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Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes

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Abstract: The European goals to reduce CO_2 emissions by up to 40% by 2030 and reach carbon neutrality by 2050 cannot ignore the building sector, that accounts for 27% of global greenhouse gas emissions. In the context of the sustainable development goals, it is a key point to consider the reduction of the heat island effect in the urban environment. Considering this background and the proven absence of the clear promotion of urban mitigation measures, the research aims at investigating the influence on several micro-climate parameters of different retrofitting strategies at the building level (green façades) and the cooling strategies at the urban scale (e.g., cool pavements, trees). As a case study, the application of these measures in an industrial district located in Italy is evaluated. ENVI-met software was adopted to perform the outdoor environmental simulations, in order to assess the effectiveness of the mitigation strategies proposed, considering both the whole district and a portion, focusing on urban canyons. Cool pavements proved to be the most promising strategy to both reduce the air temperature and increase the relative humidity. Slighter effects on environmental conditions can be achieved by planting trees and installing green walls that, by contrast, significantly affect the mean radiant temperature and buildings' surface temperatures, respectively.

Keywords: urban microclimate; urban heat island effects; mitigation strategies; green walls; ENVI-met; environmental codes

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1. Background

1.1. Green Infrastructure and European Codes

Green infrastructures are defined by the European Commission as: "a network of (semi) natural areas which are protected and enhanced to deliver ecosystem services, while also benefiting the biodiversity and society more widely" [1]. They can be active elements for the achievement of the European goals of a carbon-neutral economy by 2050 [2], to avoid the increase in the external air temperature connected with climate change, in the mitigation of the heat islands effect in urban areas characterized by a high construction density and in the reduction of greenhouse gas (GHG) emissions and pollutants concentration [3]. Furthermore, the adoption of green strategies certainly enables to obtain benefits that are not only environmental but also economic and social [4].

At the European standard level, there is a lack of common and unitary energy and environmental codes or guidelines that consider and outline the requirements or principles to properly design a GI for high density urban areas or buildings and to quantify the consequent advantages. Starting from the Kyoto Protocol [5], many initiatives to tackle the climate change and to reduce GHG emissions in the atmosphere can be retraced but for longtime GIs were considered only aesthetical interventions. Nowadays, a new attention on this topic is developing and several points, implying the use of GIs, can be found among the Sustainable Developments Goals (SDGs): (i) Goal 11 refers to the mitigation and adaptation to climate change, (ii) Goal 13 highlights that the measures to tackle the climate change must be included in national policies, planning and management, (iii) Goal

15 promotes a sustainable management of forests, enhancing reforestation interventions and avoiding further deterioration of natural environments [6]. Moreover, in the context of the European Green Deal [7], a biodiversity strategy is included as an action plan to protect nature through concrete and direct interventions by 2030. In contrast, no specific reference, in terms of code prescriptions or standard requirements for public or private investors to assess the possible integration of GIs in an urban context, can be found. At the same time, an effective communicative campaign, led by public institutions themselves to make the population aware of the undoubted advantages ensured by green infrastructures for the different sectors (economic, energy, social and environmental) is missing.

As it regards the building level, the last European Directive UE 2018/843 [8], concerned with energy efficiency in buildings, does not specifically deal with green infrastructures and their adoption at the facility scale. Furthermore, the European cost-optimal methodology [9] proposed as a guideline method to outline the most cost-effective measures to redevelop existing buildings, mainly focuses on economic aspects. As a result, retrofitting measures integrating green strategies at the building level (i.e., green roofs or green walls) or interventions to achieve a standard NZEB, are penalized by their high initial investment costs, as the environmental benefits are not adequately evaluated [10].

As far as energy and environmental certifications are concerned, they assign points, mainly referring to the minimization of the heat island effects, concerning both urban and building levels. The LEED (Leadership in Energy and Environmental Design) [11] protocol assigns two points for the reduction of the heat islands effect (Credit SS), by applying different mitigation strategies for external ground paving and roofs, with a minimum percentage requirement. For instance, the use of vegetation or the utilization of structures to shade outdoor paving areas for the former; the installation of a green roof technological solution (50% of the total surface) or a floor finish with a specific solar reflectance index for the latter. The ITACA (Italian agency for the innovations and procurement transparency and environmental compatibility) Protocol [12] refers to the reduction of the heat islands effect (Credit C.6.8), concerning the percentage of green areas and a finish characterized by a specific value of the SRI (tabulated, based on materials) with respect to the whole surface of the construction site, with a maximum of five points. This protocol aims to ensure thermal comfort in outdoor environments during the summer season. Finally, BREEAM (Building Research establishment for Environmental Assessment Method) [13] deals with greenery, mainly in the category of land use and ecology (with a maximum of 10 points). It is intended to enhance the site ecology and to maintain the ecological value of the construction site and its ecological features.

This European regulation gap should be solved at both the member state and local levels, because the adoption of such green strategies is obviously related to construction site specific characteristics. In this regard, a series of local initiatives promoted by different cities in Europe can be retrieved. Starting from major towns of Germany, nowadays several European states are promoting the use of green infrastructure in the urban environment (Table 1) and outlining the indications and requirements to be met, as a measure capable of improving the quality of human life and both outdoor and indoor wellbeing [14].

Table 1. Local initiatives promoted by different European states.

State	City	Year	Description
Germany	Berlin	1994	Biotope Area Factor (BAF) concept was included in the municipal regulations to express the use of green infrastructure (public green area at ground level, green roofs, and green façades) for urban areas, characterized by a higher density and significant GHG emissions [15].
Sweden	Stockholm	2010	Green Space Factor (GSF) was introduced to calculate the green space requirements for new urban development areas [16,17].
Sweden	Malmö	2010	Green Space Factor (GSF) and Green Points System, setting a checklist of different infrastructure alternatives for developers to provide a minimum level of green/blue spaces [16,17].
United Kingdom	North-West England	2008 and 2010	"Northwest Green Infrastructure Guide", The Green Infrastructure Score was introduced as a voluntary adoption of a scoring system to evaluate the benefits of greenery solutions, concerning their impacts on different aspects [18].
Austria	Wien	-	"Fassadenbegrünung", a guideline to include green facades in the urban environment for both private and public buildings, highlighting the related ecological functions and design options [19].

1.2. Green Infrastructure and Italian Codes

In Italy, only Law n. 10, 14 January 2013 "Norme per lo sviluppo degli spazi urbani" [20] regulates the development of the urban environment to meet the Kyoto Protocols, especially highlighting the role of trees. Moreover, it promotes the introduction of green roofs and façades in urban areas that require the introduction of rules at the municipal level standards. However, looking at the regulations currently adopted by major Italian cities, the requirements can be found but are mainly related to the introduction of trees, based on the built volume and number of public parking areas and the minimum percentage of permeable areas, compared to the total surface of the construction site.

Focusing on the technical standards in Italy only, the UNI (Italian national Unification Board) 11235: 2015 "Istruzioni per la progettazione, l'esecuzione, il controllo e la manutenzione di coperture Verdi" [21] can be found, but it deals exclusively with green roofs, without providing any indication for sizing, plant species choice and benefits estimation.

Sometimes, this kind of green infrastructure (green roofs and green walls) are not attractive for private and public owners, due to the higher initial investment cost or to the demanding maintenance during its service life. In this context the promotion of the adoption of these GIs occurs only in an economical way, through incentives, as confirmed by Liberalesso et al. [22]. Nowadays in Italy, the Green Bonus [23] is currently available and it provides a decrease of 36% of the initial investment cost for two kinds of interventions: green landscaping of external areas facing existing buildings and the construction of green roofs.

Despite the lack of Italian national policy to promote the introduction of green facades in buildings, with respect to incentive policy, it is worth highlighting that some municipal standards are available about this topic. However, none of them indicates the sizing criteria for the green technology and benefits evaluation. The main ones are listed in Table 2.

Table 2. Italian cities that introduce into municipal regulations, the use of green walls. In the table: R.E. stands for municipal building codes, Art. stands for article, R.C. means the municipal regulation for the urban environment for public and private greenery for Rome, and R.V. stands for the municipal regulation for public and private greenery for Turin.

Region	Province	Year	Regulation Article	Assessment Topic Considered
Basilicata	Potenza	2009	Art. 86 subsection 1 e 4; Art.72 comma 2 e 3; Art.73_R.E. [24]	L *
Emilia-Romagna	Bologna	2021	Art. 61 subsection 2_R.E. [25]	A/D/E/G *
Friuli-Venezia Giulia	Pordenone	2020	Art. 65 subsection 3_R.E. [26]	B/C/D/F/H/L/M/N *
Lazio	Roma	2018	Art. 23 subsection 1 R.C. n.37726 [27]	N *
Liguria	Genova	2020	Art. 56 subsection 1_R.E. [28]	A/B/C/E/F *
Lombardia	Brescia	2022	Art. 31 subsection 37_R.E. [29]	B/C/E/H/M *
	Cremona	2012	Art. 137_R.E. [30]	A/L *
	Milano	2022	Action 4.2.2 Air Climate Plan [31]	A/F/L *
Piemonte	Torino	2020	Art.21 subsection 11_R.V. [32]	N *
Puglia	Bari	2022	Art.29.2.16.3_R.E. [33]	B/D/E/F/H/I *
Toscana	Siena	2016	Art.5 subsection 4 Appendix H_R.E. [34]	B/E *

* A: Buildings' environmental quality, B: indoor thermal-hygrometric conditions, C: heat island effect mitigation, D: pollutant reduction, E: building insulation, F: improved air quality, G: energy saving, H: acoustic insulation, I: aesthetic quality, L: improved climatic conditions, M: rainwater control, N: improved urban greenery.

1.3. Benefits of Vertical Greenery

By contrast, the topic of vertical greenery has become much debated and is addressed in the scientific literature over the last few years. Many authors classified the different type of vertical greenery because it is not currently available in legislation. Their classification is based on the vegetative species (extensive or intensive), soil (hydroponic or substrates) and substructure (rigid or tensioned) [35,36]. The most studied topic in the literature is related to the reduction of the heat island effect, to avoid the increase in the external air temperature. Koch et al. [37] pointed out how vertical greenery can be applied to mitigate the air temperature at building and street levels and highlighted which parameters are necessary to be considered (WLAI—wall leaf area index, the presence and kind of substrate, the season and orientation). Shafiee et al. [38] estimated the effect of a green living wall on both the internal and external air temperature, registering a decrease of about 8 °C during the warmest hours. At the same time, some authors pointed out that vertical greenery produces advantages, in terms of the external surface temperature reduction. Kenai et al. [39] evaluated the thermal performance of vertical greenery on thermal isolated and non-isolated buildings. They demonstrated that with the inclusion of a green wall, it is possible to reduce the thermal insulation thickness. Furthermore, many authors studied the influence of vertical greenery on microclimate characteristics, using helpful tools and software, such as ENVI-met [40]. For instance, Peng et al. [41] used ENVI-met, combined with Energy plus, to analyze the influence of vertical greenery on the energy needs for the summer period, concerning different urban layouts. Viecco et al. [42] studied how green walls and green roofs affect the level of particulates ($PM_{2.5}$) in high density urban areas in Chile. They concluded that the particulate reduction depends on many factors, such as the buildings' height, vegetation type, urban infrastructures and the proximity of the pollutants source with respect to the vertical greenery.

In this context, the aim of the research is to investigate how the introduction of green retrofitting strategies at the building level (green façades) and cooling strategies at the urban scale (e.g., cool pavements, trees planting), influences several micro-climate parameters. The proposed green infrastructure applications are evaluated, with reference to an industrial district located in Tuscany (Italy), as detailed in Section 2.1. The goal is at first to evaluate the heat island mitigation achievable at the urban scale, concerning the introduction of green and cooling strategies. Moving on, the research highlights how the installation of green walls on buildings can affect their external surface temperature and, as a consequence, reduce the cooling demand during the summer months. This detailed analysis is performed to promote a possible and valuable integration into the national regulations, these kinds of green infrastructures, that are not yet properly regulated. Moreover, in the literature, no studies dealing with the adoption of similar mitigation measures can be retrieved, that refer to industrial areas and manufacturing facilities. Considering the peculiarities of this kind of urban environment (both addressing the district scale and building level), the evidence collected in the case study analyzed, can be easily extended to other districts with a similar intended use and building stock. The paper develops in four different sections: (i) the background (current section) highlights the regulations about the green infrastructure and some detailed notes concerning vertical greenery, (ii) the method adopted for the research, including the case study area description and the ENVI-met set up for the simulations, (iii) the results and discussion of the main findings and (iv) the conclusions, outlining some future developments.

2. Method

An Italian industrial district located in Tuscany was chosen for the case study, to assess the impact of the implementation of several green redeveloping strategies. The industrial district was modelled in the ENVI-met environment, considering at first the entire surface area and then focusing on a limited portion of it, in order to better evaluate the influence of the different green retrofitting measures. Their effects are evaluated at both the urban and building levels. The former concerns the introduction of trees into the urban environment where possible, and cool pavements in the main streets. The latter considers the use of green façades; these were applied at first on southern fronts and in the main broader urban canyons, and then added also in the internal canyons, corresponding to manufacture loading and unloading areas. Outdoor air temperature (°C), relative humidity (%), mean radiant temperature (°C) and buildings' external surface temperature (°C) are the parameters considered to evaluate the benefits of the green redevelopment, with respect to the current configuration of the industrial district. At the end, some considerations and notes are included and green retrofitting strategies in energy and environmental codes are proposed.

2.1. Case Study Area

The area selected for the case study is an industrial district located in the municipality of Barberino del Mugello (133.7 km^2, 10937 inhabitants) [43], in the province of Florence. This precise district was chosen, following an exhaustive analysis of the industrial building stock carried out in two different areas of Tuscany [44,45], as it proved to be adequately representative of a considerable amount of similar districts, both in terms of building typologies and in terms of urban layout. The urban industrial district is located at the border of the village, housing 68 buildings for production activities of different manufacturing sectors, over an area of 318,842 m^2. The most distinctive features of the area analyzed are presented in Table 3. For the paved surfaces, all covered in asphalt, an albedo and emissivity equal to 0.20 and 0.90, respectively, were assumed.

Table 3. Main characteristics of the district considered: in the table, S stands for surface (for trees it is measured as the number of trees per square meter [n/m^2]) and R stands for ratio (it is calculated with respect the total surface of the industrial district considered).

	Green Paved Areas	Paved Areas	Building Footprint	Trees	Public Roads
S (m^2)—(n/m^2)	31,854	148,747	90,325	71 *	47,916
R (-)	0.01	0.466	0.283	-	0.150

* Excluding spontaneous vegetation, such as trees and shrubs grown on the riverbanks.

As is clearly stated in Figure 1, the site considered was first built in the late 1980s but the site was expanded in the 1990s and continued until the early 2000s. For this reason, two different models were considered, during the simulation phase: one considering the whole district (M1) and one focusing on a portion of the most recent sector (M2), on the left side of the small river flowing in the area. The latter is characterized by broader public roads and buildings with uniform shapes and heights, because of the standardization of construction technologies achieved over the years and nowadays applied to buildings this kind of facility. A clearer insight into the urban layout distribution and building dimensions is provided in Figure 2, where a plan view of the M2 district is shown along with the vertical sections corresponding to the urban canyons that will be discussed later.

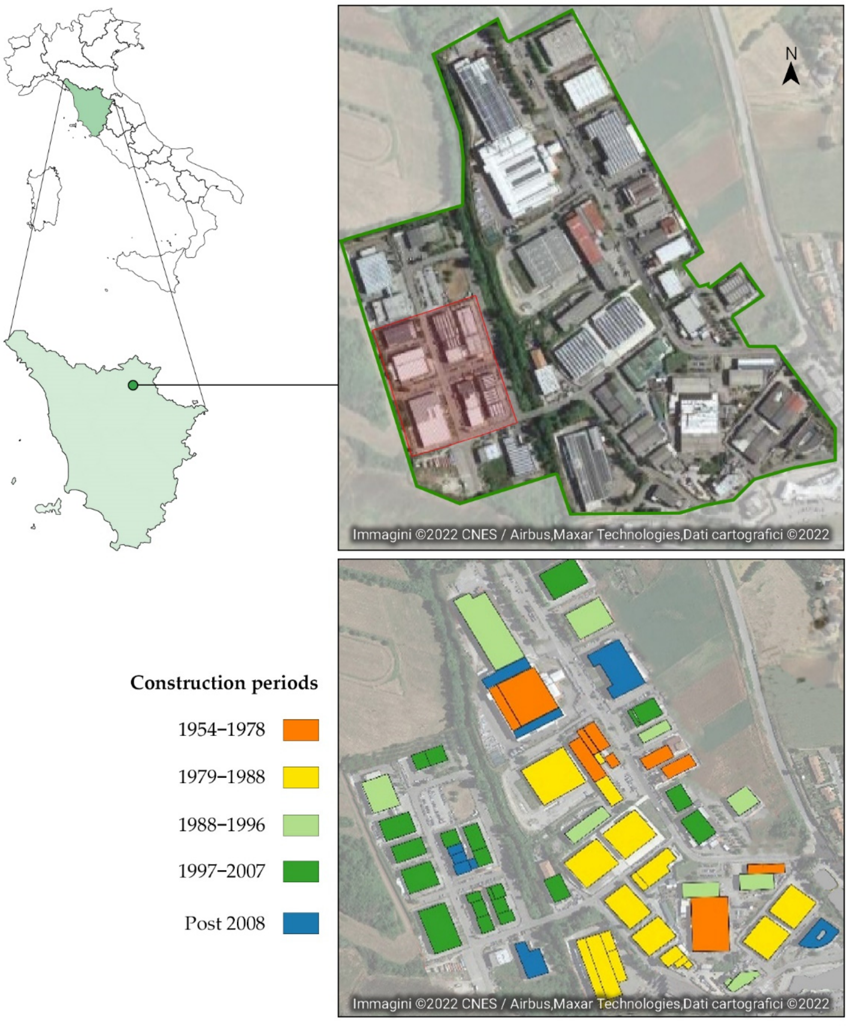

Figure 1. Aerial view of the case study area and its location in the regional and national territory. Within the area, M1 is highlighted with green borders while its internal subset M2, is colored in red. A classification of the buildings according to their construction periods is also provided.

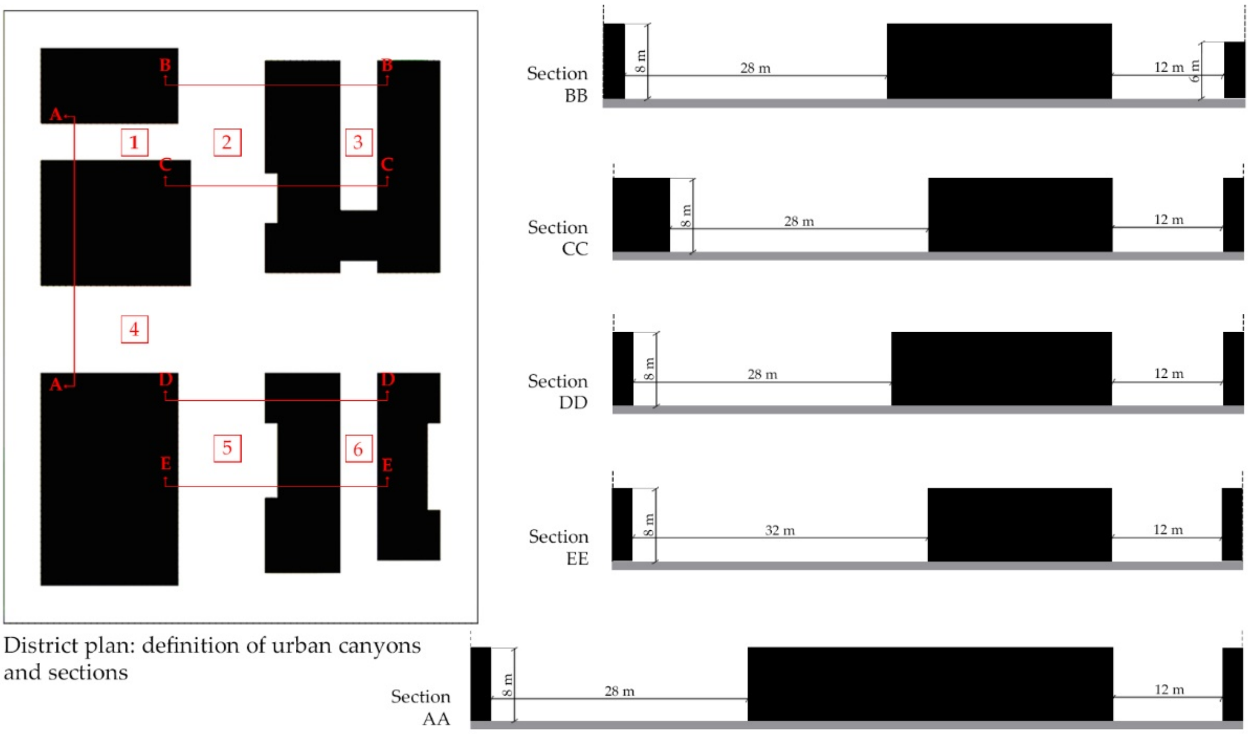

Figure 2. M2 district: plan view and the individuation of the different urban canyons and the corresponding vertical sections.

With regards to the building materials, the preliminary considerations were performed, based on the evidence collected after an extensive analysis of the industrial building stock of the district and comparing it with the results of similar research carried out in different geographical areas. In order to simplify the modelling phase, the external walls chosen for every building were precast concrete panels as they proved to be the most recurrent technological solution. Two distinct configurations, that is to say the fiber-cement tiles and the waterproofing membrane, were identified as the most adopted for the roof finishing layers and were correctly applied to each building in the model. In Tables 4–6, a more exhaustive description of the stratigraphy used is presented for both wall and roof components.

Table 4. Stratigraphy settings for the precast concrete panels used in the buildings' external walls.

Material	Thickness (m)	Conductivity (W/Mk)	Specific Heat (J/kgK)	Absorption (%)	Reflection (%)
Precast concrete	0.04	0.85	840	70	30
Expanded Sintered Polystyrene EPS	0.08	0.035	1000	30	-
Precast concrete	0.04	0.85	840	70	30

Table 5. Stratigraphy settings for the building roofs, using fiber-cement tiles.

Material	Thickness (m)	Conductivity (W/mK)	Specific Heat (J/kgK)	Absorption (%)	Emissivity
Fiber Cement	0.02	0.60	1000	60	0.90
Air	0.70	0.025	1006	-	0.96
Rock Wool	0.06	0.034	1000	42	0.90
Fiber Cement	0.02	0.60	1000	60	0.90

Table 6. Stratigraphy settings for the building roofs, using a waterproofing membrane.

Material	Thickness (m)	Conductivity (W/mK)	Specific Heat (J/kgK)	Absorption (%)	Emissivity
Elastomeric Bituminous Sheath	0.004	0.17	1000	60	0.90
Expanded Polyethylene	0.05	0.035	1000	30	0.90
Concrete	0.08	0.85	840	70	0.90

2.2. Mitigation Strategies

Three different interventions were tested, as reported in Figure 3, referring to the M1 district: the adoption of cool pavement materials, the planting of a series of medium-sized deciduous tree tiles and the installation of green walls over the external surfaces of the buildings.

Figure 3. Different configurations of the green strategies applied in the entire industrial district (M1). In the figure (**a**) is the base case, (**b**) is the configuration with cool pavement, (**c**) is the configuration with trees, (**d**) is the mitigation strategy with green walls. In the case of (**d**), the red lines represent the green façades.

The substitution of the current asphalt with the cool pavement materials, whose properties are compared in Table 7, was applied only on the public roads, as well as the tree-planting. The arboreal species chosen for this application was Tilia cordata "Rancho", a medium-sized deciduous tree, suitable for this kind of intervention in urban environments. Tables 8 and 9 provide a more detailed insight into the tree specifics and green wall solutions, respectively. With regards to the latter, an indirect green façade was considered. This technological solution implies the use of climbing plants rooted on the ground and growing over a series of metal grids or cables fixed onto the external walls of buildings. With this way, it is possible to avoid the presence of heavier substratum layers that are not compatible with the structural characteristics of the building itself. Contrary to living walls solutions, this kind of green façade does not require automatic irrigation systems and can be also created using vegetation species that are particularly suitable, in the case of potentially highly polluted environments, as certified by specific studies on this topic [46,47]. At first, green walls were considered to be implemented on the south oriented façades of the buildings and on the walls facing the main urban canyons, represented by the public roads of the district. In a second phase, their effectiveness was analyzed more in detail, assuming their adoption also in the narrower urban canyons, but only for the M2 model, as clarified in Figure 3. In both cases, the vertical greenery was assumed to cover about 75% of the buildings' façade, in order to maintain adequate empty sections for the windowed portions.

Table 7. Settings for the road pavement in the case of the cool pavement adoption (CP).

Intervention	Pavement	Albedo	Emissivity	Extension
CP_M1 CP_M2	Concrete pavement light	0.80	0.90	All public roads

Table 8. Settings for the green walls retrofit (GW).

Intervention	Greening	Thickness [m]	Leaf Area Index [m^2/m^2]	Leaf Angle Distribution	Facades Involved
GW.1_M1 GW.1_M2	Elix Hedera	0.30	1.5	0.5	South oriented and prospecting wider urban canyons
GW.2_M2	Elix Hedera	0.30	1.5	0.5	South oriented and prospecting all urban canyons

Table 9. Settings for the tree species in the case of the tree planting intervention (TP).

Intervention	Tree	Width (m)	Height (m)	Leaf Area Density (m^2/m^3)	Number of Trees
TP_M1	Tilia cordata "Rancho"	4.05 × 5.78	8.63	1.5	345
TP_M2	Tilia cordata "Rancho"	4.05 × 5.78	8.63	1.5	68

Since the case study area is classified as climatic zone E [41], the climatic data from the Bologna Borgo Panigale meteorological station were adopted in all of the simulations, and were carried out with reference to 21 June, between 11 a.m. and 1 p.m. In Table 10, the climatic characteristics for the meteorological station chosen, are synthetized; with reference to the wind characteristics, the annual average value was reported while for the direction of the prevailing winds and the real wind velocity in the period considered for the analysis, these are autonomously assumed by the simulation engine reading the epw climate file.

Table 10. Climate data for Borgo Panigale. In the table: HDD means heating degree day, GH stands for global horizontal radiation, Dh means diffuse radiation, Bn means direct normal radiation, Ta stands for air temperature, Td stands for dewpoint temperature and FF means wind speed. The climate data are the annual means.

Latitude	Longitude	Climate Zone	Heating Period	HDD (K/d)	Gh (kWh/m^2a)	Dh (kWh/m^2a)	Bn (kWh/m^2a)	Ta (°C)	Td (°C)	FF (m/s)
44.31° N	11.16° E	E	15/10–15/04	2259	1309	652	1204	14.2	7.9	2.6

2.3. ENVI-met Set Up

The case study area was modelled in the ENVI-MET Spaces module. The geometry of the district was modelled by importing aerial views taken by Google Maps sources [48] in bmp format. Following the edges of roads and the facilities, it was possible to recreate the plan configuration of the whole area, to add green spaces and insert trees. The external total heights of the buildings were retrieved, thanks to the indications provided by cad files, downloaded from the regional database of the topography system [49]. Moreover, an on-field survey was performed to assess the accuracy of the information collected and to verify the vegetation species currently in place. At first, the model of the entire district considered

(M1) was created and later on, the M2 portion. In Table 2, the general geometrical settings of the two models are listed. The Dz grid size was set for both models, equal to 1 m with an increment of 30%, starting from the 2 m height. During the simulation procedures, ENVI-met calculated the punctual values in the centroid of each volume (Dx × Dy × Dz) of the mesh and this setting for the Dz step allowed to avoid the detailed calculations at heights where no person would be present. It is worth noting that, to get more accurate results, in the M2 model, the mesh was refined by halving the size of both the x and y axis steps, as reported in Table 11. Performing a deeper analysis only on a reduced portion of the general model, allowed to avoid extremely time-consuming simulation procedures. Moreover, in this way, it was possible to assess the effects of the geometrical boundary conditions on the stability of the simulation and its results. The climate conditions were set in the simulation engine by importing the data from the epw file relative to the Borgo Panigale station. The simulations were carried out for 21 June 2020, and at a time interval ranging from 11 am to 1 pm, while the results were read with reference to noon at 1.5 m height. It is stressed that the values obtained are not interpolated, but are just punctual outcomes because of the data format in the climate file.

Table 11. Model geometry settings in the ENVI-MET Spaces module.

Model	X Size (m)	Y Size (m)	Z Size (m)	Dx (m)	Dy (m)	Dz (m)	Telescoping Factor	Nesting Grids
M1 Whole district	604	748	43.62	4	4	1	30% after 2 m height	3 in each direction
M1 District portion	152	196	43.62	2	2	1	30% after 2 m height	3 in each direction

Once the current conditions were modelled, different models to investigate the efficiency of the different mitigation measures proposed, were realized. For the green wall interventions, in each cell of the façades, the greenery was set in accordance with the specifications in Table 8. For model M2, both GW.1 and GW.2 configurations were considered while in model M1, only the former was evaluated. In the case of TP measure, the number of trees and their properties are listed in Table 9. As an example of the final aspect of the retrofit models, in Figure 4 the different configurations tested for M2 are collected.

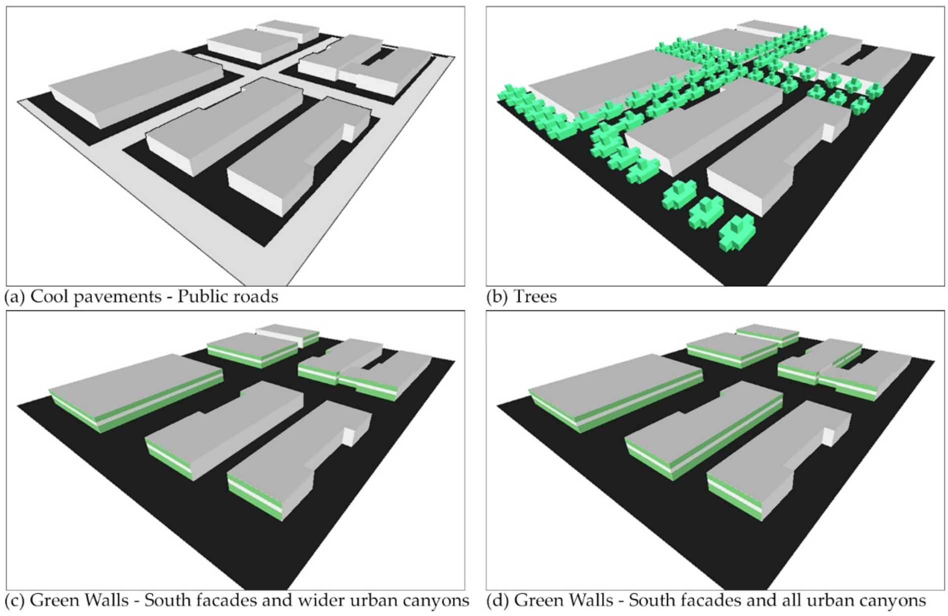

Figure 4. Different configurations of the green strategies applied to the portion of the industrial district (M2). In the Figure (**a**) is the configuration with cool pavements, (**b**) is the one with trees, (**c**) is the configuration with green walls on southern facades and wider urban canyons, (**d**) is the configuration with green walls for southern facades and all urban canyons.

3. Results

3.1. District M1

In order to better analyze the results, the data obtained after the simulations were performed in the M1 model have been refined to exclude all of the points not properly included in the industrial district. These points are not directly affected by the interventions proposed in the research and moreover could be subjected to border effects. Keeping in mind these necessary premises, the graphs in Figure 5 allow to compare the effects of the different interventions evaluated on the hygrothermal conditions at a district scale. Looking at the air temperature values (graph a), all of the measures lead to a mitigation of the most critical conditions by reducing the peak temperature and shifting the distribution of the points toward the lower values. This effect is particularly evident in case of solution CP that ensures the most significant reduction of the air temperature values: looking at the average value, starting from 28.87 °C registered, the base case it is reduced to 28.42 °C. The TP (tree planting) and GW.1 (green walls) are by far less effective, and their global results can be almost comparable, leading to a mean air temperature of 28.85 °C and 28.84 °C, respectively. Similar results are obtained for the relative humidity. In this case all the interventions evaluated tend to tackle the lowest values with a general increase of the mean relative humidity in the area equal to 1.72%, 0.06% and 0.25% for CP, TP and GW.1, respectively.

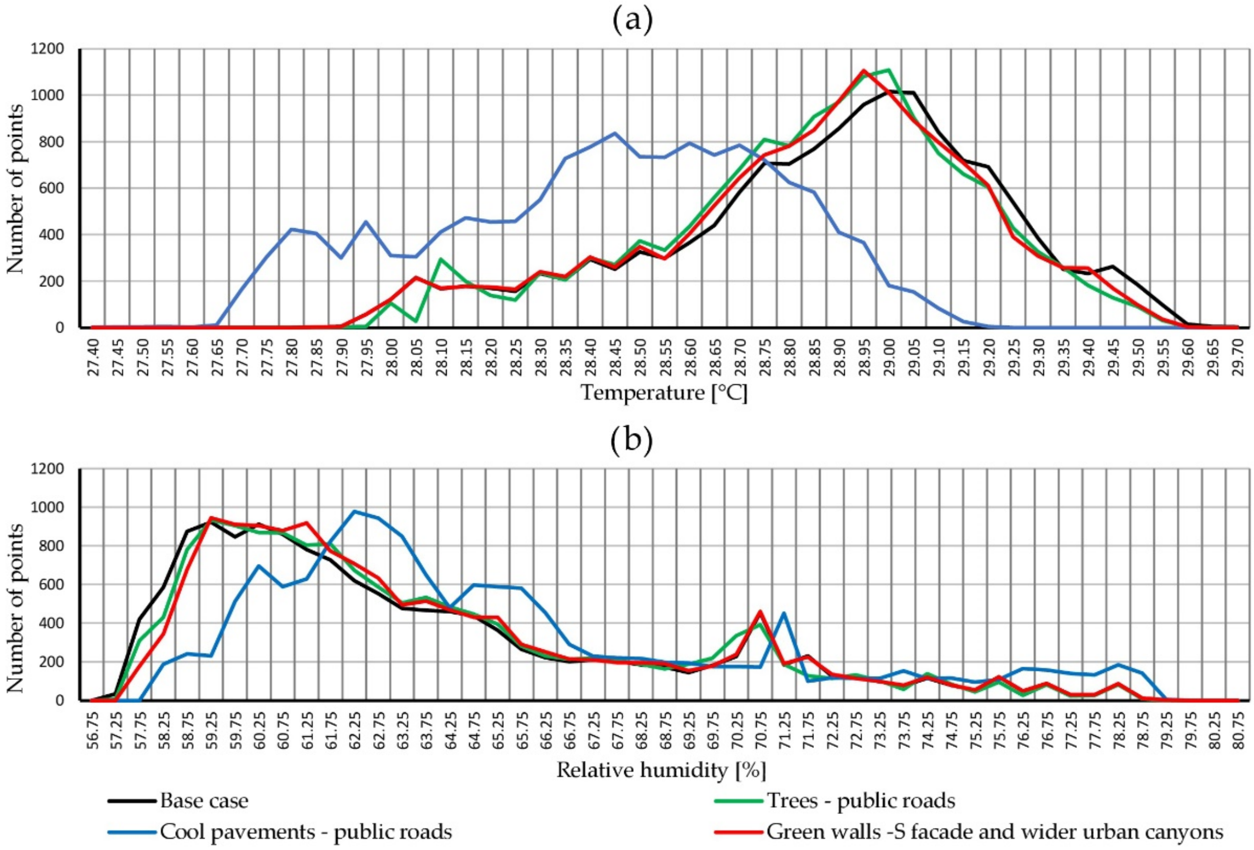

Figure 5. Distribution of the points in the M1 model related to the external air temperature (**a**) (°C) and the relative humidity (**b**) (%) considering the base case, two configurations for the urban retrofitting with trees, cool pavements and green walls.

Further considerations can be obtained by comparing the results obtained, in terms of the air and mean radiant temperature, as suggested in Figure 6. The CP proves to be the most effective solution, in terms of the outdoor air temperature reduction, leading to a generalized mitigation of the external condition in larger portions of the district. By contrast, the TP and GW.1 result in a less appreciable effect also because of their much more limited extension, in terms of the covered surface. However, considering the variation of the mean radiant temperature, the cool pavements lead to a sensible increase of this parameter because of the higher reflectivity of the surface. The opposite effect is produced by GW.1 and TP. The first to produce reductions of up to 2 °C are much more appreciable in the areas close to the external walls where greenery is introduced, the latter allow to achieve a significant decrease of the mean radiant temperature (about 9 °C) in all of the portions shadowed by the trees themselves and thus can be regarded as the most effective measure for this purpose.

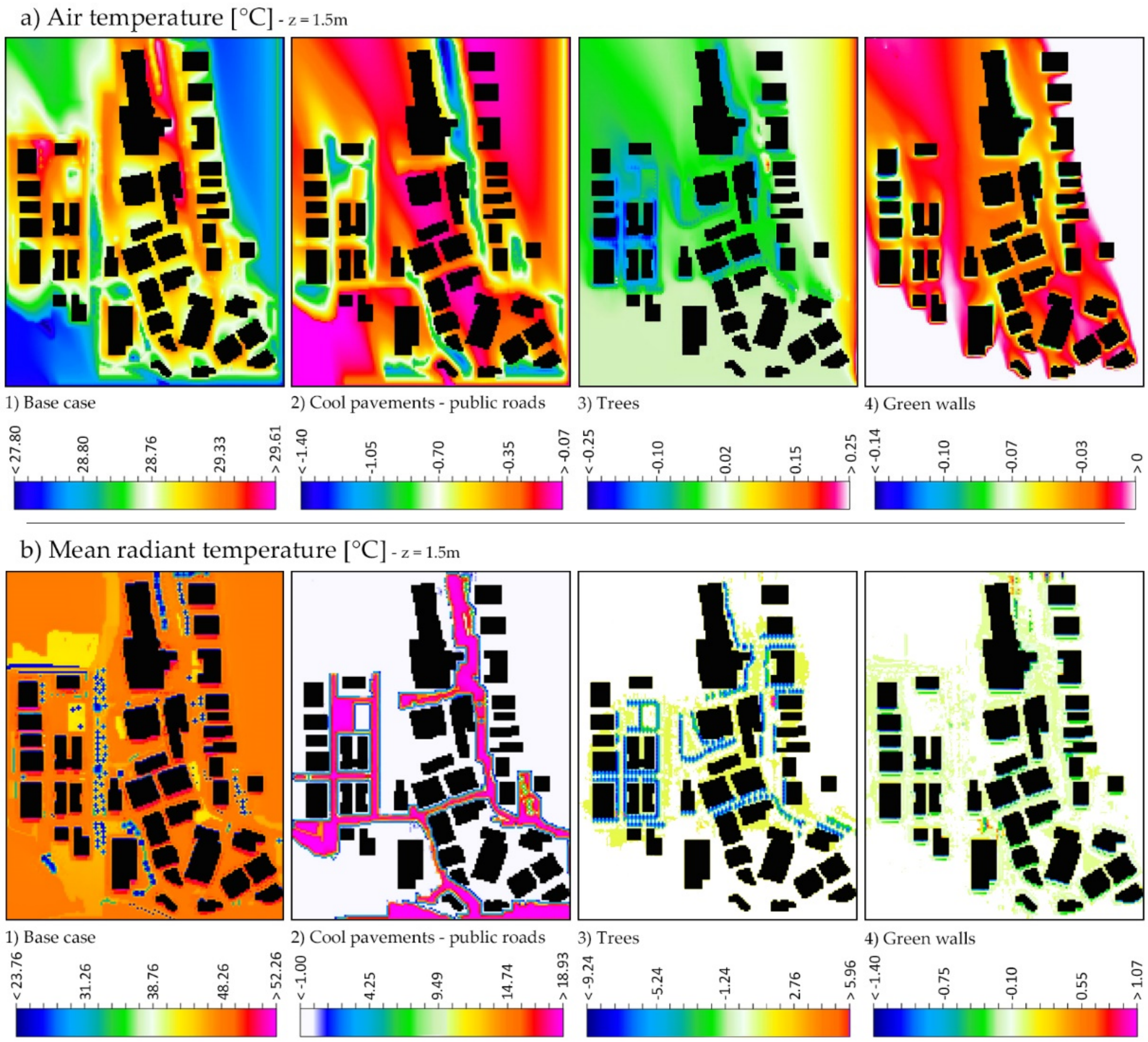

Figure 6. Variation in the air temperature between the base case (**a.1**) and the configurations adopting the cool pavements, tree planting and green wall installations (**a.2**, **a.3**, **a.4**, respectively). In section b, a comparison between the values of the mean radiant temperature in the base case (**b.1**) and the ones achieved by implementing the different interventions proposed.

3.2. District M2

Following the discussion of the results related to the whole industrial district, it is worth noting the trend of the outdoor air temperature and relative humidity in the M2 portion. As highlighted in Figure 7, the CP is the most effective retrofitting measure. The highest temperature measured in the district (29.40 °C) decreases and consequently an increase in the number of points included in the lower temperature ranges occurs. As graph a in Figure 7 proves, there are no more points characterized by the outdoor air temperature > 29 °C. If the average temperature reduction is considered, a decrease of about 0.5 °C is registered. With regards to the TP, the average external air temperature reduction is about 0.1 °C. Furthermore, in this configuration, a shift to the left side of the graph and a reduction of the number of points characterized by the higher temperature is achieved.

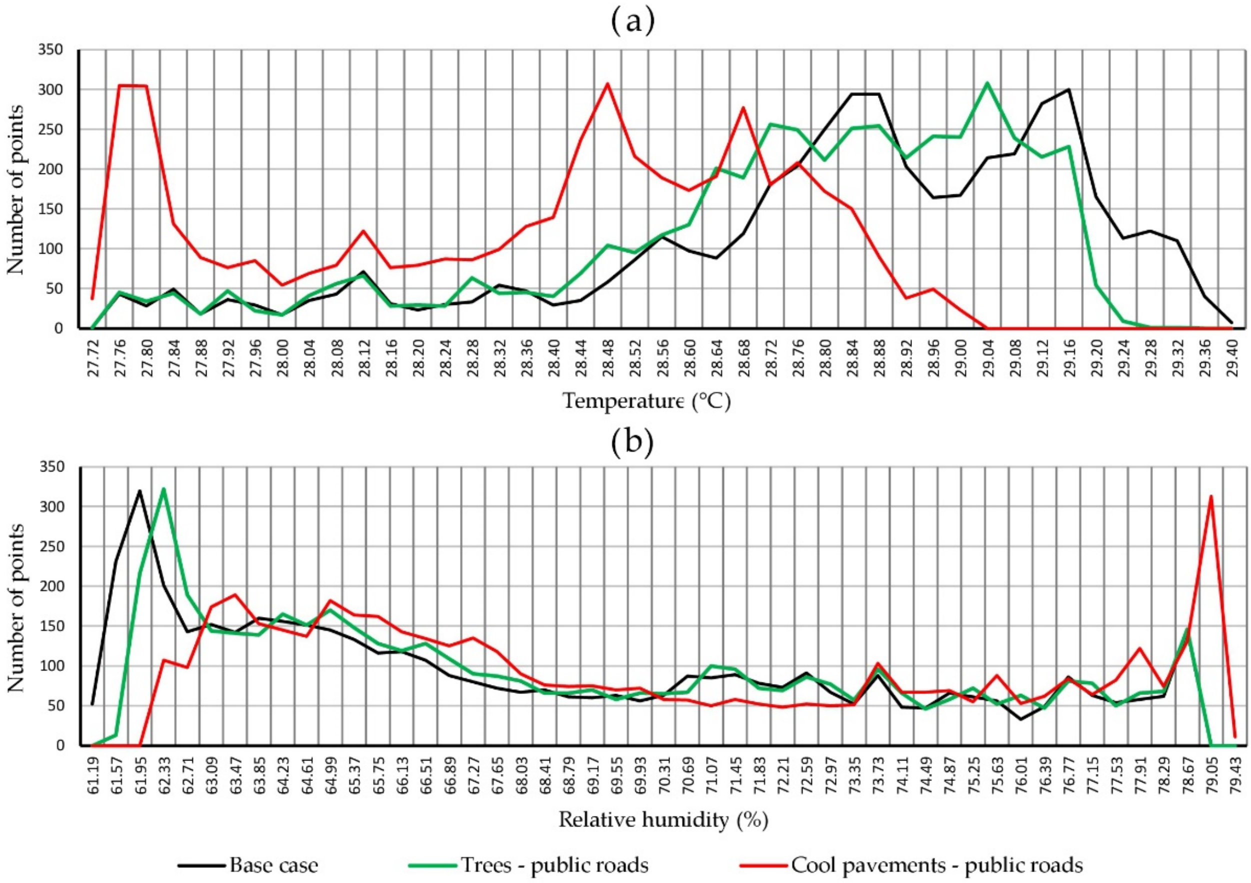

Figure 7. Distribution of the number of points in the modelled grid related to the external air temperature (**a**) (°C) and the relative humidity (**b**) (%) considering the base case and the two configurations for the urban retrofitting with trees and cool pavements included on the public roads of the industrial district.

As far as the relative humidity is concerned, a slight increase (0.5%) is registered for the TP, while a rise of about 2% occurs in case of the CP solution.

Figure 8 shows the difference in the external air temperature and the relative humidity, by comparing the base case with the results obtained in case of the TP and the CP, elating with the district layout. Section a of Figure 8 proves that the TP allows for a decrease in the outdoor air temperature, mainly appreciable in areas underneath vegetation (>0.25 °C). This result is obviously more evident in case of the southern and southern-eastern bands and for the ones closest to the buildings' facades. This phenomenon is mainly due to the natural shadow cast by the trees. With regards to the value of the relative humidity, an increase locally, exceeding 1% is registered.

Moving on, the CP proves once again to be undoubtedly the most effective retrofitting measure. In the portions of the urban canyons exposed to direct solar radiation, the outdoor external temperature decreases by about °C and the relative humidity increases by about 5%, compared to the base case.

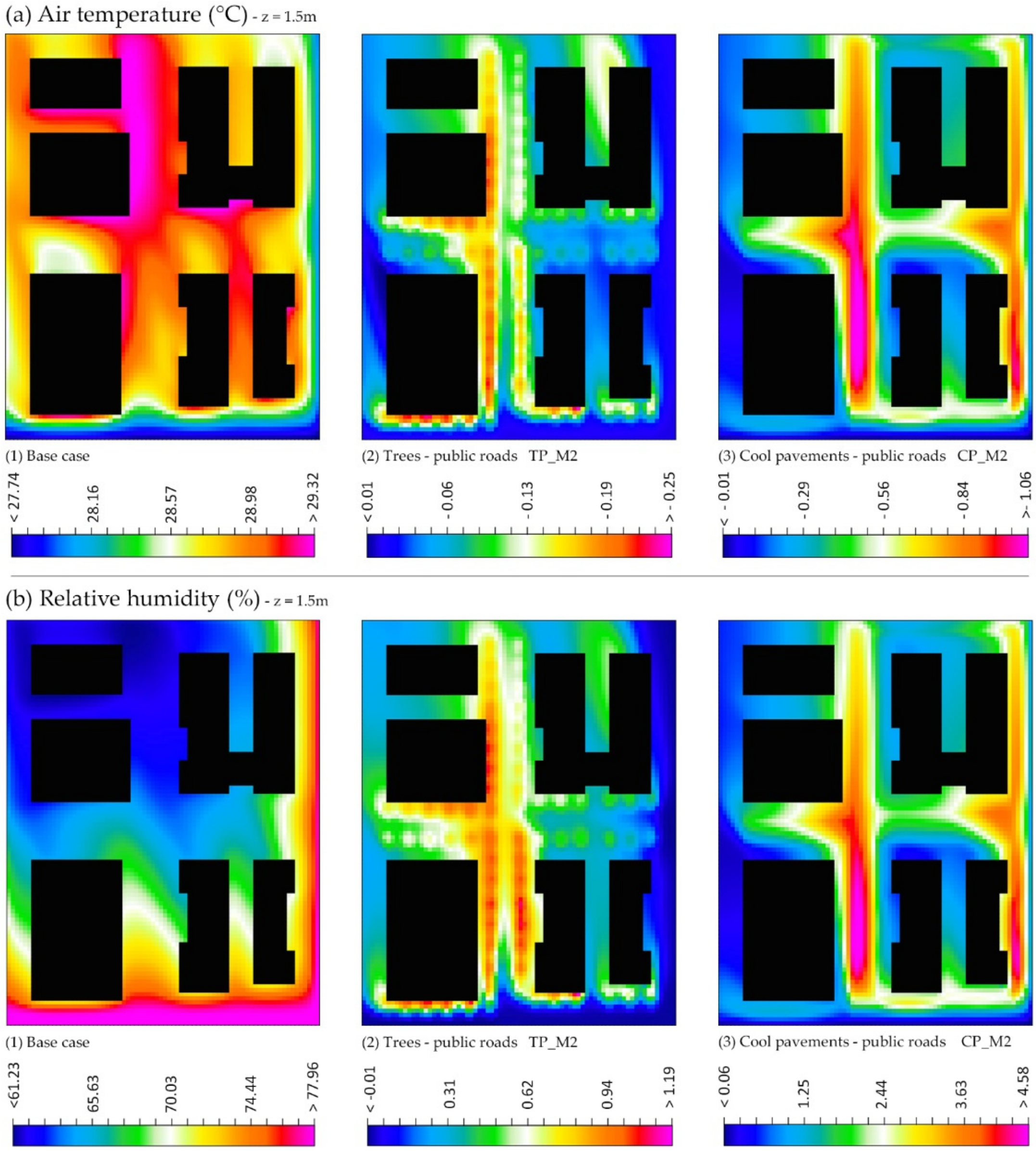

Figure 8. Distribution of the outdoor air temperature and the relative humidity for the base case (**a.1** and **b.1**, respectively) and the map related to both parameters illustrating the difference between the base case and the two different redevelopment measures considered: introduction of the trees in the public roads and the use of cool pavements in the public roads.

In Figure 9, the effects of the urban redeveloping strategies (TP and CP) are compared with the ones produced by GW.2, using the outdoor surface temperature as the reference parameter. Considering the base case, the external surface temperature is equal to 47.43 °C for the southern façades and 27.70 °C for northern ones (the latter are not visible in the cited figure) in the central building in the first row. The CP has a detrimental effect in this regard, while the TP can lead to a local reduction, equal to about 4 °C, in the external surface temperatures, in the portions shadowed by the trees. The effectiveness of this redevelopment measure is particularly evident in the bottom band of the buildings and, by contrast, its influence is practically negligible concerning the top one.

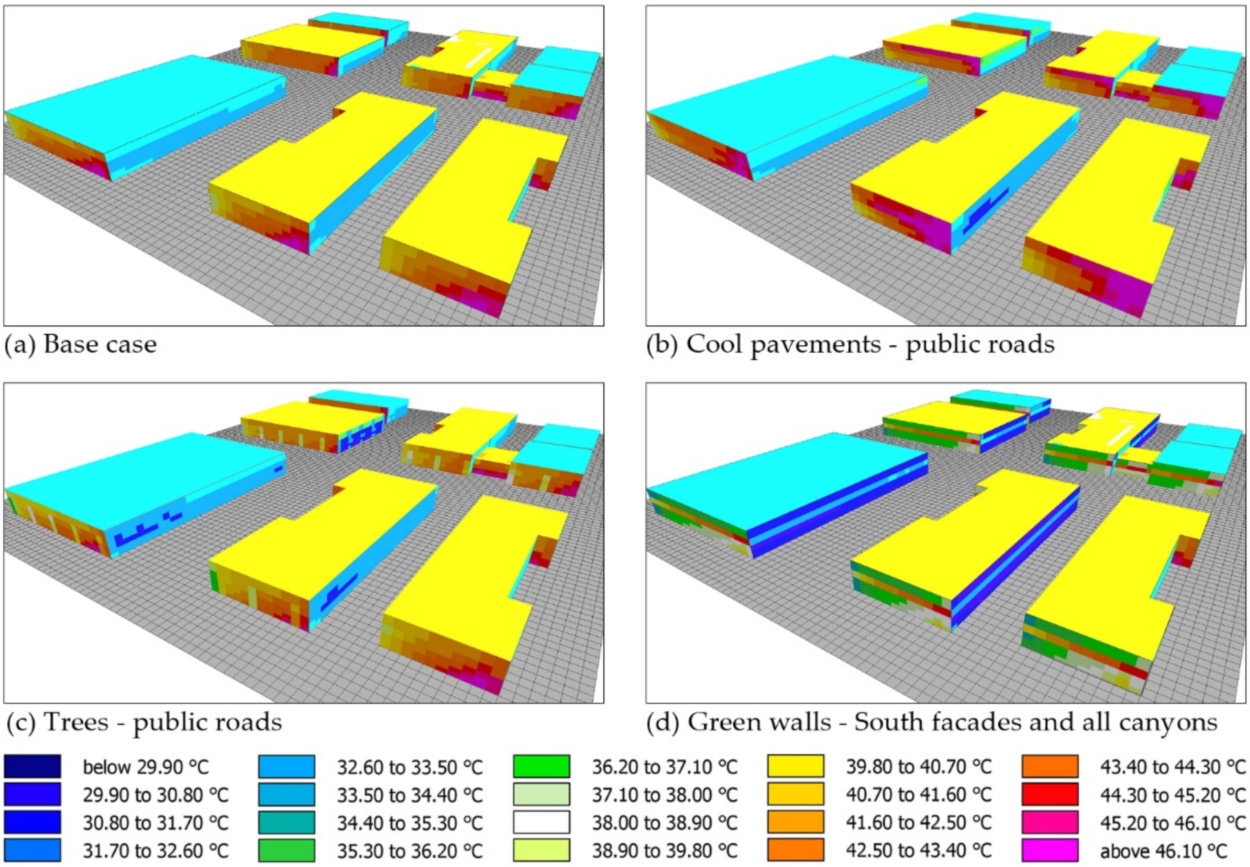

Figure 9. Axonometric view of the industrial district portion, showing the facades' temperatures in the different configurations: base case (**a**), CP (cool pavements in the public roads) (**b**), TP (trees in the public roads) (**c**) and (**d**) GW.2 (green façades for the southern front and all urban canyons).

As highlighted in Figure 9, the most effective solution for a significant reduction in the value of the external surface temperature is the adoption of green walls: the decrease is equal to about 8 °C for the southern oriented facades, while it is equal to 1.78 °C and 3 °C for the eastern and western oriented ones, respectively.

For completeness, the introduction of green facades is evaluated by considering the value of the external air temperature and the relative humidity.

Figure 10 shows the variation of both the outdoor air temperature (°C) and the relative humidity (%) for M2, considering the vertical greeneries in both configuration GW.1 and GW.2. It is worth noting that the right and bottom portions of the three maps show points characterized by the lower and constant temperature. Such evidence is mainly due to the prevailing wind directions or the local effects at the frontiers of the model and consequently, in these areas, the influence of the green façades is expected to be less relevant. Even if a slight decrease in the external air temperature is noticeable for the wider urban canyon, the variation is more significant in the narrower ones and for this reason, a detailed study focused on the latter will follow in the paper. The reduction of the air temperature, along with a slight increase in the relative humidity, contributes to positive affect of the heat island effect, as retrievable in Figure 10.

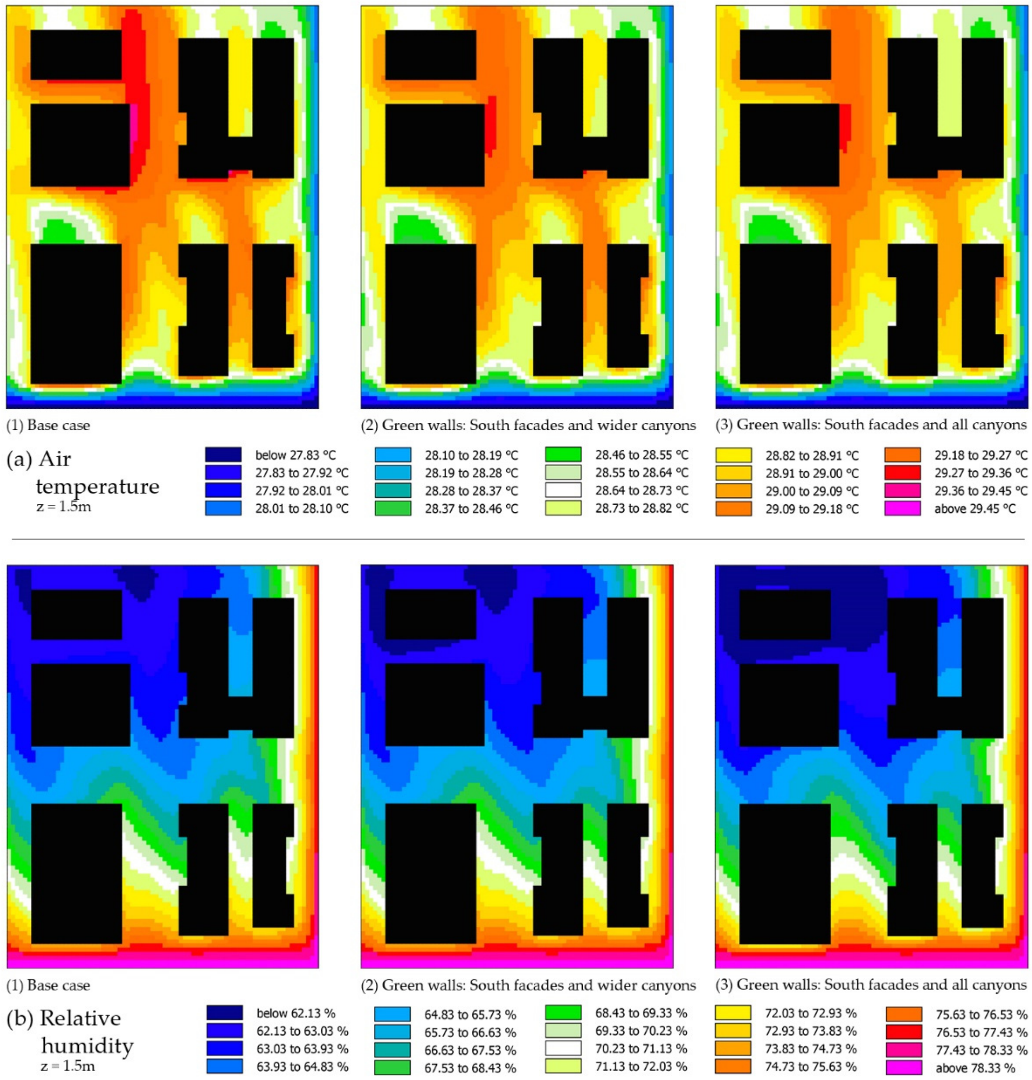

Figure 10. Distribution of the outdoor air temperature and the relative humidity for the base case (**a.1** and **b.1**, respectively) and the map related to the introduction of the green walls on the buildings fronts, first for the southern oriented facades and the wider urban canyons and then, adding green walls for all urban canyons.

These results are also detailed in the graphs in Figure 11. Considering the external air temperature, the retrofit configrations proposed provoke a shift towards the left side of the graph, caused by the reduction in the number of points with a higher temperature, altought the same trend is maintained. With regards to the relative humidity values, the comparison between the base case and the redeveloped configurations is less meaningful as it is retrievable in graph b. The higher variation is related in this case to the points characterized by the lower relative humidity. GW.2, introducing the green façades in all urban canyons, positively influences the microclimate characteristics, with a reduction of the external air temperature (maximum measured equal to 0.17 °C) and a rise in the relative humidity (maximum measured equal to 1.50%).

In order to provide more significant insights into the influence of the urban layout on the green retrofitting efficiency, the thermal-hygrometric conditions are analyzed in six different urban canyons and four different sections with reference to Figure 2.

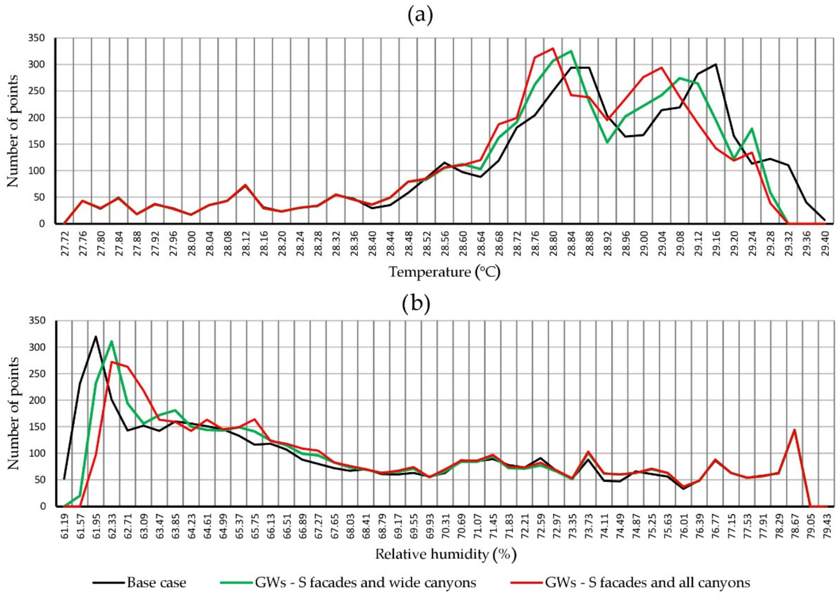

Figure 11. Distribution of the number of points in the modelled grid, related to the external air temperature (°C) (**a**) and the relative humidity (%) (**b**) considering the base case and the two configurations for the green walls GW.1 and GW.2 in district M2.

Starting with canyon number 1 (Figure 2), Figure 12 illustrates the variation of the number of points for the dfferent ranges of both the external air temperature (graph ga) and the relative humidity (graph b). For the base case, the severe temperature changes are registered mainly related to the difference between south and north oriented surfaces. If the green facades are considered to be installed only on the former (GW.1), the number of points related to the highest air external temperature dramatically decreases. Adding green walls on both sides of the considered canyon (GW.2), in addition, the general trend of the graph is reshaped presenting no more severe temperature changes. In this case, an average reduction of about 0.12 °C for the external are temperature is measured while an increase in the relative humidity equal to 1% is registered.

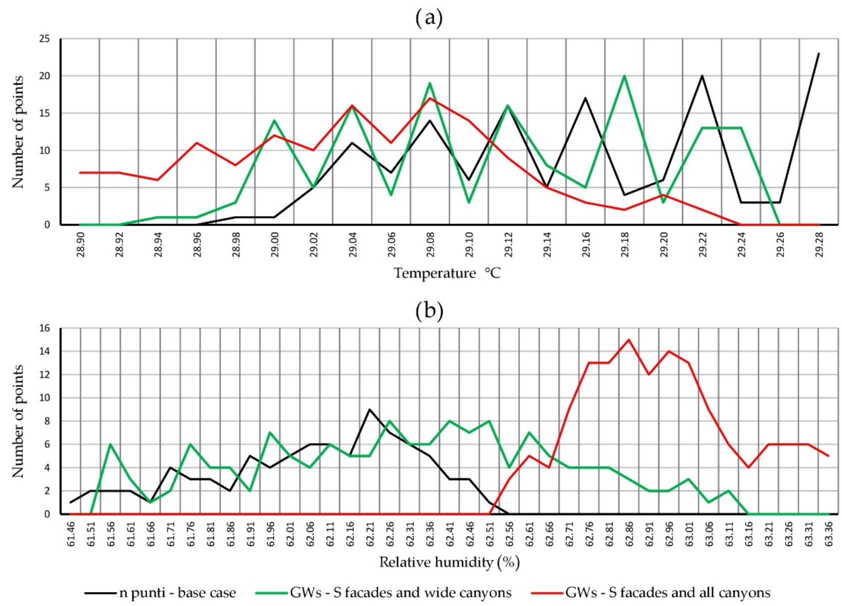

Figure 12. Distribution of the number of points in the modelled urban canyon number 1 (Figure 8) related to both the external air temperature (**a**) and the relative humidity (**b**), considering the base case, GW.1 and GW.2.

With reference to same urban canyon, Figure 13, illustrates the variation of the cited environmental parameters in the plant and elevation section, following the adoption of the GW.2 intervention. The temperature reduction reaches its maximum, right next to the green walls exposed to direct sunlight (above 0.17 °C) but it is still noticeable on the opposite front (0.13 °C). The effectiveness of the green walls progressively decreases, moving to the borders of the urban canyon and, considering the elevation section, going towards the top of the buildings. Despite the reduction in the external air temperature, it proves to be inversely proportional with respect to the building height, the influence of the green walls can be retraced at the roof floor height as well, even if with a reduced effectiveness.

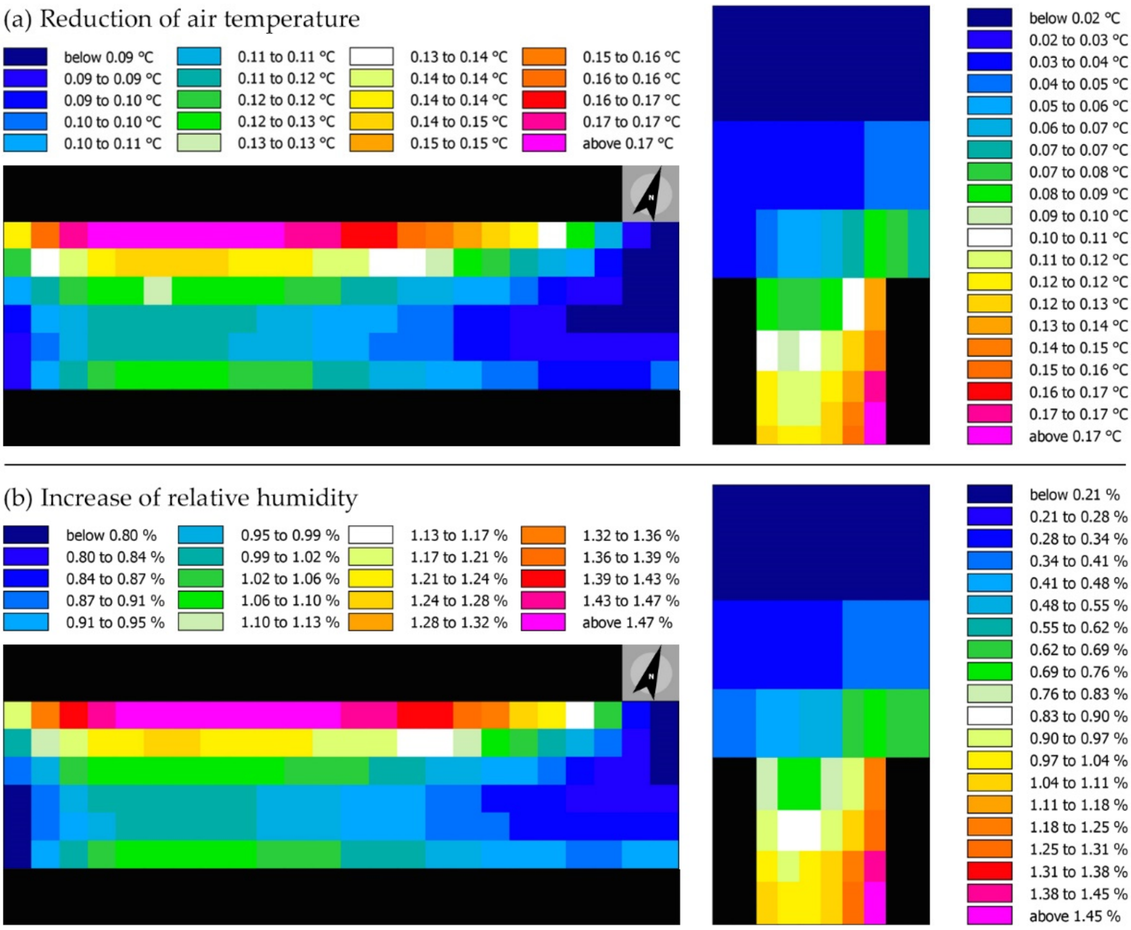

Figure 13. Variation of the external air temperature (°C) (**a**) and the relative humidity (%) (**b**) for canyon number 1, due to the GW.2 measure, considering the plan (on the left) and the section (on the right) views.

Figure 14 shows the results related to section AA (Figure 2), comparing the canyon number 1 and number 4 and illustrating the influence of the urban canyon width on the efficiency of the green walls (GW.2 configuration). In the wider urban canyon (number 4), its effectiveness is evidently less significant: considering the average temperature reduction only accounts for 0.04 °C, compared to the 0.11 °C achieved in canyon 1, that is to say a reduction of more than twice as much. An average increase of about 1.10% with a peak equal to 1.4% at 1 m buildings' height is measured in canyon number 1. By contrast, in canyon number 4, the central points in the middle of the public roads are not affected by the intervention.

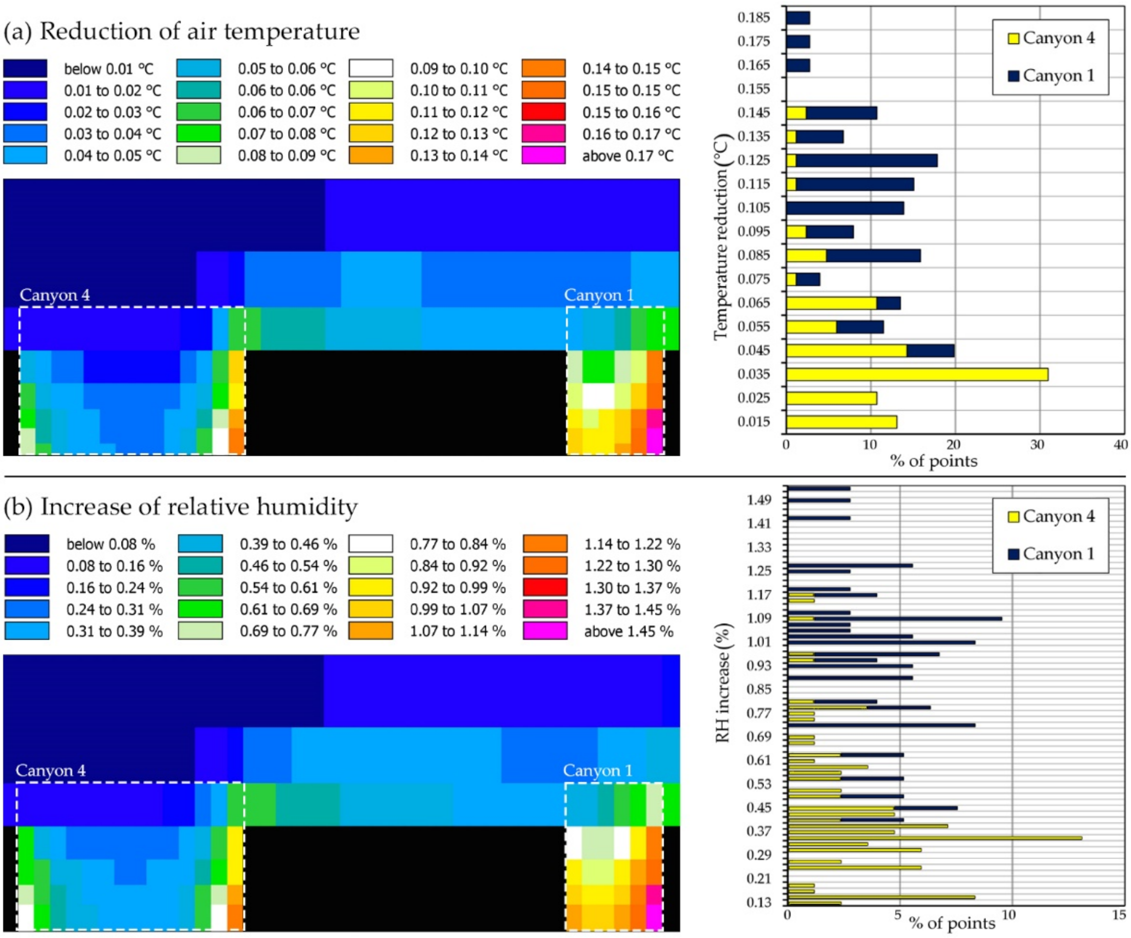

Figure 14. Section AA (Figure 2): external air temperature (°C) (**a**) and relative humidity (%) (**b**) variation recurring to GW.2 solution.

The analysis is then extended with reference to all of the other sections indicated in Figure 2, namely BB, CC, DD and EE. The evidence obtained are illustrated in Figure 15, considering once again the air temperature reduction and the increase in the relative humidity as a consequence of the GW.2 measure. For section BB, not affected by the presence of winds and the model boundary conditions, the efficiency of the green facades is comparable for both urban canyons included. In this case, the mean reduction in the external air temperature is about 0.08 °C. Furthermore, for section CC, it is worth pointing out that the effectiveness of GW.2 in canyon number 3, is partially reduced by the particular disposition of the buildings that cast shadows on it. Moreover, for section DD, a significant reduction in the external air temperature (>0.1 °C) is registered in canyon 6, where the green walls prove to be more efficient than in the wider one (canyon 5), where the effects are appreciable only for the points close to the buildings' façades. Finally, for section EE, such a trend seems to be inverted but this can be related to the presence of the prevailing winds on the border of the model. The effectiveness of the green intervention on the external air temperature is reduced but is still appreciable in the narrower canyon, while the effects in the broader one noted an increased number of points, with respect to section DD. The results related to the relative humidity are in line with the ones just specified for the air external temperature.

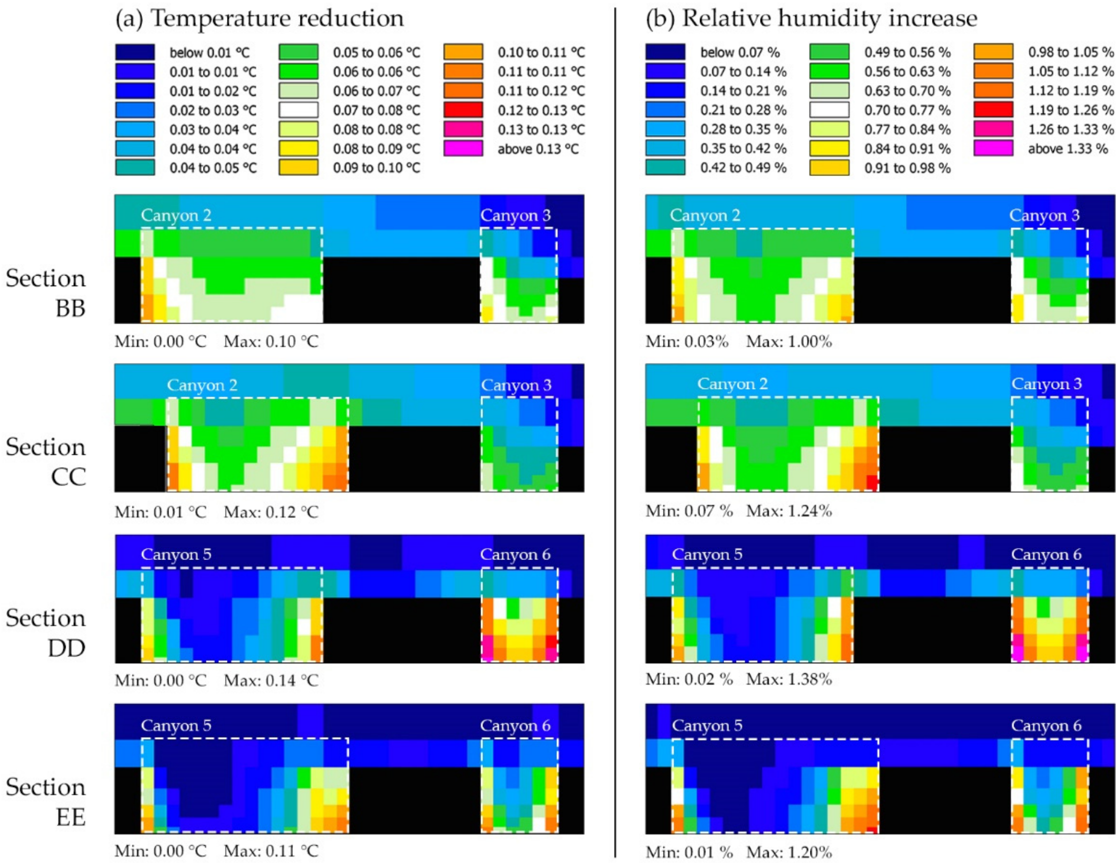

Figure 15. Differences for each urban canyon (Figure 2) considered inside the industrial district, in terms of the external air temperature (°C) (**a**) and the relative humidity (%) (**b**), comparing the base case and GW.2.

4. Discussion

The research outlined so far allowed to produce considerations about the impact of the different mitigation strategies, with particular reference to the vertical greenery solutions. The results obtained can be a useful reference to implement retrofitting interventions at the district scale and promote their integration in code initiatives. Moreover, the results achieved are in line with the findings of similar studies performed with relation to different urban contexts and building types. The CP emerged as the most effective retrofitting strategy at the urban level, in mitigating the external air temperature, as proved also by other studies in this field [50–53]. Its efficiency is undoubtedly connected also to the wider area covered but its adoption can also result in some side effects. Despite reducing the air temperature, the augmented reflectivity causes an increase in the radiation re-emitted by the paved surfaces. This effect, highlighted also by other researchers, in the literature [54], would heavily affect the comfort conditions for pedestrians during hot days, exposing them to an increased amount of thermal radiation. Keeping the focus on the mean radiant temperature reduction, the values registered by adopting the GW and TP are comparable with the ones assessed by Jaafar et al. [55], that using vegetation in an urban-residential district in Lebanon, achieved a decrease equal to 10.5 °C. For these reasons, coupling the trees planting over pedestrian sidewalks and cool pavements over vehicle transit areas, could lead to interesting results, since in this way, the overheating effects produced on people by the increased reflectance of the paved surfaces would be sensibly mitigated. At the same time, the trees bands guarantee adequate shadowing effects and have positive impacts on the microclimate conditions. Focusing on the latter and considering the external air temperature, the results obtained in case of the TP for district M2, are in line with the previous findings of other authors [56]. More significant reductions were achieved by

Abdallah et al., considering the Egyptian climate and highlighting the positive effects of increasing the vegetation density [57]. However in case of the industrial district, installing several rows of trees, could be complicated because of the necessary preservation of the adequate manoeuvre areas for trucks, vehicles and working operations.

The mitigation strategies analyzed until now, not only affect the environmental parameters but also influence the external surface temperatures of the buildings, having results on their energy performance especially during the cooling season, as assessed also by other researchers [58]. If cool pavements in public roads lead to a rise in building external surface temperatures, trees can partially reduce them. However, as their efficiency is related to the shading of the direct solar radiation, trees planted close to building facades can hardly tackle the diffuse one, and for this reason the global results achieved are heavily affected by solar exposition, building orientation and plant characteristics [59].

The green walls implementation proved to be the most effective measure in contrasting the overheating of the external wall surfaces and the results obtained are in line with the experimental evidence collected in other studies in the Mediterranean area [60].

However, as retrieved in Figure 9, the presence of the windowed portions sensibly reduces the global efficacy of the vertical greenery solution. Industrial buildings, generally characterized by a limited amount of glazed openings, are for this reason particularly suitable and can also benefit from an improvement of the aesthetic quality ensured by green facades. When considering facilities with other intended uses, the window-to-wall ratio becomes a non-negligible factor capable of deeply influencing the energy loads and greenery effectiveness, as assessed by Poddar et al. [61]. Moreover other researchers highlight that regularity of building volumes and the simplicity of the internal room distributions, typical in case of industrial facilities, are enhancing factors for the effectiveness of green walls, in tackling the energy demand [62]. Considering the specific case of an industrial urban district, green walls allow also to maintain, at the same time, adequate loading/unloading areas and maneuvering external spaces because of the limited space requirements for their installation.

Looking at the effects of green walls on outdoor microclimate conditions, it is possible to outline that their implementation on narrower urban canyons has a greater impact because both fronts can contribute to reduce the air temperature and increase the relative humidity. According to Lilliana et al. [41], a high-density urban layout can benefit the most by positive vertical greening effects.

As a concluding remark, it is worth noting that the effectiveness of green walls on affecting microclimate conditions is highly influenced by their location with respect to the prevailing wind actions, natural shading and incident direct solar radiation.

5. Conclusions

In conclusion, each of the redevelopment measures considered the results in different benefits for the industrial district analyzed. The adoption of cool pavements as public roads allows to obtain a decrease in the outdoor air temperature and an increase in the relative humidity. By contrast at the same time, this measure results in a significant increase in both the mean radiant temperature and the buildings external surface temperatures, due to the increased reflectivity of the paving materials. Planting trees in public roads lets to achieve only a slight effect on the external air temperature and relative humidity but allows a sensible decrease of the mean radiant temperature of up to 9 °C. Moreover, they contribute to partially shadow the building facades, even if this result is significantly affected by the solar radiation direction and the buildings’ orientations. With regards to the buildings retrofitted using green walls, this intervention shows a limited influence on both the external air temperature and the relative humidity considered at the district level. By the way, vertical greeneries guarantee a slight reduction in the mean radiant temperature and at the same time ensure a significant decrease of the buildings’ external surface temperatures, equal to 8 °C for southern oriented façades.

The effectiveness of green walls in altering outdoor environmental conditions, however, is considerably influenced by the geometry of the urban canyons where they are applied. The most favorable effects are obtained in case of narrow urban canyons with vertical greenery on both opposing buildings' fronts. This is a suitable solution especially for tight urban spaces where it would be impossible to adopt trees or vegetation, due to the limited space available.

The considerations reported until now are based on the results obtained in the modelling case study area at two different levels of resolution and focusing on the whole district and on a reduced portion. In this regard, it was highlighted that by not including the adequate perimeter area in the model, it can affect the final results because of the different boundary conditions.

Considering the code background, the state of the art review proved the existence of a significant gap in the promotion of green infrastructure at both the urban and building levels as a mitigation measure against the heat island effect and building overheating. More in detail, the absence of the systematic reference to address urban policy and guidelines for designers to choose and size the vertical greenery measures, was assessed. Within this context, the current research demonstrates that the adoption of this kind of retrofitting intervention in building facades, also at the local level, allows to achieve slightly better microclimate conditions in the industrial district considered and consequently a better outdoor environmental comfort as well as a reduced energy cooling demand.

The proposal is to outline the guidelines or protocols that address designers dealing with greenery interventions to approximately evaluate, during the early stage of the design process, the benefits, in terms of microclimate characteristics at the urban scale and the energy consumption at the building level. For instance, the percentage of the vertical greenery should be outlined for each urban scenario, obviously considering their geometrical features and the climate characteristics. The percentage should be completed with a preliminary estimation of the reduction in external air temperature and the decrease in the cooling consumption for buildings, due to the reduction of the external surface temperature, However, the research presented can be further deepened also in relation to its current limitations. The simulations carried out until now, exclusively deal with the summer period, in order to assess the heat island effect mitigation, due to these measures, but the analysis should be extended also to the winter season. However, yearly simulations are extremely time-consuming and for this reason, focusing on specific representative days can be suggested. Moreover, at this stage, the proposed interventions were considered separately to assess the main effects provided by each of them. Starting from the evidence collected, the opportunity to analyze the potential impact achievable through their combination emerged. Dealing with this specific aspect, further simulations should be carried out to prove the real effectiveness of such solutions. Finally, a global evaluation of the suitability of each different measure or their joint implementation should be completed, also considering the economic aspects within a life cycle assessment perspective.

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