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Landscape Design for Improved Thermal Environment: An Optimized Tree Arrangement Design for Climate-Responsive Outdoor Spaces in Residential Buildings Complexes

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ABSTRACT

The heat reduction effect of trees has been investigated through numerical simulations; however, there are still challenges to applying the scientific results to the planning process due to the model's complexity and the computational resources required. This study investigates a rapid spatial evaluation method for heat stress potential, measured by mean radiant temperature (MRT), by decomposing radiation into sub-radiation using a multilayer MRT model. This method also enables the reproduction of optimized layouts considering the effect of tree arrangement in residential buildings. Multi-objectives were achieved through an evolutionary algorithm, resulting in more effective design layouts combining tree types and arrangements, all within a standard budget. By adopting this study's approach, landscape designers can create climate-responsive tree layouts with reduced heat exposure and generate customized planting designs tailored to their preferences.

1. Introduction

The utilization of green spaces solution to address the intensifying phenomenon of urbanization has been proposed for over 150 years (Kang, 2017; Loughran, 2020). Furthermore, research on green infrastructure has been conducted to mitigate urban heat island effects exacerbated by increasing urban density (Feyisa et al., 2014; Li et al., 2019; Manoli et al., 2019). Recently, in response to the challenges posed by climate change, the idea of green spaces as a nature-based solution (NbS) has once again gained prominence (Chausson et al., 2020; Osaka et al., 2021). Trees' role in mitigating climate change's effects is being increasingly studied within this context (Gülten et al., 2016; C. He et al., 2021; Morakinyo et al., 2020; Wang & Akbari, 2016; Yun et al., 2020).

The green infrastructure surrounding residential buildings has been recognized as a crucial strategy to mitigate urban heat island effects and respond to climate change. Increased population density due to urbanization has led to a shortage of resources and a trend toward high-rise residential buildings, resulting in the emergence of open spaces. Quantitative evaluations of the effects of trees within this space have become increasingly important in recent studies, particularly those focused on improving thermal comfort (Abdollahzadeh & Biloria, 2021; Atwa et al.,

Abbreviation: LW, Longwave radiation; SW1, Reflect and diffuse shortwave radiation; SW2, Direct shortwave radiation; HSP, Heat stress potential; RH_A, Radiant heat changes due to distance from the shaded building wall; RH_B, Radiant heat changes due to distance from the sunlit building wall; RH_C, Radiant heat changes due to tree shadow effect; RH_D, Radiant heat changes due to evapotranspiration effect of surrounding trees.

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Acronym

MRT	Mean Radiant Temperature
EBM	Energy Balance Models
CFD	Computational Fluid Dynamics
MMRT	Multilayer Mean Radiant Temperature model proposed by C. Y. Park (2018)
LAI	Leaf Area Index
LAD	Leaf Area Density
SVF	Sky View Factor
NSGA-II	Non-Dominated Sorting Genetic Algorithm II

2020; Zhao et al., 2018; Zölch et al., 2019). Additionally, research is being performed to integrate the evaluation results of trees' heat reduction or shading effects as decision support material for urban and street planning (Azcarate et al., 2021; Cheshmehzangi et al., 2021; He, 2022; Peeters et al., 2020).

To ensure pedestrian thermal comfort, it is essential to evaluate thermal stress spatially by considering radiation exchange in the context of buildings and trees, as the surroundings change depending on an individual's position. For trees and buildings, mutual shading, emission, and reflection processes cause shortwave and longwave radiation exchange through the radiative effects of trees (Krayenhoff et al., 2014). In order to incorporate the impact of trees into the planning process, it is essential to use a simulator that can capture various radiation-related physical processes mentioned earlier while providing a prompt evaluation of the performance of different tree arrangements.

Numerical simulation models commonly used in current research, such as RayMan, SOLWEIG, and green-CTTC, are employed as Energy Balance Models (EBMs), while ENVI-met, OPENFOAM, FLUENT, and STAR-CCM+ are utilized as Computational Fluid Dynamics (CFD) models (Yang et al., 2019) to represent 3D urban forms and simulate reality. Although these models offer approximate results, they pose several challenges when it comes to evaluating and comparing multiple scenarios and integrating the outcomes into the design and planning process. EBM models like RayMan have relatively fast run times but simplify calculations for diffuse shortwave and longwave radiation using the sky view factor (Park et al., 2018). CFD models, on the other hand, are computationally complex and demand extensive computational time for each simulation. Consequently, challenges remain in generating diverse alternatives based on preferences, instantly evaluating scenarios, and incorporating scientific assessments into design decisions.

This study employs a distance-based spatial evaluation approach to compare randomly generated alternatives for tree arrangement (planting design) through immediate alternative evaluation and optimize the results for climate response. In this regard, the study utilizes the Multilayer Mean Radiant Temperature (MMRT) model proposed by Park et al. (2018), which applies the Monte Carlo ray tracing method to evaluate the thermal comfort of pedestrians in street canyons. This methodology facilitates the derivation of an optimized climate response for various planting design alternatives through accurate evaluation. It serves as a decision-making tool for evidence-based planning and allows for the simulation and comparison of numerous design options. Accordingly, this study addresses three primary research questions: 1) Can a method generate various alternatives, instantly evaluate scenarios, and integrate scientific evaluations into design decisions? 2) How do the density and arrangement of trees impact heat stress on local thermal conditions in urban environments? 3) Which types and arrangements of trees are most effective for reducing heat in urban environments?

The research questions are investigated through the utilization of decomposing methods to approximate radiation transfer in a spatial grid. The impact of different tree types and arrangements under predefined artificial conditions is compared, aiming to develop an optimized alternative that fulfills the objective goal for use in the design decision process.

The study introduces a method for planting design in high-rise residential spaces, derives an optimized design plan based on the methodology, and applies it to a real-world site. The structure of the remaining work is as follows: Section 2 presents a method for exploring various planting designs for standardized residential complexes while effectively responding to thermal stress without excessive costs. In particular, Section 2.3 introduces a decomposition-recomposition method to assess heat stress potential, while Section 2.4 presents the application of the multi-objective optimization method to evaluate a broad range of planting designs and fulfill the goals by applying standard landscaping budgets. Section 3 analyzes the results obtained from the study, and Section 4 discusses the methodology used in the research, which enables the decomposition of thermal radiation, facilitating repetitive and simultaneous evaluations and thus offering a variety of planting design options. Finally, the findings are summarized and concluded in Section 5.

2. Method

This study uses an optimization methodology to assess thermal stress in urban spaces. The evaluation unit in this study is Mean Radiant Temperature (MRT), which quantifies the heat stress potential experienced at each location due to surrounding objects. High MRT areas have high heat flux and are either subjected to large amounts of short-wave radiation or reflect large amounts of long-wave radiation from surrounding things.

The Multilayer Mean Radiant Temperature (MMRT) model was used to reflect the building and tree elements that comprise the urban environment (Park et al., 2018, 2019) The MMRT model simulates the urban spatial structure based on distance (Park et al., 2018). and can calculate 2.5 dimensions based on the location of trees and buildings in an infinitely extending urban canyon. The latent heat change due to trees can also be reflected to compare the before and aftereffects of using plant materials (Yun et al., 2020). The design drawing was divided into grid units, and the "heat stress potential" was simulated in MRT units. The location of the building was designated as a fixed parameter. Still, the tree arrangement design was optimized by comparing and optimizing the reduction effect in each grid using a genetic algorithm (Fig. 1).

The analysis consists of four steps: (1) dividing the design drawing into spatial units and calculating the impact of surrounding buildings on each unit, (2) classifying the tree species in the design plan into tree types that reflect their structural and physiological characteristics, (3) calculating heat stress potential reflecting the planting design plan, and (4) optimizing the design plan that responds to heat stress using a genetic algorithm.

2.1. Compartmentalizing drawings into spatial units

The cooling effect of trees is determined not only by the presence of green spaces but also by the urban geometry, such as the height and density of buildings (Segura et al., 2022; Shashua-Bar et al., 2011). Therefore, when evaluating the thermal environment, spatial elements of both buildings and ground surfaces that make up the urban space should be considered. Additionally, the level of thermal stress depends on their radiative properties, such as albedo and emissivity. To determine the impact of radiant heat within the urban space, the design area was divided into grid units, and the constituent spatial elements within each grid were considered (Fig. 2). These elements include information about the buildings and ground surfaces that make up the urban environment. The heat stress potential (thermal radiation) experienced in each area is influenced by the radiant properties of the building components, such as the height of the buildings, the material composition of

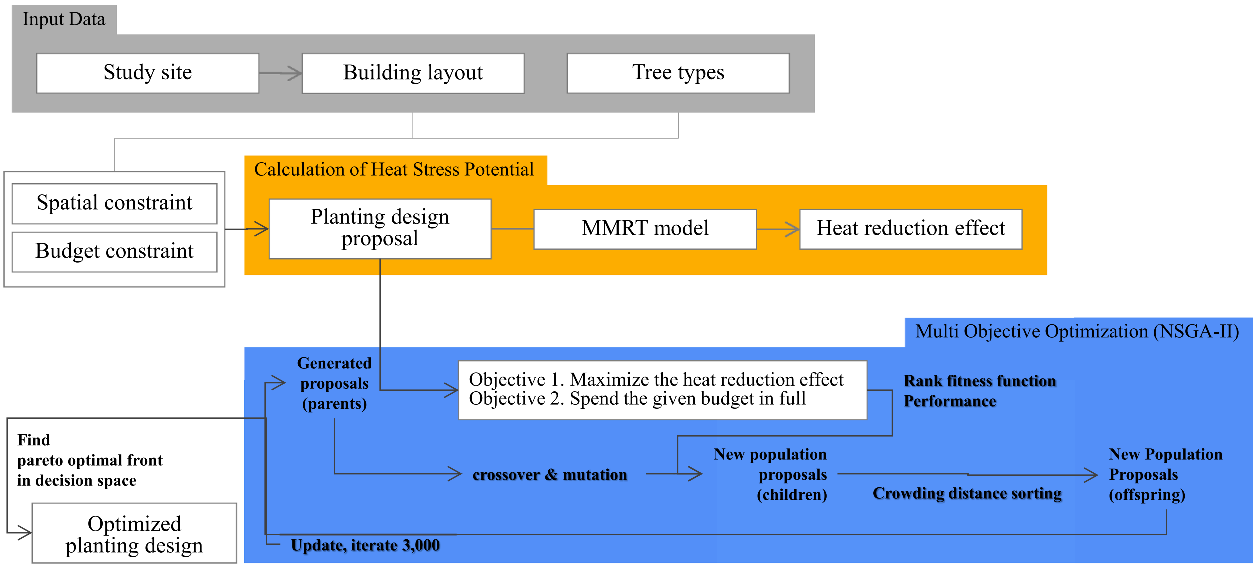


Fig. 1. The research flow involved the optimization process in deriving climate change-responsive planting designs, with the heat reduction effect being assessed based on changes in radiant heat calculated using the MMRT model.

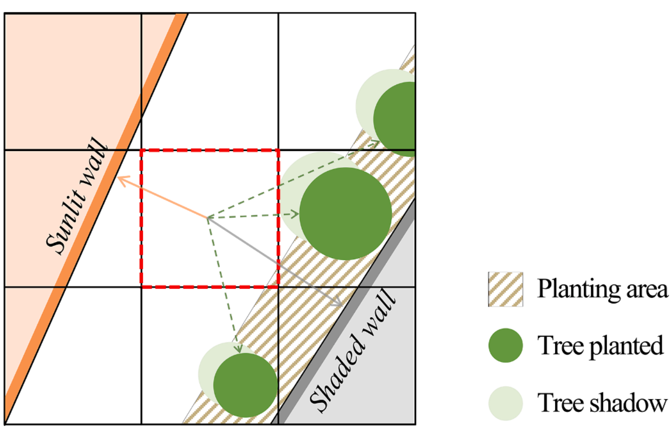


Fig. 2. A conceptual diagram for calculating heat stress potential within a given spatial unit. This drawing reflects the distribution of buildings and trees within the surrounding eight grids to evaluate the thermal conditions accurately. The distances from the shaded and sunlit walls are considered and incorporated into the calculation to determine the radiant heat values. Any changes in radiation caused by the presence of trees are also accounted for.

the building surfaces, the presence or absence of shading based on the building orientation, and the nature of the ground surface (e.g., concrete or grass).

The utilization of ArcGIS 10.5 was adopted for spatial analysis in this study. The methodology involved the creation of a grid system using the Create Fishnet function to encompass the entire drawing range. The Euclidean Distance function was then employed to calculate the distances of each grid to n buildings. The center point of each grid was designated as the reference point for distance calculation using the Zonal Statistics method. Subsequently, the distance from the building wall with the lowest value was partitioned into shaded and sunlit components. The shadow area analysis was performed using the Sun Shadow Volume function in ArcScene10.5 to classify building walls into shaded and sunlit. The time selected for study was 1:00 pm on June 21, representing the shortest shadow length during the summer solstice, the longest day of sun exposure in the northern hemisphere. It was assumed that the impact of the building wall on the thermal environment is significant only up to a distance equivalent to the building's height.

2.2. Categorizing tree types for classification

The reduction of heat by trees can be attributed to two mechanisms: 1) shading, in which solar radiation is reduced through absorption, reflection, and transmission, and 2) evapotranspiration cooling, in which water vapor is released through the stomata of leaves (Kong et al., 2017, as shown in Fig. 3). The magnitude of the reduction effect depends on the shadow area created by the canopy crown (Kong et al., 2017) or the nature of transmission (Armson et al., 2012).

In the case of extreme heat events in urban areas, street trees can effectively reduce daytime heat stress by reducing mean radiant temperature rather than air temperature (Segura et al., 2022). Trees with multiple leaf layers can absorb incoming radiation better during the processes of absorption, reflection, and transmission (Shahidan et al., 2010) while increasing canopy cover can maximize cooling effects (Feyisa et al., 2014). Trees with large multi-layer crowns, short trunks, and dense canopies have also been found to reduce heat radiation effectively (Kong et al., 2017). Numerous structural and physiological traits, including canopy aspect ratio, crown diameter, Leaf Area Index (LAI), tree height, stomatal conductance, or growth rate, along with physical factors like position, plant cover, planting densities, patterns, leaf variety, and albedo, have been demonstrated to impact transpiration and latent heat in reducing heat stress (Hami et al., 2019; Smithers et al., 2018).

Tree type classification is a widely used method to analyze the effect of trees on the microclimate. It specifies various tree effects based on physical shapes and plant physiological factors. The classification can be carried out in several ways, including classifying trees according to deciduousness, canopy volume, azimuth relationship, or distance from the building (Rouhollahi et al., 2022). Alternatively, the classification can be based on features such as trunk and crown morphology, radiation permeability, and leaf shape (de Abreu-Harbich et al., 2015). The use of typology enables the simulation and evaluation of the microclimate effect of trees.

In this study, the heat reduction effect of trees was characterized by utilizing tree height, shape, and Leaf Area Density (LAD) as typifying variables (Table 1). These variables were chosen based on the understanding that the heat reduction effect varies according to trees' structural and physiological characteristics, particularly their influence on the tree shadow effect (Gómez-Muñoz et al., 2010). The MMRT model treats the tree canopy as a box structure-like building and assumes its

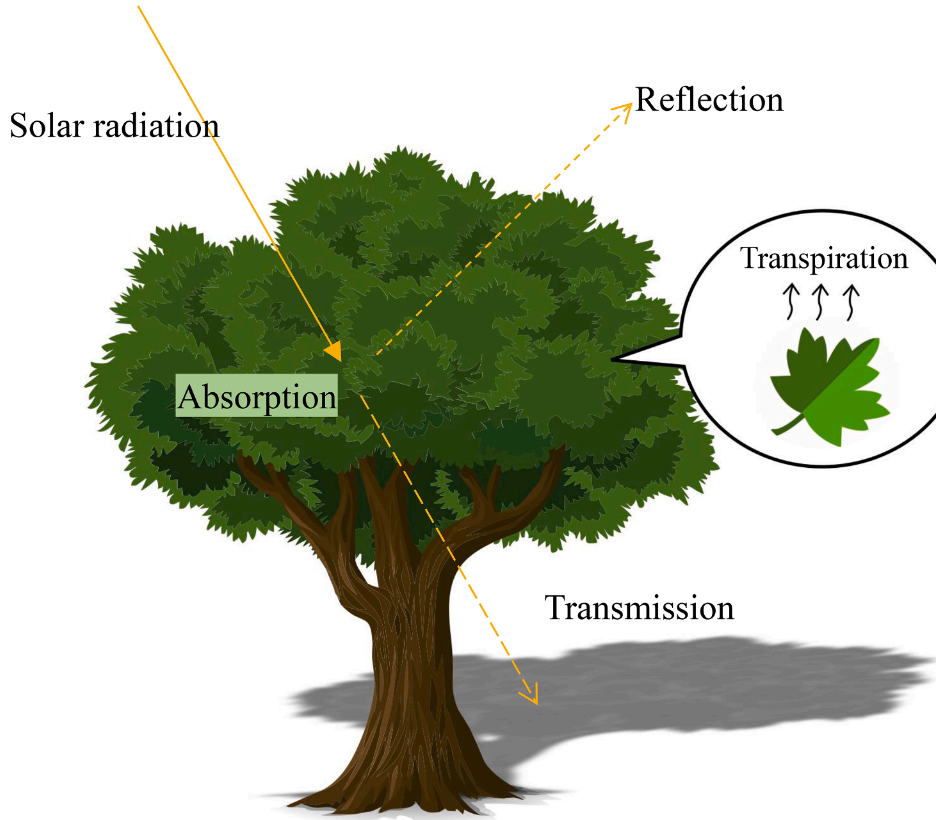


Fig. 3. Diagram depicting the conceptual understanding of the tree shadow effect and evapotranspiration effect.

Table 1
Tree types. The types were categorized into four sizes, three shapes, and two densities. However, the shape has no significance for shrubs (X), which have a height of less than 1m; thus, they were distinguished solely by density. This resulted in the creation of two types of shrubs (X), six types of small trees (S), six types of medium-sized trees (M), and six types of large trees (L), for a total of 20 tree types.

Variables	Character (Code)			
Height (m)	0 ~ 1 (X)	1 ~ 5 (S)	5 ~ 10 (M)	10 ~ 15 (L)
Shape	Irregular (I)	Round (R)	Pyramid (P)	
Leaf Area Density (m^2/m^3)	Dense: LAD 1 (2)		Sparse: LAD 0.5 (1)	

form based on leaf density (LAD). This approach enables the effective capture of variations in thermal effects. The LAD variable was categorized into types based on the sky's visibility through the canopy crown using the Sky View Factor (SVF) concept.

2.3. A calculation of heat reduction in each grid unit

Radiant heat is crucial for thermal comfort when assessing the thermal environment and mean radiant temperature (MRT) is an essential measure of the net radiant heat gain and loss in the environment and needs to be considered (H. Li, 2016). In contrast, ambient air temperature is only a measure of the average air temperature in the environment and may not accurately represent thermal comfort for individuals, because shadings do not significantly affect the air temperature (Nasrollahi et al., 2021). For example, dense tree canopies can reduce aerodynamic roughness and increase air temperature, depending on their arrangement and wind direction (Meili et al., 2021). However, the impact of the tree effect on MRT is significant compared to air temperature (Heris et al., 2020).

Thus, this study focused on radiant heat exchange to determine the effect of trees on the thermal environment. The MMRT model developed by Park et al. (2018) is employed to quantify the degree of heat stress. This model calculates the radiation transfer in complex street canyon environments and provides a more comprehensive evaluation of the thermal environment by considering radiant heat exchange, among other environmental factors. This model calculates the radiant heat exchange at the urban canyon scale, considering the distance between objects and the angle of solar radiation. The shadow effect, influenced by trees and their changes in long and short-wave radiation, can also be estimated through this model (Park et al., 2018, 2019). Furthermore, Yun et al. (2020) enhanced the MMRT model by incorporating the impact of evapotranspiration through a simultaneous calculation and feedback loop approach.

$$MRT = \left[\frac{1}{\sigma}\left\{\sum_{i=1}^{n} F_{i\to p}\left(\overbrace{LE_{up}(i)}^{LW} + \overbrace{\xi_k\frac{K_{up}E(i)}{\varepsilon_p}}^{SW1}\right) + \overbrace{\xi_k\frac{K_{dir}P}{\varepsilon_p}}^{SW2}\right\}\right]^{0.25} - 273.15$$

$$\begin{gathered} where: \\ \sigma = 5.6704\times10^{-8} \\ \xi_k = 0.7 \\ \varepsilon_p = 0.97 \end{gathered} \tag{1}$$

Equation 1 Mean Radiant Temperature (MRT) calculation formula in MMRT model (Park et al., 2018). *LW*: longwave radiation, *SW1*: reflect and diffuse shortwave radiation, *SW2*: direct shortwave radiation. ξ_k is the absorption coefficient, and ε_p is the emissivity of the pedestrian, has the standard value 0.7 and 0.97 respectively.

In the thermal model, heat stress is calculated based on three types of radiation. The first component, known as *longwave radiation* (LW), is emitted by the object, and its magnitude is proportional to the surface temperature of the object. The second component, referred to as *reflectd and diffuse shortwave radiation* (SW1), arises from the reflection of direct solar radiation from the object's surface. This value is influenced by the albedo or reflectance and the shortwave radiation scattered in the atmosphere, which is calculated based on the Sky View Factor (SVF), which is the reflectance from the sky. The third component, *direct shortwave radiation* (SW2) is from the sun and can be obstructed by shadows. The Mean Radiant Temperature (MRT) is computed based on these three radiation components. It can be considered a temperature equivalent of an individual's total radiation at a particular location. If the MRT exceeds 50°C, there is an increased risk of heat-related illnesses; if it exceeds 60°C, the thermal risk is considered severe (Monteiro et al., 2013; Thorsson et al., 2014).

The analysis was based on the center of the grid (8m x 8m) to determine the heat stress potential of a specific grid. The heat variation of a grid space is decomposed by four factors: the distance from shaded walls, the distance from sunlit walls, the shadow effects of trees, and the evapotranspiration effects of surrounding trees. These four factors are represented as RH_A, RH_B, RH_C, and RH_D, respectively, and each change is further divided into LW, SW1, and SW2 components (Fig. 4, Figure A.2).

The calculation of RH_A and RH_B was based on the distance from the building wall and the solar radiation angle, taking into account the location coordinates of the building in the MMRT model. The effect of the building wall material was also considered, as the radiant heat change depended on the material's radiative properties, such as albedo and emissivity.

The calculation of RH_C assumed that the grid point is located in the planted tree's shadow area. RH_D was calculated based on the evapotranspiration effect of the trees located in the surrounding grids. The MMRT model was based on a 2D model that led to an infinitely expanding 3D space, and the radiant heat change was calculated based on the surrounding trees on the left and right (Fig. 5). The changes in LW, SW1, and SW2, resulting from the distance from the wall and the material of the wall surface (concrete/grass) (RH_A, RH_B), as well as the changes in tree type and position (RH_C, RH_D), are depicted in Figure A.1.

2.4. Optimizing design solution: Utilizing a genetic algorithm approach

Evolutionary optimization techniques have been extensively studied, and among them, the genetic algorithm is one of the most well-known and oldest approaches (Slowik & Kwasnicka, 2020). In this technique, each potential solution to a problem is represented by an individual called a chromosome, and the problem to be solved is defined by an objective function. An individual's fitness is evaluated based on the objective function, and the probability of belonging to a new generation is determined accordingly.

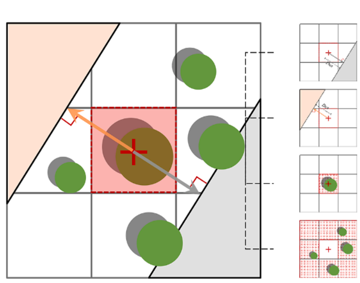
The multi-objective evolutionary algorithm decomposes the optimization problem into several subproblems (Zhang & Li, 2007; Wang et al., 2020) or evolves the population based on Pareto advantage to approximate the optimal solution set. In this process, it is essential to increase the fitness of alternatives (high exploitation) while widening the search range (high exploration) to create new offspring and achieve a better solution set (Črepinšek et al., 2013; Slowik & Kwasnicka, 2020). In other words, achieving a balance between two performance metrics, convergence and diversity, is crucial (Deb et al., 2002; Li et al., 2015).

The optimization approach adopted in this study is not aimed at finding the best-single solution but at finding a set of solutions that are not dominated (Hyun et al., 2021). A multi-objective genetic algorithm with two or more objective functions can create alternatives that satisfy various conditions instead of using a single objective function. This study employed the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) algorithm, which is widely used for multi-objective optimization (Deb et al., 2002; Verma et al., 2021). The algorithm uses the crowding distance concept and considers the diversity of each solution on the non-dominated front. Although NSGA-III, a reference-point-based multi-objective evolutionary algorithm (Deb & Jain, 2014), can broaden the search range to achieve more diverse objectives (Chaudhari et al., 2022). In this study, NSGA-II was adopted as it achieves only two objectives.

The planting design plan includes the area around the high-rise residential building. It is divided into two-dimensional spatial units, each represented by a location ID and the number of trees to be planted for each tree type, including trees, shrubs, and ground cover. The aim of this study is to compare which planting design is more effective for minimizing heat stress potential when utilizing available resources under identical microclimatic conditions. Consequently, a landscaping budget must be established for generating and comparing alternatives. This budget prevents the creation of unfeasible alternatives that, while minimizing heat stress potential, would inadvertently maximize costs. Specifically, the design is evaluated by two objective functions, the first

$$MRT = \left[\frac{1}{\sigma}\left\{\sum_{i=1}^{n} F_{i\to P}\left(\overbrace{LE_{up}(i)}^{LW} + \overbrace{\zeta_k \frac{K_{up}E(i)}{\epsilon_p}}^{SW1}\right) + \overbrace{\zeta_k \frac{K_{dir}P}{\epsilon_p}}^{SW2}\right\}\right]^{0.25} - 273.15$$

$$\mathrm{HSP}(LW,\ SW1,\ SW2) = [\{\ LW + (SW1 + SW2)\times(0.7/0.97)\}\ /\ 5.6704\times10^{-8}\ ]^{0.25} - 273.15$$



grid$_x$ and neighborhood

1) $\mathrm{RH\_A} = [\ LW_A - LW_R,\ SW1_A - SW1_R,\ SW2_A - SW2_R\ ]$

2) $\mathrm{RH\_B} = [\ LW_B - LW_R,\ SW1_B - SW1_R,\ SW2_B - SW2_R\ ]$

3) $\mathrm{RH\_C} = [\ LW_C - LW_R,\ SW1_C - SW1_R,\ SW2_C - SW2_R\ ]$

4) $\mathrm{RH\_D} = [\ LW_D - LW_R,\ SW1_D - SW1_R,\ SW2_D - SW2_R\ ]$

$\mathrm{RH} = \mathrm{RH\_A} + \mathrm{RH\_B} + \mathrm{RH\_C} + \mathrm{RH\_D}$

i.e. $\mathrm{HSP}(grid_x) = \mathrm{HSP}(LW_{\mathrm{RH}},\ SW1_{\mathrm{RH}},\ SW2_{\mathrm{RH}})$

Fig. 4. Composition of radiant heat changes. 1) RH_A due to the distance from the shaded building wall, 2) RH_B due to the distance from the sunlit building wall, 3) RH_C due to the tree shadow effect, and 4) RH_D due to the evapotranspiration effect of surrounding trees.

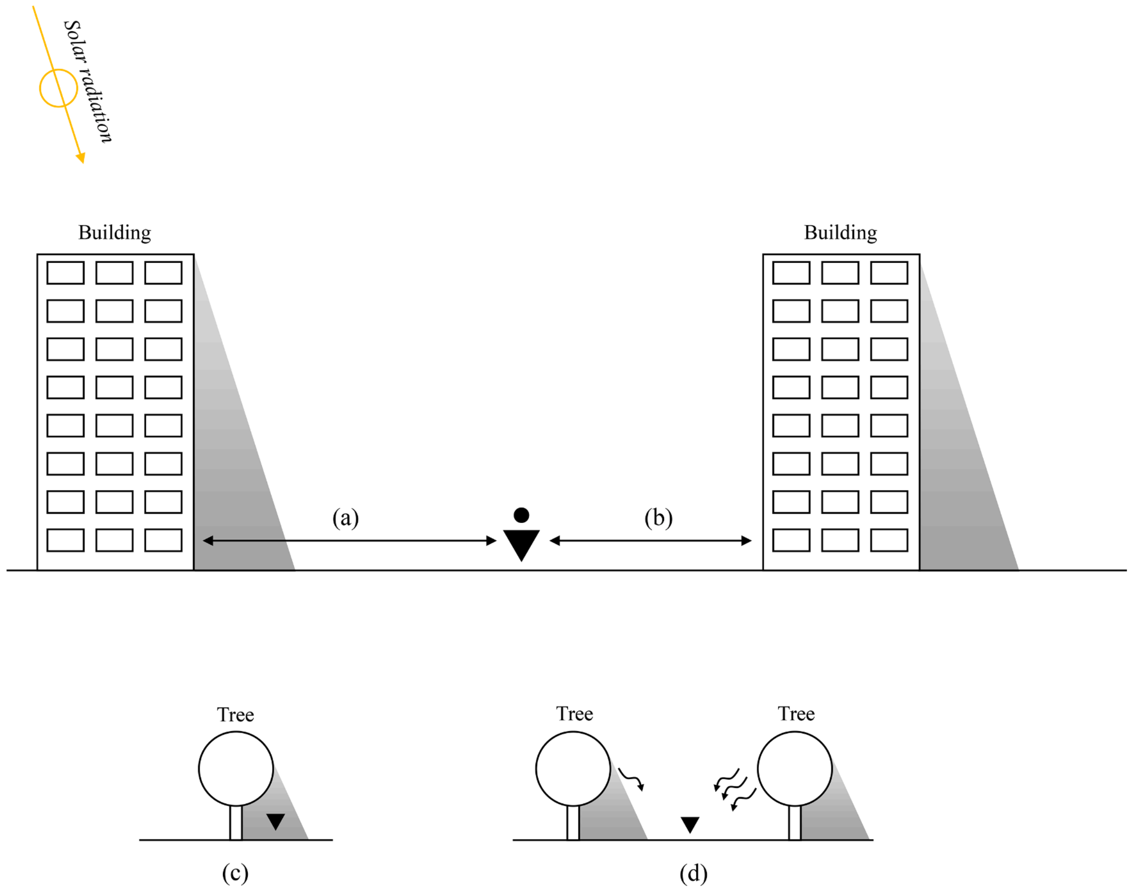


Fig. 5. Four classifications of radiant heat change for calculating radiant heat at a specific point. (a) Radiant heat changes reflecting distance from the shaded wall (RH_A), (b) Radiant heat changes reflecting distance from the sunlit wall (RH_B), (c) Radiant heat changes due to tree shadow (RH_C), (d) Radiant heat changes due to transpiration effect of surrounding trees (RH_D).

of which aims to minimize the gap between the overall planting design cost and the general complex landscaping cost of USD 1.6 million, while the second objective is to minimize the heat stress potential of the entire space (maximizing the heat reduction effect) (Equation 2). The available budget was set based on the actual unit price of the implementing agency.

An initial design is randomly generated to optimize the planting design, and its heat stress reduction effect is evaluated and scored. The design is constrained by the availability of planting space and the crown width limit for each tree in a grid of 8m x 8m. The optimization process involves generating a new generation of planting designs by applying crossover and mutation to plans located on the Pareto front–a set of optimal solutions that are non-dominated to each other but superior to the rest of the solutions in the search space–, ranked according to the degree to which the objective function is satisfied (Fig. 6).

In multi-objective optimization, convergence (increasing fitness) and diversity (widening the search range) are two primary goals. Deb et al. (2002) introduced performance metrics, namely upsilon (ϒ) and delta (Δ), to gauge these aspects. Upsilon measures the Euclidean distance and variance from the Pareto optimal, indicative of exploitation. On the other hand, delta, indicative of exploration, calculates the extent of the spread of obtained solutions. The population size and iteration number for the optimization were determined to be 200 and 3000, respectively, through repetitive test executions. During the pilot test, convergence was achieved around iteration 500 or 1000, but diversity maintained its variation.

$$Objective1 = minimize\left\{\left|budget - \sum_{k=1}^{n} cost(grid_k)\right|\right\}$$
$$Objective2 = minimize\left\{\left|\sum_{k=1}^{n} HSP(grip_k)\right|\right\} \quad (2)$$

Equation 2 Objective functions utilized in the optimization process.

3. Result

3.1. Optimization result for achieving objective function

The analysis was conducted at a latitude of 37.044144 and a longitude of 127.023484. The analysis date was set to Day of Year (DOY) 172, with the background microclimate condition at 1 PM being 30.5°C in temperature and relative humidity of 30%. In the optimization algorithm, each gene represents a planting design layout, and for the study area, a total of 1517 grids with an 8m-by-8m area were randomly generated with various tree type combinations. The Mean Radiant Temperature (MRT) value of the 'no building' condition was 55.8°C. In comparison. In comparison, the alternatives in the final Pareto front ranged from approximately 54.48 to 54.49°C, with additional costs of around 40 to 58 thousand dollars. These results were obtained by considering a typical plant material budget of $1.6 million for a residential complex with 800 households and an area of 40,621 m^2 (Fig. 7, Figure A.1). To minimize the gap with the first objective function, the budget, the search range started at around $3 million and gradually increased cost efficiency. Simultaneously, the Pareto front solution was generated to minimize the average MRT value, reducing heat stress potential from 56°C to 54.4°C.

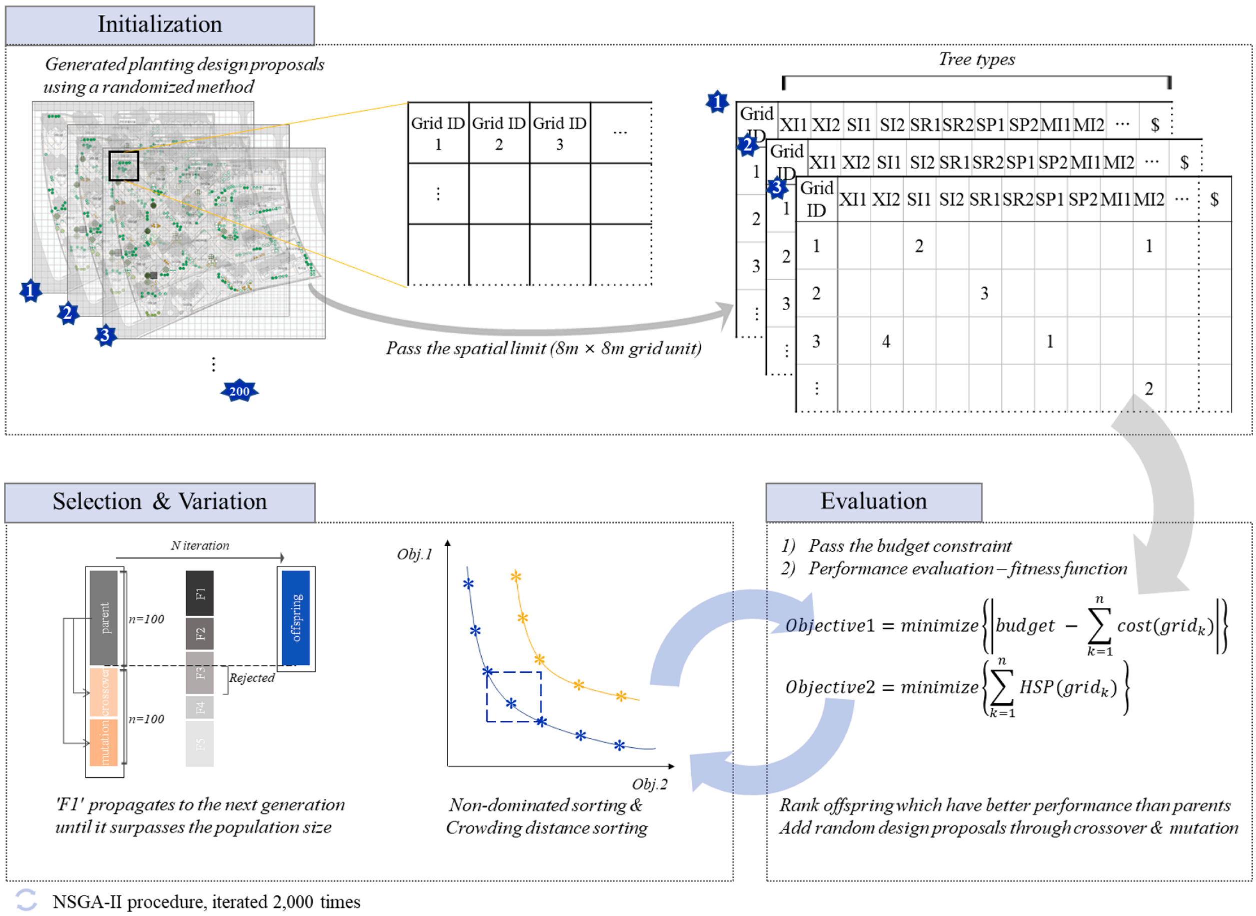


Fig. 6. Diagram of evolutionary algorithm (NSGA-II) for optimizing tree planting design.

The successful performance of the optimization algorithm can be represented by convergence and diversity metrics, while the hypervolume value indicates the quality of the solutions. The upsilon convergence metric represents exploitation and shows the efficiency of achieving the fitness function among the currently verified alternatives. The delta diversity metric represents the exploration and assesses the area of the searching space. Upsilon converges quickly within 400 iterations (with values approaching 0 afterward) and is adjusted based on the population size. In Fig. 8, Upsilon gradually decreases up to iteration 400, then approaches almost 0, indicating that the distance between solutions after iteration 1400 is nearly nonexistent compared to initialization. Similarly, the hypervolume stabilizes after 150 iterations, gradually decreases, and approaches 0 after 1200 iterations.

3.2. Comparison of tree arrangements derived from the methodology

The effects of planting design based on tree type selection and tree arrangement were mapped in terms of Mean Radiant Temperature (MRT) units (Fig. 9). When an alternative with a median budget value from the Pareto front was visualized as an optimized design, it was compared to the effect of the existing design plan (Table 2). When only buildings were present, the heat stress potential ranged from a minimum of 20.42°C to a maximum of 68.17°C, with an average MRT value of 55.8°C. In this regard, the reduction effects of general design tree arrangement and optimized tree arrangement were 0.08°C and 1.32°C, respectively (for the entire complex). When compared to Buildings only (A), the maximum effect of General design (B) was 15.2°C, higher than the 12.04°C maximum effect of Optimized design (C). However, the overall average reduction effect was only 0.08°C, indicating that excessive reduction effects only appear in specific areas and the overall reduction effect is almost negligible. The average reduction effect of the optimized design was 1.24°C (mean) and 1.01°C (median) lower compared to the general design, confirming that the heat stress potential of the entire space was reduced by more than 1°C.

By comparing the effects of the two arrangements (Fig. 9 (d) and (e)), excessive effects occurred in some courtyard spaces between specific buildings in the general design, whereas the MRT increased around the buildings. In contrast, the effects were higher for the optimized design, primarily along the walkways created for movement between buildings rather than in the open square farther from the buildings. It demonstrates that the impact is significant when the available planting area blocks the radiation reflected from the building.

3.3. Synergistic effects of grass surface

The change in radiation composition due to trees can vary depending on the tree type, their relative position to buildings, and the type of surface (Fig. 10). For trees situated on grass surfaces, more effective heat reduction can be expected due to latent heat release. When examining the number of grids based on MRT value ranges, the optimized design (dash, green line) showed an increase in the range below 65°C. This suggests that the optimization process intentionally increased the planting amount on grass surfaces, introducing relatively more MI2 (tree type composed of medium height, irregular shape, dense LAD) and MR2 (tree type composed of medium height, irregular shape, sparse LAD) trees. This indicates that the shadows created by M-grade trees with heights between 5-10m are more effective than those created by S-grade trees with heights between 1-5m, and trees with a LAD code of 2 are more effective in shortwave absorption compared to those with a LAD code of 1.

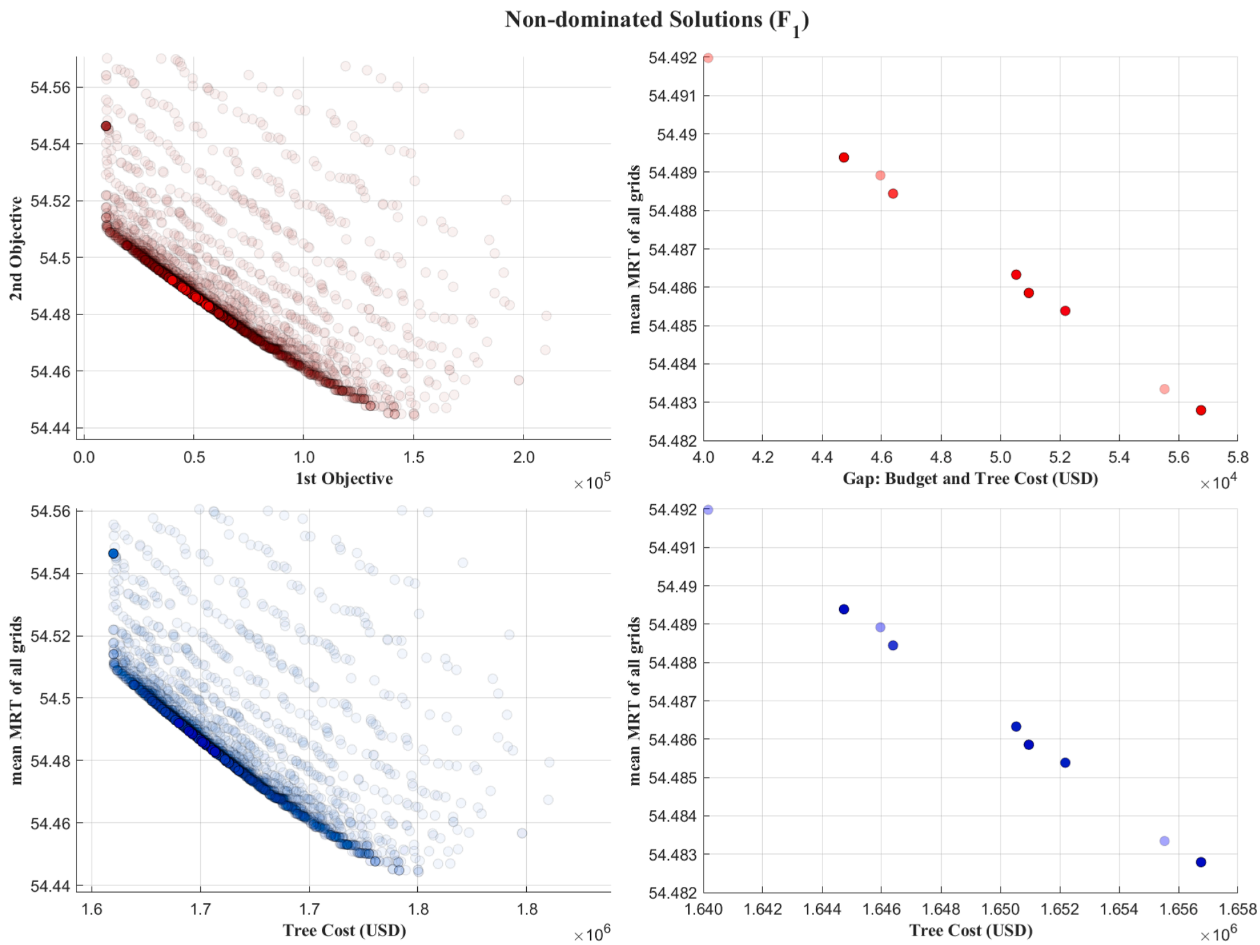


Fig. 7. (left) The Pareto front of non-dominated solutions at an interval of 20 iterations. (right) The last Pareto front of all iterations. The figure shows that with a budget of USD 1.6 million, a minimum additional cost of about USD 40 thousand to a maximum of USD 58 thousand was required to achieve an overall mean radiant temperature (MRT) of 54.48°C for the entire space.

4. Discussion

4.1. Efficiency of distance-based evaluation methods in achieving objectives

This study evaluates the heat stress reduction effect of tree type selection and arrangement at the highest risk and heat point (summer solstice, 1 PM) with fixed background conditions due to building walls, presenting the optimal tree type and arrangement combination. To achieve this, we applied a distance-based evaluation by decomposing radiation method.

With the artificial background conditions set in advance, the evaluation time for one iteration with a population size of 300 was approximately 5.19 seconds, taking 2 hours and 53 minutes for 2000 repeated iterations. Considering the performance comparison process, a total of 600 thousand design alternatives are evaluated, with an evaluation time of approximately 0.017 seconds for each design. This efficiency is realized due to the maximized utilization of parallelization in the algorithm structure.

Evolutionary algorithms are well-suited for parallelization, allowing for evaluating more generations in less time (Eiben & Smith, 2015). This study improved time efficiency by parallelizing all possible evaluation processes in the optimization algorithm. The mapped planting design alternatives were compared through this improved evaluation efficiency, deriving a climate-responsive optimized design using a genetic algorithm. Additionally, as evolutionary algorithms are probabilistic methods, different results can be obtained each time they are executed. The future focus should be placed on ensuring the repeatability of the generated results (Slowik & Kwasnicka, 2020). To prevent early convergence and getting stuck in local optima (Črepinšek et al., 2013), an increase in the mutation rate was implemented and tests were conducted to secure a minimum number of iterations through repetitive simulations, in the setting of 2000 iterations. It is crucial to set an appropriate number of iterations if the objective changes to a partial area, the number of tree types increases, or other variables change in the future.

4.2. Effects of trees and considerations for future studies

The primary mechanisms through which trees mitigate heat stress are the shadow effect and the evapotranspiration effect, which stem from the trees' structural and physiological characteristics (Park et al., 2021; Smithers et al., 2018; Zölch et al., 2019). To account for these factors, this study classified 20 tree types, excluding trees taller than 10m (L type) due to transplanting constraints. This categorization may not fully encapsulate the preferences of actual residential areas, which often favor aesthetically pleasing trees like *Pinus densiflora* at entrances or squares within complexes.

It is important to note that treating plant materials as identical in form and specifications to conventional construction materials simplifies each tree's unique growth and physiological traits. This issue is only possible to address by conducting species/site-specific research. Prior studies have explored the tree's capacity to decrease heat stress by considering variables such as tree location (Abdollahzadeh & Biloria,

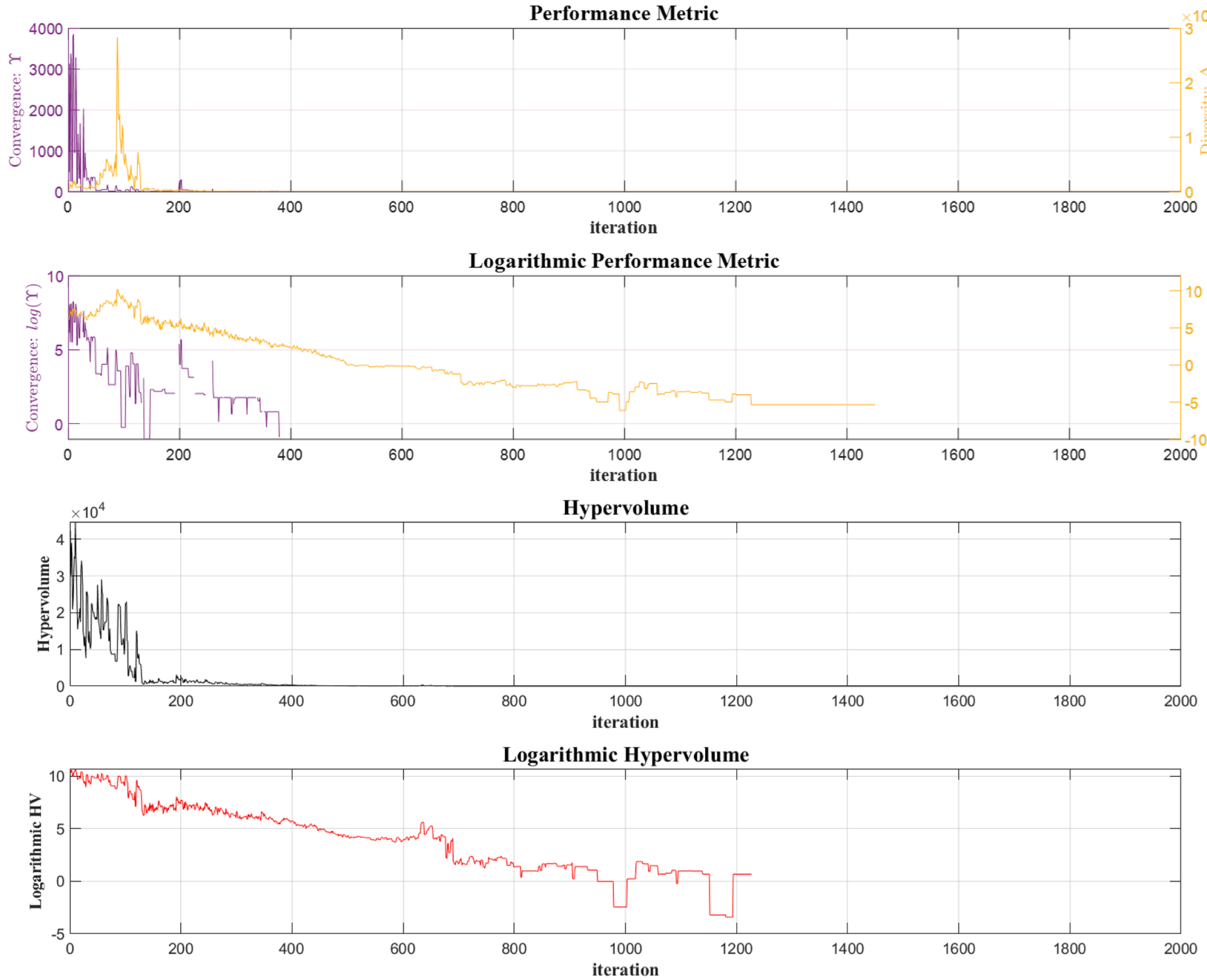


Fig. 8. Performance Metrics of the Optimization Model: Convergence and Diversity based on the Equation by Deb et al. (2002) and its Logarithmic Transformation.

2021; Atwa et al., 2020), tree type, volume, orientation, and distance from buildings (Rouhollahi et al., 2022) or pattern effects, the arrangement of diverse plant species, shrubs, landscape patch connectivity, and the organization of trees based on wind conditions (Hami et al., 2019).

Under the conditions set in this study, medium-height trees (5-10m, designated as 'M' type) combined with grass surfaces were found to be the most effective (Fig. 10). Simultaneously, the number of other tree types introduced decreased. This suggests that planting trees too densely can trigger excessive longwave radiation. Consequently, the results demonstrate that planting medium-height trees with some spacing can be more effective in reducing heat stress than densely planting smaller trees.

In other words, planting trees has several thermal effects on their surroundings. On the positive side, evapotranspiration reduces the area's heat by providing latent heat, thereby reducing radiation. On the other hand, this process may contribute to increased longwave radiation reflected by trees, which raises heat levels - a negative effect. Moreover, certain areas may experience increased heat due to high tree density. The interplay of these effects demonstrates the complex impact of trees on local thermal conditions.

By applying the distance-based evaluation presented in this study, it is possible to reflect each tree type's effects based on each region's microclimatic conditions. If a species-specific analysis is possible, not only the functional effects of trees but also a more enhanced customized optimization based on the actual transaction prices of trees and the preferences of space users can be achieved. Indeed, in this study, there have been cases where price differences and citizen preferences between different tree species within the same tree type have become ambiguous due to the limitations of typification. Despite significant differences in the price information of tree species included in each tree type depending on the transaction volume and supply network, including the average value as a representative value led to a result that only considered the functional aspects. Therefore, future research should focus on the overall heat reduction function and on varying the options for each space within the complex, allowing the spatial design to occur in various ways, such as specialized space, resident preference, or seasonality.

4.3. Spatial constraints and tree density in applying the methodology to actual design

The functional effects may vary even if the same area of green space is created. In this study, we randomly assigned the positions of trees within the plantable area presented in the general design and ultimately derived a design with a more effective reduction effect for the entire complex within the same area.

To maximize tree cooling benefits, designers should arrange trees without canopy overlap, provide more shading to buildings, and create good ventilation conditions by avoiding blocking existing wind corridors between buildings (Rouhollahi et al., 2022). Using the radiation decomposing method in this study, it appears that tree density increases sharply when the overlap level is high, leading to an overestimation of MRT. It is because every object with a surface temperature emits

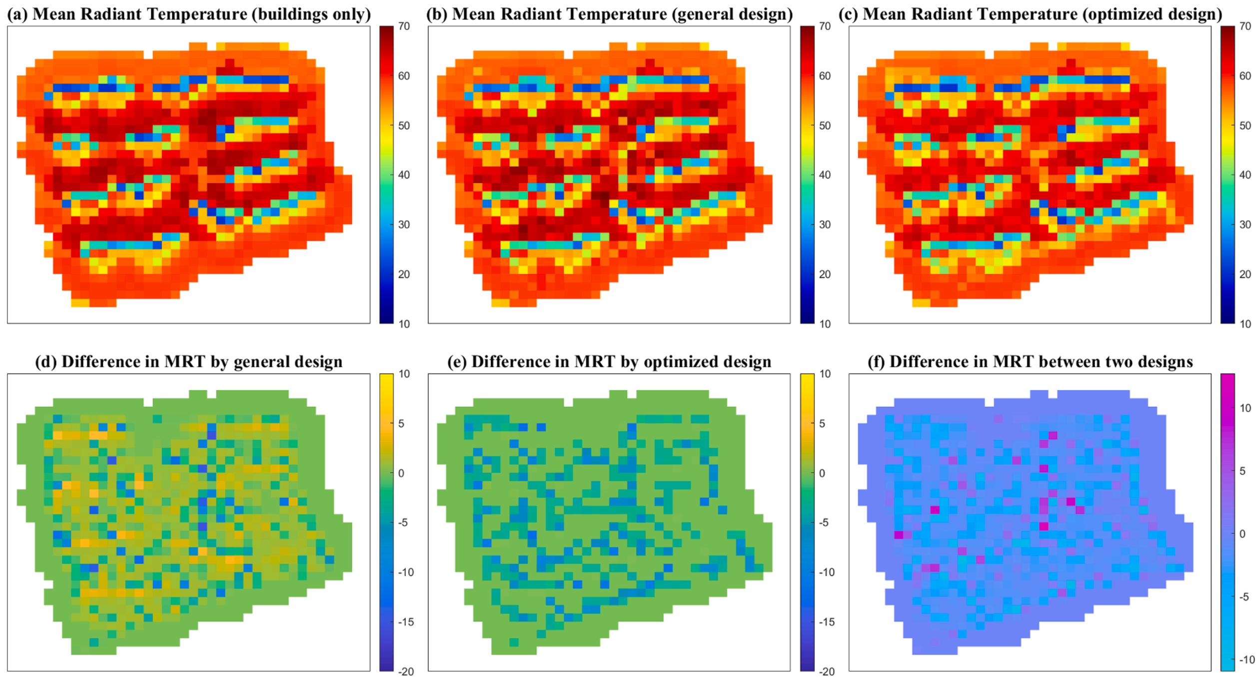


Fig. 9. The Mapping of Mean Radiant Temperature (MRT) and its difference of tree arrangement. (a) MRT of background (buildings only), (b) MRT of general design (buildings + original tree arrangement), (c) MRT of optimized design (buildings + climate-responsive tree arrangement), (d) Difference in background heat stress and general design (b-a), (e) Difference in background heat stress and optimized design (c-a), (f) Difference in two designs (c-b).

Table 2
Statistical summary of each design proposal. MRT (°C) comparison of general and optimized proposals D and E with A (no tree), and difference between each proposal (C-B) represented by F.

Tree arrangement	Min	Median	Max	Mean	Std
A (buildings only)	20.42	58.27	68.17	55.80	10.08
B (general design)	21.71	58.26	69.98	55.72	9.71
C (optimized design)	20.39	57.47	67.12	54.49	9.99
D (B-A)	-15.20	0.00	5.39	-0.08	2.48
E (C-A)	-12.04	0.00	0.49	-1.32	2.40
F (C-B)	-10.98	-1.01	12.73	-1.24	2.39

longwave radiation (Park et al., 2018). Despite this, securing the advantages of multi-layered planting structures in reducing fine dust and various landscape aspects will be supplementary measures for applying the research results to actual sites.

In this study, shrubs (those of 1m in height or less, labeled as 'X') were assumed to occupy an area with a diameter of 1m each. However, to emulate the density observed in actual landscape design, at least 9 to 16 times the number of shrubs is required. This is because the specification for shrubs is based on root diameter, and their coverage is relatively small. In addition, some tree types can be replaced with similar types for cluster planting. The results of applying the actual residential complex by replacing it with a site-constructible planting design can be found in Figure A.3.

5. Conclusion

This study quantitatively evaluated the impact of landscaping planting on climate change phenomena and confirmed its potential use in design. By decomposing radiation transfer in four ways for the effects

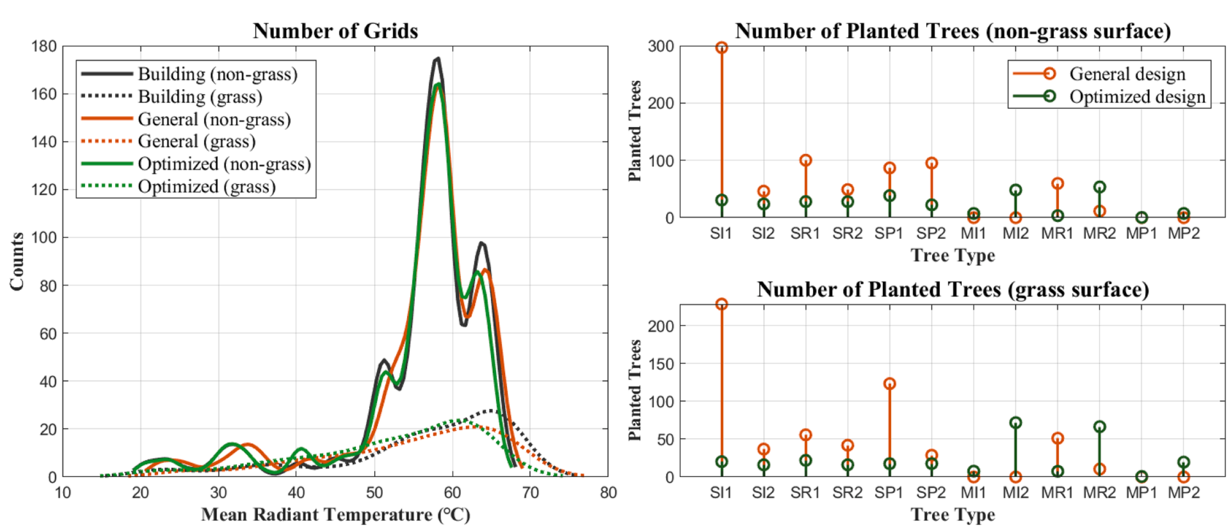


Fig. 10. Number of grid count and tree scales in green/non-green surfaces.

of buildings and trees and evaluating heat stress potential through recomposition, this study contributes to the planning process by enabling prompt evaluation and comparison between alternative planting designs.

The radiation decomposition and recomposition approach drastically shortened the evaluation time for heat reduction effects, allowing for the assessment of 600,000 design alternatives in under three hours. Each planting design took about 0.017 seconds to evaluate, which was made possible by maximizing the parallelization of the optimization algorithm. Although simplifying the actual characteristics of tree species is a limitation, the heat reduction effect in planting design showed that dense trees of 'M' size were the most efficient among 20 types of trees. However, this is due to the introduction limitation of 'L' type size trees in the transplantation process. Thus, planting dense 'M' type trees, which grow faster, can be more efficient in reducing heat in the area in the long term. The simulated results showed that the optimized plans reduced the heat stress potential by 1.24°C at 1 PM for a residential complex with 800 households and an area of 40,621 m^2, with a budget of USD 1.6 million. When trees are planted densely, the negative effect from longwave radiation of the tree bodies can be overestimated, exceeding the positive effect of latent heat increase by the evapotranspiration effect of surrounding trees. Hence, the study results suggest that it is more efficient to plant larger trees while maintaining an appropriate distance within an acceptable area.

The study applied the genetic algorithm to create tree types and arrangements for a fixed building shape in a residential complex, deriving an optimized climate-responsive design for the urban heat island phenomenon within budget constraints. While the primary goal of this study was to reduce the overall heat of the complex, other possibilities include designing specialized spaces within the complex, adjusting the proportion of fruit trees, or reflecting tree species according to resident preferences. Presenting differently optimized results based on stakeholder preferences to support the decision-making process is crucial. This study can serve as a helpful decision-support tool that briefly showcases the climate-responsive effects of trees while simultaneously achieving the diverse objectives mentioned above.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104762.

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