
Climate-sensitive Urban Planning through Optimization of Tree Placements

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Abstract

Climate change is increasing the intensity and frequency of many extreme weather events, including heatwaves, which results in increased thermal discomfort and mortality rates. While global mitigation action is undoubtedly necessary, so is climate adaptation, e.g., through climate-sensitive urban planning. Among the most promising strategies is harnessing the benefits of urban trees in shading and cooling pedestrian-level environments. Our work investigates the challenge of optimal placement of such trees. Physical simulations can estimate the radiative and thermal impact of trees on human thermal comfort but induce high computational costs. This rules out optimization of tree placements over large areas and considering effects over longer time scales. Hence, we employ neural networks to simulate the point-wise mean radiant temperatures—a driving factor of outdoor human thermal comfort—across various time scales, spanning from daily variations to extended time scales of heatwave events and even decades. To optimize tree placements, we harness the innate local effect of trees within the iterated local search framework with tailored adaptations. We show the efficacy of our approach across a wide spectrum of study areas and time scales. We believe that our approach is a step towards empowering decision-makers, urban designers and planners to proactively and effectively assess the potential of urban trees to mitigate heat stress.

1 Introduction

Climate change will have profound implications on many aspects of our lives, ranging from the quality of outdoor environments and biodiversity, to the safety and well-being of the human populace [United Nations, 2023]. Particularly noteworthy is the observation that densely populated urban regions, typically characterized by high levels of built and sealed surfaces, face an elevated exposure and vulnerability to heat stress, which in turn raises the risk of mortality during heatwaves [Gabriel and Endlicher, 2011]. The mean radiant temperature (T_{mrt} , °C) is one of the main factors affecting daytime outdoor human thermal comfort [Holst and Mayer, 2011, Kántor and Unger, 2011, Cohen et al., 2012].¹ High T_{mrt} can negatively affect human health [Mayer et al., 2008] and T_{mrt} has a higher correlation with mortality than air temperature [Thorsson et al., 2014]. Consequently, climate-sensitive urban planning should try to lower maximum T_{mrt} as a suitable climate adaption strategy to enhance (or at least maintain) current levels of outdoor human thermal comfort.

Among the array of climate adaption strategies considered for mitigation of adverse urban thermal conditions, urban greening, specifically urban trees, has garnered significant attention due to their numerous benefits, including a reduction of T_{mrt} , transpirative cooling, air quality [Nowak et al., 2006], and aesthetic appeal [Lindemann-Matthies and Brieger, 2016]. Previous studies found the strong

¹ T_{mrt} is introduced in more detail in Appendix A.

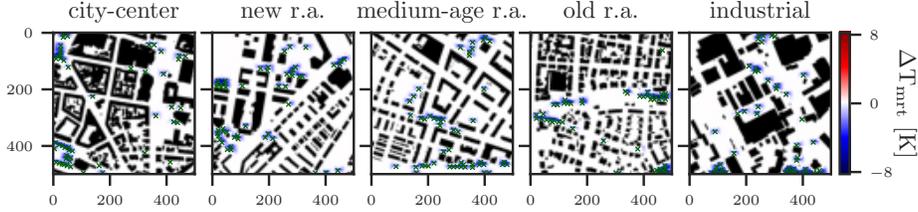


Figure 1: Optimizing tree placements can substantially reduce point-wise T_{mrt} , e.g., during heatwaves, leading to improved outdoor human thermal comfort. Optimized placements of 50 added trees for the hottest week in 2020 across diverse urban neighborhoods (from left to right: city-center, recently developed new r.a. (residential area), medium-age r.a., old r.a., industrial area).

influence of tree positions [Zhao et al., 2018, Abdi et al., 2020, Lee et al., 2020] and correspondingly other works optimized them [Chen et al., 2008, Ooka et al., 2008, Zhao et al., 2017, Stojakovic et al., 2020, Wallenberg et al., 2022]. However, these works were limited by the computational cost of physical models, which rendered the optimization of tree placements over large areas or long time scales infeasible. On the other hand, there has been increased interest in machine learning for climate science [Rolnick et al., 2022]. However, previous work mostly focused on efficiency gains [Briegel et al., 2023, Huang and Hoefler, 2023], raised climate awareness [Schmidt et al., 2022], improved the analytical capabilities [Albert et al., 2017, Blanchard et al., 2022, Teng et al., 2023, Otness et al., 2023], or used it for urban planning [Shen et al., 2020, Wang et al., 2020, 2021, 2023, Zheng et al., 2023]. Our work deviates from these prior works, as it directly optimizes a meteorological quantity (T_{mrt}) that correlates well with heat stress experienced by humans (outdoor human thermal comfort).

In this work, we present a simple, scalable yet effective optimization approach for positioning trees in urban districts to facilitate *climate-sensitive urban planning* to adapt to climate change in cities.² We use the iterated local search framework [Lourenço et al., 2003, 2019] with tailored adaptations, coupled with a fast estimation of T_{mrt} from spatial-temporal input data using a neural network. Our evaluation shows the efficacy of our approach as a means to improve outdoor human thermal comfort by decreasing point-wise T_{mrt} over various time periods and study areas, e.g., see Figure 1 for an heatwave event. Our results indicate the potential of our method for climate-sensitive urban planning to *empower decision-makers in effectively adapting cities to the effects of climate change*.

2 Methods

We consider a function $f_{T_{\text{mrt}}}(s, m)$ to model point-wise $T_{\text{mrt}} \in \mathbb{R}^{h \times w}$ of a spatial resolution of $h \times w$. It can be either a physical or machine learning model and operates on a composite input space of spatial $s = [s_v, s_{-v}] \in \mathbb{R}^{|S| \times h \times w}$ and meteorological inputs $m \in M$ from time period M , e.g., a heatwave event. The spatial inputs S consist of vegetation-related s_v (digital surface model for vegetation, sky view factor maps induced by vegetation) and non-vegetation-related spatial inputs s_{-v} (digital surface model for buildings, digital elevation model, land cover class map, wall aspect and height, sky view factor maps induced by buildings). Appendix B provides more details on the data. We followed Briegel et al. [2023] in training a deep learning model $f_{T_{\text{mrt}}}$ on data generated by the physical model SOLWEIG [Lindberg et al., 2008]. Vegetation-related spatial inputs s_v are further induced by the positions $T_p \in \mathbb{N}^{k \times h \times w}$ and geometry t_g of k trees by function $f_v(t_p, t_g)$. During optimization we modify the digital surface model for vegetation and update depending spatial inputs. To enhance outdoor human thermal comfort, we want to minimize the aggregated, point-wise $T_{\text{mrt}}^{M, \phi} \in \mathbb{R}^{h \times w}$ for a given aggregation function ϕ , e.g., mean, and time period M by seeking the tree positions

$$t_p^* \in \arg \min_{t_p'} \phi(\{f_{T_{\text{mrt}}}([f_v(t_p', t_g), s_{-v}], m) \mid \forall m \in M\}) \quad , \quad (1)$$

in the urban landscape, where we keep tree geometry t_g fixed for the sake of simplicity.

Optimization of tree placements To search tree placements, we adopted the iterated local search framework from Lourenço et al. [2003, 2019] with tailored adaptations to leverage that the effectiveness of trees is bound to a local neighborhood. The core principle of iterated local search is the iterative refinement of the current local optimum through the alternation of perturbation and local

²Code is available at <https://github.com/lmb-freiburg/tree-planting>.

Algorithm 1 Iterated local search to find the best tree positions.

- 1: **Input:** ΔT_{mrt}^t , $f_{T_{\text{mrt}}^{M,\phi}}$, number of trees k , number of iterations I , local optima buffer size b
 - 2: **Output:** best found tree s_* in S_*
 - 3: $s_* \leftarrow \text{TopK}(\Delta T_{\text{mrt}}^t, k)$ # Initialization
 - 4: **for** $i = 1, \dots, I$ **do**
 - 5: $s' \leftarrow \text{PerturbationWithGA}(S_*, \Delta T_{\text{mrt}}^t)$ # Perturbation
 - 6: $s'_* \leftarrow \text{HillClimbing}(s')$ # Local search
 - 7: $S_* \leftarrow \text{TopK}(\{f_{T_{\text{mrt}}^{M,\phi}}(s) | s \in S_* \cup s'_*\}, b)$ # Acceptance criterion
 - 8: **end for**
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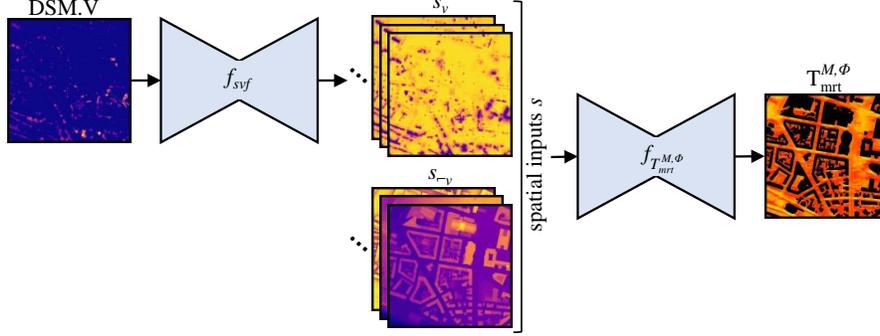


Figure 2: Overview of $T_{\text{mrt}}^{M,\phi}$ modeling. To account for changes in vegetation during optimization, we modify the digital surface model for vegetation (DSM.V) and update depending spatial inputs (sky view factor maps for vegetation) with the model f_{svf} . The model $f_{T_{\text{mrt}}^{M,\phi}}$ takes these updated vegetation-related s_v and non-vegetation-related spatial inputs s_{-v} to estimate the aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for a given aggregation function ϕ , e.g., mean, and time period M , e.g., heatwave event.

search procedures. We initialize the first local optimum by a simple greedy heuristic. Specifically, we compute the difference in T_{mrt} (ΔT_{mrt}^t) resulting from the presence or absence of a single tree at every possible position on the spatial grid. Subsequently, we greedily select the positions based on the maximal ΔT_{mrt}^t (TopK). During the iterative refinement, we perturb the current local optimum using a genetic algorithm [Srinivas and Patnaik, 1994] (PerturbationWithGA). The initial population of the genetic algorithm comprises the current best (local) optima—we keep track of the five best optima—and randomly generated placements based on a sampling probability of

$$p_{\Delta T_{\text{mrt}}^t} = \frac{\exp \Delta T_{\text{mrt}_{i,j}}^t / \tau}{\sum_{i,j} \exp \Delta T_{\text{mrt}_{i,j}}^t / \tau}, \quad (2)$$

where the temperature τ governs the entropy of $p_{\Delta T_{\text{mrt}}^t}$. Subsequently, we refine the perturbed tree positions from the genetic algorithm with the hill climbing algorithm (HillClimbing), similar to Wallenberg et al. [2022]. If the candidate s'_* improves upon our current optima S_* , we accept and add it to our history of local optima S_* . Throughout the search, we ensure that trees are not placed on buildings nor water, and trees have no overlapping canopies. Algorithm 1 provides pseudocode. Further, we prove in Appendix C that our optimization method finds the optimal tree placements given an unbounded number of iterations and sufficiently good T_{mrt} modeling.

Mapping of tree placements to the spatial inputs During our optimization procedure, we optimize the placement of trees by directly modifying the digital surface model for vegetation that represents the trees’ canopies. However, depending spatial inputs (i.e., sky view factor maps for vegetation) cannot be directly modified and conventional procedures are computationally expensive. Hence, we propose to estimate the sky view factor maps from the digital surface model for vegetation with a U-Net model f_{svf} . To train this model f_{svf} , we repurposed the conventionally computed sky view factor maps, that were already required for computing point-wise T_{mrt} with SOLWEIG.

Aggregated, point-wise mean radiant temperature modeling Above optimization procedure is zero-order and, thus, requires fast evaluations of T_{mrt} to be computationally feasible. In particular, we are interested in reducing aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for an aggregation function ϕ , e.g., mean,

and time period M , e.g., multiple days of a heatwave event, as a means to improve outdoor human thermal comfort. However, computing the point-wise T_{mrt} for all $|M|$ meteorological inputs of the time period M (similar to Briegel et al. [2023]), followed by the aggregation with function ϕ becomes prohibitively computationally expensive for large time periods.⁵ To mitigate this computational bottleneck, we propose to learn a U-Net model

$$f_{T_{\text{mrt}}^{M,\phi}}(\cdot) \approx \phi(\{f_{T_{\text{mrt}}}(\cdot, m) \mid \forall m \in M\}) \quad (3)$$

that directly approximates aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for a given aggregation function ϕ and time period M . For training data, we computed aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for a specified aggregation function ϕ and time period M with aforementioned (slow) procedure. However, note that this computation has to be done only once for the generation of training data. During inference, the computational complexity is effectively reduced by a factor of $\mathcal{O}(|M|)$.

3 Experimental evaluation

We assessed our optimization method by searching for the positions of k newly added trees (uniform tree specimens with spherical crowns, tree height of 12 m, canopy diameter of 9 m, and trunk height of 25 % of the tree height) in the city of Freiburg im Breisgau (48°00' N, 07°51' E, southwest of Germany (Baden-Württemberg)). We provide details about the spatial and meteorological data, and experiments in Appendix B or E, respectively. We assessed the quality of our T_{mrt} modeling in Appendix H.1.

Figure 1 illustrates the efficacy of our approach in reducing point-wise T_{mrt} across diverse urban landscapes for a heatwave event. For other time periods refer to Appendix H.2. We observe that trees predominantly assume positions on east-to-west aligned streets and large, often sealed spaces. Table 1 affirms that our optimization method consistently finds better tree positions compared to various baselines. Interestingly, we found that trees exhibit a dual influence—contributing to reductions in T_{mrt} in daytime and summer, and conversely causing increases in nighttime and winter (Appendix H.3). We also found that trees have diminishing returns as we increase the extent of canopy cover, achieved either by adding more trees or by using larger trees (Appendix H.3). Lastly, we investigated the counterfactual question whether alternative tree positions could have retrospectively yielded reduced amounts of heat stress and can answer it in the affirmative in Appendix H.4.

Table 1: Quantitative comparison to baselines.

Method	day	week	year	decade
random	-0.12	-0.1	0.01	0.02
greedy T_{mrt}	-0.18	-0.12	0.02	0.02
greedy ΔT_{mrt}	-0.22	-0.18	-0.02	-0.02
genetic	-0.26	-0.19	-0.02	-0.02
ILS [†] (ours)	-0.3	-0.23	-0.03	-0.03

[†]: ILS = iterated local search.

4 Conclusion

We presented a simple and scalable method to optimize tree placements across large urban areas and time scales to mitigate pedestrian-level heat stress by optimizing human thermal comfort expressed by T_{mrt} . We proposed a novel approach to efficiently model aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for a specified aggregation function and time period, and optimized tree placements through an instantiation of the iterated local search framework with tailored adaptations. Our experimental results corroborate the efficacy of our approach. We discuss limitations, broader impact, and provide a carbon footprint estimate in Appendices I to K, respectively.

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⁵For sake of simplicity, we assumed that the spatial input is static over the entire time period.

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A Mean radiant temperature

The mean radiant temperature T_{mrt} [°C] is a driving meteorological parameter for assessing the radiation load on humans. During the day, it is of particular importance in determining human outdoor thermal comfort. T_{mrt} varies spatially, e.g., standing in direct sunlight on a hot day results in a less favorable thermal experience for the human body than seeking shelter in shaded areas. T_{mrt} is defined as the “uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” by ASHRAE [2001]. That is, T_{mrt} can be calculated by measured values of surrounding objects and their position w.r.t. the person. Formally, T_{mrt} can be computed by

$$T_{\text{mrt}}^4 = \sum_{i=1}^N T_i^4 F_{p-i} \quad , \quad (4)$$

where T_i is the surface temperature of the i -th surface and F_{p-i} is the angular factor between a person and the i -th surface [ASHRAE, 2001]. Alternatively, we can use the six-directional approach of Höppe [1992] through estimation of short- and longwave radiation fluxes of six directions (upward, downward, and the four cardinal directions), as follows:

$$T_{\text{mrt}} = \frac{0.08(T_p^{\text{up}} + T_p^{\text{down}}) + 0.23(T_p^{\text{left}} + T_p^{\text{right}}) + 0.35(T_p^{\text{front}} + T_p^{\text{back}})}{2(0.08 + 0.23 + 0.35)} \quad , \quad (5)$$

where T_{pr} is the plane radiant temperature [Korsgaard, 1949].

B Data

Our study focuses on the city of Freiburg im Breisgau (48°00' N, 07°51' E, southwest of Germany (Baden-Württemberg))⁴. Following Briegel et al. [2023], we used spatial (geometric) and temporal (meteorological) inputs to model point-wise T_{mrt} . The spatial inputs include:

- Digital elevation model [m]: representation of elevation data of terrain excluding surface objects.
- Digital surface model with heights of ground and buildings [m]: heights of ground and buildings above sea level.
- Digital surface model with heights of vegetation [m]: heights of vegetation above ground level.
- Land cover class map [{paved, building, grass, bare soil, water}]: specifies the land-usage.
- Wall aspect [°]: aspect of walls where a north-facing wall has a value of zero.
- Wall height [m]: specifies the height of a wall of a building.
- Sky view factor maps [%]: cosine-corrected proportion of the visible sky hemisphere from a specific location from earth’s surface by the total solid angle of the entire sky hemisphere.

Spatial inputs are of a size of 500 m x 500 m with a resolution of 1 m. Raw LIDAR and building outline (derived from CityGML with detail level of 1) data were provided by the City of Freiburg [2018, 2021] and pre-processed spatial data were provided by Briegel et al. [2023]. We used air temperature, wind speed, wind direction, incoming shortwave radiation, precipitation, relative humidity, barometric pressure, solar elevation angle, and solar azimuth angle as temporally varying meteorological inputs. We used past hourly measurements for training and hourly ERA5 reanalysis data [Hersbach et al., 2020] for optimization. Table 2 provides exemplar temporal (meteorological) inputs.

C Theoretical analysis of the optimization method

It is easy to show that our optimization method finds the optimal tree placements given an unbounded number of iterations and sufficiently good T_{mrt} modeling.

⁴The placeholder ensures double blindness and will be replaced upon acceptance.

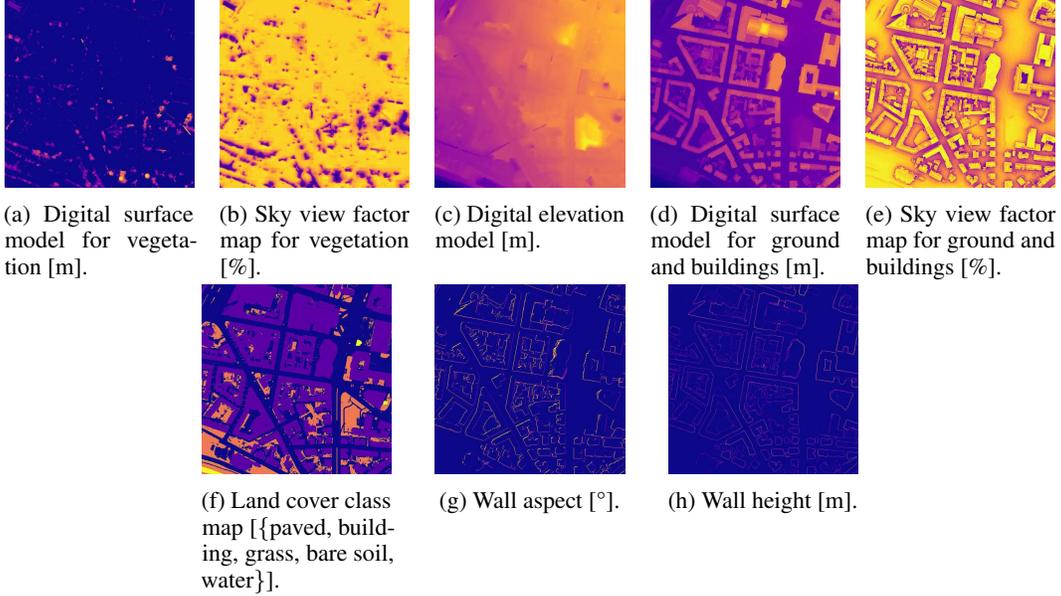


Figure 3: Exemplar spatial inputs. Note that we omit sky view factor maps for vegetation or ground and building for the four cardinal directions (north, east, south, west) for visualization for visualization.

Table 2: Exemplar meteorological inputs.

Date & time	Air temperature [°C]	Wind speed [ms ⁻¹]	Wind direction [°]	Incoming shortwave radiation [Wm ⁻²]	Precipitation [mm]	Relative humidity [%]	Barometric pressure [kPA]	Elevation angle [°]	Azimuth angle [°]
2020-01-01 00:00:00	-1.31	1.97	107.72	0.0	0.0	75.88	976.4	0.0	343.009
2020-03-20 06:00:00	9.07	0.64	114.71	0.0	0.0	83.46	964.7	0.0	83.264
2020-06-20 11:00:00	18.43	1.15	314.46	652.27	0.02	68.04	966.2	59.601	135.899
2020-09-22 16:00:00	22.35	1.43	245.3	310.98	0.04	56.1	955.1	22.754	242.247
2020-12-21 21:00:00	7.19	4.25	202.69	0.0	0.51	87.82	963.0	0.0	282.195

Lemma 1 ($p_{\Delta T_{\text{mrt},i,j}^t} > 0$). *The probability for all possible tree positions (i, j) is $p_{\Delta T_{\text{mrt},i,j}^t} > 0$.*

Proof. Since the exponential function \exp in Equation 2 is always positive, it follows that $p_{\Delta T_{\text{mrt},i,j}^t} > 0$ and the denominator is always non-zero. Thus, the probabilities are well-defined. \square

Theorem 1 (Convergence to global optimum). *Our optimization method converges to the globally optimal tree positions as (i) the number of iterations approaches infinity and (ii) the estimates of our T_{mrt} modeling are proportional to the true aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for an aggregation function ϕ and time period M .*

Proof. We are guaranteed to sample the globally optimal tree positions with an infinite budget (assumption (i)), as the perturbation step in our optimization method (PerturbationWithGA) randomly interleaves tree positions with positive probability (Lemma 1). Since our optimization method directly compares the effectiveness of tree positions using our $T_{\text{mrt}}^{M,\phi}$ modeling pipeline—that yields estimates that are proportional to true $T_{\text{mrt}}^{M,\phi}$ values (assumption (ii))—we will accept them throughout all steps of our optimization method and, consequently, find the global optimum. \square

D Mean radiant temperature modeling with SOLWEIG

SOLWEIG [Lindberg et al., 2008] uses spatial and temporal (meteorological) inputs to model T_{mrt} for a height of 1.1 m of a standing or walking rotationally symmetric person using the six-dimension approach presented in Appendix A. We used the default model parameters:

- Emissivity ground: 0.95.

- Emissivity walls: 0.9.
- Albedo ground: 0.15.
- Albedo walls: 0.2.
- Transmissivity: 3 %.
- Trunk height: 25 % of tree height.

E Experimental details

We evaluated our optimization approach for tree placements across diverse study areas and time periods. We considered the following five study areas: `city-center` an old city-center, `new r.a.` a recently developed residential area (r.a.) with age <5 years, `medium-age r.a.` a medium, primarily residential district built 25-35 years ago, `old r.a.` an old building district where the majority of buildings are older than 100 years, and `industrial` an industrial area. These areas vary considerably in their characteristics, e.g., existing amount of vegetation or proportion of sealed surfaces. Further, we considered the following time periods M : hottest day (and week) in 2020 based on the (average of) maximum daily air temperature, the entire year of 2020, and the decade from 2011 to 2020. While the first two time periods focus on the most extreme heat stress events, the latter two provide assessment over the course of longer time periods, including seasonal variations. We compared our approach with `random` (positioning based on random chance), `greedy T_{mrt}` (maximal T_{mrt}), `greedy ΔT_{mrt}` (maximal ΔT_{mrt}), and a `genetic` algorithm. We provide the hyperparameters of our optimization method in Appendix F. Model and training details for T_{mrt} and $T_{\text{mrt}}^{M,\phi}$ estimation are provided in Appendix G. Throughout our experiments, we used the mean as aggregation function ϕ . While all optimization algorithms used the faster direct estimation of aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ with the model $f_{T_{\text{mrt}}^{M,\phi}}$, we evaluated the final found tree placements by first predicting point-wise T_{mrt} for all $|M|$ meteorological inputs across the specified time period M with the model $f_{T_{\text{mrt}}}$ and subsequently aggregated these estimations. To quantitatively assess the efficacy of tree placements, we quantified the change in point-wise T_{mrt} (ΔT_{mrt} [K]), averaged over the 500 m x 500 m study area ($\Delta T_{\text{mrt}} \text{ area}^{-1}$ [Km⁻²]), or averaged over the size of the canopy area ($\Delta T_{\text{mrt}} \text{ canopy area}^{-1}$ [Km⁻²]). We excluded building footprints and open water areas from our evaluation criteria. Throughout our experiments, we assumed that tree placements can be considered on both public and private property.

F Hyperparameter choices of optimization

We implemented the genetic algorithm with PyGAD⁵. Throughout our experiments, we used a population size of 20 with steady-state selection for parents, random mutation and single-point crossover. We used the current best optima (up to five) and random samples for the initial population. We set the temperature τ of Equation 2 to 1. We kept the best solution throughout the evolution. We used 1000 iterations within our optimization method. For the baseline `genetic` algorithm, we used 5000 iterations to account for larger compute due to the iterative design of our optimization approach.

For the `HillClimbing` algorithm, we adopted the design by Wallenberg et al. [2022]. That is, we repeatedly cycle over all trees and try to move them within the adjacent eight neighbors. We accept the move if it improves upon the current aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$. We repeat this process until no further improvement can be found.

Lastly, we used five iterations within our iterated local search. We found this resulted in a good trade-off between the efficacy of the final tree placements and total runtime.

G Model and training details

Model details We adopted the U-Net architecture from Briegel et al. [2023]. Specifically, the models $f_{T_{\text{mrt}}}$ and $f_{T_{\text{mrt}}^{M,\phi}}$ receive inputs of size $16 \times h \times w$ and predict T_{mrt} or $T_{\text{mrt}}^{M,\phi}$, respectively, of size of $h \times w$, where h and w are the height and width of the spatial input, respectively. The model f_{svf} receives an input of size $h \times w$ (digital surface model for vegetation) and outputs the sky view

⁵<https://github.com/ahmedfgad/GeneticAlgorithmPython>

factor maps for vegetation of size of $5 \times h \times w$. All models use the U-Net architecture [Ronneberger et al., 2015] with a depth of 3 and base dimensionality of 64. Each stage of the encoder and decoder consist of a convolution or transposed convolution, respectively, followed by batch normalization [Ioffe and Szegedy, 2015] and ReLU non-linearity.

Training details In the following, we provide the specific training details of all models.

- $f_{T_{\text{mrt}}}$: We trained the model with L1 loss function for ten epochs using the Adam optimizer [Kingma and Ba, 2015] with learning rate of 0.001 and exponential learning rate decay schedule. We randomly cropped (256x256) the inputs during training.
- $f_{T_{\text{mrt}}^{M,\phi}}$: We trained the model with L1 loss function for 5000 epochs and batch size of 32 with Adam optimizer [Kingma and Ba, 2015] with learning rate of 0.001 and exponential decay learning rate schedule. We randomly cropped (256x256) the inputs during training.
- f_{svf} : We trained the model with L1 loss function for 20 epochs with Adam optimizer [Kingma and Ba, 2015] with learning rate of 0.001 and exponential decay learning rate schedule. We randomly cropped (256x256) the inputs during training.

H Additional experimental results

H.1 Evaluation of mean radiant temperature modeling

We assessed the quality of our T_{mrt} and $T_{\text{mrt}}^{M,\phi}$ modeling. Our model for estimating point-wise T_{mrt} ($f_{T_{\text{mrt}}}$) achieved a L1 error of 1.93 K compared to the point-wise T_{mrt} calculated by the physical model SOLWEIG [Lindberg et al., 2008]. This regression performance is in line with Briegel et al. [2023] who reported a L1 error of 2.4 K. Next, we assessed our proposed model $f_{T_{\text{mrt}}^{M,\phi}}$ that estimates aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for aggregation function ϕ (i.e., mean) over a specified time period M . We found only a modest increase in L1 error by 0.46 K (for time period $M=\text{day}$), 0.42 K (week), 0.35 K (year), and 0.18 K (decade) compared to first predicting point-wise T_{mrt} for all M meteorological inputs with model $f_{T_{\text{mrt}}}$ and then aggregating them. While model $f_{T_{\text{mrt}}^{M,\phi}}$ is slightly worse in regression performance, we want to emphasize its substantial computational speed-ups. To evaluate the computational speed-up, we used a single NVIDIA RTX 3090 GPU and averaged estimation times for $T_{\text{mrt}}^{M,\phi}$ over five runs. We found computational speed-ups by up to 400,000x (for the time period decade with $|M| = 87,672$ meteorological inputs). Lastly, our estimation of sky view factors from the digital surface model for vegetation with model f_{svf} achieved a mere L1 error of 0.047% when compared to conventionally computed sky view factor maps. Substituting the conventionally computed sky view factor maps with our estimates resulted in only a negligible regression performance decrease of ca. 0.2 K compared to SOLWEIG’s estimates using the conventionally computed sky view factor maps.

H.2 Optimization results on other time periods

Figure 4 provides qualitative results for the hottest day in 2020, the entire year of 2020, and the decade from 2011 till 2020. We optimized the positions of 50 trees, each with a height of 12 m and crown diameter of 9 m.

H.3 Analyses

Given the found tree placements from our experiments in Section 3 and Appendix H.2, we conducted analyses on various aspects (daily variation, seasonal variation, number of trees, tree geometry variation). Figure 5 shows a noteworthy duality caused by daily and seasonal variations. Specifically, trees exert a dual influence, reducing T_{mrt} during daytime and summer season, while conversely increasing it during nighttime and winter season. To understand the impact of meteorological parameters on this, we trained an XGBoost classifier [Chen et al., 2015] on each study area and all meteorological inputs from 2020 (year) to predict whether the additional trees reduce or increase T_{mrt} . We assessed feature importance using SHAP [Shapley, 1953, Lundberg and Lee, 2017] and found that incoming shortwave radiation I_g emerges as the most influential meteorological parameter.

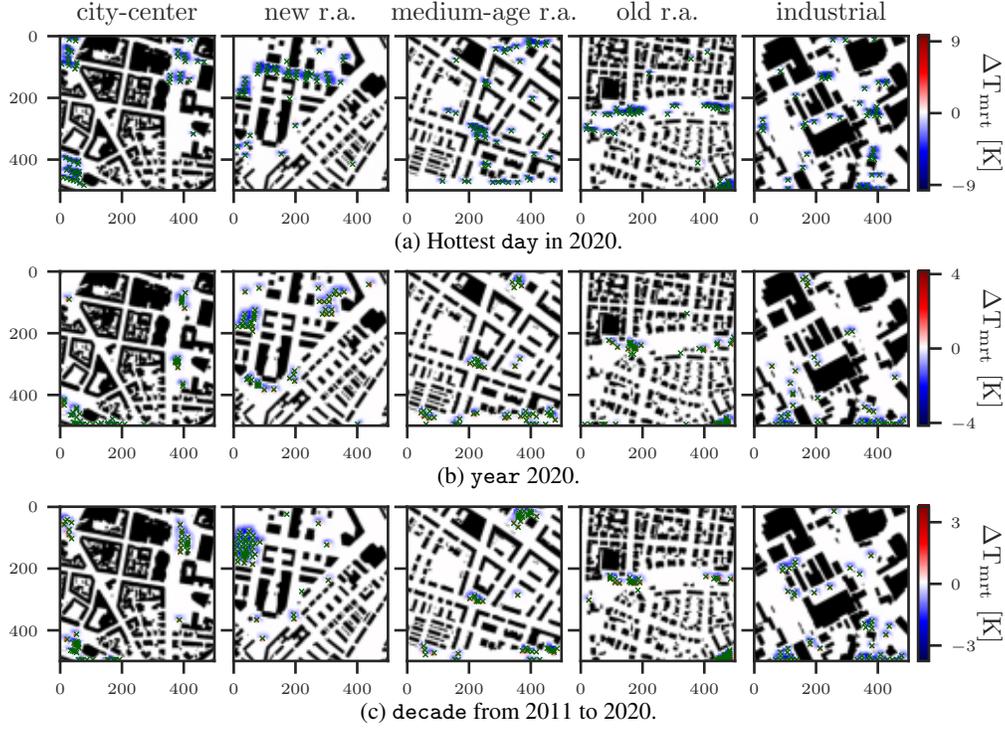


Figure 4: Optimizing tree placements can substantially reduce point-wise T_{mrt} , e.g., during heatwaves, leading to improved outdoor human thermal comfort. Optimized placements of 50 added trees, each with a height of 12 m and crown diameter of 9 m, for the hottest day (4(a)) in 2020, the entire year 2020 (4(b)), and the entire decade from 2011 to 2020 (4(c)) across diverse urban neighborhoods (from left to right: city-center, recently developed new r.a. (residential area), medium-age r.a., old r.a., industrial area).

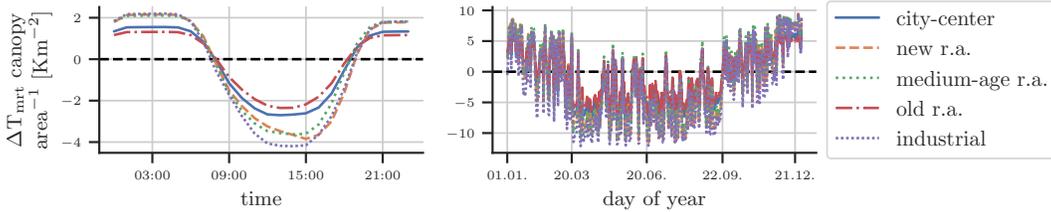


Figure 5: Daily (left) and seasonal variation (right) reduce T_{mrt} during daytime and summer season, while conversely increase it during nighttime and winter season. Results based on experiments adding 50 trees, each with a height of 12 m and a crown diameter of 9 m, for the time period year.

Remarkably, a simple classifier of the form

$$y = \begin{cases} T_{\text{mrt}} \text{ decreases,} & I_g > 96 \text{ Wm}^{-2} \\ T_{\text{mrt}} \text{ increases,} & \text{otherwise} \end{cases}, \quad (6)$$

achieves an average accuracy of $97.9\% \pm 0.005\%$, highlighting its predictive prowess.

Besides the above, Figure 6 reveals a pattern of diminishing returns as we increase the extent of canopy cover, achieved either by adding more trees or by using larger trees. This trend suggests that there may be a point of saturation beyond which achieving further reductions in T_{mrt} becomes progressively more challenging. To corroborate this trend quantitatively, we computed Spearman rank correlations between $\Delta T_{\text{mrt}} \text{ canopy area}^{-1}$ and the size of the canopy area; also including pre-existing trees with a minimum height of 3 m. We found high Spearman rank correlations of 0.72 or 0.73 for varying number of trees or tree heights, respectively. Notwithstanding the presence of diminishing

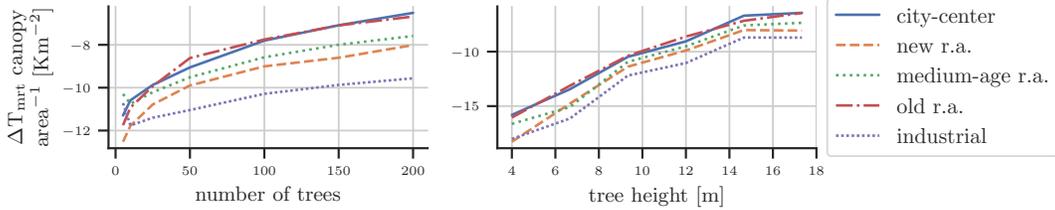


Figure 6: Increasing the number of trees (left) and tree height (right) has diminishing returns for the reduction of T_{mrt} . Results are based on the experiment adding trees for the time period week.

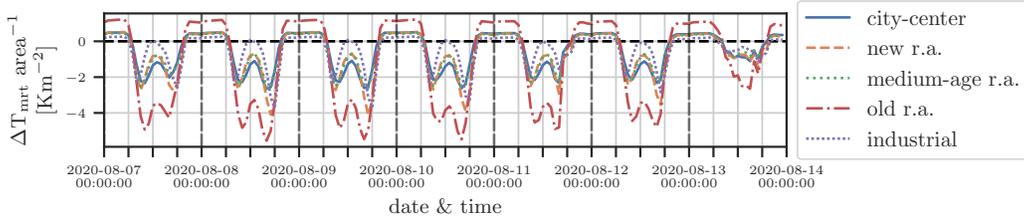


Figure 7: Alternative placements of existing trees substantially reduces T_{mrt} during daytime. Optimization ran for the hottest week in 2020 (heatwave condition).

returns, we still emphasize that each tree leads to a palpable decrease in T_{mrt} , thereby enhancing outdoor human thermal comfort—an observation that remains steadfast despite these trends.

H.4 Counterfactual placement of trees

In our other experiments, we always added trees to the existing urban vegetation. However, it remains uncertain whether the placement of existing trees, determined by natural evolution or human-made planning, represents an optimal spatial arrangement of trees. Thus, we pose the counterfactual question [Pearl, 2009]: *could alternative tree positions have retrospectively yielded a reduced amount of heat stress?* To answer this counterfactual question, we identified all existing trees from the digital surface model for vegetation with a simple procedure based on the watershed algorithm [Soille and Ansoult, 1990, Beucher and Meyer, 2018]—which is optimal in identifying non-overlapping trees, i.e., the maximum point of the tree does not overlap with any other tree, with strictly increasing canopies towards each maximum point—and optimized their placements for the hottest week in 2020 (heatwave condition). We only considered vegetation of a minimum height of 3 m and ensured that the post-extraction size of the canopy area does not exceed the size of the (f)actual canopy area.

Results We found alternative tree placements that would have led to a substantial reduction of T_{mrt} by an average of 0.83 K. Furthermore, it would have resulted in a substantial reduction of T_{mrt} exceeding 60°C —a recognized threshold for heat stress [Lee et al., 2013, Thorsson et al., 2017]—by on average 19.7% throughout the duration of the heatwave event (week). This strongly suggests that the existing placements of trees may not be fully harnessed to their optimal capacity. Notably, the improvement by relocation of existing trees is significantly larger than the effect of 50 added trees (0.23 K; see Table 1). Figure 7 visualizes the change in T_{mrt} across each hour of the hottest week in 2020. Intriguingly, they reveal peaks during morning and afternoon hours. By inspecting the relocations of trees (see Figure 8), we found that trees tend to be relocated from spaces with already ample shading from tree canopies and buildings to large, open, typically sealed spaces without trees, such as parking lots or sealed plazas.

H.5 Ablation study

We conducted an ablation study by selectively ablating components of our optimization method. Specifically, we studied the contributions of the greedy initialization strategy (TopK) by substituting it with random initialization, as well as (de)activating perturbation (PerturbationWithGA), local search (HillClimbing), or the iterative design (Iterations). Table 3 shows the positive effect of each component. It is noteworthy that the iterated design may exhibit a relatively diminished impact in scenarios where the greedy initialization or first iteration already yield good or even the (globally) optimal tree positions.

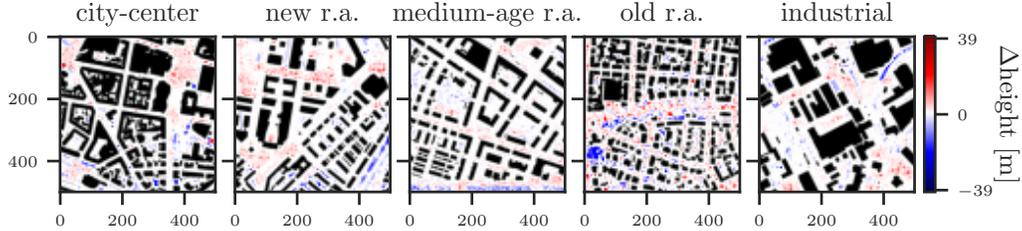


Figure 8: The alternative tree placements (Appendix H.4) often move from north-to-south streets to west-to-east streets as well as open, typically paved spaces. Red indicates that vegetation (i.e., tree) was added, whereas blue indicates that vegetation was removed.

Table 3: Ablation study over different choices of our optimization method for the time period week averaged across the five study areas for 50 added trees of height of 12 m and crown diameter of 9 m.

TopK	PerturbationWithGA	HillClimbing	Iterations	$\Delta T_{\text{mrt}} \text{ area}^{-1} [\text{Km}^{-2}]$
✓	-	-	-	-0.1793
-	✓	✓	✓	-0.1955
✓	-	✓	✓	-0.2094
✓	✓	-	✓	-0.2337
✓	✓	✓	-	-0.2302
✓	✓	✓	✓	-0.2345

I Limitations

The main limitation, or strength, of our approach is assumption (ii) from Theorem 1 that the model $f_{T_{\text{mrt}}^{M,\phi}}$ yields estimates for that are (at least) proportional to the true aggregated, point-wise $T_{\text{mrt}}^{M,\phi}$ for aggregation function ϕ and time period M . Our experimental evaluation affirms the viability of this approximation, but it remains an assumption. Another limitation is that we assumed a static urban environment, contrasting the dynamic real world. Further, we acknowledge the uniform tree parameterization, i.e., same tree geometry, species, or transmissivity. While varying tree geometry could be explored further in future works, both latter are limitations of SOLWEIG, which we rely on to train our models. In a similar vein, our experiments focused on a single city, which may not fully encompass the diversity of cities worldwide. We believe that easier data acquisition of spatial input data, e.g., through advances in canopy and building height estimation [Lindemann-Matthies and Brieger, 2016, Tolan et al., 2023], could facilitate the adoption of our approach to other cities. Our experiments lack a distinction between public and private property, as well as does not incorporate considerations regarding the actual ecological and regulatory feasibility of tree positions, e.g., trees may be placed in the middle of streets. Lastly, our approach does not consider the actual zones of activity and pathways of pedestrians. Future work could address these limitations by incorporating comprehensive data regarding the feasibility, cost of tree placements and pedestrian pathways, with insights from, e.g., urban forestry or legal experts, as well as considering the point-wise likelihood of humans sojourning at a certain location. Finally, other factors, such as wind, air temperature, and humidity, also influence human thermal comfort, however vary less distinctly spatially but keep the integration of such for future work.

J Broader impact

We believe that our approach can empower urban decision-makers selecting effective measures for climate-sensitive urban planning and climate adaptation, reduces power consumption, and democratizes access to planning tools to smaller communities as well as citizens. However, our approach could also be used improperly for urban planning by ignoring other important factors, such as the influence of trees on wind patterns, heavy rain events, or legal requirements. Moreover, adverse

individuals may manipulate results to further their personal goals, e.g., they do not want trees in front of their homes, which may not necessarily align with societal goals.

K Carbon footprint estimate

All components of our optimization approach cause carbon dioxide emissions. We estimated the emissions for our final experiments (including training of models, optimization, ablations etc.) using the calculator by [Lacoste et al. \[2019\]](#).⁶ Experiments were conducted using an internal infrastructure, which has a carbon efficiency of 0.385 kgCO₂eq/kWh⁷. A cumulative of ca. 380 h of computation was performed on various GPU hardware. Emissions are estimated to be ca. 39 kgCO₂eq. Note that the actual carbon emissions over the course of this project is multiple times larger.

⁶<https://mlco2.github.io/impact/>

⁷Note that carbon efficiency figures for 2023 were not released at time of writing.