vice versa.

Shade maps also make it possible to examine the relative dependence of the level of shading in streets, public spaces, or neighborhoods on tree shading. By comparing a shade map showing the current state of shading with a shade map showing the state of shading excluding the shade cast by trees (Figure 4 and Figure 5), it is possible first to locate street segments and zones where there is a particularly high dependence on shade trees to secure reasonable levels of shading and then to invest tree conservation efforts in those locations. A significant difference in the Shade Index between existing conditions and the shading condition excluding the effect of trees also indicates that in Holon, urban morphology (the physical characteristics of the built environment, such as density and height of buildings and width and orientation of streets) has almost no positive effect on improving shading, although it is possible to achieve reasonable and even good levels of shading solely through the proper design of buildings. **In the Israeli context, the comparison highlights the advantage in shading the street area by using buildings for streets oriented on a north-to-south axis. However, in streets with an east-west orientation, it is difficult to achieve acceptable levels of shading without a significant and continuous layer of shade trees or other shading elements. The comparison also shows that densely built streets make it possible to reach high levels of shading due to the narrow proportions of the street canyon (relatively tall buildings bordering on a relatively narrow right-of-way).**

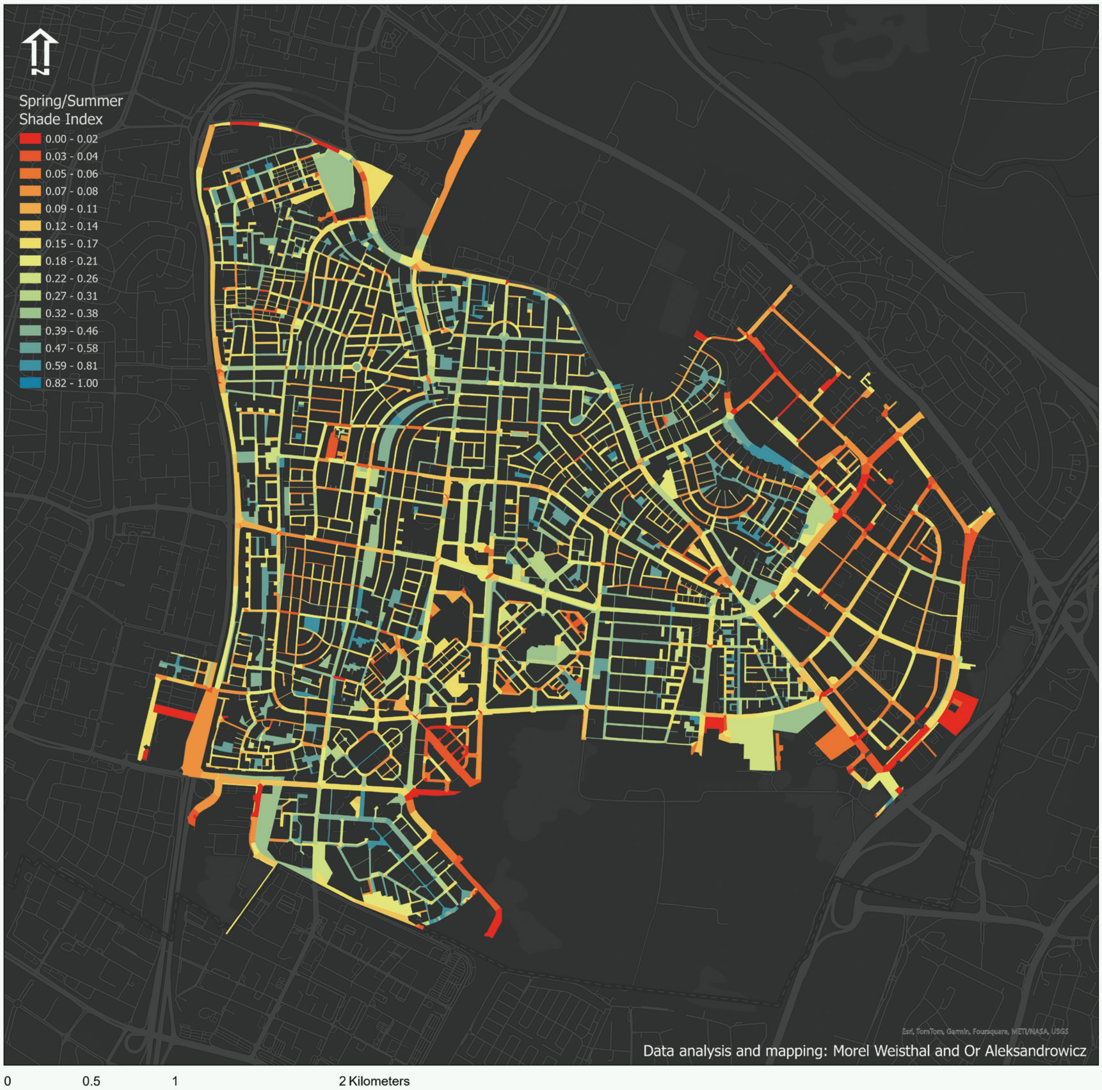


Figure 1: Shade map of street segments and open public spaces in Holon using the spatial Shade Index (SI), which ranges from 0 (no shade) to 1 (full shade) (mapping: Morel Weisthal and Or Aleksandrowicz). Noticeable differences in shading levels are evident.

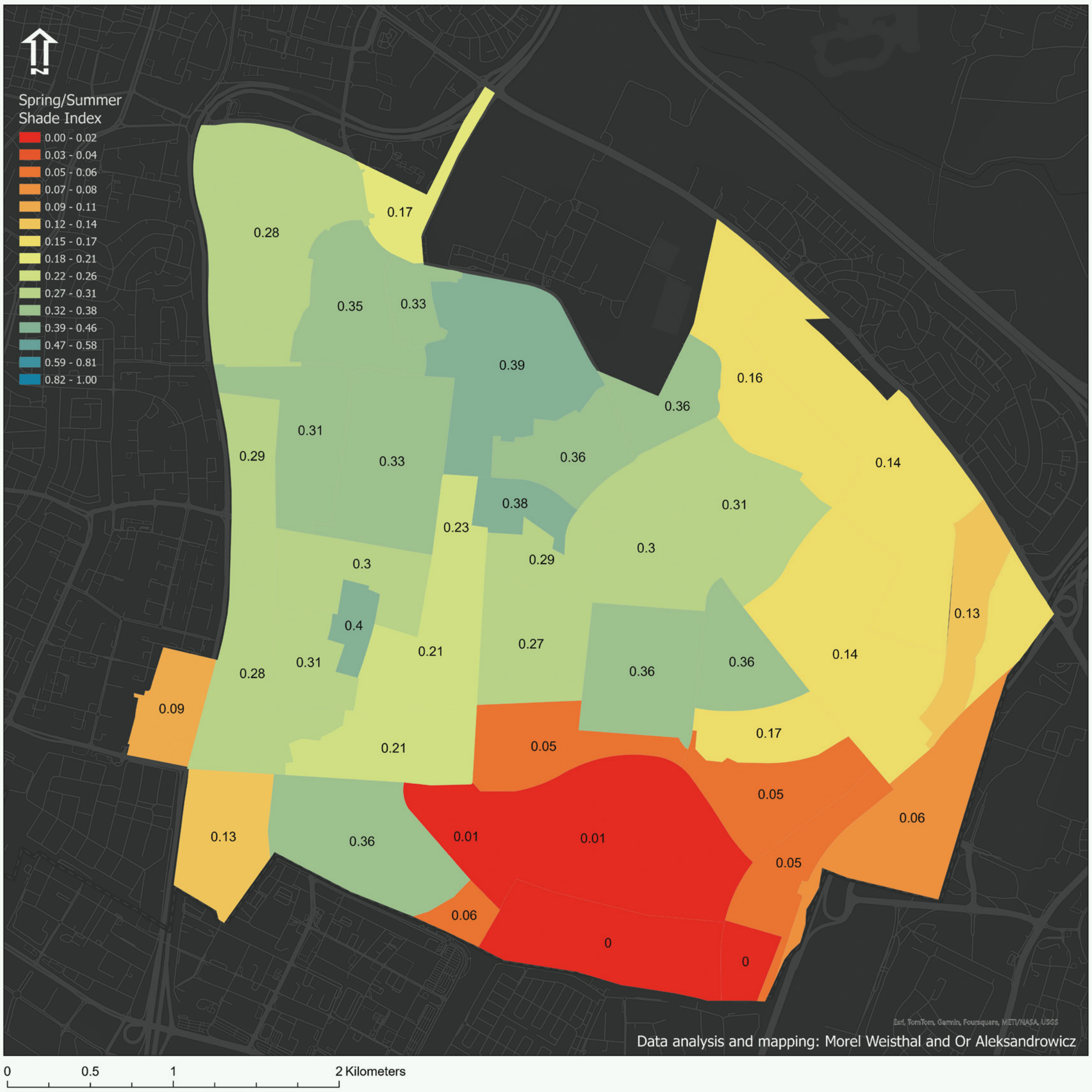


Figure 2: Zonal shade map of urban spaces in Holon (mapping: Morel Weisthal and Or Aleksandrowicz). This map makes it possible to locate entire urban environments with improved average shading conditions according to the spatial Shade Index (SI).

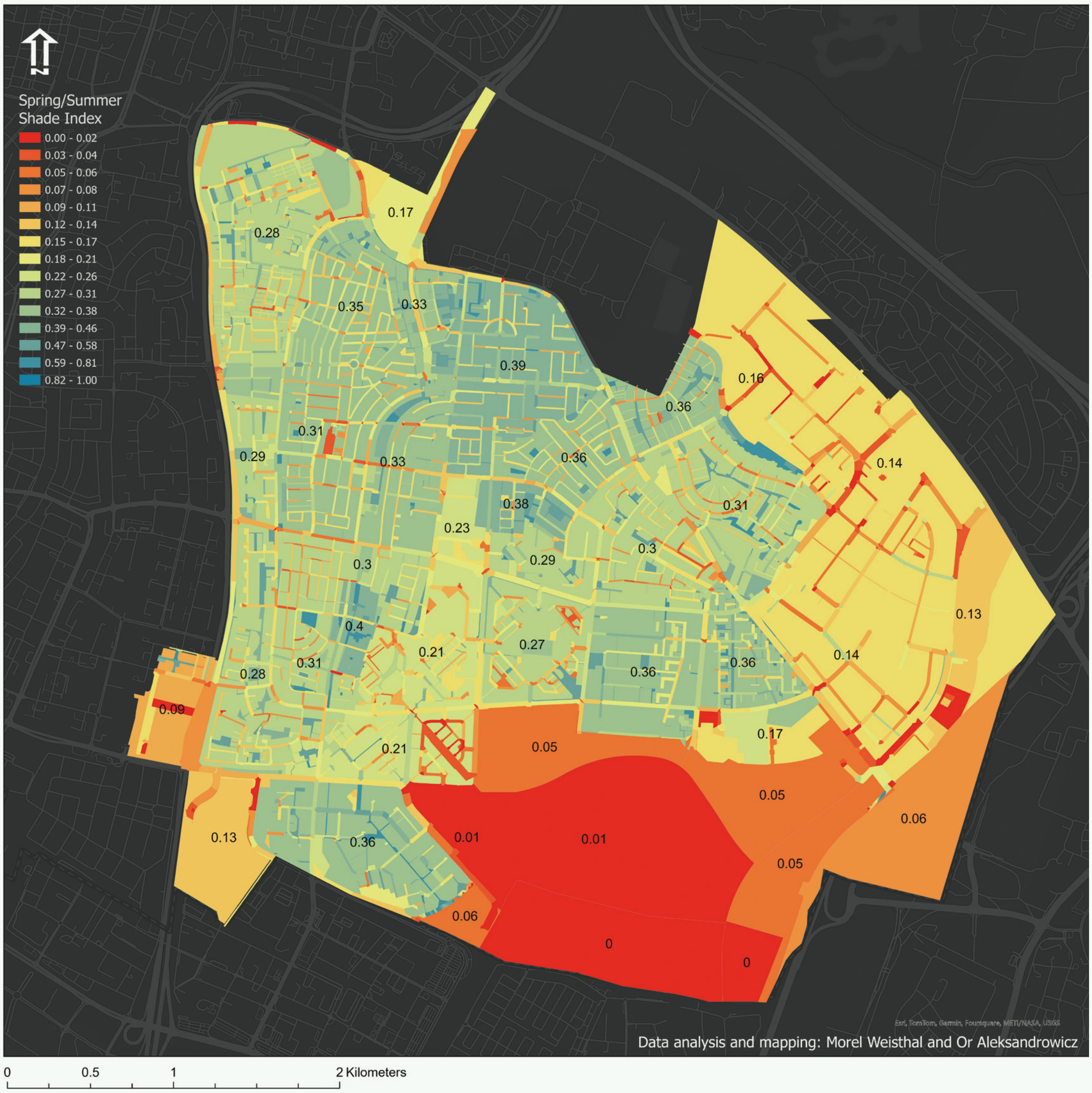
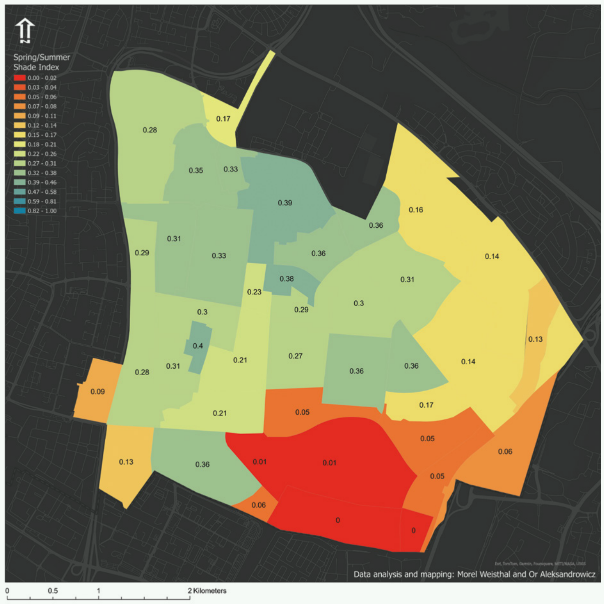


Figure 3: A combination of a shade map of streets and open public spaces and a zonal shade map for the city of Holon (mapping: Morel Weisthal and Or Aleksandrowicz). Exceptionally better-shaded or worse-shaded streets or areas relative to their surroundings can be easily located.

Figure 4: Shade maps of the streets and open public spaces of Holon (mapping: Morel Weisthal and Or Aleksandrowicz): a comparison between the current situation, including shading from trees (right) and a reference mode that excludes shading from trees (left).



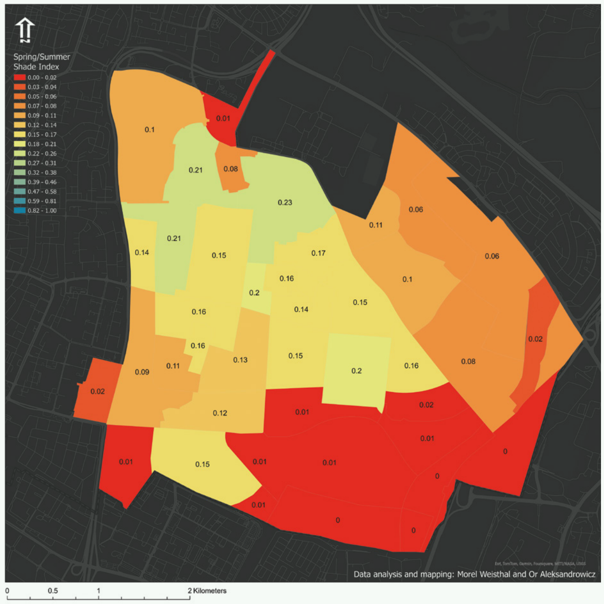


Figure 5: Shade maps of Holon's planning zones (mapping: Morel Weisthal and Or Aleksandrowicz): a comparison between the current situation, including shading from trees (right) and a reference mode that excludes shading from trees (left).

Prioritizing sites for shade intensification

The second stage in determining an urban shading strategy is prioritizing intervention actions. City-wide shade analysis using shade maps makes it possible to comparatively evaluate the advantages or disadvantages of certain areas over others in terms of shading conditions and to determine sites for intervention based on this assessment. A comparative examination can help in determining the spatial magnitude of the lack of shade and in locating streets or parts of the city where shading conditions are very successful. From that point, it is also possible to propose two types of urban spatial intervention in terms of shading: “shade intensification” in areas with low shading levels and “shade conservation,” mainly through avoiding tree felling and sustainable maintenance of trees, in areas where levels of shading are exceptionally good. These highly shaded areas, easily located by using shade maps, can also inspire methods for adding shade elsewhere.

In addition to defining intervention sites, municipalities also need to prioritize intervention activities in those sites and to define the sites for which action is most urgently needed. Indeed, a municipality may rely exclusively on the spatial Shade Index to delineate the streets in which shading levels are below a certain threshold (for example, 0.2) as streets that are not sufficiently shaded and, therefore, to designate them for high-priority shade intensification. However, setting a numerical threshold based solely on the spatial Shade Index for intensifying or conserving shade may not be sufficient to prioritize municipal actions, because the number of street segments designated for intervention may be very large and thus exceed the municipality's available resources. Lowering the threshold to reduce the number of intervention sites may result in many street segments with poor shading conditions not being considered as candidates for shade intensification, even if those segments are centrally located. Therefore, the municipality must examine additional considerations in the process of prioritizing actions in a manner that will enable it to determine the order of actions and the pace of execution of projects according to the resources allocated for this purpose. These additional considerations should help the municipality direct its actions to sites where their impact will be particularly noticeable (for example, a main commercial street that attracts a large number of pedestrians or a neighborhood with an elderly population) out of all sites with similar levels of shading.

Defining the additional considerations for prioritizing shading actions is a matter of values stemming from familiarity with local urban needs. Due to variations in local conditions and planning preferences in each city, we believe that it would not be correct to define a uniform and binding method for ranking considerations that will affect the prioritization of shading operations. However, every city that formulates a shading strategy must establish clear and measurable criteria for prioritizing shading actions that would go beyond quantifying shading levels using the spatial Shade Index (SI). These criteria can relate to social, environmental, and planning aspects that are not directly related to the existing levels of spatial shading, for example:

Walkability – Urban spaces where the municipality sees potential for increased pedestrian traffic or where there are already many pedestrians may be preferred spaces for shade intensification or conservation (due to negative impacts of exposure to sunlight and heat stress on pedestrians). Therefore, taking into consideration the walkability or connectivity of streets and different parts of a city may ensure that future shading actions benefit the largest number of non-motorized road users.

Health vulnerability – The elderly and children, along with people suffering from various chronic diseases, are populations that are particularly sensitive or vulnerable to heat stress. Improving shading conditions in the daily living environment of areas with a high concentration of such populations may prevent specific or ongoing health damage and ameliorate further deterioration of these conditions. Therefore, prioritizing shading activities according to the presence of exceptionally high concentrations of health-vulnerable populations may bring special relief to those for whom shading is a vital need.

Economic vulnerability – Low socioeconomic status populations tend to rely more than others on walking and public transportation, including walking to and from transport stations. Such populations may be more vulnerable to hot conditions due to the lack of efficient cooling means in their homes. Therefore, prioritizing actions to promote shading in neighborhoods with populations with low economic means may serve residents who have no better alternatives than walking and gathering in open public spaces.

Urban renewal – The dimensions of street canyons and building densities can significantly contribute to the shading of streets. Priority could be given to shade design in areas designated for urban renewal such that shading in those areas will be based largely on building morphology alongside planting a sufficient number of trees. In contrast, shade intensification actions should not be given preference in areas in which urban renewal is in full swing until a significant part of the construction activities are completed.

Detailed shading design: the Shade Availability Index

After locating streets designated for shade intensification, a detailed shade design should be the third step in determining an urban shading strategy. To become effective, shade design must meet quantitative objectives formulated using a uniform index describing the extent to which sufficient shading conditions exist during the daytime hours at the height of summer. The need to set shading targets according to a uniform quantitative index stems from the current difficulties of conducting a systematic assessment of shade quality, of comparing the shading quality in different planning scenarios, and of ensuring that municipal actions for shade intensification will be both effective and efficient. The **Shade Availability Index** (SAI),[20] the index that we present here for determining normative shading targets, is relatively easy to calculate and allows the quantification of the degree of

20 Aleksandrowicz, O., & Ozery, E. (2023). A parametric tool for outdoor shade design: Harnessing quantitative indices and visual feedback for effective and efficient climatic design of streets. In M. Turrin, C. Andriotis, & A. Rafiee (Eds.), *Computer-Aided Architectural Design. INTERCONNECTIONS: Co-computing Beyond Boundaries* (pp. 302–316). Springer Nature, Switzerland.

shading on sidewalks or walking paths during the detailed design stage. It can be used to evaluate the relative quality of shading and to examine the effect of design modifications on the state of shading. Importantly, it overcomes the disadvantages of existing shade evaluation methods that we reviewed in the previous chapter.

A review of the methods currently available in Israel and other countries for evaluating shade in urban environments revealed that shading targets are currently set only in a small number of locations and that these are almost always based on simple geometric indexes (for example, the tree canopy cover ratio). Most of the methods for evaluating shade do not take into consideration the shading provided by buildings, the times at which shading is most necessary, and the difference in the shading patterns obtained at different hours and on different dates. Existing indexes are problematic because they seldom present a realistic picture of the state of shading in urban spaces and because they ignore many physical differences in the environment that directly impact the shading conditions in a particular space. In addition, these indexes sometimes set high threshold levels for shading targets in a way that does not represent realistic planning scenarios from either physical or economic perspectives. The Shade Availability Index provides a solution to these shortcomings, because it takes into account the shading obtained from buildings and trees, quantifies the level of shading according to the actual shade coverage at ground level over a large number of hours at the height of summer, and is based on an extensive systematic examination of the possibilities of meeting thresholds set under reasonable planning scenarios.

The Shade Availability Index is based on a geometric calculation of the shaded area of a reference surface without quantifying the effect of shading on reducing human heat stress. The choice to avoid weighting thermal comfort in calculating the index stems, first and foremost, from the complexity of the precise calculation of heat stress intensity, which depends on the unique physical characteristics of each urban environment and its impact on the climatic variables included in the heat stress calculation: air temperature, relative humidity, wind speed, and radiation flux intensity on the human body. Since we do not have reliable and fast computational tools for calculating a thermal comfort index for different design tasks, a systematic assessment of heat stress in urban space for purposes of urban planning should be performed by developing more efficient calculation methods, even at the expense of obtaining a less accurate metric for quantifying heat stress. In Israel's summer climatic conditions, the way to do this is by focusing on shade because we can assume, with a high degree of confidence, that sufficient shading can ensure a significant reduction in heat stress. This premise is supported by the extensive set of measurements that we conducted in 2020 and 2021 in Tel Aviv (207 measurement points) and Kfar Saba (100 measurement points): The measurements revealed that, during the hot season in Israel, shading played a decisive role in significantly reducing heat stress. However, it is important to emphasize that the measurements also revealed that shading cannot guarantee absolute thermal comfort in the summer: **for none of the shaded points** that we measured in summer (146 points in Tel Aviv and 73 points in Kfar Saba) was there a single time that presented complete thermal neutrality, and at the vast majority of points there was light to moderate heat stress (Figure 6 and Figure 7).[21]

21 Determining the degree of heat stress according to the PET index was made according to a scale of values adapted to climatic conditions in Israel, as defined in Cohen, P., Potchter, O., & Matzarakis, A. (2013). Human thermal perception of Coastal Mediterranean outdoor urban environments. *Applied Geography*, 37(1), 1–10.

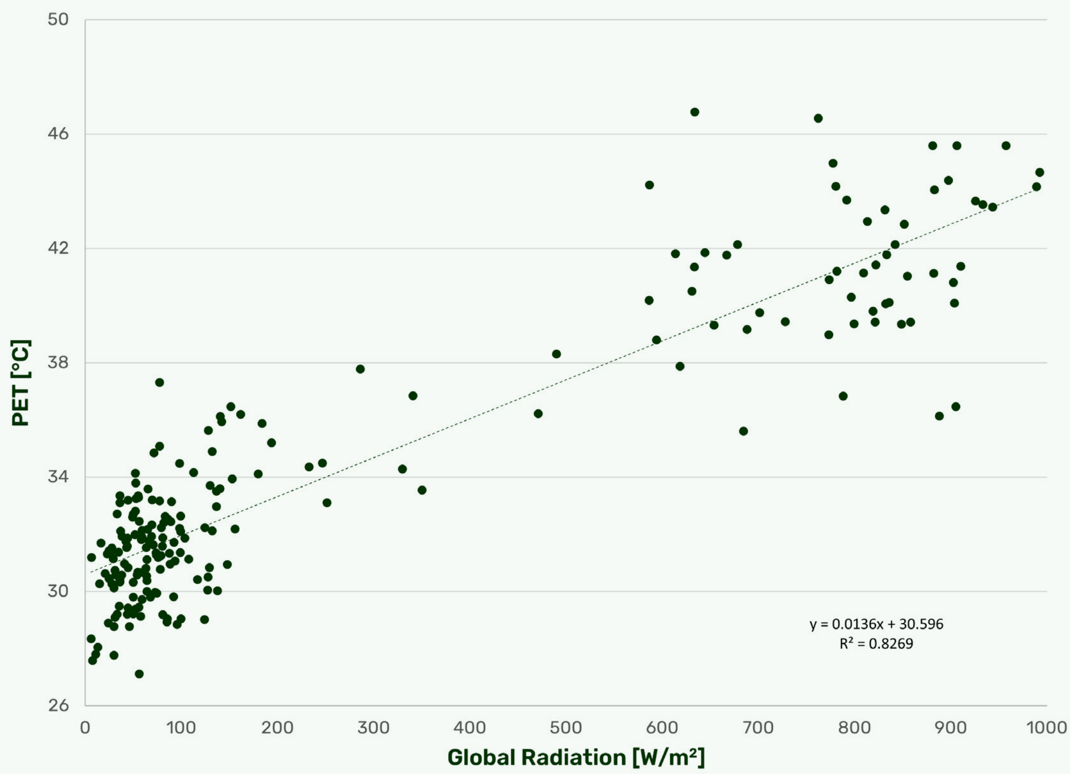


Figure 6: Relationship between global radiation and thermal comfort according to the physiological equivalent temperature (PET) index, as shown in measurements conducted in Tel Aviv between 5 July 2020 and 1 September 2020 (207 measuring points). Not a single measurement showed complete thermal neutrality (PET below 26°C). Almost every measurement in the shade indicated heat stress (PET above 28°C), even in cases where the shading was of high quality (global radiation of less than 100 W/m²).

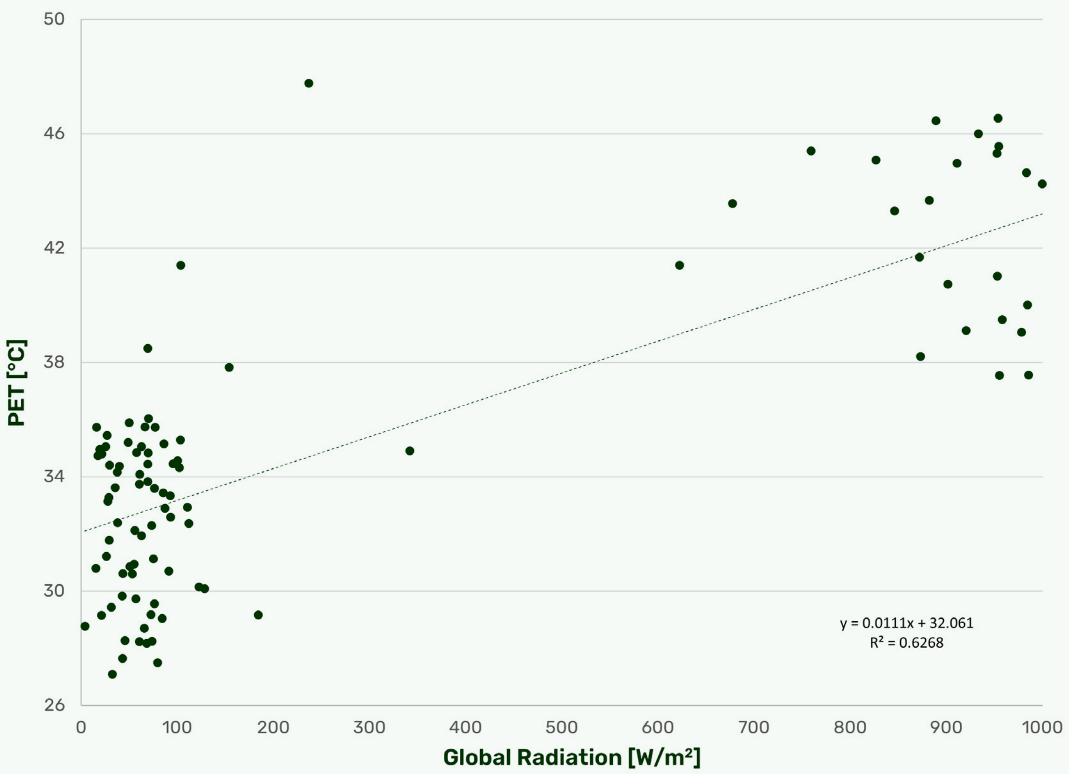


Figure 7: The relationship between global radiation and thermal comfort according to the PET index, as shown in measurements conducted in Kfar Saba between 15 June 2021 and 11 August 2021 (100 measurement points). This set of measurements also yielded similar findings regarding the realistic impossibility of ensuring absolute thermal neutrality in the shade during a summer day.

Our measurements also revealed that the positive effect of shading on heat stress relief far exceeds heat stress relief caused by a slight drop in air temperature or relative humidity or an increase in wind speed.[22] Under summer conditions in Israel, improvement in these climatic variables is limited in intensity and does not come close to the degree of heat stress relief created by shading. This was especially true when we measured two adjacent outdoor points. Three main reasons can explain this finding: first, the air temperature in the city during summer in Israel is relatively high, and combined with high relative humidity in some areas of the country, basic conditions of heat stress are created even without the influence of solar radiation; second, air turbulence causes an almost completely uniform mix of air temperatures between areas exposed to sunlight and adjacent shaded areas on urban streets; and third, in most cases the urban environment causes a significant decrease in wind speed and thus significantly reduces the ability of wind to bring relief from heat stress.

The series of measurements that we conducted, therefore, revealed that in the climatic conditions prevailing in the summer in Israel, it is sufficient to examine whether there is adequate shading in a particular environment to conclude that the prevailing heat stress will be significantly lower than that in a similar but unshaded physical environment. The results of our measurements also showed that **the formulation of shading targets in Israel, at least on the coastal plain, cannot be based on an unrealistic**

22 Aleksandrowicz, O., & Pearlmutter, D. (2023). The significance of shade provision in reducing street-level summer heat stress in a hot Mediterranean climate. *Landscape and Urban Planning*, 229, 104588; see also: Middel, A., AlKhaled, S., Schneider, F. A., Hagen, B., & Coseo, P. (2021). 50 Grades of Shade. *Bulletin of the American Meteorological Society*, 102(9).

wish to achieve total thermal neutrality in the summer, but should rather focus on optimizing the blocking of direct sunlight in urban walking and gathering spaces.

In developing any shade index, it is important to provide accurate and clear answers to three fundamental questions: What is the reference area for which the shading ratio is calculated? What is the reference time for which the shading ratio is calculated? When is it possible to determine that a point in space is shaded? The answers to these questions may also affect the degree of correlation between the index and the degree of heat stress reduction during the hot season caused by reducing solar exposure. The proposed Shade Availability Index addresses these three questions as follows:

- The primary reference area for which the Shade Availability Index is calculated is the total area of a sidewalk on a given street segment, where a street segment is defined as a part of a street bounded by two road junctions. A street segment usually has two sidewalks, one on either side of a road (or carriageway), although there are streets (for example, pedestrian streets) where the area of the sidewalk is equal to the area of the right-of-way. The reason for choosing sidewalk space in a street segment as the spatial reference unit for which the index is calculated derives from the understanding that shading is especially essential for non-motorized road users and that it is important to maintain a shaded continuum along the entire sidewalk in a given segment to ensure a significant reduction in heat stress for the walker.

- The **reference time** for calculating shading comprises the greater part of the daylight hours on a typical summer day. In Israel, we set the reference time to 08:00 to 17:00 (daylight saving time) on 6 August, which lies half between the longest day of the year (21 June) and the autumnal equinox (22 September). Due to the high daytime air temperatures, this day also represents the peak of annual heat stress.[23] This date corresponds to 6 May in terms of the sun's position in the sky and the resulting shading patterns, and the same reference time may therefore also be used for quantifying shading conditions in the spring.

- In calculating the index, **a point in space is regarded as shaded** when direct solar radiation does not hit it at ground level (unlike at head height or at the center of gravity of the human body). The index does not take into consideration the effect of reflected radiation, because the heat load caused by reflected radiation is largely negligible relative to the heat stress caused by direct sunlight and because of the difficulty in accurately estimating the reflection coefficients of all surfaces in the street space.

Based on these definitions, we defined a **Shade Availability Index** as describing, on a scale from 0 to 1, the relative amount of time out of the entire reference period (08:00 to 17:00 on 6 August) that the reference area (sidewalk) is in a sufficient state of shading. The answer to the question

23 This is because air temperature is affected by several factors, the most important of which is the Earth's heat capacity. The Earth surface, warmed by the sun, radiates heat into the atmosphere in a slow process that usually takes between 4 to 6 weeks, which is why the hottest days in Israel are the days in early August, about a month and a half after the day when the amount of radiation hitting the surface is the highest; *see Dagan, S.* (2010). Why is August the hottest month of the year? Davidson Institute, the educational arm of the Weizmann Institute of Science.

of what constitutes a “sufficient state” of shading is normative, and there is no unequivocal scientific answer. Here, we choose to define a sufficient state of shading of a reference area (for example, a single sidewalk) at a given moment as **at least 50% of the area being shaded**, assuming that the buildings and the shading elements on the street are more or less distributed along it at regular spacings. We believe that, under these conditions, when half of the area of a sidewalk is in continuous shade, sidewalk users can choose equally between moving in the shade and moving with full exposure to sunlight (Figure 8). When at least 50% of the sidewalk area is in intermittent shade (Figure 9), the sidewalk user will enjoy a sufficiently shaded walking path from one end of the street segment to another, even though the shaded area of the sidewalk also includes intermittent patches of solar exposure. It is important to emphasize that in cases where the street section varies substantially along a single street segment, the Shade Availability Index must be calculated separately for each part of the street segment for which the shade morphology is uniform.

Understandably, we could have set a more ambitious target (for example, 75% of the sidewalk area or even its entire area) as a starting point for calculating the Shade Availability Index. But the question that must be asked is to what extent such an ambitious target can be realized under realistic planning conditions and to what extent it can substantially improve the reasonable possibility of providing sufficient shade for walking on the sidewalk. We believe that shading 50% of the sidewalk area as a “satisfactory condition” provides a balanced response to the planning challenge of shading walking spaces because this ratio ensures a sufficiently shaded overall area for continuous walking on a sidewalk that is 3 m wide or more.

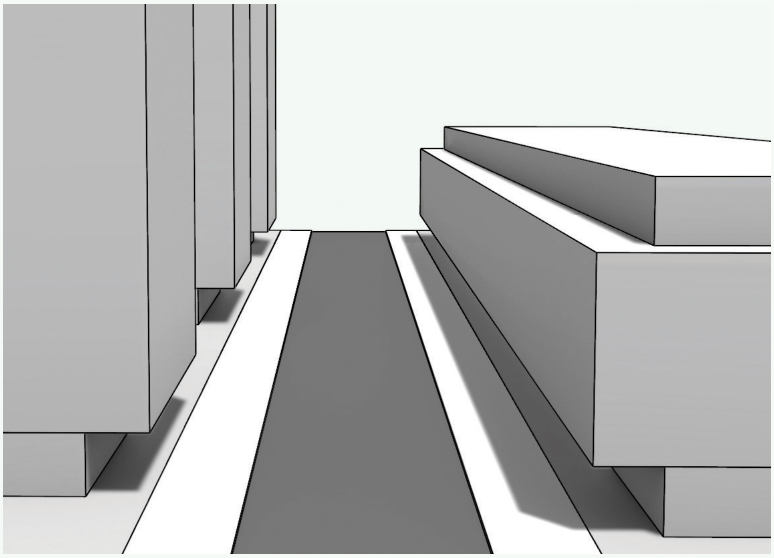


Figure 8: An example of continuous shading exceeding 50% of the sidewalk area on the right sidewalk.

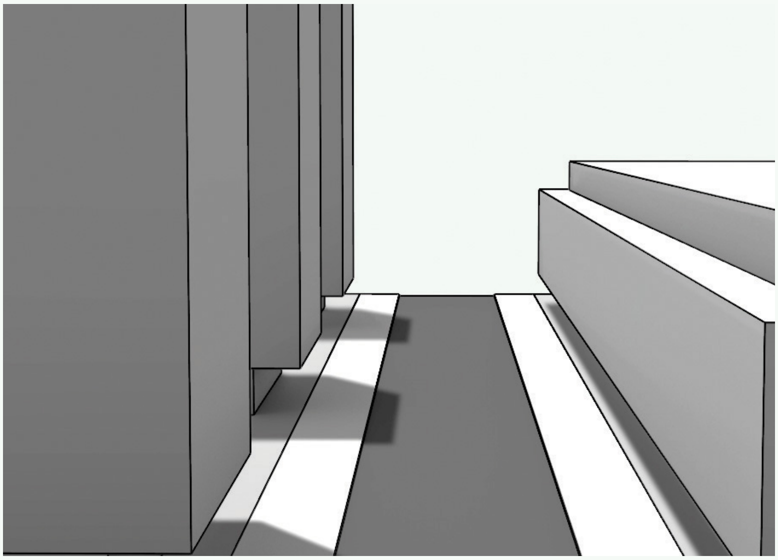


Figure 9: An example of intermittent shading exceeding 50% of the sidewalk area on the left sidewalk.

Thus, to calculate a sidewalk's Shade Availability Index, it is necessary to check whether, at each full hour between 08:00 and 17:00 (a total of 10 time points) on 6 August, at least 50% of the sidewalk area is shaded. The Shade Availability Index describes the ratio between the number of full hours during which the sidewalk is in the state of sufficient shading (50% or more of the area is shaded) and the total number of full hours of the reference time (as defined above, 10 hours). The higher the number of full hours during which at least 50% of the sidewalk area is shaded during the reference time, the higher the Shade Availability Index (and the closer it is to 1). For example, if more than 50% of the sidewalk area is shaded at 6 full hours during the reference time, the sidewalk's Shade Availability Index would be 0.6.

The advantage of using the Shade Availability Index lies in simplifying the quantification of shade to a geometric calculation and in the ability to adopt it as a normative measure that is easy to understand, because it mainly expresses the proportion of time during a summer day during which proper shading conditions prevail (without the need for complex calculations quantifying the effect of solar radiation on heat stress intensity). For example, it is relatively easy to understand that a Shade Availability Index of 0.3 does not guarantee reasonable shading conditions because it means that during 70% of the reference time the sidewalk does not have sufficient shaded space. It also follows that a normative scale of desired shade availability levels can be determined based on quantifying the amount of time during which a sidewalk is sufficiently shaded. For Israeli conditions, we propose setting three levels of shading as desirable normative targets in shading-oriented urban planning. These three levels are:

Acceptable shading

Shade Availability Index value of 0.5 or higher

Very good shading

Shade Availability Index value of 0.7 or higher

Excellent shading

Shade Availability Index value of 0.9 or higher

The ability to set three levels of shade availability allows the planner to establish gradual targets for shade intensification based on current and projected resources. For example, a municipality can determine that certain streets should reach a state where **acceptable** shading will be achieved within five years, while **very good** shading should be achieved within ten years. To meet these targets, the municipality will take ongoing actions that will also include monitoring the progress of the shading situation during the entire time frame. However, in view of the practical limitations of realizing shade intensification operations, it is important that the choice of the desired level of shade availability be made in accordance with local considerations and the resources available to the planning authorities, after an exploratory examination of the actions required to meet a particular target. In the following sections, we will expand on how design decisions can affect the level of shade availability according to the index presented here. We will also show that it is almost always possible to meet even the highest levels of the index with proper planning and a precise and efficient combination of shading from buildings and trees or artificial shading elements (pergolas, awnings, etc.).

As discussed above, the Shade Availability Index is calculated for each sidewalk separately, and this calculation method allows flexibility in setting shading targets that are not identical on each sidewalk or walking strip on a street. For example, it is ostensibly possible to set, as a planning goal, that for an entire street to be considered a shaded street, it is sufficient for one of two sidewalks on the street to meet a certain shading threshold. In the same way, it is ostensibly possible to determine that it is sufficient that only a walking boulevard in the middle of a street to meet a certain shading threshold while avoiding setting shading thresholds for its flanking sidewalks. However, we believe that such partial targets may miss the main purpose for which the index was created, which is to encourage non-motorized street traffic during the day, because partial targets would sometimes force road users to give up on the shortest lane of movement in search of shade. Therefore, when setting shading targets, we recommend that **all walking lanes on a particular street segment meet at least the lowest shading threshold** (acceptable shading, Shade Availability Index value of 0.5 or higher).

Example of using the Shade Availability Index in design

This section presents an example of shade design conforming to the targets detailed above. For this purpose, we used the Grasshopper code **Kikayon** developed by Or Aleksandrowicz and Ezra Ozery in work funded by the Israel 100 Initiative (for a detailed explanation of the tool see Appendix B).[24] In this design task, the street segment is 200 m long, each of its sidewalks is 6.5 m wide, and the walking boulevard at its center is

24 Aleksandrowicz, O., & Ozery, E. (2023). A parametric tool for outdoor shade design: Harnessing quantitative indices and visual feedback for effective and efficient climatic design of streets. In M. Turrin, C. Andriotis, & A. Rafiee (Eds.), *Computer-Aided Architectural Design. INTERCONNECTIONS: Co-computing Beyond Boundaries* (pp. 302–316). Springer Nature, Switzerland; see also, https://israel100.org/project/1891.

15 m wide. The street is precisely oriented on an east-west axis, which means that the contribution of its buildings to shading is low. On the south side of the street there is a continuous building 15 m high, and on the north side there are three buildings 36 m high and 34 m wide, with a lateral distance of 32 m between them. In the original street plan, there are no trees. The calculation of the Shade Availability Index shows that shading on the sidewalks and the boulevard is very poor (Figure 10): Each sidewalk has sufficient shading for only 1 hour out of 10, and the shading on the boulevard is not sufficient at any of the reference time hours.

The first planning action deals with the design of shading on the boulevard. For this purpose, it is planned to plant two rows of *Delonix regia* trees at a spacing of 12.5 m. The shading calculation considers the condition of the trees 10 years after planting when the tree canopy diameter is expected to have reached 8 m. Under these conditions, the Shade Availability Index for the boulevard jumps from 0 to 1 (Figure 11). For the sidewalks, the first scenario to be examined is planting *Delonix regia* trees at 20 m spacing on each sidewalk. In this scenario (Figure 12), the southern sidewalk receives excellent shading (Shade Availability Index value of 1.0), while the northern sidewalk is reasonably shaded (Shade Availability Index value of 0.6). The shading on the latter sidewalk can be improved by reducing the planting spacing to 12.5 m (Figure 13).

Although the above shade design ostensibly yielded an excellent solution, in practice, it is a solution that is expected to have an effect only about a decade after its realization due to the rate at which the trees grow. Therefore, it is important to check the state of shading after five years of growth for the same tree-planting layout. During that period, *Delonix regia* trees are expected to develop a crown diameter of only 5 m. In that scenario, the Shade Availability Index will be very low on the northern sidewalk and on the boulevard and will reach an acceptable level only on the southern sidewalk (Figure 14). Therefore, a much larger number of trees is necessary to ensure excellent shading on the street after five years.

In the tree intensification scenario, the planting spacing on the southern sidewalk is taken to be 10 m and that on the boulevard and on northern sidewalk to be 6 m. In this scenario, on both sidewalks, the Shade Availability Index reaches the maximum threshold (1.0), while the level of shading on the boulevard reaches an acceptable level (Figure 15). By reducing the planting spacing in the boulevard to 5 m, the number of trees so added will bring shading in the boulevard to the maximum level (Figure 16). It is worth noting that this situation would be reached even at a relatively low value (30%) of the **street's** tree canopy cover ratio.

After calculating shading levels in the different planning scenarios, planners will have at their disposal several possible solutions for a significant improvement in shading on the street. The difference between the solutions relates not only to the levels of shading that can be achieved with trees but also to when a significant change in street shading conditions may be expected. Another significant difference is the number of trees required in each planning solution, ranging from 56 for the largest planting distance to 132. Although the decision as to which planning scenario to choose is based on quantifying shading levels using the Shade Availability Index, it must involve additional considerations relating to the resources available for planting trees alongside more general planning and governance goals.

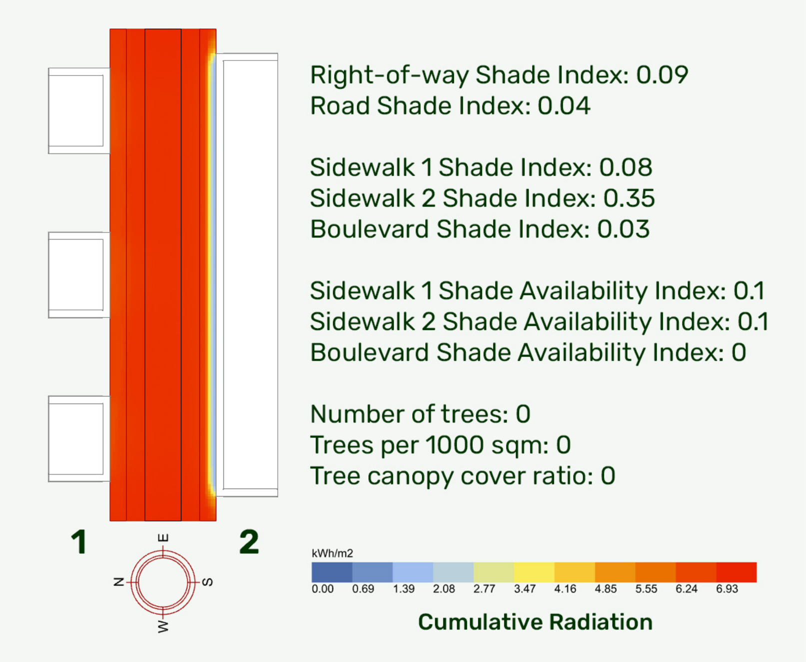


Figure 10: Shading on the street in its initial state - without shade trees.

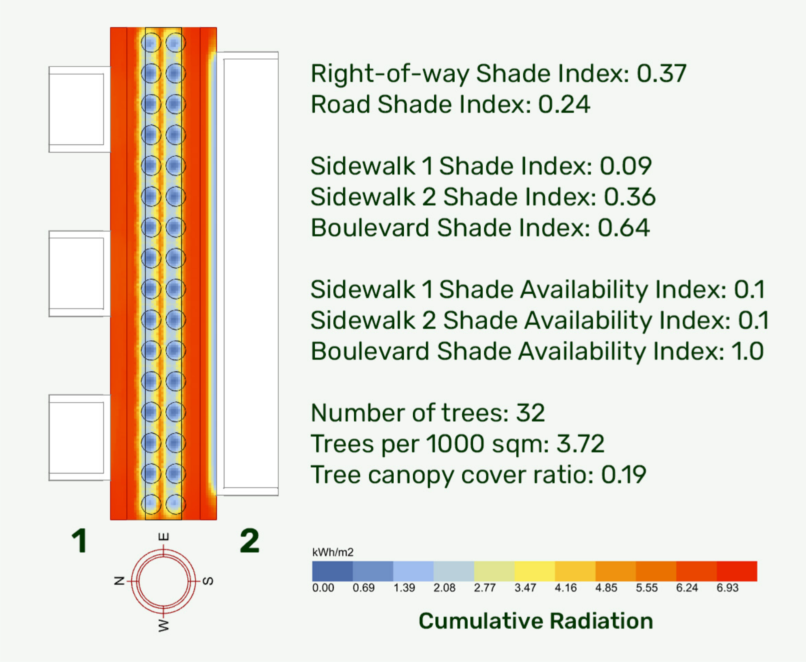


Figure 11: Shading on the boulevard after the addition of trees.

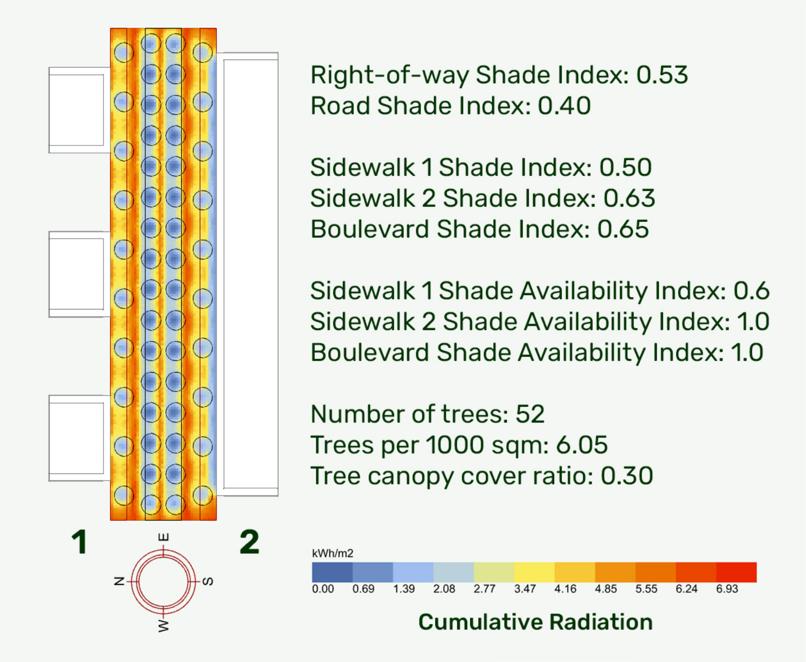


Figure 12: Shading on the sidewalks after the addition of trees.

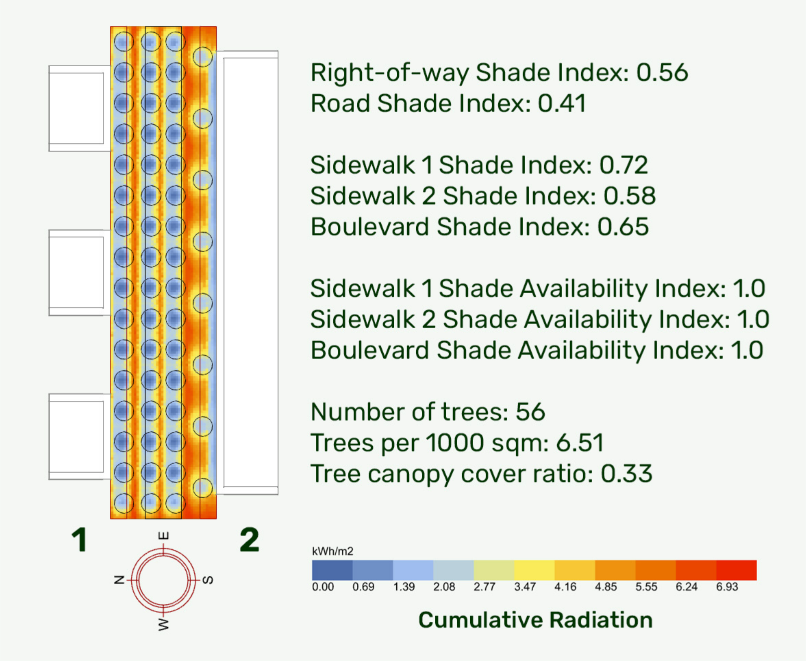


Figure 13: Improved shading on the northern sidewalk after reducing the spacing of the shade trees.

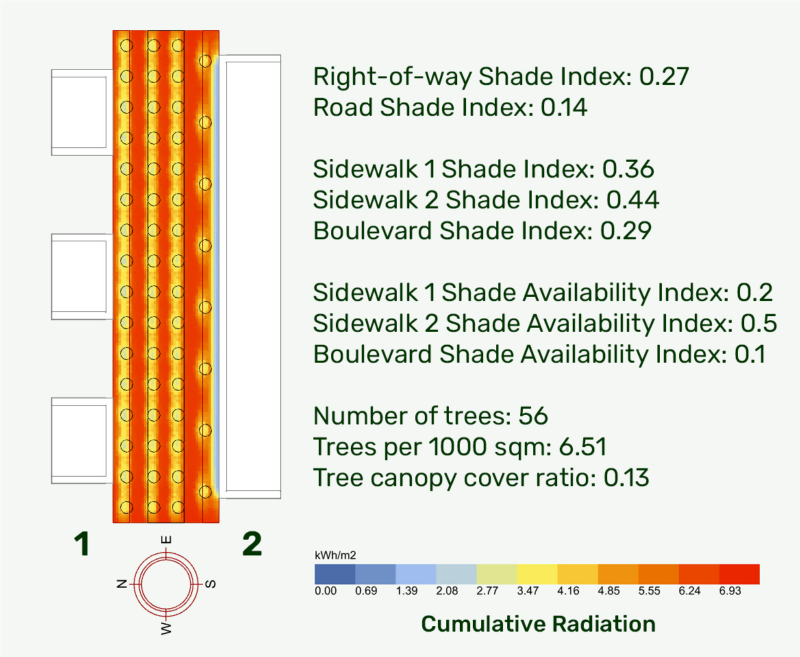


Figure 14: Shading on the sidewalks and the boulevard after five years of growth.

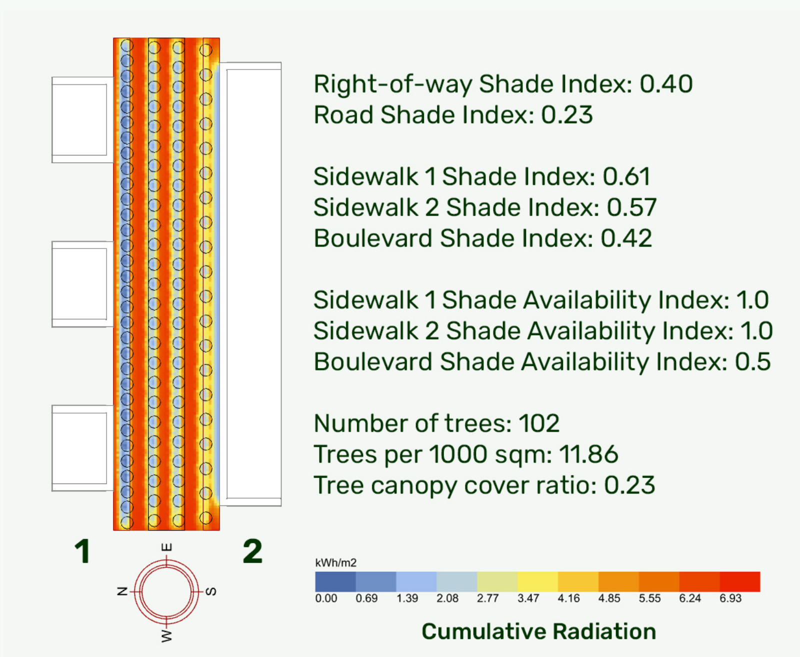


Figure 15: Shading on the sidewalks and the boulevard after five years of growth after adding a significant number of trees to the boulevard.

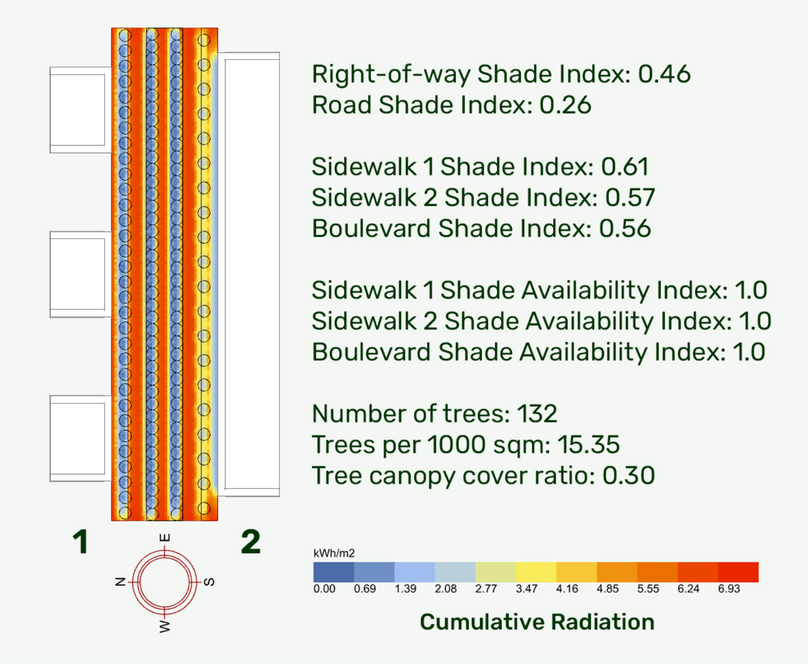


Figure 16: Shading on the sidewalks and the boulevard after five years of growth after adding more trees to the boulevard.

EFFECT OF STREET DESIGN ON SIDEWALK SHADE AVAILABILITY

The Shade Availability Index makes it possible to comparatively examine different design scenarios while quantifying the effect of changing certain design elements on improving or worsening shading conditions. Without a quantitative index, shade design may be based on incomplete or incorrect information, leading to an overestimation or underestimation of differences between different design options. For example, shade design without a quantitative index may lead to planting a large number of trees on sidewalks when the relative positive effect of additional trees on shading conditions is limited due to sufficient shading from existing buildings or trees. The investment that would have been made in these excess trees could then be directed to planting on streets where the level of shading is substantially lower.

For detailed street shade design, we recommend beginning with calculating the Shade Availability Index obtained without trees or with external shading elements, such as pergolas or awnings. In this way, it is possible to better understand the basic level of shading created by the permanent physical infrastructure of the street, i.e., street orientation, sidewalk width, right-of-way height-to-width ratio, and gaps between buildings. After calculating the Shade Availability Index, it is easy to examine different methods for increasing shade availability by including trees or other elements. Importantly, the Shade Availability Index can be leveraged to achieve a reasonable balance between meeting quantitative shading targets and reducing the public expenditure required to meet them (adding elements to cast shadows to complement the insufficient shading from buildings is relatively expensive and the cost of installing and maintaining them is likely to be met by the public).

A detailed shade design process should consider the unique primary conditions of each street designated for shade intensification based on accurate documentation of the street's main elements, including its trees. Here it should be remembered that minor differences in street design can sometimes significantly change shade availability levels. Nonetheless, the level of shade availability will usually rely on fundamental planning decisions relating to three areas of design decisions: street orientation, street morphology (height, location, and density of buildings and the width of the right-of-way), and the dimensions, density, and location of shade trees. The comparisons presented above between different design scenarios and the levels of shade availability resulting from them are intended to demonstrate the impact of each of these domains. At the same time, the comparisons show that meeting the shading targets defined in these guidelines does not depend on a single "optimal" solution, but can be achieved through a wide range of different design approaches.

Effect of street orientation on the Shade Availability Index

The sun's relative position in the sky varies both over the course of the day and from season to season. During the Israeli summer, the sun appears at a relatively low angle of 30 degrees, and its position relative to the Earth continues to change towards the south until the middle of the day. At that time, the sun's rays hit the ground at an angle of about 75 degrees. Thereafter, the position of the sun gradually moves westward in a mirror-like trajectory to the first half of the day (Figure 17). This means, for example, that an eastern row of buildings on a street oriented on a north-south axis will cast a long shadow on the western side of the street in the morning but will cease to cast shadows on the street area (road and sidewalks) from noon. The situation is completely different on streets oriented on an east-west axis, because the high midday sun causes buildings on the south side of the street to cast a relatively short shadow into the street area.

Figure 18 shows a comparison of four design scenarios that are identical in all their characteristics (e.g., street height/width ratio 0.6, top of tree crowns 9 m from the ground) other than the street orientation, along with the results of calculating the Shade Availability Index on each sidewalk. The figure shows the street segments in a schematic view in which outlines of buildings (white rectangles), curb stones (black vertical lines) and tree crowns (black circles) are drawn. The right-of-way area is colored in shades ranging from blue to red to show the intensity of the cumulative exposure of the ground to solar radiation (the lower the intensity and the better the quality of shading, the closer the hue to blue).

It can be seen that in the case in which shading is achieved by combining buildings and trees, the target of acceptable shading can be met on both sidewalks of a street oriented north-south and on one sidewalk in all other orientations. In the east-west orientation, there is a large difference in shading conditions between the two sidewalks: on the southern sidewalk, the Shade Availability Index is 0.8, compared to 0.2 on the northern sidewalk. In the other orientations, there are relatively small or no differences in the shading conditions between the two sidewalks. The comparison highlights the relative advantage of north-south streets in terms of shading for sidewalks (mainly due to the shading provided by buildings lining the street area) over streets oriented east-west. On the latter streets, it is difficult to achieve acceptable levels of shading without a significant and continuous row of shade trees, especially on the northern sidewalk, where the effect of shading from buildings is negligible.

Effect of street morphology on the Shade Availability Index

The morphology of a street relates to all design decisions regarding the general dimensions of the street, the division of the right-of-way between sidewalks and traffic lanes, the number of buildings on both sides of the street and their shape and location relative to the right-of-way. The effect of morphology on shade availability levels also depends on the street's orientation, and it will be less pronounced on east-west streets. However, it can be said, in general, that the higher the ratio between the height of buildings and the width of the right-of-way between them, the greater the possibility of leveraging the buildings on both sides of the street to

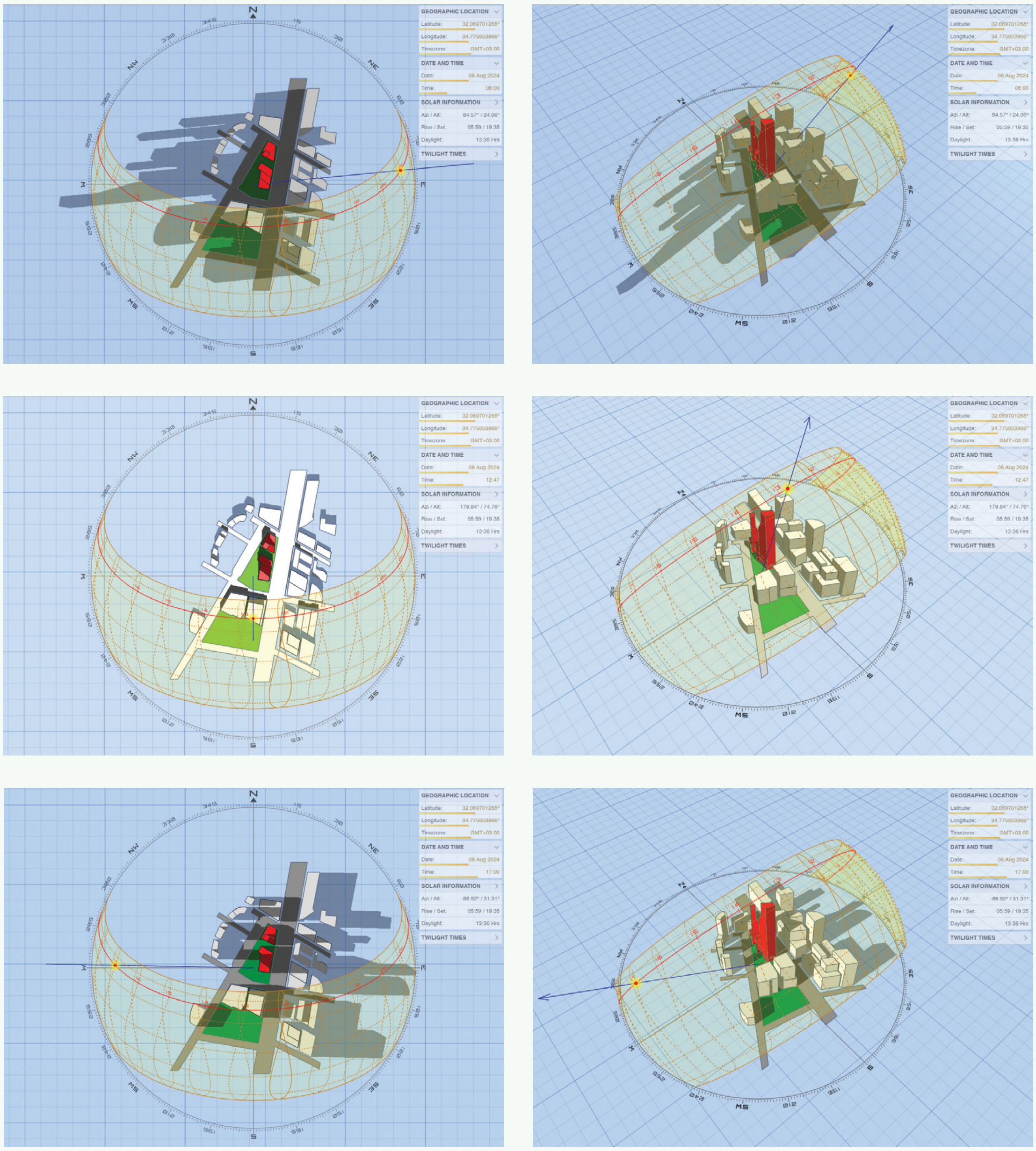


Figure 17: Schematic depiction of the sun's path in the sky on 6 August in Tel Aviv (red line), showing the incidence angle of the sun (blue arrow) at three particular times of the day (daylight saving time): 08:00 (top row), 12:47 (solar midday, middle row), and 17:00 (bottom row). For each of the three times, a perspective view from the southwest (right) and a top view (left) are shown. The images were produced using the **Sunpath3d** website created by Dr. Andrew J. Marsh.

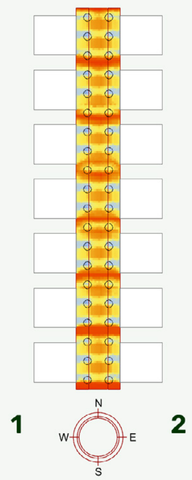
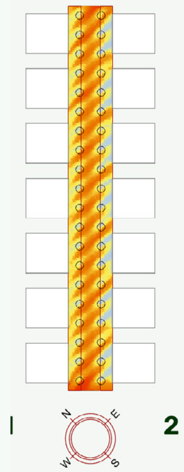
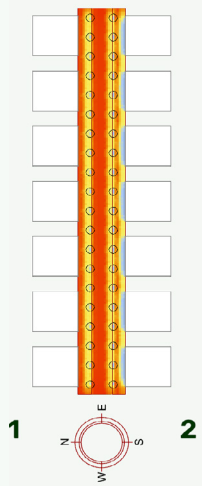
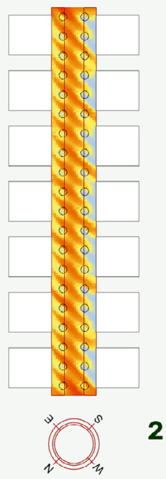
North-South	Northeast-Southwest	East-West	Southeast-Northwest
			
SAI 1: 0.5 SAI 2: 0.6	SAI 1: 0.3 SAI 2: 0.6	SAI 1: 0.2 SAI 2: 0.8	SAI 1: 0.4 SAI 2: 0.5

Figure 18: Comparison of the Shade Availability Index (SAI) on streets of different orientations. Each street's height-to-width ratio is 0.6.

increase the availability of shade on sidewalks, even without the addition of trees or other means of shading in the sidewalk area.

Figure 19 shows three shading scenarios for north-south streets, each with a different right-of-way, road, and sidewalk width. The scenarios are identical in terms of the height (13 m) and number of the buildings, the setback of the front building line from the parcel line, the lateral building lines, and the lack of trees. The scenario in which shade availability is highest is also the scenario in which the road (11 m) and sidewalk (3 m each) widths are the narrowest, while the scenario in which the road (18 m) and sidewalks (8 m each) are the widest is also the one in which the Shade Availability Index is the lowest. These results indicate that for certain orientations, acceptable levels of shading can be reached on narrow streets by relying only on shading from the buildings themselves. Examining the intermediate scenario, in which the sidewalk is relatively narrow (3 m wide), is instructive, since the road is wide (18 m): although the sidewalk width and building height are identical in this scenario and the narrowest street scenario, the index is lower. The reason for the difference in this case is the additional shading provided by the buildings on the opposite side of the road, the effect of which decreases as the width of the road between the sidewalks increases. This indicates that the width of the road has a negative impact on the levels of shading on sidewalks in orientations where there is a significant potential for shading from buildings on the opposite side of the street.

Figure 20 shows the positive effect of increasing building height on sidewalk shade availability. The four scenarios shown in this figure relate to a north-south street without trees, with each sidewalk 9 m wide and the total right-of-way 36 m wide. A comparison of the Shade Availability Index values in the different scenarios shows that shade availability on sidewalks can be improved by significantly increasing building height on both sides of the street, even without adding trees. However, it is important to remember that such an effect is mainly characteristic of north-south streets, and its intensity will decrease as the width of the right-of-way increases.

Effect of planting shade trees on the Shade Availability Index

Shade trees are trees whose crown is sufficiently wide and dense to cast a relatively uniform shadow on the ground. Therefore, not every tree planted in built-up areas is a shade tree, even if the tree itself is of a species recommended for street planting. The design assumption should be that a tree defined as a shade tree will be a tree whose growing, pruning, and maintenance conditions allow its crown to block at least 90% of the direct sunlight that hits the top layer of the tree crown and whose shade on the ground is continuous and relatively

Road width: 11 m Sidewalk width: 3 m	Road width: 18 m Sidewalk width: 3 m	Road width: 18 m Sidewalk width: 8 m

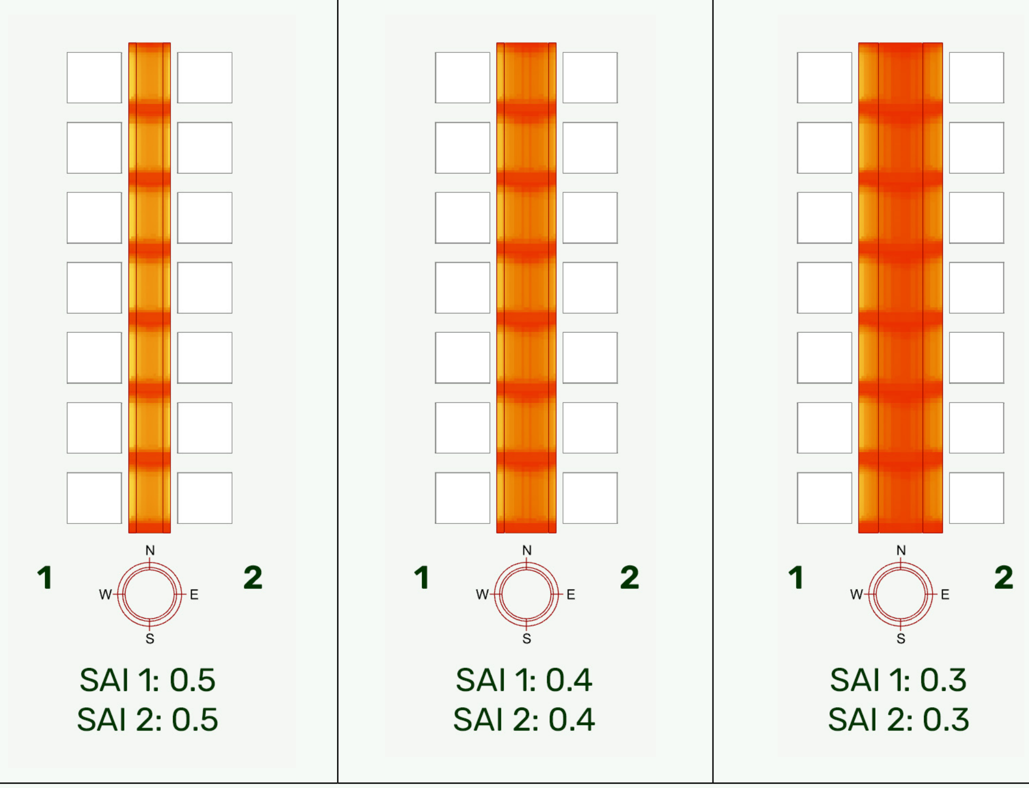


Figure 19: Comparison of the Shade Availability Index (SAI) on streets with varying road and sidewalk widths. The height of the buildings is 13 m.

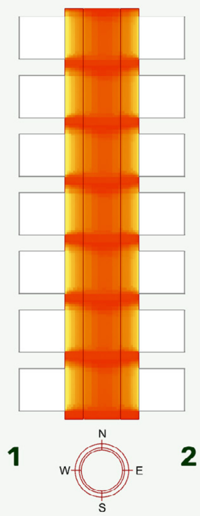
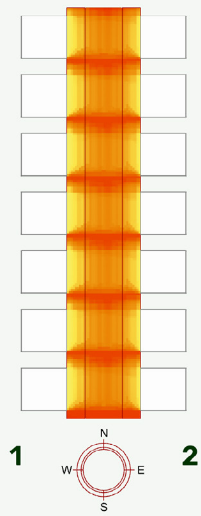
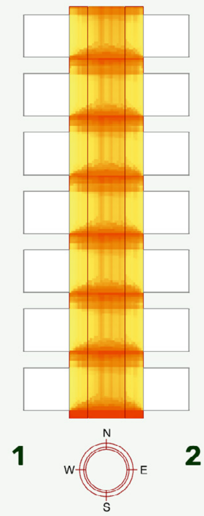
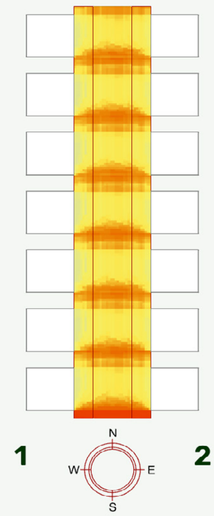
4-story buildings	6-story buildings	8-story buildings	10-story buildings
			
SAI 1: 0.4 SAI 2: 0.3	SAI 1: 0.5 SAI 2: 0.5	SAI 1: 0.5 SAI 2: 0.6	SAI 1: 0.7 SAI 2: 0.6

Figure 20: Comparison of the Shade Availability Index (SAI) on streets with buildings of different heights. Right-of-way width: 36 m.

uniform.[25] Evidently, the presence of trees in urban spaces may have positive or negative environmental impacts regardless of the shade they provide, and these effects should be considered when designing shading that is at least partially based on the use of shade trees. However, the Shade Availability Index is not intended to quantitatively examine these effects, but is rather meant to quantify the effect of shade trees on **improving** the state of shading on sidewalks.

Planting shade trees constitutes a central tool that can improve the state of shading on existing or projected streets within a period of a few years. However, similar to the effect of street morphology on shade availability on sidewalks, planting of trees may prove ineffective at improving shade conditions for two main reasons: i) due to soil volume and maintenance limitations, the trees do not reach their full growth potential and develop a relatively limited crown size because their habitat does not support optimal growth, and ii) even in a situation of full growth of the tree crown, the locations of the trees or the planting spaces between them do not provide sufficient shade coverage on sidewalks. When seeking to improve the state of street shading by planting trees, it is also important to examine the effect of different planting scenarios on the relative improvement in the

25 In Israel, almost no systematic studies have examined the ratio of solar radiation penetration through tree crowns of different tree species. An exception is the study of Limor Shashua-Bar et al. on three tree species in Tel Aviv (*Ficus retusa*, date palm, *Tipuana tipu*); Shashua-Bar, L., Potchter, O., Bitan, A., Boltansky, D., & Yaakov, Y. (2010). Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel. *International Journal of Climatology*, 30(1), 44–57. Much broader work has been done in the United States and may indicate the light transmittance through tree crowns of several tree species planted in Israel, considering the different growing conditions between the two countries. See McPherson, E. G., Xiao, Q., van Doorn, N. S., Johnson, N., Albers, S., &; Peper, P. J. (2018). Shade factors for 149 taxa of in-leaf urban trees in the USA. *Urban Forestry & Urban Greening*, 31(March), 204–211.

level of shade availability and to take into account that the growth rate of a street's tree canopy may be slower than expected.[26] Generally, it is better to plant a small number of large trees that will form a continuous canopy rather than a larger number of small trees with smaller foliage that require more resources (mainly irrigation, pruning, and soil management). Hence, it is possible to calculate an "optimal" planting density above which the "marginal output" of each additional tree in terms of the level of shade availability on sidewalks decreases sharply.

This report would not be complete without a comparison between the proposed Shade Availability Index and a widely accepted index for quantifying shade levels, namely, the tree canopy cover (TCC) ratio. This is a simple geometric index between 0 and 1 that is calculated by dividing the total area of the projection on a horizontal surface of all tree crowns in a defined space (for example, right-of-way in a street segment) by the total area of that space. This index does not take into account the impact of the direction of direct solar radiation or the direction and size of the resulting shadow projection. As a result, it can give the false impression that high levels of shading can be realized on streets only when the tree canopy cover ratio is high. As we will see in the following examples, the relationship between street tree canopy cover ratio and shade availability on sidewalks becomes more tenuous as the cover ratio decreases, meaning that **it should not be concluded that a low tree canopy cover ratio inevitably leads to low shading levels**. Therefore, using the tree canopy cover ratio to

26 Eilon, Y. (2015). Sustainable design of street trees [in Hebrew]. *Landscape Architecture*, 54, 26-28.

develop a municipal planting plan may lead to erroneous conclusions regarding the number of trees required for planting.

Figure 21 shows five **north-south** shading scenarios with shade trees at different numbers of years from planting and different planting spacings. The scenarios are identical in terms of building height (24 m), road width (25 m) and sidewalk width (10 m). The left scenario shows a street without trees and to its right, two scenarios at planting spacing of 10 m between trees. In the first of these two scenarios, five years after planting, the shade trees have not yet grown a significant crown and, therefore, do not give an improvement in the Shade Availability Index. However, for the trees at ten years from planting (the central scenario), excellent shading is obtained. In the two rightmost scenarios, the planting spacing between the trees is 5 m. Although this spacing provides a significant improvement in shading levels as early as five years after planting, the level of shading after ten years is similar to the shading obtained from planting at 10 m spacing, and the benefit of doubling the number of trees on the street (from 40 to 80 trees) turns out to be only marginal. These results mean that in this orientation, the better decision might have been the choice of planting trees every 10 m, because the basic level of shading of the street, even without trees, would have been acceptable.

Figure 22 shows five shading scenarios similar to those in Figure 21, but this time, the street orientation is **east-west**. In this orientation, buildings have almost no effect on the level of shading on the northern sidewalk. Still, on the southern sidewalk, as early as five years after planting a significant improvement in the Shade Availability Index can be achieved, even at a planting spacing of 10 m. In both scenarios in which the planting spacing is 5 m between trees, there is no improvement in the state of shading relative to the corresponding situation at a planting spacing of 10 m. This is because, in this direction, the shadows cast by the trees fall within the sidewalk area during most hours, unlike the situation on north-south streets. This comparison also shows that even a particularly dense planting of a single row of trees on the northern sidewalk cannot guarantee an acceptable level of shading after five years. In this case, planners should examine additional methods of adding shade, whether using temporary shading elements or adding another row of trees closer to the building facades.

Figure 21 and Figure 22 also show the tree canopy cover ratio obtained in each scenario, along with the Shade Availability Index, on each sidewalk. A comparison between the tree canopy cover values and the shade availability values reveals that there is no direct relationship between the two values, and that even a low tree canopy cover ratio (0.17 or 0.22) can yield very good and even excellent shading levels. Moreover, in some of these design scenarios, an acceptable level of shading can be ensured even when the street tree canopy cover ratio is very low (0.09). It follows that the value of tree canopy cover ratio as a successful predictor of the level of shade availability is extremely low, especially at low tree canopy cover levels. This is because the tree canopy cover ratio does not take into consideration the contribution of buildings to the state of shading on the street or the direction of the shadows cast by trees.

Figure 23 shows a comparison of streets where shading is provided only by trees. This situation arises when there are no buildings next to the sidewalks, when buildings adjacent to sidewalks are very low, or when buildings are very far from the front parcel line. In each of the three scenarios, the widths of the roads (18 m) and sidewalks (7 m each) are the same, as are the type of tree (ten-year-old shade trees) and the planting spacing (10 m) between trees. The difference between the scenarios lies in the street orientation. Although the trees are well developed, some sidewalks do not receive an acceptable level of shading, and apart from the southern sidewalk of the east-west street, shading levels are not high. This comparison emphasizes the importance of the contribution of shading from buildings even when sufficient shade trees are planted on the street.

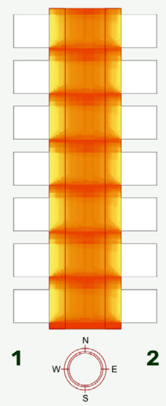
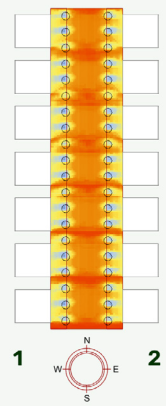
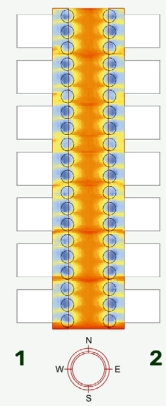
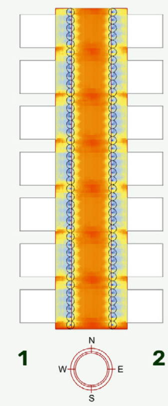
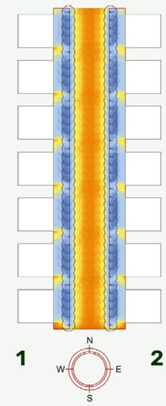
No trees	5 years from planting; planting distance of 10 m	10 years from planting; planting distance of 10 m	5 years from planting; planting distance of 5 m	10 years from planting; planting distance of 5 m
				
SAI 1: 0.4 SAI 2: 0.5 TCC: 0	SAI 1: 0.5 SAI 2: 0.5 TCC: 0.09	SAI 1: 0.9 SAI 2: 0.9 TCC: 0.22	SAI 1: 0.8 SAI 2: 0.8 TCC: 0.17	SAI 1: 0.9 SAI 2: 1.0 TCC: 0.33

Figure 21: Comparison of Shade Availability Index (SAI) on north-south streets without trees and with trees at different planting spacings and growth times.

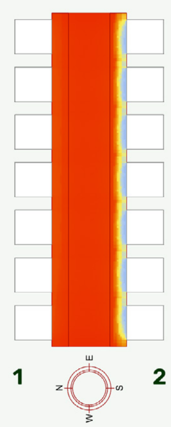
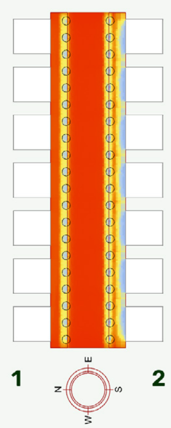
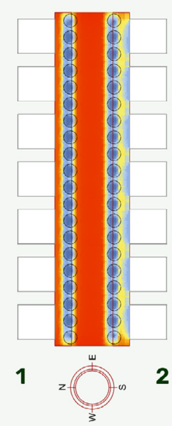
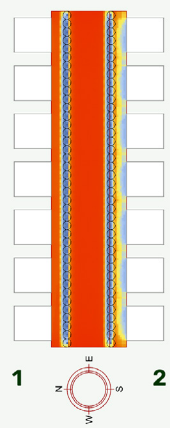
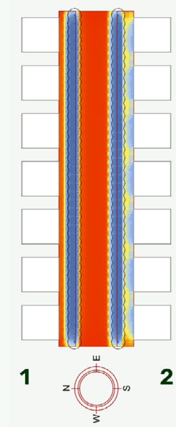
No trees	5 years from planting; planting distance of 10 m	10 years from planting; planting distance of 10 m	5 years from planting; planting distance of 5 m	10 years from planting; planting distance of 5 m
				
SAI 1: 0 SAI 2: 0.5 TCC: 0	SAI 1: 0.2 SAI 2: 0.8 TCC: 0.09	SAI 1: 1.0 SAI 2: 1.0 TCC: 0.22	SAI 1: 0.2 SAI 2: 0.8 TCC: 0.17	SAI 1: 1.0 SAI 2: 1.0 TCC: 0.33

Figure 22: Comparison of Shade Availability Index (SAI) on east-west streets without trees and with trees at different planting spacings and growth times.

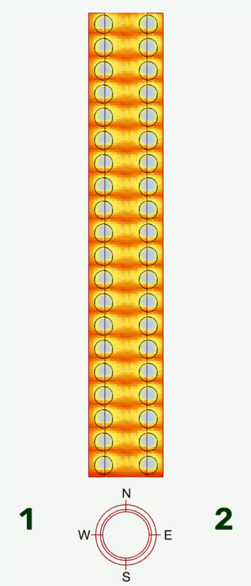
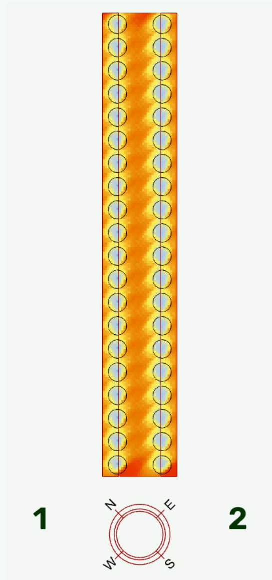
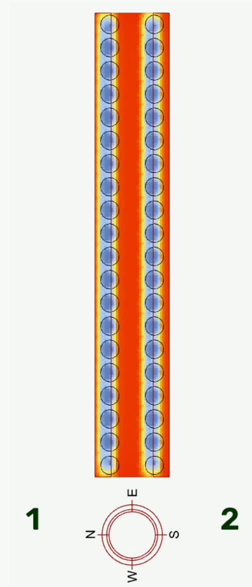
North- South	North East- South West	East- West
 SAI 1: 0.5 SAI 2: 0.6	 SAI 1: 0.6 SAI 2: 0.4	 SAI 1: 1.0 SAI 2: 0.4

Figure 23: Comparison of Shade Availability Index (SAI) on streets with no buildings (when shading is provided only by trees) at different street orientations.

FEASIBILITY OF MEETING SHADING TARGETS UNDER DIFFERENT PLANNING SCENARIOS

Setting measurable quantitative targets may prove ineffective if those targets cannot be met under reasonable, realistic conditions. Therefore, during the formulation of the normative degrees of shade availability, we examined the extent of the difficulty to meet the targets we had set in a wide range of reasonable planning scenarios. The test was performed by modeling about 20,000 design scenarios using the parametric code that we had developed in a previous project (see Appendix B) and calculating the Shade Availability Index for each sidewalk in each design scenario. The resulting dataset enabled us to statistically examine the compliance rate for the shade availability targets at the various Shade Availability Index levels (0.5, 0.7 and 0.9) in all the scenarios examined. The results showed that realizing the highest shading target is indeed possible in almost any planning situation typical of urban areas in Israel. However, reaching this target often depends on planting shade trees on the sidewalks.

The modeling was performed using the Kikayon code (see above, footnote 24). The scenarios were designed to cover a wide range of street designs for main and side streets, which were examined separately. In each scenario, the shade availability levels without trees were examined alongside different tree planting scenarios. The basic model consisted of a 200-m long straight street (without turns) with one sidewalk on each side of the street and a road in its center. All street elements, including the buildings, were modeled in several possible conformations, assuming them to be identical on each side of the street, as follows (Figure 24):

Street orientation: We modeled three street orientations: north-south, northeast-southwest, and east-west. Due to the symmetrical path of the sun in the sky and the calculation of the Shade Availability Index to represent the cumulative state for most of the daylight hours, the results for the northeast-southwest direction were essentially identical to the results for the southeast-northwest direction, and therefore it was not necessary to model those scenarios as well.

Sidewalk width: On main streets, the sidewalk width was 7, 8, 9, or 10 m, assuming the sidewalk to include a bicycle lane and a continuous planting strip. On side streets, the sidewalk width was 2, 3, 4, or 5 m, with no bicycle lane and without a wide planting strip.

Road width: The premise in each scenario was a 2-m-wide parking strip on each side of the road. On main streets, 2-, 4-, or 6-lane roads were considered, and on side streets, one- or two-lane roads were examined. Each lane was set to 3.5 m in width. The total road width on main streets was, therefore, 11, 18, or 25 m, and on side streets, 7.5 or 11 m.

Number of buildings along the street: We modeled scenarios with 3, 5, or 7 buildings on either side of the street.

Lateral building line: We modeled two scenarios: a lateral building line of 4 or 8 m from the parcel line, which translates to a lateral gap of 8 or 16 m between buildings.

Front building line: We modeled two scenarios: a front building line of 0 or 3 m.

Building height: We modeled four building heights: 3, 5, 7, or 9 floors above the ground floor. The height of the ground floor was 4 m, and the height of a typical floor was 3 m. Therefore, the total height of the buildings was 13, 19, 25, or 31 m, respectively.

The tree planting scenarios in each model consisted only of shade trees, at a planting spacing of 5 or 10 m, where a shade tree was taken as a large tree, usually from the broadleaf botanical group, planted to provide significant shade in its vicinity. The natural morphology of shade trees creates a wide canopy, which combined with dense foliage, provides optimal blocking of the solar radiation that falls on the tree crown. However, the urban environment is a hostile and challenging living space for trees whose natural habitat is forests and woodlands. In particular, the urban street is saturated with engineering infrastructure: Concrete and asphalt flooring seal the soil and significantly reduce gas exchange, surface runoff seepage, and water evaporation between the local soil and the atmosphere.

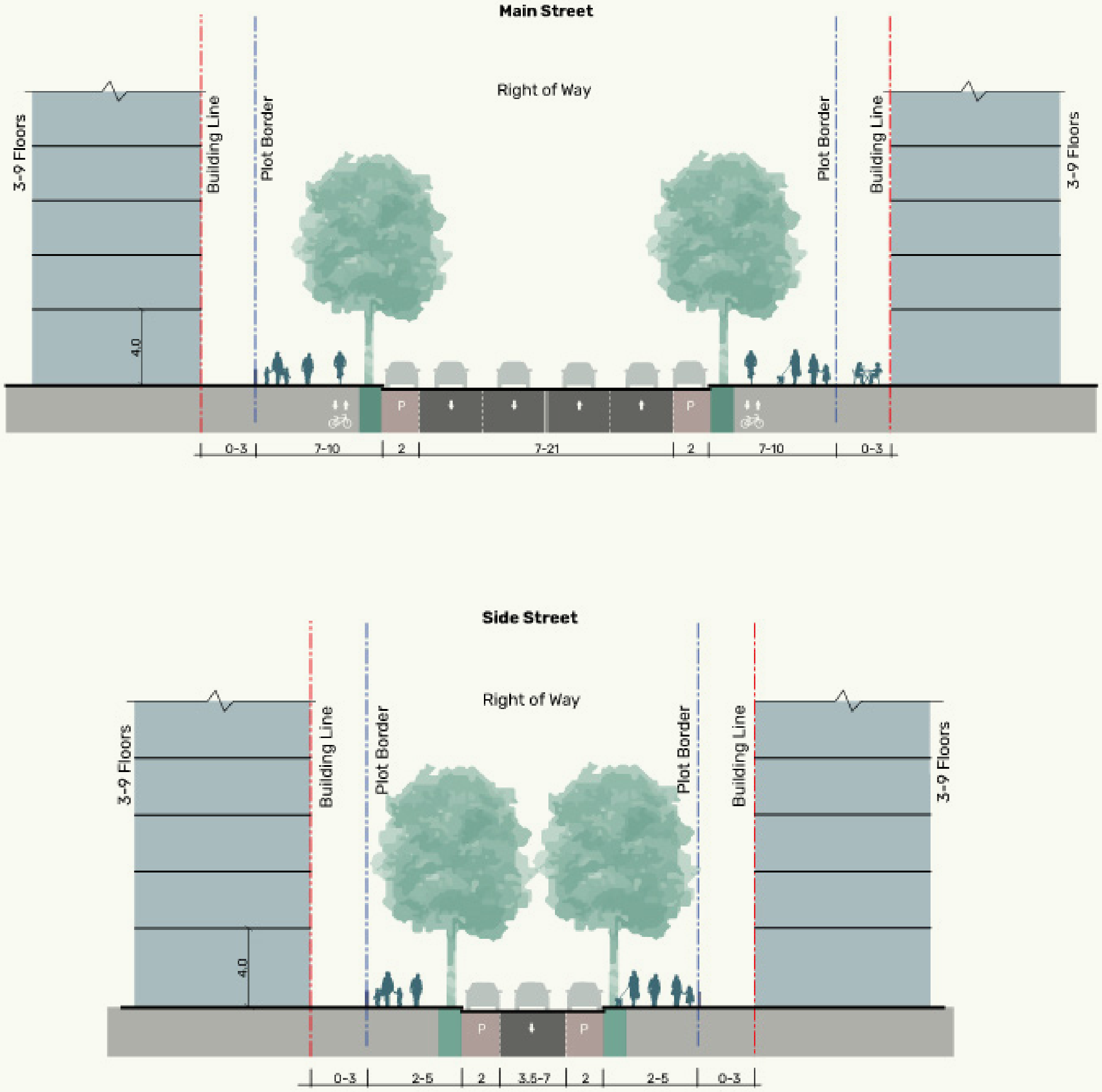


Figure 24: Schematic representation of a street section showing the fixed and variable components in the models examined for a main street (top) and a side street (bottom).

Moreover, in many cases, the urban soil under the sidewalk has been exposed to many years of industrialization, construction, and pollution processes from road waste. Above all, the most limiting factor in the growth of an urban street tree is the lack of sufficient soil volume for its roots. We note here that the basic assumption in modeling the trees has been that they are supplied with conditions that support proper growth, namely, a sufficient soil volume for rooting, irrigation, ventilation and drainage in accordance with high standards of tree habitats within a hard-paved environment.[27]

We modeled the trees at two points in time, 5 and 10 years after planting, during which time a tree may have already grown a significant shading crown even before reaching its maximum size. The planting scenarios were based on the growth scales of two common shade trees in Israel, *Celtis bungeana* and *Delonix regia*.[28] *Celtis bungeana* is a deciduous tree native to China and Korea, with a rapid growth rate and a rounded crown, about 15 m high and 10 m in diameter as a mature tree. *Delonix regia*, is a tree native to Madagascar, with a conditionally deciduous character and a very fast growth rate; the umbrella-like crown of a mature tree is about 12 m high and about 20 m in diameter. At the time points modeled (5 and 10 years), the tree crown of *Celtis bungeana* was taken as 4 or 8 m in diameter and 7 or 9 m in height, respectively; the *Delonix regia* crown was taken as 5 or 8 m in diameter and 7 or 9 m in height, respectively. Therefore, the results

27 Zur, S. (2018). *Guidelines for planting details and living space for street trees in Tel Aviv* [in Hebrew]. Tel Aviv-Yafo Municipality.
28 The growth scales used in this work are based on the work of landscape architect Yaakov Eilon and his many years of personal experience.

obtained were essentially identical for the two species after 10 years of growth, but different 5 years after planting.

A summary of the statistical analysis of the modeling results is given in Tables 3–8. The tables show the percentage of scenarios that met one of the three levels of shade availability out of all the scenarios of the same type. Scenarios in which the shading target is achieved in more than 90% of cases are highlighted in light green, and those in which the shading target is achieved in 75–90% of cases are highlighted in light orange. For example, in a table showing all the planning scenarios for north-south main streets (Table 3), it can be seen that through buildings alone (for all types of building and street dimensions examined) the target of acceptable shade availability (0.5) can be met in 56% of the scenarios examined on the eastern sidewalk and 55% on the western sidewalk. Several general conclusions can be drawn from the analysis of the results with regard to the feasibility of meeting the shading targets, as follows:

Street orientation: Street orientation significantly impacts meeting shade availability thresholds. It is easier to achieve high levels of shading, even without using trees or with little use of trees, on north-south streets or on streets located on a diagonal orientation (northeast-southwest or southeast-northwest). The most difficult streets to shade without trees are east-west streets, but it is important to remember that even on those streets, buildings can have some positive effect on shading at certain times.

Shade trees: It is difficult, and in many cases impossible, to reach the highest level of shade availability (0.9) without planting street trees that develop an optimal crown within 10 years of planting. To achieve this target, it is important to ensure optimal underground habitats for root growth and constant maintenance (deliberate pruning, irrigation) over the years.

Planning flexibility: There are countless ways to meet each of the three levels of shade availability with the right combination of shading from buildings and trees. Therefore, the obligation to meet the shading levels should not limit planning flexibility or the realization of planning goals that go beyond shading.

Setting high targets: The lowest shading threshold (acceptable shading) is designed to create a low common denominator as a starting point for improvement and is not an end in itself. The highest shading targets can be met using trees of almost any morphology and orientation (assuming urban buildings above four stories high, even on relatively wide streets). Hence, an ambitious shading policy is indeed achievable in most cases.

Table 3: Rate of compliance with the levels of shade availability on main streets oriented north-south for all the modeled scenarios

Design scenario (main street)	Planting distance between trees	Percentage of cases in which acceptable shading is achieved (shade availability index: 0.5)		Percentage of cases in which very good shading is achieved (shade availability index: 0.7)		Percentage of cases in which excellent shading is achieved (shade availability index: 0.9)	
		Western sidewalk	Eastern sidewalk	Western sidewalk	Eastern sidewalk	Western sidewalk	Eastern sidewalk
Buildings only		55	56	7	7	0	0
Buildings and *Celtis bungeana* trees after 5 years of growth	10 m	66	65	14	13	0	0
Buildings and *Delonix regia* trees after 5 years of growth		70	68	19	18	0	0
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	99	98	97	69	72
Buildings and *C. bungeana* trees after 5 years of growth	5 m	78	83	44	53	9	7
Buildings and *D. regia* trees after 5 years of growth		100	97	89	84	33	32
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	100	100	100	99	95

Table 4: Rate of compliance with the levels of shade availability on main streets oriented northeast-southwest for all the modeled scenarios

Design scenario (main street)	Planting distance between trees	Percentage of cases in which acceptable shading is achieved (shade availability index: 0.5)		Percentage of cases in which very good shading is achieved (shade availability index: 0.7)		Percentage of cases in which excellent shading is achieved (shade availability index: 0.9)	
		South-western sidewalk	North-eastern sidewalk	South-western sidewalk	North-eastern sidewalk	South-western sidewalk	North-eastern sidewalk
Buildings only		10	59	0	7	0	0
Buildings and *Celtis bungeana* trees after 5 years of growth	10 m	25	69	2	15	0	0
Buildings and *Delonix regia* trees after 5 years of growth		34	73	3	19	0	0
Buildings and shade trees (*C. bungeana* /*D. regia)* trees after 10 years of growth		100	100	100	97	82	84
Buildings and *C. bungeana* trees after 5 years of growth	5 m	82	92	28	71	0	22
Buildings and *D. regia* trees after 5 years of growth		100	96	76	80	40	43
Buildings and shade trees *(C. bungeana* /*D. regia)* trees after 10 years of growth		100	100	100	95	99	96

Table 5: Rate of compliance with the levels of shade availability on main streets oriented east-west for all the modeled scenarios

Design scenario (main street)	Planting distance between trees	Percentage of cases in which acceptable shading is achieved (shade availability index: 0.5)		Percentage of cases in which very good shading is achieved (shade availability index: 0.7)		Percentage of cases in which excellent shading is achieved (shade availability index: 0.9)	
		Northern sidewalk	Southern sidewalk	Northern sidewalk	Southern sidewalk	Northern sidewalk	Southern sidewalk
Buildings only		0	31	0	7	0	0
Buildings and *Celtis bungeana* trees after 5 years of growth	10 m	0	44	0	32	0	4
Buildings and *Delonix regia* trees after 5 years of growth		0	51	0	41	0	16
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	86	100	82	97	79
Buildings and *C. bungeana* trees after 5 years of growth	5 m	22	60	19	52	0	28
Buildings and *D. regia* trees after 5 years of growth		51	70	46	64	25	44
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	94	100	93	97	88

Table 6: Rate of compliance with the levels of shade availability on side streets oriented north-south for all the modeled scenarios

Design scenario (side street)	**Planting distance between trees**	**Percentage of cases in which acceptable shading is achieved (shade availability index: 0.5)**		**Percentage of cases in which very good shading is achieved (shade availability index: 0.7)**		**Percentage of cases in which excellent shading is achieved (shade availability index: 0.9)**	
		Western sidewalk	Eastern sidewalk	Western sidewalk	Eastern sidewalk	Eastern sidewalk	Western sidewalk
Buildings only		89	92	53	59	0	10
Buildings and *Celtis bungeana* trees after 5 years of growth	10 m	98	94	70	77	16	25
Buildings and *Delonix regia* trees after 5 years of growth		99	95	73	82	19	41
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	100	100	100	100	100
Buildings and *C. bungeana* trees after 5 years of growth	5 m	100	100	99	98	80	85
Buildings and *D. regia* trees after 5 years of growth		100	100	100	100	98	96
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	100	100	100	100	100

Table 7: Rate of compliance with the levels of shade availability on side streets oriented northeast-southwest for all the modeled scenarios

Design scenario (side street)	**Planting distance between trees**	**Percentage of cases in which acceptable shading is achieved (shade availability index: 0.5)**		**Percentage of cases in which very good shading is achieved (shade availability index: 0.7)**		**Percentage of cases in which excellent shading is achieved (shade availability index: 0.9)**	
		South-western sidewalk	North-eastern sidewalk	South-western sidewalk	North-eastern sidewalk	South-western sidewalk	North-eastern sidewalk
Buildings only		70	93	30	65	0	9
Buildings and *Celtis bungeana* trees after 5 years of growth	10 m	81	96	47	77	0	24
Buildings and *Delonix regia* trees after 5 years of growth		89	100	66	95	23	73
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	100	100	100	100	100
Buildings and *C. bungeana* trees after 5 years of growth	5 m	100	100	100	100	84	93
Buildings and *D. regia* trees after 5 years of growth		100	100	100	100	98	99
Buildings and shade trees (*C. bungeana/ D. regia*) trees after 10 years of growth		100	100	100	100	100	100

Table 8: Rate of compliance with the levels of shade availability on side streets oriented east-west for all the modeled scenarios

Design scenario (side street)	Planting distance between trees	Percentage of cases in which acceptable shading is achieved (shade availability index: 0.5)		Percentage of cases in which very good shading is achieved (shade availability index: 0.7)		Percentage of cases in which excellent shading is achieved (shade availability index: 0.9)	
		Northern sidewalk	Southern sidewalk	Northern sidewalk	Southern sidewalk	Northern sidewalk	Southern sidewalk
Buildings only		0	71	0	46	0	0
Buildings and *Celtis bungeana* trees after 5 years of growth	10 m	71	86	5	84	0	75
Buildings and *Delonix regia* trees after 5 years of growth		96	90	75	88	2	80
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	100	100	100	100	99
Buildings and *C. bungeana* trees after 5 years of growth	5 m	100	93	100	92	100	84
Buildings and *D. regia* trees after 5 years of growth		100	98	100	96	100	94
Buildings and shade trees (*C. bungeana/D. regia*) trees after 10 years of growth		100	100	100	100	100	100

CONCLUSIONS

This document presents a practical method for formulating an urban shading strategy based on uniform quantitative indexes. The method is intended for application at different scales of urban planning, from formulating a national policy on shading to directing interventions in urban spaces. At the municipal level, the method is based on a three-stage process that includes mapping the urban shade hierarchy, prioritizing intervention areas for additional shading, and designing a detailed shading configuration on the scale of a single street segment. The method of mapping the urban shade hierarchy that appears in this document is based on a computational method previously developed by the authors, which has been applied in more than a dozen cities in Israel to date. With regard to the method of prioritizing intervention areas, such a method should combine the results of shade mapping with data on other issues relating to the urban environment, such as walking comfort, health and economic vulnerability of residents, as well as city-wide planning processes, including urban renewal. The main innovation in this work is the presentation of a uniform index for quantifying shading on sidewalks - the **Shade Availability Index,** which not only enables quantitative comparisons between the levels of shading on different streets but also sets measurable normative shading targets for realizing interventions to improve the state of shading and to monitor their success.

The Shade Availability Index is a measure that quantifies the shaded area available for walking throughout most of the daylight hours on a typical summer day. It expresses the quality of shading in terms of the relative number of hours in which sufficient spatial shading is achieved on a sidewalk. Its advantage lies in a realistic representation of the combined effect of shading from buildings, trees, and other shading elements on the state of shading on sidewalks while maintaining a relatively simple and essentially geometric calculation method. This simplicity facilitates the use of this index to determine normative thresholds that can be intuitively understood even without deep knowledge of the influence of different climatic factors on a person's perceived thermal comfort. For Israeli conditions, we propose setting three levels of shading as desirable normative targets in shading-oriented urban planning, as follows:

Acceptable shading

Shade Availability Index value of 0.5 or higher

Very good shading

Shade Availability Index value of 0.7 or higher

Excellent shading

Shade Availability Index value of 0.9 or higher

We propose formulating minimum targets for the design of new streets nationwide based on these thresholds. Regarding interventions in existing streets, recognizing the practical limitations of realizing shade intensification operations and out of familiarity with the problematic shading situation in countless streets and urban spaces in Israel, our recommendation is to allow each municipal authority flexibility in choosing the level of shading it wishes to reach at different intervention sites. At the same time, cities should adopt the lowest level of shade availability defined here (acceptable shading on each sidewalk) as an obligatory threshold below which a street cannot be considered a shaded street.

We are aware that to promote a significant change in the state of street shading in many cities in Israel, general urban targets must be set, such as the percentage of streets that must meet a certain shading threshold. However, we believe that setting such targets is possible only on the basis of a systematic analysis of the current situation and of the scope of economic investment required to realize urban goals. The Shade Availability Index makes it possible to make such informed evaluations. Still, before such evaluations are made, we recommend avoiding setting sweeping quantitative targets that may prove unfeasible in the short or long term.

Setting quantitative targets related to shading also depends on the development of uniform calculation tools that are open for use by all planning entities that may be involved in promoting the state of shading in urban spaces, from government and public bodies to planners operating in the private market. The indexes that we present in this work were developed with simple applications as digital computing tools in mind. Without the development of such tools, it will be difficult to effectively monitor the implementation of shading plans that are being promoted today or will be promoted in the future. It will also be difficult to ensure that the adoption of the indexes presented in this work is correct or accurate, even though the method of calculating the indicators is clearly presented. Moreover, without the adoption of uniform quantitative indexes and uniform calculation tools, it will be difficult to comparatively examine the promotion of shading in urban spaces between different cities in Israel and to update national shading targets based on such an examination. The adoption of a uniform measurement method for shading in urban spaces is a necessity, without which the state will find it difficult to efficiently and effectively promote the issue, despite decisions made at the national or municipal level.

Finally, it should be emphasized that the index presented in this guide is intended for the design of sidewalk shading only, focusing on shading for pedestrian or non-motorized traffic in urban spaces. Although it is possible to develop the concept further and extend it to other urban land uses where shading is required, such as squares, public gardens and parks, playgrounds, central street intersections, and entrance plazas to public buildings, complementary work will be required to examine the shading needs in each of these spatial typologies and the quantitative indexes applicable in those cases.

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APPENDIX A | THE SPATIAL SHADE INDEX

The spatial **Shade Index** provides a relative quantification of the amount of global radiation blocked before reaching ground level on a typical summer day. It is calculated based on high-resolution three-dimensional mapping of the built-up space, distinguishing between buildings and trees. Computationally, this distinction is necessary because a tree's crown extends beyond its trunk, thereby exerting a shading effect in the space directly below it. The index considers the variation in solar radiation intensity throughout the day and compares the cumulative blocked insolation at a certain location and the maximal cumulative insolation of an unobstructed surface at the same time and location. The formula used to calculate the index is:

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

where SI_p is the Shade Index at a certain point, *Insolationp* is the insolation at that point, and *Insolationr* is the insolation at the unobstructed reference point. It follows that the higher the level of shading, the closer the value of the Shade Index is to 1.

The calculation resolution of the Shade Index depends on the mapping quality on which it is based. However, to reflect significant differences in the insolation intensity of the human body, it is recommended to calculate the index at spatial intervals not exceeding 50 cm. The index is calculated as **an average** shading value per a defined unit of area, usually a street segment or a neighborhood, based on calculating the individual Shade Index values at each sampling point included in the area unit. In principle, it is possible to calculate a spatial Shade Index not only for an entire right-of-way but also for each sidewalk separately, but in the absence of precise mapping of sidewalks in most cities in Israel, it is currently impractical to produce shade maps of sidewalks alone, excluding the shading on the road next to them.

To reflect the average level of shading over a typical summer day, shade maps show a spatial Shade Index that takes into account the intensity of **cumulative** exposure of the ground surface to solar irradiance between 08:00 and 17:00 (daylight saving time) on 6 August, which is the day half way between the longest day of the year (21 June) and the autumnal equinox (22 September), and also represents the peak annual heat stress in Israel resulting from peak daytime air temperatures. However, the spatial Shade Index can be calculated for other periods (for other hours or dates), but such calculations may yield different results due to differences in the direction and intensity of the impact of solar radiation at different times of the year.

Shade maps based on the spatial Shade Index are produced using spatial analyses and calculations in a GIS environment. The input data required to produce urban shade maps are:

- Digital Surface Model (DSM) with a resolution of 0.5 m per pixel.
- Digital Terrain Model (DTM) with a resolution of 0.5 m per pixel.
- A vector file of the city's tree canopy contours.
- A vector file of the land use boundaries in the city.
- A vector file of all building footprints in the city (not mandatory but highly recommended).

To the extent possible, it is also advisable to provide the following layers:

- An orthophoto (preferably one that includes an NIR channel) with a resolution of 0.2 m per pixel, corresponding to the input DSM (the orthophoto can help to detect errors in the other mapping layers)
- For calculating shade levels in neighborhood-level spatial units that differ from a city's statistical zones, a vector file of the city's neighborhood boundaries.
- For calculating sidewalk shade levels, a vector file of the contours of all sidewalks in the city.

- For calculating the density of tree planting in a city and its effect on shading conditions on streets and open public spaces, a vector file containing precise locations of all tree trunks in the city.

It is important to note that shade maps document a situation that may change substantially due to changes in the urban space (urban renewal, cutting down trees, or planting trees). Therefore, **we recommend that shade maps be produced at intervals of at least every three to five years,** depending on the intensity of development activities in the city. Therefore, it is also important to ensure, at the national level, that the basic data necessary to produce shade maps is produced at least as frequently.

By processing and analyzing the raw mapping data listed above, one can generate the following shade maps:

- Map showing a spatial Shade Index in street segments and open spaces.
- Map showing a spatial Shade Index in street segments and open spaces, excluding the effect of trees on this index.
- A spatial Shade Index in statistical zones, according to the current spatial definitions published by the Central Bureau of Statistics, or in any other spatial units used by a municipality (districts, neighborhoods, planning zones).
- A spatial Shade Index in areas excluding the effect of trees on this index.

APPENDIX B | KIKAYON, A PARAMETRIC CODE FOR CALCULATING SHADE ON STREETS

The Kikayon code is a Grasshopper code developed by Or Aleksandrowicz and Ezra Ozery in work funded by the Israel 100 Initiative.[29] The code allows us to conduct a parametric examination of the effect of street design on the street's shading conditions, to compare different shading scenarios, and to evaluate, based on quantitative indexes, the effect of different designs on improving shading conditions on the street (Figures B1 and B2). The code receives a three-dimensional design of a street segment and calculates the values of two different shading indexes:

- **Shade Index:** As detailed in Appendix A of this document.

- **Shade Availability Index:** As detailed in the main text of this document.

29 Aleksandrowicz, O., & Ozery, E. (2023). A Parametric Tool for Outdoor Shade Design: Harnessing Quantitative Indices and Visual Feedback for Effective and Efficient Climatic Design of Streets. In M. Turrin, C. Andriotis, & A. Rafiee (Eds.), *Computer-Aided Architectural Design. INTERCONNECTIONS: Co-computing Beyond Boundaries* (pp. 302–316). Springer Nature Switzerland.

The spatial Shade Index is calculated for several parts of the street as follows:

- **Right-of-way as a whole:** The entire area of the street segment, including the two sidewalks, the road, and a central walking boulevard (when existing).

- **Road:** The total area allocated for the passage of cars and vehicles. If a walking boulevard is planned in the center of the street, the area of the road includes the two carriageways that flank the boulevard on either side.

- **Left sidewalk (Sidewalk 1):** This area does not include private open space between the front parcel line and the front building line.

- **Right sidewalk (Sidewalk 2):** This area does not include a private open space between the front parcel line and the front building line.

- **A central walking boulevard,** when existing.

The Shade Availability Index is calculated only for the sidewalks and the central walking boulevard. In addition, the code calculates three quantitative measures relating to trees if these are incorporated into the design:

- **Number of trees:** The total number of trees planned on the street, without distinction between tree types.

- **Tree density per unit area (trees per dunam):** The number of trees per 1000 sqm of right-of-way area. The recommended value is 10 trees per dunam, to the extent that the physical layout of the street allows.

- **Tree canopy cover:** The ratio of the total area of vertical projections of tree crowns within the street to the total area of the street (the entire right-of-way).

For the calculation, users must first build a 3D model of a street segment by entering the dimensions or quantities of the many physical components that make up the street model, as follows:

- Street segment length
- Street orientation
- Traffic strip width
- Parking strip width, on one side of the street or both sides
- Walking boulevard width at the center of the street, if there is one
- Walking strip width
- Street furniture strip
- Bike lane width
- Planting strip width
- Number of buildings on each side of the street

- Depth of each building (i.e., the length of the building side) on each side of the street
- Front building line and the lateral building lines of the ground floor on each side of the street
- Ground floor height of buildings on each side of the street
- Number of typical floors above ground floor of buildings on each side of the street
- Typical floor height of buildings on each side of the street
- Front building line and lateral building lines of a typical floor of buildings on each side of the street
- Number of roof floors of buildings on each side of the street

- Roof floor height of buildings on each side of the street
- Front building line and the lateral building lines of the roof floors of buildings on each side of the street
- Number of rows of trees on each sidewalk or on a central walking boulevard
- The position of each row of trees relative to the curb stones
- The types of trees in each row of trees (from a predefined list)
- Planting spacing between trees in each row of trees
- Depth of a shading awning above the ground floor on each side of the street

The code can be downloaded via the following GitHub repository:
https://github.com/oraleks/Kikayon

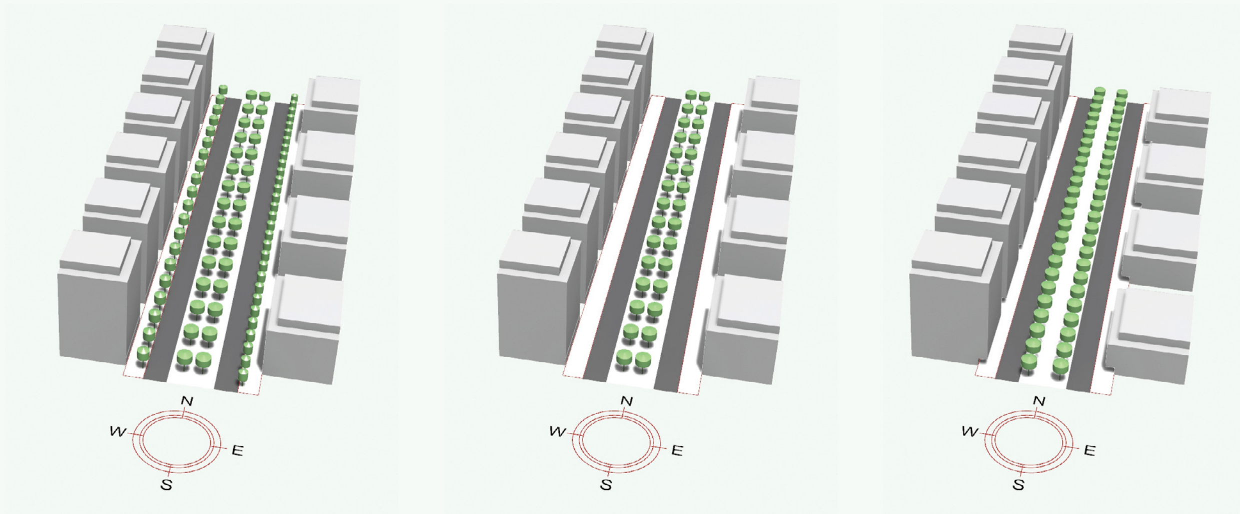

Figure B1: Modelling different design scenarios using the Kikayon parametric code.

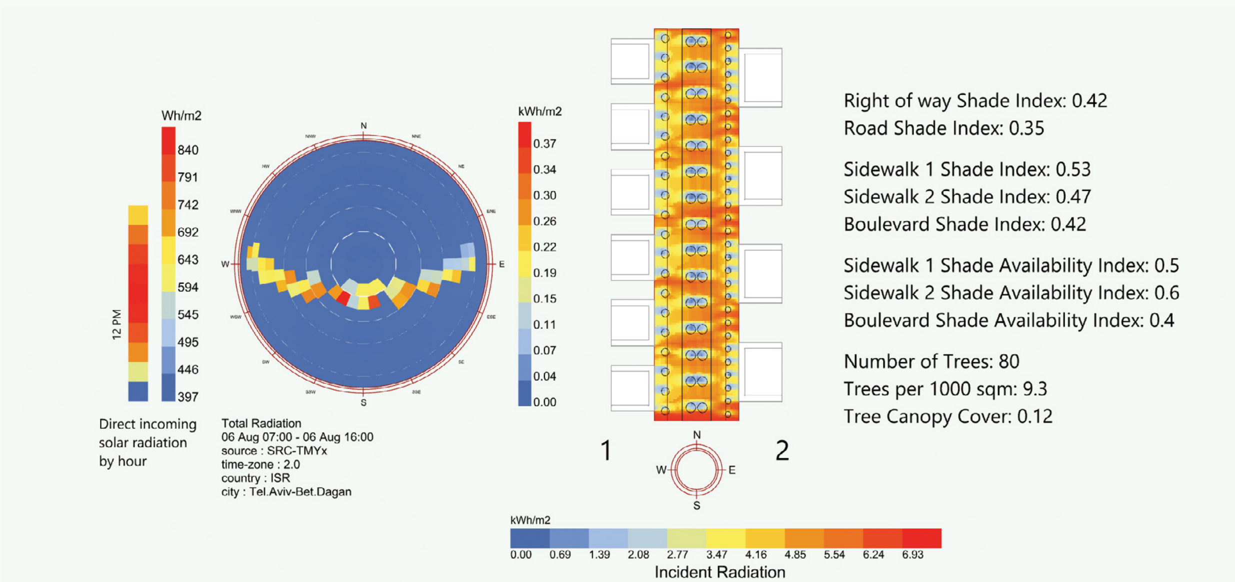

Figure B2: Kikayon's results screen shows an overview of the modeled street, the cumulative shade layout on the ground, and numerical values calculated for each quantitative indicator.

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