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ARTICLE

Ventilation-Sensitive Placement of Nature-Based Cooling for Peak Pedestrian Heat Relief in a Compact Cologne District

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Abstract

The heat adaptation strategy of the compact mid-rise districts must reduce pedestrian heat load without affecting the poor air exchange which still persists in such narrow streets and courtyards. In this study, the cooling pathway scores for compact districts are determined based on radiation–ventilation-gated district-level heat adaptation intervention allocation. This case study involves the Volksgartenviertel district, an 16 ha compact district in Cologne, Germany. The scores are assigned based on district characteristics including the land cover, vegetation, 2022 July meteorology, and the air-temperature–physiological equivalent temperature response relationship. The district consists of traffic area, parks, buildings, and inner courtyards covering approximately 25 %, 20 %, 25 %, and 30 % of the district, respectively. Present greening within the district is unbalanced; there are 285 street trees belonging to 18 different species and two green roof areas. There is also one completely covered facade greening and 11 tree–shrub–grass front yards out of 221 front yards surveyed. The intervention set consists of 158 *Acer platanoides* street trees, 146 facade and roof greening interventions, and 2410 grass grid pavers which correspond to 9640 m^2 or 0.964 ha permeable grounds. For the hottest days during 18–20 July 2022, the district maximum air temperature is 40.2 °C, and mean air temperature and wind speed are approximately 28.7 °C and 0.29 m/s, respectively. The mean air-temperature reduction over 72 h is -0.49 K, which is accompanied by -0.91 K of PET reduction. The maximum reduction of both air temperature and PET locally is -5.28 K and -7.66 K, respectively. While PET reduction over 72 h is 3.13 times of air-temperature reduction, locally maximum PET reduction reaches -26.10 K during the hottest hour.

Keywords: compact mid-rise district; urban heat; nature-based cooling; physiological equivalent temperature; street trees; green roofs; facade greening; permeable surfaces; urban ventilation

1. Introduction

Heat stress in dense urban neighbourhoods arises not only due to air warming. Access to solar radiation, longwave radiation emitted by warm building walls and road surfaces, heat storage in building materials, evaporation from

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leaves and roads, the geometry of the streets, and wind availability are some of the factors determining the thermal environment at pedestrian level. The energetic urban heat island concept identifies these phenomena as consequences of altered surface energy budget, anthropogenic heat production, heat storage, and turbulence [21]. By introducing local climate zones, scientists were able to explain the different impacts of urbanisation on the environment despite similar regional climatic conditions [25]. As a result, the challenge posed by adaptation to hot summer days in compact mid-rise districts involves designing cooling measures in such a way that they take advantage of their specific cooling effect without decreasing the district's capacity for ventilation.

The body of empirical studies shows that urban greening is capable of reducing heat, although it highlights the significance of local context in the effectiveness of different cooling techniques. Numerous syntheses of evidence indicate that green spaces are indeed beneficial to pedestrians, although the extent of the impact varies according to local conditions [2, 10]. Studies simulating the impacts of greening on microclimates suggest that greening is able to lower air temperatures and improve outdoor boundary conditions, even if its impact is dependent on the form and density of the plants and street geometry [20, 29]. The same research demonstrates that greening measures aimed at improving comfort need to be implemented within a district on the pedestrian-scale as local thermal benefits often outweigh district-wide cooling effects [14, 26].

The impact of greening measures differs due to their unique cooling properties. Urban trees are mostly capable of blocking short-wave radiation, shading pavements, and providing a source for evaporative cooling through transpiration if growing conditions are suitable. Roof greening affects roof-surface temperature, heat storage in the substrate and in-building heat exchange; in the case of very low or tightly connected buildings, roof greening can provide a cooling effect on pedestrians. Facade greening reduces wall heat and influences longwave radiation exchange in street canyons, since walls are known to significantly increase mean radiant temperature there [1, 3, 27]. Vegetation in permeable ground lowers surface temperature and provides opportunities for evaporative cooling while leaving the air space free for ventilation [8, 19].

The necessity to separate pathways becomes crucial in cases when densely planted vegetation may produce conflicting outcomes. Dense canopy may block incoming radiation, but it can also lower wind speed and decrease convective exchange. Evaporation produces cooling, although poor ventilation may make moist air uncomfortable for pedestrians. The importance of wind speed, humidity, and mean radiant temperature along with air temperature and clothing in regulating the comfort of people outdoors is highlighted by reviews of outdoor comfort and cooling potential of urban greening [4, 12, 15]. For this reason, merely lowering air temperature is insufficient in determining whether a cooling measure will help people feel more comfortable outdoors during extreme heat.

Physiological Equivalent Temperature (PET) allows to convert air temperature, humidity, wind speed, radiant exposure, clothing level, and metabolic heat rate to a thermal indicator understandable to non-specialists [12, 15]. The PET indicator shows substantial improvements in the shade even if air temperature does not change significantly, due to a person's high sensitivity to mean radiant temperature. The significant physiological and psychological role of street vegetation has been demonstrated by research on urban comfort in temperate streets. The results prove that street trees and front gardens contribute to both comfort and perceived thermal conditions [14]. This distinction becomes key in the case of compact mid-rise neighbourhoods as the entire volume of air cannot be altered, but radiation exposure and radiant cooling can be changed for pedestrians by proper placement of trees, facade vegetation, and permeable ground.

In the current paper, we examine the impact of greening measures implemented in the Volksgartenviertel and discuss whether the cooling effects of 158 new *Acer platanoides* trees, 146 roof and facade greening measures, and 2410 grass-grid-paver cells are independent from one another or represent the cooling properties specific to their location in order to reduce peak pedestrian heat.

The research aims to create a placement strategy based on district-specific inventory and response to a heat wave. Cooling pathway scores are used to define the role of each greening measure. The ventilation gate filters out dense vegetation, prioritising less dense vegetation on the basis of possible adverse effects on the air circulation. Next, air temperature and PET are used to assess the significance of assigned greening measures in reducing heat stress.

2. Materials and methods

2.1. Urban district and July 2022 heat episode

For the purpose of this study, the district of Volksgartenviertel in Cologne, Germany was selected. The area of the district is 16 ha, and it consists of approximately 25 % traffic areas, 20 % parklands, 25 % buildings, and 30 % inner courtyards. In addition, it comprises various forms of urban spaces, including dense perimeter blocks, streets, corridors, school yards, front yards, private courtyards, and Volksgarten park.

From Figure 1 we can infer the reason why the analyzed area cannot be viewed as a thermally homogeneous district. There are several green spots, however, green-building envelopes and good front-yard greening have never been observed in the area. In total, 285 trees representing 18 species were registered, out of which *Robinia pseudoacacia* includes 95 specimens. Moreover, there are only two green roofs and only one fully covered green facade among all buildings. Among the 221 investigated front yards, there were 11 of those containing a combination of a tree, shrubs, and grass. This shows that large-scale unused opportunities for reducing the ambient temperature exist everywhere except the mentioned open spots.

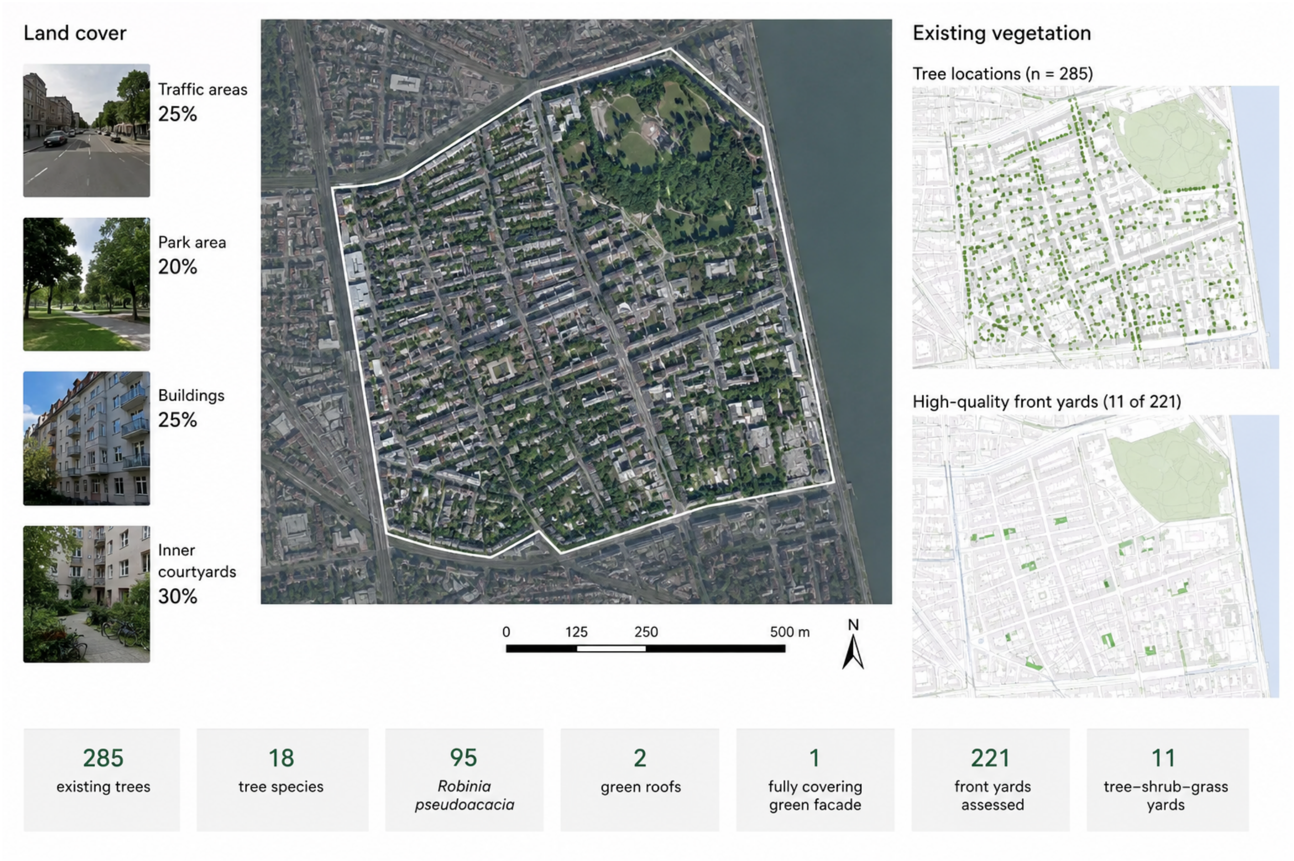

Figure 1. District cooling inventory.

A chosen heat episode was recorded from 18 to 20 July 2022. During a three-day observation period, the maximum air temperature was found to reach 40.2 °C, and the average air temperature was equal to 28.7 °C. Mean wind speed during this period was estimated as approximately 0.29 m/s with dominant south-easterly flow and high-pressure stability prevailing at this time. Such conditions of heat wave characterized by high temperatures and very slow winds are important to compact urban areas since radiant loads and latent heat storage can develop effectively, and advection cooling will not take place efficiently.

It is obvious from the event graphics shown in Figure 2 that the episode is characterized by both extremely high temperatures during the daytime and low wind speed. While the temperature graph shows the maximum temperature of 40.2 °C and 72-hour mean 28.7 °C, the wind speed graph highlights the weak air movement during which dense vegetation will have to be placed. The heat strip proves that the crucial problem is not associated only with one particular hour; rather, repetitive heating during the day and warm nights make it challenging for pedestrians and residents to feel comfortable over three days.

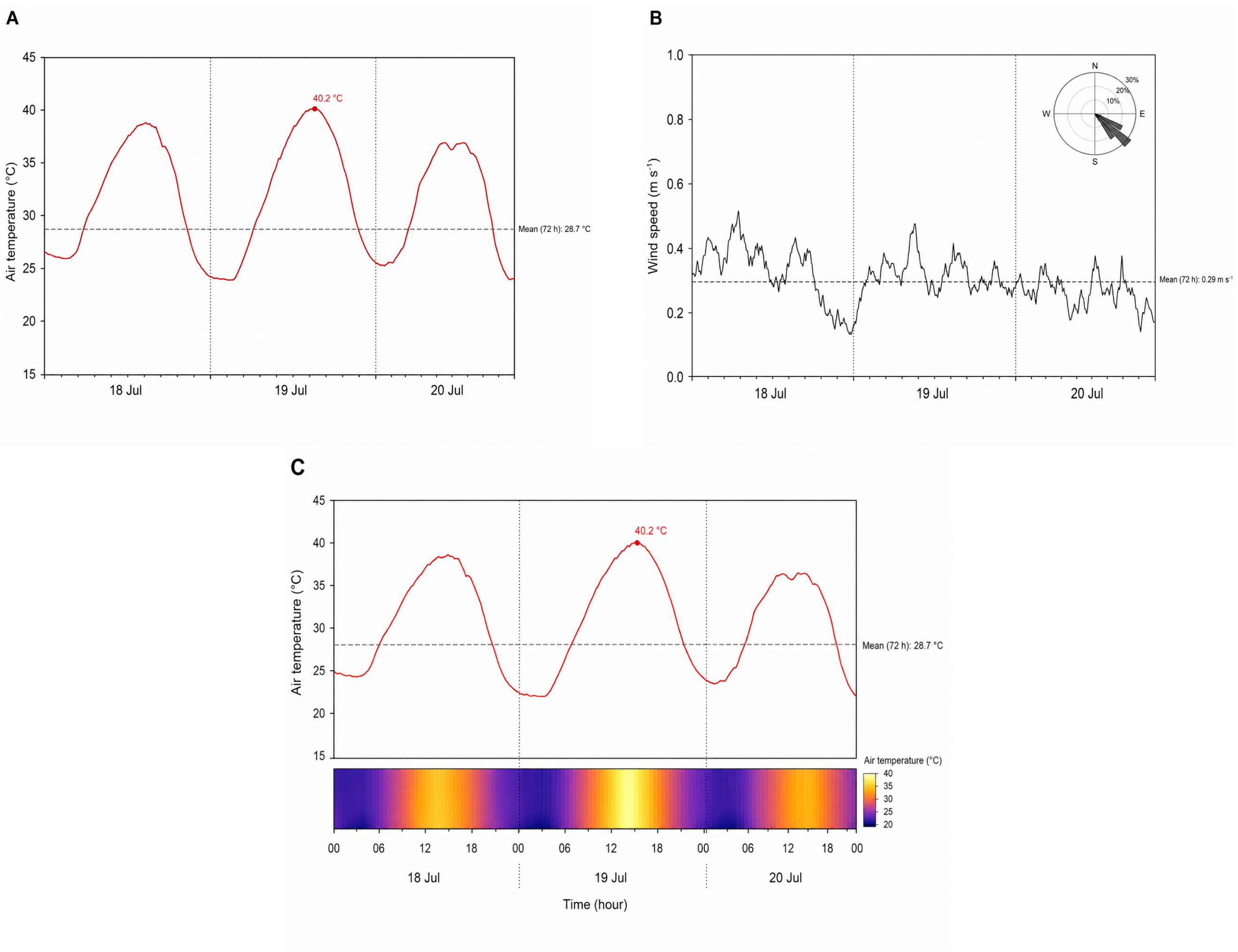

Figure 2. Heat-episode conditions.

2.2. Intervention inventory and surface classes

There are three physical interventions in the inventory used. First, 158 trees of the kind of *Acer platanoides* were added to the streets. These are modelled as trees with the average height of about 15 m and the crown radius of 7 m. The addition of trees makes the number of them equal to 443, which is 55.4% more than in the inventory, meaning that 9.9 trees are added per 1 ha. *Acer platanoides* is not considered as an ideal solution but just as an implementable option; there are other tree species such as *Quercus robur*, *Platanus acerifolia*, *Juglans nigra*, and *Acer pseudoplatanus* whose shade producing properties should be taken into account.

The second intervention consists of 146 building greening interventions including roof and facade greening. It is worth mentioning that currently there is no such practice, despite the great contribution of the buildings to heat exchange and storage; thus, this type of intervention plays a significant role in the project. While roof greening is targeted at reducing building heat storage and exchanging heat, facade greening is aimed at wall radiation in pedestrian zones. Equating the two practices would not allow highlighting differences in their effects; thus, the allocation process treats them separately.

Third, there is grass-grid-paver intervention when sealed ground is replaced by the corresponding surface in 2410 grid cells. In terms of 2 m spatial resolution, each cell represents 4 m^2; thus, the total area is equal to 9640 m^2

(0.964 ha) which constitutes 6% of the area of the district. Unlike adding another park-like surface, this is a dispersed change in small zones where heat storage, pedestrian heat exposure, and ventilation sensitivity all play their roles.

The Table 1 describes the physical dimensions of the proposed intervention. The tree element has relatively large numbers in comparison to the baseline condition, the ground element has a sufficiently large figure to impact the surface balance in the district, and the roof / facade elements address an underutilized section of the building envelope. These figures also highlight the reason why a general greening target would not be sufficiently specific: 0.964 ha of permeable ground, 158 trees, and 146 building surface elements become involved in the energy balance with different spatial interfaces.

Table 1. District and intervention values.

Component	**Value**
District scale	16 ha compact mid-rise district in Cologne, Germany
Land-cover composition	25 % traffic areas, 20 % park area, 25 % buildings, and 30 % inner courtyards
Heat episode	18–20 July 2022; maximum air temperature 40.2 °C; 72-h mean air temperature 28.7 °C; mean wind speed 0.29 m/s
Existing tree stock	285 trees across 18 species; *Robinia pseudoacacia* represented by 95 individuals
Existing building greening	Two green roofs and one effective fully covering green facade
Existing front-yard structure	221 assessed front yards; 11 with tree–shrub–grass composition
Added trees	158 *Acer platanoides*; approximately 9.9 new trees per hectare
Added permeable ground	2410 grass-grid-paver cells; 9640 m^2, or 0.964 ha, at 2 m spatial resolution
Added roof and facade greening	146 measures on building surfaces

2.3. Cooling-pathway scoring

The first step of the allocation procedure involves conversion of the elements from each intervention family into cooling-pathway scores. Four families are recognized: street trees, green roofs, vertical greening, and permeable ground surfaces. Trees are scored according to shade, size of the tree canopy, maturity as determined by diameter, leaf area index, and transpiration. Roofs are scored based on system intensity, plant density, leaf area index, leaf thickness, leaf colour, and substrate-based thermal properties. Walls are scored based on orientation, coverage, system intensity, leaf area index, and transpiration.

The photographic panels in Figure 3 emphasise that the intervention families are not substitutes for one another. Street trees act directly on pedestrian shade, green roofs act on upper-surface heat exchange, facade greening acts on wall radiation, and permeable ground acts on sealed-surface storage while leaving the air volume open. This visual separation is central to the method because it prevents roof greening, street trees, and permeable ground from being collapsed into a single greenness category.

For intervention family j, the cooling-pathway score is calculated as

$$S_j = \frac{{}^{n_j}_{p=1}\, w_p r_{jp}}{5\,{}^{n_j}_{p=1}\, w_p}, \tag{1}$$

where r_{jp} is the five-level rating for process p, w_p is the process weight, and n_j is the number of processes used for family j. The denominator normalises the score to the interval from 0 to 1. A value near 1 indicates that the intervention has a strong process state for the cooling pathway being evaluated.

Equation (1) provides a planning-level translation of the five-level cooling classifications into a comparable score. Its usefulness comes from process separation. Shade is weighted strongly for trees because short-wave radiation dominates pedestrian PET in exposed streets and school yards. Orientation and coverage are weighted strongly for facade greening because wall exposure controls long-wave exchange in canyons. Permeability and vegetation layering are weighted strongly for ground surfaces because they reduce storage and support evaporative exchange without blocking the air path.

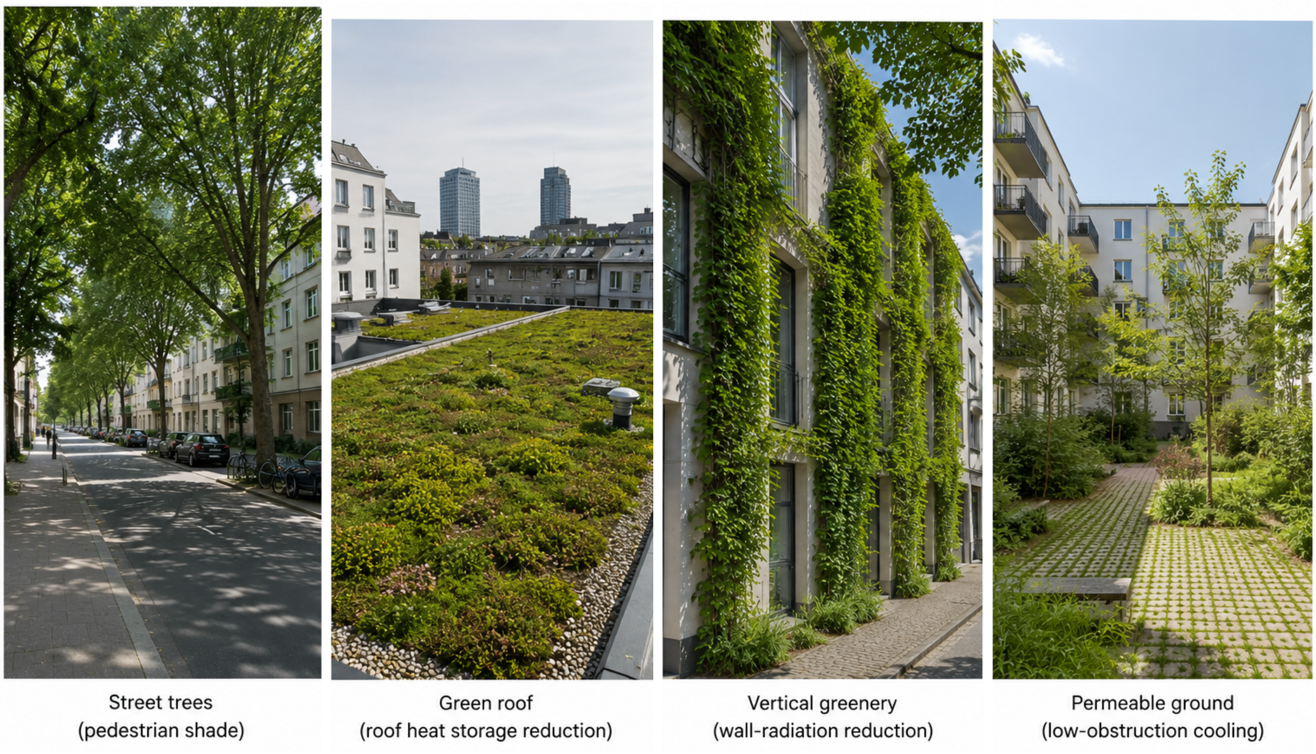

Figure 3. Cooling pathways.

2.4. Ventilation-gated placement

Cooling-pathway strength alone is not sufficient for placement. The allocation score combines pathway strength, local heat exposure, pedestrian relevance, and ventilation sensitivity. For intervention family j in zone z, the score is

$$A_{jz} = 100\, S_j H_z Q_z V_{jz}, \tag{2}$$

where H_z is local heat exposure, Q_z is pedestrian relevance, and V_{jz} is the ventilation gate. The heat-exposure term increases where sealed ground, high radiant exposure, weak existing vegetation, and heat storage occur together. The pedestrian-relevance term increases in school yards, sidewalks, front yards, and courtyards where people are likely to remain outdoors during warm periods. The ventilation gate lowers priority where dense vegetation is likely to reduce air exchange.

The ledger in Figure 4 clarifies the logic of the score. A high greening pathway does not automatically create the highest priority. The measure must also correspond to a hot surface or air space, serve a place where pedestrian exposure is important, and remain compatible with local ventilation. This is why facade greening can receive high priority in a narrow canyon even if its air-temperature effect is smaller than that of a large tree, and why grass-grid pavers can be highly suitable in courtyards where air exchange should remain open.

The ventilation gate is defined as

$$V_{jz} = \max\left(V_{\min}, 1 - \lambda_j B_z\right), \tag{3}$$

where B_z is local obstruction sensitivity, λ_j is the obstruction coefficient of intervention family j, and $V_{\min}$ preserves partial suitability when a measure still has cooling value. Low vegetation and permeable ground receive small obstruction coefficients. Facade greening receives a moderate coefficient because it occupies wall surfaces rather than the main air passage. Continuous dense tree planting receives a larger coefficient in narrow canyons because crowns can reduce air access when spacing is uncontrolled.

The gate functions as a placement restraint, not as a rejection of tree planting. Street trees remain essential because they deliver the strongest direct shade. The gate instead changes how trees are arranged: crown spacing, canopy height, rooting strips, and permeable ground beneath the trees become part of the cooling specification. In places

Figure 4. Allocation components.

where the street section is narrow, facade greening shares the radiant-load function while reducing the need for continuous canopy closure across the canyon.

The three settings in Figure 5 show how built form changes intervention suitability. An open school yard can accept multi-layer planting and permeable ground because air exchange is less constrained. A semi-enclosed courtyard benefits from ground replacement and selective canopy, with planting density moderated by the surrounding walls. A narrow street canyon requires shade, but the most suitable arrangement is spaced trees combined with facade greening rather than continuous crown closure across the air passage.

2.5. Comfort-response calculations

Three indicators distinguish general cooling from pedestrian relief. The PET leverage ratio is

$$L_{\mathrm{PET}} = \frac{|\Delta \mathrm{PET}|}{|\Delta T_a|}, \tag{4}$$

Figure 5. Ventilation-sensitive placement.

where ΔT_a is the air-temperature difference and $\Delta\mathrm{PET}$ is the physiological equivalent temperature difference. Values above 1 mean that comfort relief is larger than air-temperature cooling.

The concentration ratio is

$$C_x = \frac{|\Delta x_{\mathrm{local}}|}{|\Delta x_{\mathrm{district}}|}, \tag{5}$$

where x is either air temperature or PET. A high value means that cooling is concentrated in local heat-exposed spaces rather than distributed evenly across the entire district.

The peak-hour multiplier is

$$P_x = \frac{|\Delta x_{\mathrm{hottest}}|}{|\Delta x_{\mathrm{72h}}|}, \tag{6}$$

where $\Delta x_{\mathrm{hottest}}$ is the response during the hottest hour and Δx_{72h} is the 72-h mean response. A value above 1 indicates that the intervention set becomes more effective during the period of greatest heat stress.

Such computations differentiate between district-scale cooling effects and pedestrian-scale cooling effects. An indication of a high PET leverage ratio is when radiant-load effects are significant. An indication of a high concentration ratio is that cooling is occurring in exposed urban spaces rather than being spread out through the entire district. An indication of a high peak-hour multiplier is that the intervention set shows a strong response at the peak hour rather than just responding based on average events.

3. Results

3.1. Current cooling capacity and surfaces available for cooling interventions

The district data provided in Table 1 indicate that there are opportunities for cooling distributed among several urban surfaces. The 20 % park coverage represents a valuable cooling core within the district, but the other traffic, building, and courtyard surfaces comprise the greater proportion of pedestrian exposure to the environment. The existence of 285 trees indicates that the district is not barren of greenery; the problem is the poor distribution of greenery and small surface areas. The small numbers of green roofs, green facades, and good front yards show that most of the potential exists on existing surfaces in the district.

There are three quantities representing different thermal surfaces. Increasing 158 trees produces an opportunity for shade cover which needs to be distributed strategically among pedestrian routes and yard areas. Replacing 0.964 ha of urban surfaces by grass-grid pavers reduces heat storage in small areas which do not have dense vegetation. Implementing 146 roof and facade surfaces increases radiant cooling and heat storage on rooftops and walls.

158 street trees
Acer platanoides

146 roof and facade greening
on buildings

2410 grass-grid-paver cells
0.964 ha of permeable ground

Figure 6. Intervention stock.

The interventions captured in Figure 6 are physical illustrations of the contrast between canopy, envelope, and ground-surface targets. Street trees provide shading at pedestrian height, roofs and façades offer cooling at skin scale, and grass-grid pavers act upon sealed ground. The value of their combination lies in the correspondence between physical surfaces and heat processes, as opposed to applying the same greening target everywhere in the district.

3.2. Cooling functions of the interventions

Tree shade is clearly the most effective means of immediate relief from direct heat at the pedestrian level. Crowns with large leaf areas are more effective at reducing the incoming radiation flux by lowering pavement temperature, thus improving PET values [11, 23, 24]. The allocation score reflects this by assigning high priority to street trees, school-yard trees, and trees within semi-open courtyards.

In turn, green roofs differ from other interventions. Dense vegetation, enough substrate, and a higher leaf area index make them more efficient at storing heat in roofs and transferring it into the buildings [17, 18]. Pedestrians benefit less than in the case of street trees since the cooling potential is concentrated on roof surfaces at heights above walking level. Hence, in blocks with limited land availability but significant contributions of surfaces to heat storage, green roofs should be prioritized over street trees.

Finally, vertical greening systems are effective when applied on exposed canyon walls. They allow the cooling effect through fully covering surfaces, which reduces radiant loads for walls and limits long-wave exchanges toward pedestrians while minimizing ground coverage [3, 27]. It is especially useful in narrow streets where full canopy closure is aerodynamically disadvantageous. In such cases, the effect of wall radiance can be decreased by applying a façade intervention.

Tree-shrub-grass compositions and permeable ground interventions are best applied in yards and courtyards. While both types cool by means of evapotranspiration, the former offers additional benefits such as shading, whereas the latter minimizes the storage potential of the ground without shading. This is another reason why permeable grounds have been found valuable in enclosed spaces by the allocation algorithm.

Table 2. Cooling pathway roles.

Intervention family	High-performing condition	Primary allocation role
Street trees	Broad or tall crowns with high leaf area index, sufficient maturity, and active transpiration	Pedestrian shade in school yards, sidewalks, and open courtyards, with spacing control in narrow canyons
Green roofs	Intensive systems with dense vegetation, adequate substrate, and high leaf area index	Roof heat-storage reduction and supplementary building-surface cooling
Vertical greening	Continuous wall coverage on highly exposed facades with dense foliage	Reduction of wall radiation in street canyons without occupying the street section
Ground-level vegetation	Tree–shrub–grass composition with compact spatial form and permeable soil	Cooling of courtyards, front yards, and school yards through shade, evapotranspiration, and storage reduction
Grass-grid pavers	Permeable vegetated cells replacing asphalt or sealed private surfaces	Low-obstruction ground replacement in enclosed or semi-enclosed spaces

3.3. Air-temperature and comfort response

The air-temperature reduction during a 72-h period on the district scale is −0.49 K. Although the mean reduction seems insignificant, the most powerful local reduction in air temperature can reach −5.28 K. It means that the concentration ratio is 10.78. In other words, the highest local impact exceeds the district mean value by a factor of about 10. The set of interventions works through a spatially concentrated cooling effect and does not aim at the district-wide air-temperature reduction.

As expected, the PET reduction is higher. The district mean PET reduction for 72 h is equal to −0.91 K. The PET leverage ratio reaches 1.86. During the same time period, the greatest PET reduction is −7.66 K. Such a finding is not surprising because PET takes into account not only air temperature but also mean radiant temperature, wind velocity, and relative humidity. In other words, PET can detect comfort gains hidden by district-wide air-temperature average values [12, 15, 16].

When analyzing the response for the hot hour, the contrast between air-temperature cooling and the enhancement of thermal comfort becomes more significant. For example, the 72-h air-temperature reduction drops from −0.49 K to −0.61 K. The same decrease in the 72-h PET reduction from −0.91 K to −1.91 K causes an increase in the PET leverage ratio up to 3.13 at district scale. The strongest local effect in terms of air-temperature reduction is −6.75 K. The local PET reduction is −26.10 K. Thus, the local PET leverage ratio reaches 3.87.

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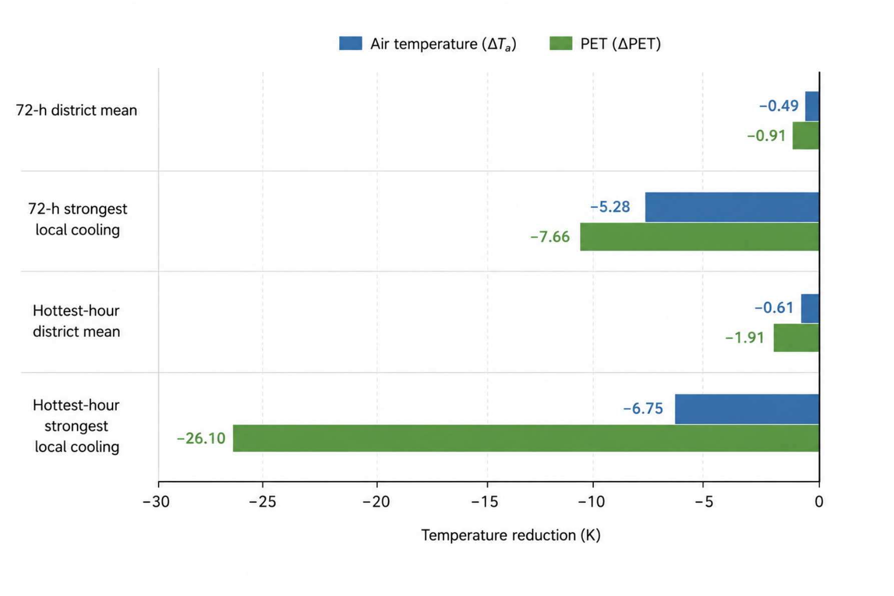

Figure 7. Air-temperature and PET reductions.

The response ladder in Figure 7 makes the central numerical result visible: PET relief is not proportional to air-temperature reduction. The longest bar is the strongest local PET reduction during the hottest hour, showing that the largest pedestrian benefit occurs when radiant exposure is greatest. This does not mean that the entire district experiences a -26.10 K PET change. It means that the best-placed local intervention can transform the comfort level of a specific heat-exposed space during peak stress.

Table 3. Thermal response indicators.

Thermal response	ΔT_a **(K)**	**ΔPET (K)**	L_{PET}	**Interpretation**
72-h district mean	-0.49	-0.91	1.86	Comfort relief exceeds air-temperature cooling
72-h strongest local cooling	-5.28	-7.66	1.45	Cooling is concentrated in exposed spaces
Hottest-hour district mean	-0.61	-1.91	3.13	PET response strengthens under peak heat
Hottest-hour strongest local cooling	-6.75	-26.10	3.87	Radiant-load reduction dominates local comfort relief

Thermal metrics from Table 3 lead to two key observations. The first is that PET is more responsive than air-temperature throughout, particularly during peak heat. The second is that local impacts are much larger than impacts based on the district average. This implies that an intervention should not be rejected simply because the district average air-temperature impact is very low. In compact fabric, the most desirable result may be a high reduction of radiant load locally where people are exposed.

3.4. Localisation and peak hour amplification

Leverage of the cooling intervention on PET is 1.86 if district average is taken for 72-h air temperature and 3.13 if district average is taken for the hottest hour. Local leverages amount to 1.45 for 72-h and 3.87 for the hottest hour, respectively. It appears clear from these values that reducing the radiant load is especially relevant for the period of highest heat stress. Thus, the intervention set will be the most effective at times when heat exposure of pedestrians is most susceptible to changes in shading.

Concentration ratios demonstrate the advantage of localised versus evenly distributed greening. The air temperature concentration ratio equals 10.78, while the PET concentration ratio amounts to 8.42. Values imply that localised reactions are significantly larger compared with the district averages. This is appropriate for a compact district where exposure is not homogeneous across all areas: the goal is not to achieve equal cooling in every cell, but rather apply cooling interventions in such places as school yards, courtyards, and streets, where the presence of heat and pedestrians overlap.

Peak hour multipliers make it possible to give the same interpretation. Air-temperature cooling of district average increases by the factor of 1.24, while PET cooling increases by the factor of 2.10 during the hottest hour. Meanwhile, the strongest reaction of air temperature rises by a factor of 1.28, while the strongest reaction of PET goes up by a factor of 3.41. Hence, the impact on comfort grows even faster than air-temperature cooling.

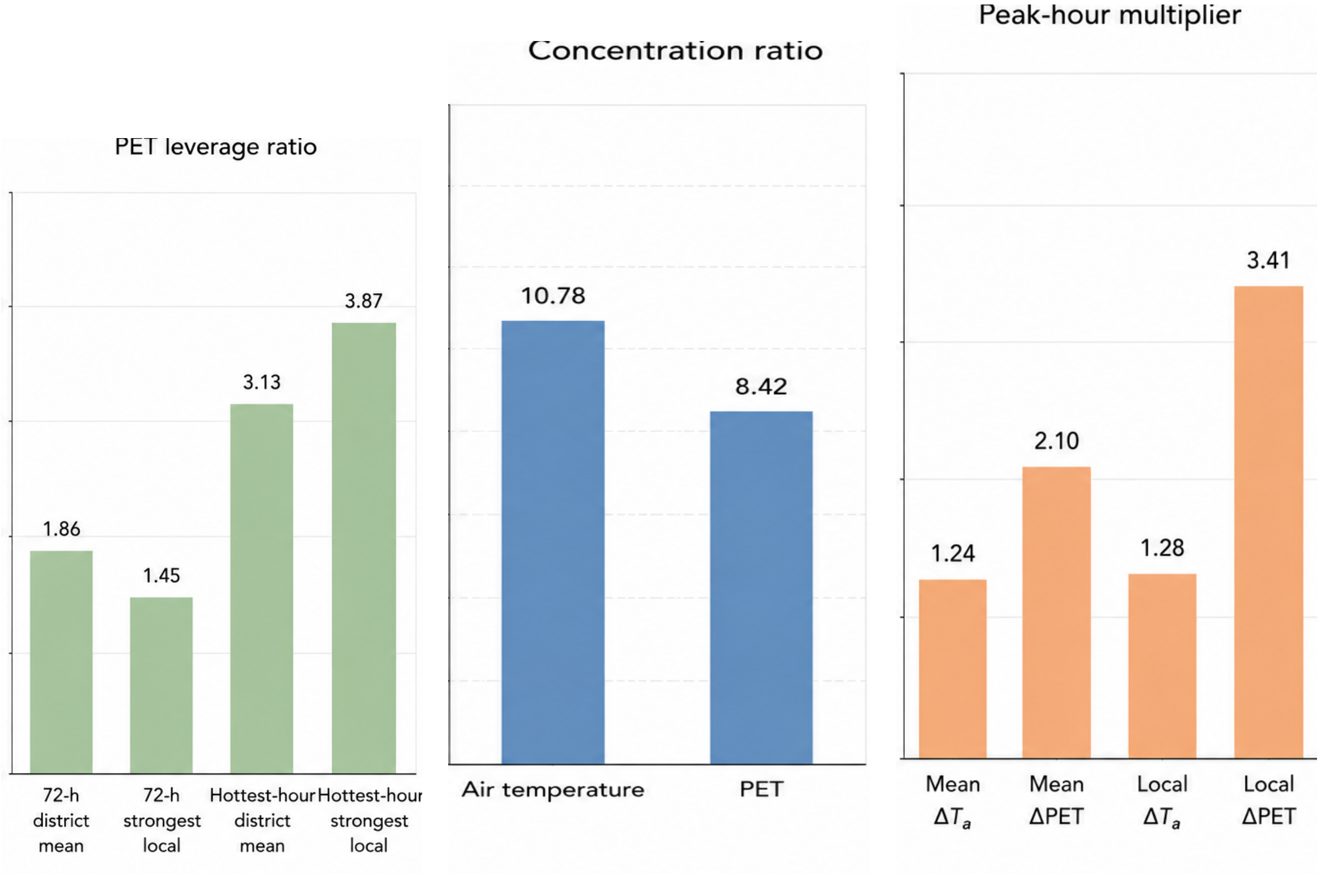

Figure 8. Response indicators.

The three panels in Figure 8 demonstrate how the numerical measures relate to placement strategies. PET leverage proves the significance of radiation-related measures, concentration confirms the relevance of directing measures towards heat-exposed places, and peak-hour amplification proves that the selected intervention portfolio is optimal in the most challenging phase of the event. These three measures together offer a more holistic interpretation than district mean air temperature alone.

4. Discussion

4.1. Comfort-oriented placement logic

The key result of the analysis is that PET relief is the more instructive indicator for mid-rise districts. A mean air-temperature reduction of −0.49 K over the course of three days may seem insignificant if measured exclusively by air temperature. The PET indicator reverses the perception, however, by showing that PET reduction is almost twice larger than the mean air-temperature reduction in terms of magnitude, and more than three times larger compared to the peak-hour air-temperature reduction. The largest local reduction of −26.10 K confirms that well-designed local interventions are capable of achieving significant human-centered cooling even if the air response appears modest.

This result aligns with the well-known physics of outdoor thermal comfort: mean radiant temperature is a key input to PET, and it depends strongly on radiation load, which can be influenced by tree shade, facade surface temperature, and canyon geometry [12, 15, 16]. In a compact city district, this means that the most efficient means of delivering immediate comfort may lie in decreasing mean radiant temperature rather than in cooling the air volume. It does not mean that the air is irrelevant – on the contrary, it answers a different question related to pedestrian experience rather than to air volume.

The findings confirm that the optimal placement rule involves the highest priority for the combination of radiant exposure, pedestrian exposure, and lack of existing cooling measures. Courtyards are critical in this case since people are present and surfaces store heat, streets are critical since they have direct exposure to solar radiation, and roofs are critical since they store large amounts of heat, though they do not substitute direct shade for pedestrians. The selection tool allows distinguishing between them through an intuitive scoring system without the need for any new calculations.

4.2. Ventilation constraints in compact form

The ventilation constraint is essential in this case, as compact districts are prone both to heat exposure and aerodynamic limitations. On the one hand, denser greening may lead to decreased wind velocity in narrow zones, and at the time of the analysis, mean wind speed in the district was roughly 0.29 m/s. On the other hand, this means that adding any further obstructions to the flow would significantly contribute to the problem. The gate thus functions as a constraint that prevents the greening density of the highest level from being selected as the highest priority.

This approach is in line with research showing that the efficiency of greening is highly dependent on urban geometry and vegetation density [20, 22, 29]. Furthermore, it corroborates the empirical data confirming that the integration of street greenery with the local conditions has high value for the comfort of pedestrians in temperate urban climates [14]. As a result, the analysis suggests that the district needs a balanced solution in which multi-layered vegetated zones are combined with permeable ground cover in more open yards, selective canopy and soil replacement are used in semi-enclosed courtyards, and spaced trees and facade greening are used in narrower street canyons.

The gate does not mean that dense vegetation cannot have positive impacts on pedestrian thermal comfort. Rather, it implies that dense greening must leave enough room for air exchange if pedestrian exposure to the wind is high and air exchange is already sufficient. Tree spacing, crown height, and the presence of permeable soil near tree roots are not merely technical aspects, but rather factors influencing the ability of the same trees to benefit pedestrians' comfort or to worsen it through air and humidity retention.

4.3. Surface-specific cooling strategy

It is best to look at the portfolio of interventions as a group of surface-specific measures. Trees cool pedestrians in the uppermost layer and achieve the greatest results where radiant exposure is high. Adding 158 *Acer platanoides* is a considerable improvement to the landscape, but its effectiveness depends on specific locations. The value of adding a single tree in a non-exposed spot is smaller than adding the same tree in a highly exposed place such as a sunlit walking route or school-yard perimeter.

Gardens cool pedestrians indirectly through reducing heat storage in roofs and moderating the exchange of energy between buildings and surroundings. While green roofs have been proven efficient as cooling elements, facade gardens modify wall temperature and long-wave radiation [1, 3, 27]. Since the existing building greenery in the district consists of two green roofs and a fully covering facade, adding 146 new measures represents an important addition to the currently underexploited cooling surface. The value of roof and facade interventions is the largest where other interventions are constrained by street width, ownership, or underground utilities.

Grass-grid paving helps to decrease the amount of sealed ground, which is a source of heat storage and release. Given that many courtyards and school yards in the district consist of sealed ground, the 0.964 ha of replaced surfaces represent an important contribution to cooling. Grass-grid paving is especially valuable because it combines low wind resistance with the opportunity to plant additional trees and shrubs without closing the air flow in semi-enclosed spaces.

The surface translation in Figure 9 shows the dominant surface assignment interpretations. Courtyard and school-yard areas need permeable ground with layering vegetation. Street canyon areas need trees that facilitate

Figure 9. Surface-specific cooling.

ventilation. Rooftops need intensive vegetation due to the heat storage of buildings. This reading differs from an overall greening approach in tying each measure to the surface and airflow condition that optimises performance.

4.4. Planning implications for compact European districts

A key lesson from the Volksgartenviertel case is that it shares characteristics with numerous other compact European districts. Such districts have established parkland and street trees but lack vegetation cover on small private or semi-private surfaces. As a result, the district appears to be green on one hand but heat-exposed on the other. For this reason, the proposed adaptive strategy needs to account for surfaces where pedestrians feel heat despite the existence of green spaces.

The allocation strategy offers a solution sequence to implement an adaptation plan. Cool elements should be preserved and connected, but new cooling capacity should be implemented where heat-exposed surfaces are located. Street trees should shade streets but leave air-exchange gaps in trees' arrangement. Facade greening should be applied to wall surfaces that radiate excessive heat into the canyons. Permeable surfaces should be applied where the enclosed space lacks green surfaces and has sealed surfaces. Roof vegetation should be implemented where building surfaces are available. In this way, the proposed goal of heat mitigation is transformed into site-specific placement strategies.

The implementation of vegetation, trees, and permeable surfaces depends on their operation, including the establishment of plants, rooting, soil condition, water supply, substrate depth, irrigation reliability, and maintenance capacity. A heat adaptation strategy that does not consider these factors risks overestimating the performance of cooling systems. That is why the score calculation should take into account operational conditions prior to constructing new facilities in a district.

4.5. Transferability and limitations

The presented method is suitable for use in planning but not design stages. The method relies on classification variables that are subject to local map accuracy. The ventilation gate indicates the direction of the obstruction problem but does not replace the flow model that is needed for complex street canyons and public health studies.

New district-level applications of this method should recalibrate process weightings and obstruction coefficients based on local climatic conditions, canyon forms, vegetation types, and water availability.

The presented approach is based on the particularity of the heat episode of July 2022. While this is correct in view of measuring the peak cooling potential of vegetation, the method should be modified in view of dry, humid, or windy episodes. A dry episode would elevate the priority of plant irrigation. A humid episode would enhance the priority of air movement through vegetation. A windy episode would reduce the cost of obstructions. These conditions do not diminish the significance of the study. On the contrary, they help specify its scope of validity.

The presented evidence builds a consistent sequence of arguments. Inventory data identify cooling surfaces that remain unutilized. Heat-event panels explain the significance of air movement in cooling the district. Pathway photographs distinguish the functions of trees, rooftops, facades, and permeable surfaces. Score data and built form sections reveal the functioning of the ventilation gate. Intervention stocks identify the amount of cooling measures. Response and indicator figures justify PET as a more informative metric. Surface translations indicate the application of results to courtyards, canyons, and roofs. All these pieces of evidence support site-specific surface allocation.

5. Conclusions

The results obtained for the Volksgartenviertel demonstrate that the ventilation-sensitive placement of measures turns the modest district-wide average air-temperature reductions into significant pedestrian PET improvements during peak heat events. The 72-h mean air-temperature reduction in the district was $-0.49\,\mathrm{K}$, whereas the mean PET reduction was $-0.91\,\mathrm{K}$. During the peak heat event, the ratio between PET and air-temperature reductions increased to 3.13. The largest pedestrian comfort improvement measured $-26.10\,\mathrm{K}$, showing that the selected surface-specific cooling strategy allows substantially reducing the radiative load of spaces despite modest district mean air-temperature changes.

As far as allocation strategy goes, the results reveal that the most effective pattern is not maximum vegetation density in all possible surfaces. It is the surface-dependent pattern that allocates vegetation to specific surfaces based on cooling pathways. Street trees should create shade along the streets. Facade vegetation should reduce radiation from canyons' walls. Permeable surfaces should reduce heat storage in enclosed spaces. Layered vegetation should be used when air movement is sufficient. In the July 2022 episode, the ventilation gate plays a critical role because it is characterized by high temperatures and low mean wind speed.

For compact mid-rise districts, the key message is that nature-based cooling measures need to be assigned based on surface, exposure, and airflow conditions. Vegetation should not be considered a homogeneous category. This research reveals that the highest heat-reducing effectiveness is achieved if each vegetation type is used based on the cooling pathway it represents. For future applications, it is necessary to retain this idea and adapt the obstruction coefficient and the assessment of operational conditions to local circumstances.

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