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Research paper

PARAMETRIC EVALUATION OF TREE LAYOUT FOR GROUND-LEVEL INSOLATION MITIGATION IN AN URBAN COURTYARD

Ivana Bajšanski[1]

Abstract

The spatial configuration of urban blocks influences the exposure of courtyards to increased solar insolation due to building arrangement and tree layout, which can negatively affect the quality of public open spaces. This research investigates the influence of tree layout on ground-level insolation within an urban courtyard surrounded by five residential buildings. The study aims to develop a parametric evaluation workflow for reducing ground-level solar insolation through the strategic placement of trees.

The research was conducted using various software applications such as Rhinoceros 3D, Grasshopper, Ladybug and Galapagos. The existing urban block configuration, consisting of 14 trees and surrounding building geometry, was first analyzed to determine ground level insolation. In order to mitigate ground level insolation, three evaluation approaches for tree distribution were tested.

The first approach employed randomly generated tree positions using the Populate component controlled by seed variation. The second approach utilized a divided surface with predefined tree placement points to prevent canopy overlap. The third approach combined a dense surface subdivision with evolutionary optimization through Galapagos, enabling the algorithm to identify improved tree layouts while indirectly minimizing canopy overlap through fitness evaluation.

The results indicate that evolutionary optimization provides the most effective and interpretable solution for reducing ground-level insolation, while also offering greater control over tree positioning compared to random seed-based methods. The study demonstrates the potential of parametric and data-driven environmental simulations for improving microclimatic conditions in urban open spaces and supporting climate-responsive urban design strategies.

Key words: *Parametric optimization, Urban courtyard, Tree layout, Inoslation, Evolutionary algorithm.*

[1] PhD, Associate Professor, Faculty of Technical Sciences, University of Novi Sad, Serbia, ivana_b@uns.ac.rs, ORCid 0000-0002-3846-1561

1. INTRODUCTION

Urban courtyards represent important semi-public open spaces within dense residential blocks, playing a significant role in providing environmental quality and opportunities for outdoor use [1,2,3]. In many urban blocks, the spatial configuration of buildings often results in unfavourable microclimatic conditions, particularly in terms of ground-level solar insolation. Depending on their geometric proportions, courtyard spaces can be exposed to high levels of solar insolation at ground level [4,5].

One of the key factors influencing ground-level solar insolation is the interaction between surrounding buildings and trees [6,7]. While buildings define the overall enclosure and shading potential of a courtyard, trees introduce a dynamic layer of shading that can significantly modify solar access conditions at pedestrian level [8,9,10]. The spatial arrangement, density, and positioning of trees therefore become critical parameters in creating microclimatic performance.

In recent years, parametric design methods and environmental simulation tools have enabled more advanced approaches to analyzing and optimizing urban spaces [11,12]. Digital tools such as Rhinoceros 3D (3D modelling software) [13], Grasshopper (Rhinoceros plug in, visual programming software) [14], and Ladybug (software for environmental simulations) [15] allow for detailed solar analysis, while evolutionary solvers such as Galapagos [16] enable the exploration of large solution spaces for spatial optimization problems. These computational approaches provide opportunities to systematically test and evaluate different tree layouts in relation to environmental performance criteria.

Within this context, this study focuses on a case study of a single urban courtyard surrounded by five residential buildings. The courtyard has an open spatial configuration, resulting in increased exposure to solar insolation at ground level. The research investigates how different tree layouts influence ground-level insolation and explores how parametric and evolutionary methods can be used to identify configurations that mitigate insolation.

The main objective of this study is to develop and test a parametric workflow for evaluating and comparing tree distribution strategies in order to reduce ground-level solar insolation. By combining environmental simulation with algorithmic optimization, the research aims to contribute to a better understanding of how vegetation design can be used as a tool for microclimatic improvement in dense urban environments.

2. METHOD

In order to evaluate ground-level solar insolation within an urban courtyard under different tree layout configurations, a parametric approach consists of the following phases:

The first phase involves modelling of the urban environment in a 3D software. The 3D model includes:

- surrounding buildings geometries;
- ground surface representing the courtyard area;
- tree geometries representing existing vegetation elements.

The courtyard geometry, consisting of five residential buildings and a central open space, is created into Rhinoceros 3D. Buildings are modelled as sphere solid, non-transparent objects that generate full shadow effects. Trees are modelled as simplified sphered representing canopy influence on solar shading. The ground surface is discretized depending on the selected analysis resolution. All geometric elements are referenced inside Grasshopper, where the parametric definition is developed and linked back to the Rhinoceros environment for visualization and iteration (*Figure 1*).

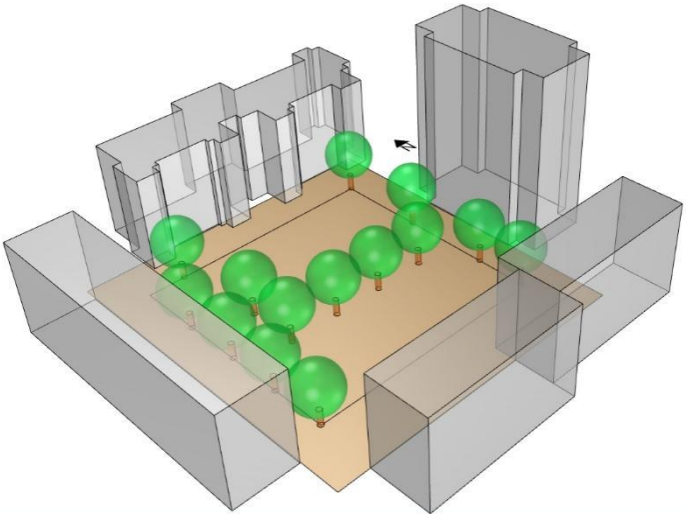


Figure 1. 3D representation of referenced building geometry and existing 14 trees placed in the courtyard. Source: Author.

The second phase refers to the generation of potential trees position. Three different approaches are implemented:

- random distribution using a Populate component controlled by seed variation (*Figure 2a*);
- structured distribution using a divided surface with predefined placement points to avoid canopy overlap (*Figure 2b*);
- dense ground surface subdivision combined with evolutionary optimization to allow flexible positioning and interaction between tree canopies (*Figure 2c*).

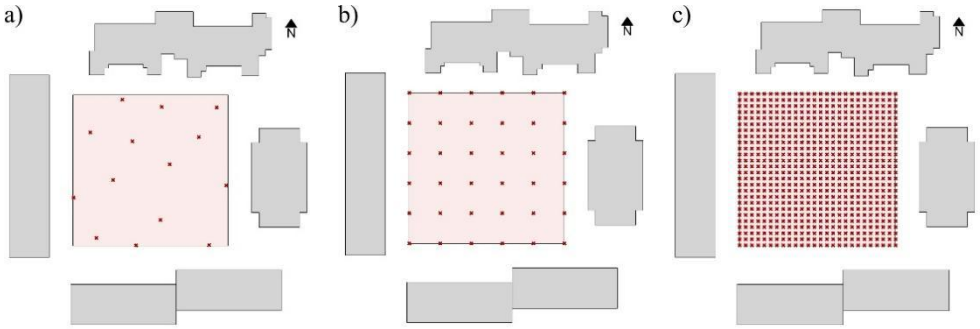


Figure 2. Tree layout configurations obtained with a) random distribution using a Populate component; b) a divided surface with predefined placement points to avoid canopy overlap and c) dense ground surface subdivision. Source: Author.

The third phase is the simulation of ground-level solar insolation using Ladybug. Ladybug uses building geometry, tree shading, and weather data to calculate solar insolation on the ground surface over a defined analysis period. The simulation outputs the average ground-level insolation expressed in kWh/m² for each tested configuration. Weather data for the selected location of Belgrade, Serbia, is imported using a standard EPW file. Ladybug take into account geometry of buildings, weather data and time (from 9pm to 15 pm) and year period (7th July) of analysis set. The Ladybug software calculates the average insolation of a ground surface in kWh/m^2.

The final phase includes the comparison and export of results from all tested configurations. The performance of each method (random, structured, and evolutionary) is evaluated based on the resulting ground-level insolation values, allowing for a comparative assessment of tree layout strategies.

3. RESULTS

The results of the study are evaluated based on the average ground-level solar insolation calculated for all simulation scenarios and compared to the baseline condition with existing placement of 14 trees (2.71 kWh/m²), which serves as the reference value for all comparative analyses (*Figure 3a*).

The random distribution strategy produced the most favorable outcome, with an average insolation value of 2.52 kWh/m² (*Figure 3b*). This corresponds to a reduction of approximately 7.01% compared to the baseline condition.

The structured distribution method, based on predefined placement points designed to avoid canopy overlap, resulted in an average insolation value of 2.54 kWh/m² (*Figure 3c*), representing a 6.27% reduction relative to the baseline. Although slightly less effective than the random distribution, this approach provides more controlled spatial organization and predictability of tree placement.

The evolutionary optimization approach, applied to a densely subdivided surface allowing flexible positioning of tree canopies, achieved an average insolation value of 2.55 kWh/m² (*Figure 3d*), corresponding to a 5.90% reduction compared to the initial condition. While this method enables adaptive optimization of tree locations, the results indicate only marginal improvement over the other tested strategies.

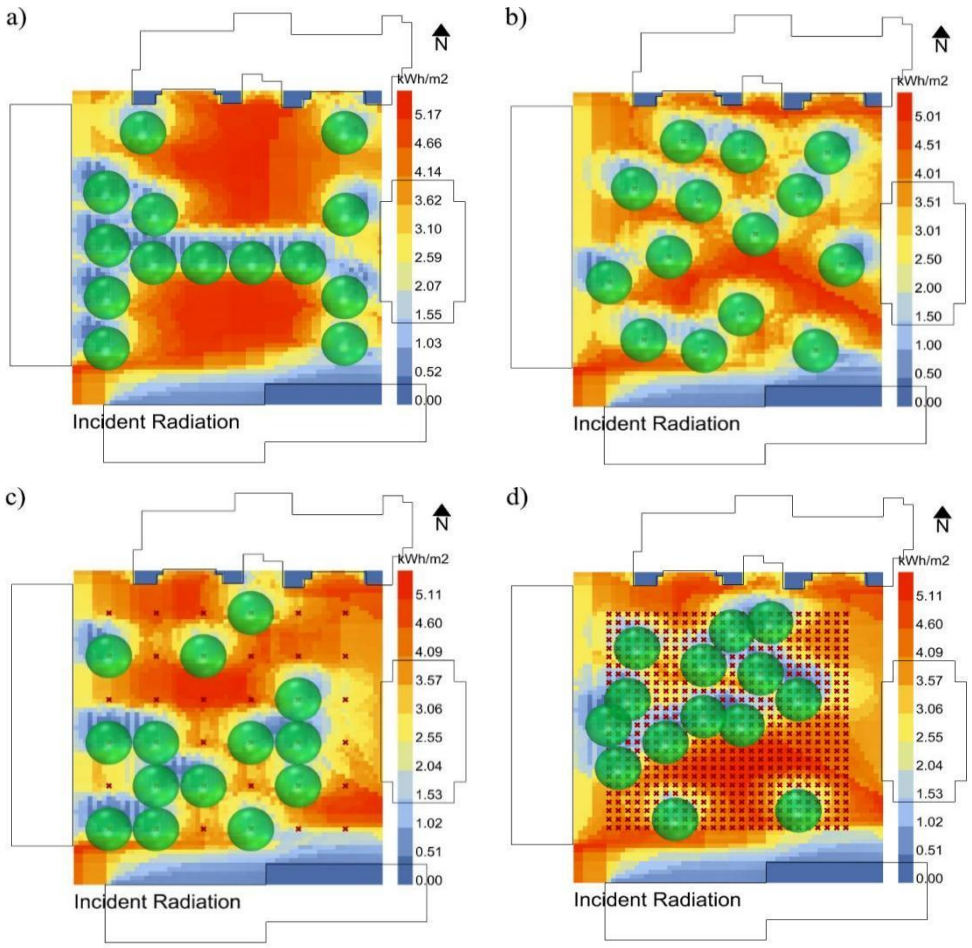


Figure 3. Insolation of tree layout configurations of a: a) baseline tree layout; b) random distribution using a Populate component; c) a divided surface with predefined placement points to avoid canopy overlap and d) dense ground surface subdivision. Source: Author.

In addition to the comparison of mean values, the variability of results was evaluated using both the range (min–max) and the standard deviation (σ) of ground-level solar irradiation values obtained from multiple simulation runs.

The random distribution strategy showed values between 2.52 and 2.61 kWh/m² (*Figure 4a*), with a standard deviation of σ = 0.02 kWh/m², indicating very low dispersion around the mean and a high level of stability across different tree configurations.

The structured distribution method resulted in a wider range of 2.54 to 2.75 kWh/m² (*Figure 4b*), with a standard deviation of σ = 0.04 kWh/m², suggesting moderate sensitivity to spatial configuration and increased variability compared to the random population-based approach.

The evolutionary optimization approach using the Galapagos solver exhibited the largest variability, with results ranging from 2.55 to 3.05 kWh/m² (*Figure 4c*), and a standard deviation of σ = 0.07 kWh/m², confirming a significantly higher dispersion of solutions due to the exploration of a broader and less constrained search space.

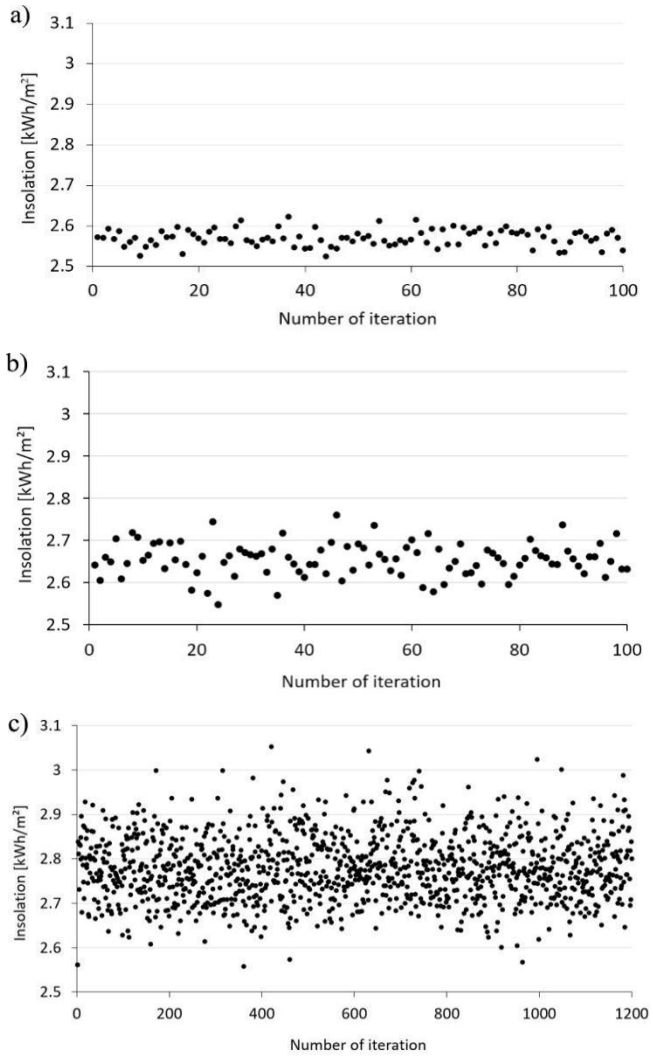


Figure 4. Insolation of ground level obtained with a: a) random tree distribution using a Populate component; b) a divided surface with predefined placement points to avoid canopy overlap and c) dense surface subdivision. Source: Author.

Overall, the comparison of standard deviations clearly indicates a trend of increasing variability with increasing algorithmic complexity. While the random distribution strategy provides the most stable and consistent outcomes, the structured distribution method introduces moderate variability, and the Galapagos-based optimization produces the least stable results despite exploring a larger solution space.

The Galapagos-based configuration is presented as a representative optimized solution generated within a search space. Although it does not yield the best mean performance, it illustrates the spatial characteristics of an evolutionary optimization outcome under the given constraints.

4. CONCLUSION

This study investigated the impact of different tree distribution strategies on ground-level solar insolation in an urban block, with the aim of evaluating both the effectiveness and robustness of generative and optimization-based placement methods.

Three approaches were analyzed: random distribution using a Populate component controlled by seed variation, structured distribution using a divided surface with predefined placement points to avoid canopy overlap, and an evolutionary optimization approach using the Galapagos solver with dense ground surface subdivision to allow flexible positioning and interaction between tree canopies. All methods resulted in a reduction of ground-level solar insolation compared to the baseline condition (2.71 kWh/m²), with mean values ranging between 2.52 and 2.55 kWh/m², corresponding to improvements of approximately 5.90% to 7.01%.

Beyond mean performance, the study highlighted significant differences in result stability. The Population-based method demonstrated the highest robustness, with the lowest standard deviation (σ = 0.02 kWh/m²), followed by the structured distribution approach (σ = 0.04 kWh/m²), while the Galapagos-based optimization exhibited the highest variability (σ = 0.07 kWh/m²). These findings indicate that increasing algorithmic complexity does not necessarily lead to more stable or consistently improved environmental performance within the defined simulation framework.

An important limitation of the evolutionary optimization approach is the difficulty in extracting a single deterministic optimal configuration due to the stochastic nature of the seed-driven process and the exploration of a large solution space. As a result, the study focuses on statistical performance indicators (mean values, range, and standard deviation) rather than a single definitive optimal tree layout.

Despite this limitation, the results provide valuable insight into the trade-off between control, randomness, and optimization in parametric urban design workflows. The findings suggest that simpler methods may offer more predictable and robust performance under similar environmental constraints, while more complex optimization strategies require additional post-processing or constraint refinement to ensure solution stability.

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