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A New Performance Indicator to Assess Building and District Cooling Strategies

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Abstract

The goal of this study is to bring out the efficiency of district landscaping on local urban heat island mitigation. Two cooling strategies at the district scale are evaluated through the coupled effect computation of microclimate and building energy demand: vegetation (trees, green walls and roofs) and high albedo values (cool roofs and façades). The study focus on an existing district, Part-Dieu, in Lyon (France). This district has a high urban density and is composed of buildings for which rehabilitation is expected to be difficult. The city is particularly sensitive to summer heatwaves that are supposed to be more regular with global warming. Two specific urban blocks, of about 10 building blocks each, are modeled: a 60,000 m² site where the urban fabric is a mix of historical buildings and 60s' buildings, and a 70,000 m² new residential site under construction, more homogeneous compared to the first one. The simulation results are processed for a summer period (hourly time step) and cooling strategies are analyzed individually and combined. Two indexes, Energy Performance Index (*EPI*) and Ambient Temperature Mitigation Index (*ATMI*), are defined to evaluate strategy efficiencies. In our case studies, cooling energy demand is mitigated by around 3% with tree growth strategy, 35% with green roofs, and 76% with increased albedo of urban surfaces. Whereas detailed results of coupled simulation are useful here for engineers, global performance indicators defined in this study give useful hints for stakeholders and urban cooling strategy design.

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Keywords: urban climate ; building energy simulation ; urban heat island mitigation index ;

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1. Introduction

For buildings in dense urban areas, the use of air conditioning systems increases urban anthropogenic heat during the most critical periods [1,2]. Urban Heat Island (UHI) effect can mitigate the heating energy demand in winter, while the cooling energy demand during summer is increased [3]. This negative feedback increases UHI and building energy demand and leads to undersized air-conditioning systems. In order to improve thermal comfort and to reduce cooling energy demand, the urban environment can be designed to mitigate UHI and its consequences. A modification of urban landscaping, such as surface albedo [4, 5, 6] or green areas can mitigate the UHI, which consequently reduces energy demand. Thus, microclimatic considerations should be taken into account in urban planning. A simulation of the different physical processes that exist in urban areas would help urban planners determining the best urban landscapes in order to increase building energy efficiency [7] and to improve outdoor thermal comfort [8]. Various microclimatic models have been developed to compute the physical processes in the urban areas [9, 10, 11]. A first category allows to compute radiative exchange in urban area and their impact on building energy demand [12,13,14]. A second category of district simulation tools computes coupled heat and mass transfer [15,16,17,18,19]. These latter are detailed coupled simulations which are often limited to a limited period, e.g. several days. However, in this study, UHI mitigation impacts are assessed for a complete summer period, from May 1 to September 30, using EnviBatE coupled models [17]. UHI intensity was studied and quantified through various indicators [20]. However, in order to compare several urban planning strategies, detailed indexes were developed considering outdoor thermal comfort such as Universal Thermal Climate Index (UTCI) [21] or Physiological Equivalent Temperature (PET) [22]. These indexes are used to quantify impacts of urban planning with detailed for each time step of the studied period. Considering energy performance of each building, many indicators have been also developed and are sometime used in building regulations [23,24]. However, considering a complete summer period and the combination of local UHI and energy demand, urban planners would need a simpler estimator that can gives a quantified overview to help decision process. We propose in this study two indicators to evaluate and compare urban planning strategies, considering both building energy demand and local microclimate. The potential use of these indexes is studied considering impacts of vegetation and albedo increase in a dense urban district, Part-Dieu (Lyon, France) particularly sensitive to summer heatwaves. Moreover, heatwave frequency and intensity should increase with global warming and most of the considered buildings are expected to be difficult to refurbish. The district is modeled with EnviBatE [17] Green and increased albedo strategies are assessed for two specific urban sub-blocks, Moncey Street and Buire Street. This case study is developed to highlight the proposed methodology use and results.

2. Modeling Tools and Methodology

2.1. Models for building and ambient heat transfers

EnviBatE, a set of coupled simulation models is used to analyze efficiency of different urban landscaping. Different meshes of the same district are needed in order to adapt to different heat and mass models at the district scale [17] The main surface mesh is discretized consistently with the zones for the building energy simulation. Each wall with a specific orientation and physical properties is defined by its own nodes. Solar radiation simulation is computed in a first stage, using SOLENE [25], for direct and diffuse solar irradiance considering each building wall and ground. SOLENE software has been validated in several studies such as the district surface temperature measures in Toulouse (France) [26]. Direct solar irradiance and sky luminance are calculated considering a triangulated submesh of the main surface mesh. Solar reflections and longwave interchanges in the urban environment are then modelled in the coupled simulation using radiosity method in EnviBatE [17]. A zonal model, based on Rockle's model [27] and using QUIC software [28], computes spatially-resolved wind fields in the urban domain. This computation method was developed to respect mass conservation [29]. QUIC software capability to model urban canopy airflow was demonstrated through several experiments such as reduced district scale models [30,31] and a real district scale in Oklahoma City [32,33]. A more detailed hexahedral mesh (regular) is used here to give accurate velocity fields throughout the studied urban canopy. These velocities are then used to compute the airflows through the rougher mesh of the coupled thermal model. These airflows are used to compute the temperature field with a zonal method including indoor and outdoor heat balances [34]. Building energy demand is computed considering building operation and indoor heat transfers (sources, ventilation, radiation, etc.). The dynamic is mainly linked to the conductive heat transfer in walls. Conductive heat fluxes are computed with the response factor method [35] for wall and ground surfaces. Vegetated surface temperature is considered in equilibrium with ambient air [36] with a constant watering. The building model equations are reduced with the weighted factors method [37]. This method was validated through several studies [38]. The model has been adapted to compute wall surface temperatures, heating and cooling power demand, and indoor temperature [17].

2.2. Performance indexes for district cooling

In this study, we propose two different indexes to evaluate several cooling strategies expressed in a formula equivalent the Solar Reflectance Index (*SRI*) definition [39]. The *SRI* index was developed to qualify the steady-state temperature of a roof surface on a typical summer afternoon [4]. The studied surface temperature is compared to two standard surfaces, a black (solar reflectance 0.20, thermal emittance 0.90) and a white surface (solar reflectance 0.80, thermal emittance 0.90). *SRI* characterizes the coolness of a material surface with a simple value from 0 for the warm surface to 1 for the cool surface. These standard values can be exceeded for warmer or cooler surfaces depending on the technology. In a similar approach, we propose indexes to characterize urban strategy coolness regarding either cooling energy demand or ambient temperature during a full season. A cooling strategy is like a different coating technique in the SRI definition and three districts cases are compared:

- The modified district, labeled *coolstrat*, with the studied cooling strategy
- The reference heat island case, labeled *ref*, defined by the existing district; this is the non-cooled case similar to the standard black surface defined for the *SRI*.
- The standard cool district, labeled *ideal*, defined by modified opaque surfaces of the same district, same morphology, where all opaque and non-vegetated surfaces have an increased albedo to 0.8 and a 0.9 thermal emittance, i.e. likewise the cool surface defined for *SRI*.

A first index is defined to quantify coolness of each strategy regarding energy demand impact. Total building energy demand of the district is computed for the reference case E_{ref} [kWh], the ideal case E_{ideal} [kWh] and a given cooling strategy $E_{coolstrat}$ [kWh]. This defines the Energy Performance Index (*EPI*) of the UHI mitigation strategy, see equation (1). A second index is defined to quantify ambient temperature mitigation impact of each cooling strategy. Degree-hours higher than 26°C in the urban canopy are computed for the reference case (DH_{ref} [°Ch]), for the ideal case (DH_{ideal} [°Ch]), and a given cooling strategy case ($DH_{coolstrat}$ [°Ch]). This defines the Ambient Temperature Mitigation Index (*ATMI*) as defined in equation (1).

$$EPI = \frac{E_{\text{ref}} - E_{coolstrat}}{E_{ref} - E_{ideal}} \quad \text{and} \quad ATMI = \frac{DH_{ref} - DH_{coolstrat}}{DH_{ref} - DH_{ideal}} \tag{1}$$

EPI and *ATMI* vary in the same way as *SRI*, i.e. from 0 to 1 considering an effective cooling strategy that does not perform better than the standard cool district. Both *EPI* and *ATMI* are independent from the case study climate or morphology and allow quantifying the inner cooling potential of the studied strategy. However, their use can be extended for morphology alterations in order to overcome urban surface modification potentials such as shading screens. Negative values of *EPI* and *ATMI* would highlight potential negative impacts of district modifications; this can be used to assess effects of green spaces urbanization or urban densification for example.

3. Case Study and Cooling Strategies

3.1. District location and characteristics

Both studied sites are located in Part-Dieu district, located in the West of Lyon, France. Built in 1968 around a big train station and a mall, this district has become the second city center and the second largest business district in France. The studied places in Part-Dieu, Buire (a) and Moncey (b) are located around the train station, respectively

900 m to the South and 700m to the West. Buire (see Fig. 1(a)) is composed of new buildings on the site of 70.000 m², which represent about 10 building blocks with 9 stories on average. Moncey (see Fig. 1(b)) is a mix of historical buildings and 60s' buildings. These are mid-high buildings with 7-storey on average, surrounded by two high-rise residential buildings, 51 m and a 153 m tower which is not already built, see Fig. 1(b).

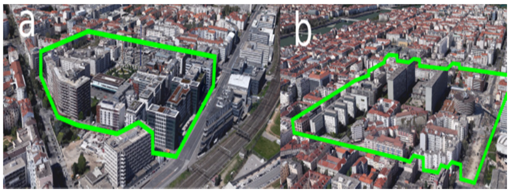

Fig. 1. Existing urban blocks of the case study in Buire (a) and Moncey (b) sites.

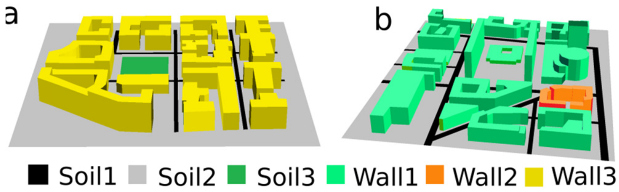

Fig. 2. Material property distributions of urban surfaces in Buire (a) and Moncey (b).

The city of Lyon is located in the broad transition zone between the Mediterranean climate of the south of the France (Western oceanic climate) and the Northern continental climate. The mean temperatures in Lyon are 3.2°C in January (coldest month) and 22°C in July (warmest month). For this study, meteorological data of 2008 is given from the nearest airport's weather station. From May 1 to September 30, the cooling season, climate data are characterized by 1,516 degree-hours higher than 26°C (the cooling temperature set point in French building regulation) and Prevailing winds from the North and the South (see Fig. 2). These meteorological data are available and used at an hourly time-step. Some data are spatially refined for EnviBatE models, such as ambient temperatures around buildings (zonal mesh), wind velocities and orientation around buildings (QUIC-URB computation), solar irradiance in the district scene (SOLENE computation).

3.2. Building casings and numerical mockup

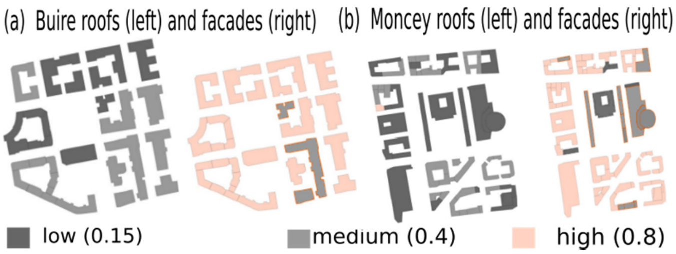

Fig. 3. Albedo variations of building envelopes in Buire (a) and Moncey (b) sites

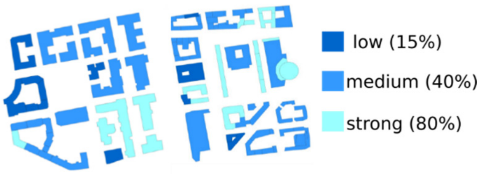

Fig. 4: Average-glazing ratio for each building façade

In order to define and manage in a simplified way characteristics of building walls, roofs, and soils, different groups are defined (see Fig. 2). Concrete structures of buildings (walls and roofs) are more or less insulated, from Wall1 to Wall3. Roads (identified as Soil1) are composed of three layers: asphalt, concrete and soil. Pavements (identified as Soil2) are composed of concrete and soil. The vegetated place is identified as Soil3. Actual albedo values are assigned in the numerical mockup to façades and roofs according to the distribution presented Fig. 3 for buildings. As for material properties, albedo variations are simplified for practical simulation data management and three groups are defined depending on the albedo level from low (0.15) to medium (0.4) and high (0.8). Soil albedo values, not represented Fig. 3, vary from 0.15 (Soil1 and Soil2) to 0.25 (Soil3). The detailed description of building façades characteristics is completed by window distributions that is mapped for both urban blocks Fig. 4. A glazing ratio (percentage of glazing surface compared to the façade surface) is defined for each building in a similar approach to automate the description of the detailed numerical mockup process. Three different classes are then defined: buildings with low (15%), medium (40%) and high (80%) glazing ratio. Indeed, the zonal mesh for EnviBatE thermal simulation is adapted to each story height including wall and window properties for façades. Each window is automatically sized and positioned, story by story, following the glazing ratio data.

3.3. Parameter variations for cooling strategies

The city decision services are interested in assessing benefits of adding vegetation or increasing albedo of urban surfaces. Three cooling strategies are then proposed and detailed depending on the district opportunities:

- A green strategy that consists in increasing the vegetation in the district
- An increased albedo strategy
- A combination of both previous cooling strategies

In the actual (reference) Buire site, only the central place is green. There are a few trees around this place, which are about 9m high, see Fig. 5 (a). For the green strategy, all spaces between buildings are greened and tree size is doubled (18m high), see Fig. 5 (c). In the actual (reference) Moncey site, see Fig. 5 (b), there is no vegetation. The green strategy consists to add trees in streets, vegetation in the central place, and adding green roofs and green walls on central buildings, see Fig. 5 (d). The main cooling effect of vegetation is not due to its albedo (0.25) but to its evapotranspiration effect.

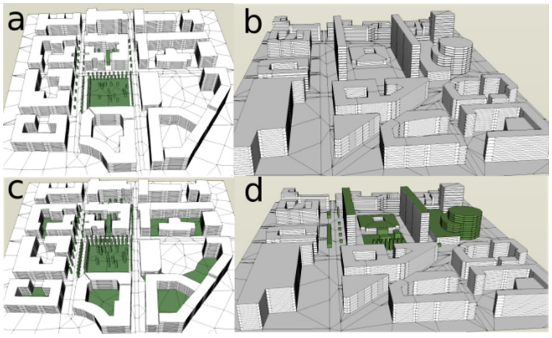

Fig. 5: Actual green areas of reference sites: Buire (a) and Moncey (b). Green strategies for the Buire (c) and Moncey site (d)

For the increased albedo strategy, low and medium albedo are improved except road surfaces (Soil1). Thus, the albedo increases for low albedo surfaces from 0.15 to 0.4, and for medium albedo surfaces from 0.4 to 0.8. This increased albedo strategy is aimed to be realistic and therefore albedo values are globally lower than the ideal case defined in section 2.2. For the last strategy, the albedo of non-vegetated surfaces in the green strategy are modified following the increased albedo strategy. To evaluate these different cooling strategies, we compare these strategies with the ideal case defined for the performance indexes in section 2.2.

4. Results and Analysis

4.1. Detailed results of reference cases

The cooling energy demand, see Fig. 6, is computed for the buildings with a common indoor set point of 26°C during the occupancy periods and 19°C otherwise. Each building occupancy period is defined depending on the building use and consistently with building regulation scenarios (hourly time step). In the Buire site, see Fig. 6 (a), 50% of the building zones have a cooling energy demand higher than 40kWh/(m².yr) with a maximum value of 54kWh/(m².yr). The surface refers to building floor area. Due to the soil effects, the lower cooling energy demand, i.e. 20kWh/(m².yr), are located in the ground floor building stories. In this site, building thermophysical properties are more homogenous than in Moncey case. Then, building energy demand is more heterogeneous in Moncey site, see

Fig. 6 (b). In this latter site, 50% of the building zones have a cooling energy demand higher than 35kWh/(m².yr), and a maximum value up to 70kWh/(m².yr). Buildings with high average glazing ratio have the maximum values. Ambient air temperatures are analyzed through Degree-Hours (*DH* [°Ch]) above the standard indoor temperature set point (26°C) and for each volume in the canopy mesh. The vertical variation, see Fig. 7, shows that zones close to the ground and building walls have higher values, which is mainly due to the transmitted heat from absorbed solar radiation. Minimum observed values (15200°Ch) are located above buildings and correspond to meteorological data. Near the ground, Fig. 7, lowers *DH* values are observed in Moncey (maximum up to 6600°Ch) than in Buire site (maximum up to 9900°Ch). Maximum values are observed in open spaces exposed to the solar radiation and protected from the prevailing winds. In narrow and shaded streets, lowest values are observed here. This is also the case in Moncey site due to the trees next to central buildings, and where observed *DH* values are low.

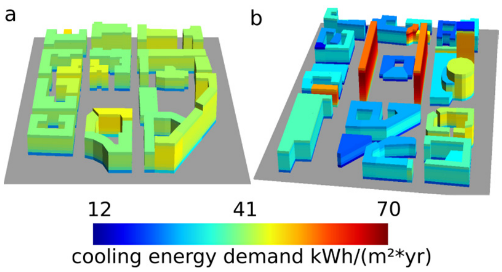

Fig. 6: Cooling energy demand related to building floor area in actual sites: Buire (a) and Moncey (b)

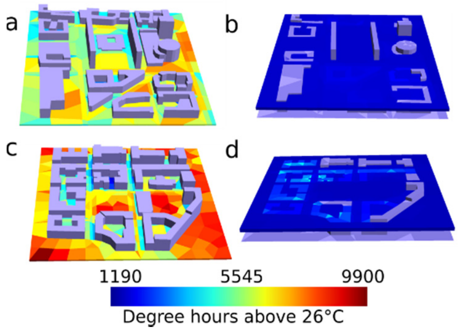

Fig. 7: Degree-hours above 26°C for ambient air from 0 to 3m high (Moncey (a) and Buire (c) sites), and from 21 to 24m (Moncey (b) and Buire (d) sites)

4.2. Cooling strategies analysis

Table 1. Simulation results and *EPI* / *ATMI* indexes for the proposed cooling strategies of Buire and Moncey sites.

Scenario		Total Cooling energy demand (MWh/yr)	*EPI* (%)	average *DH* (°Ch)	*ATMI* (%)
Buire	reference	13 188	0	1 881	0
	albedo	13 011	52	1 656	59
	vegetation	13 100	26	1 773	28
	albedo & vegetation	13 015	51	1 706	46
	ideal	12 845	100	1 500	100
Moncey	reference	17 760	0	1 719	0
	albedo	16 765	53.5	1 618	40.6
	vegetation	17 645	6.2	1 706	5.1
	albedo & vegetation	16 854	49	1 617	40.9
	ideal	15 900	100	1 469	100

Energy saving are more important in Moncey than in Buire site with a maximum decrease of 5.5% for Moncey and 1.34% for Buire, see Table 1. Indeed, buildings in Moncey site are less isolated than in Buire place. Then these buildings are more sensitive to the variation of ambient temperature due to cooling strategies. However, the EPI index variations are similar for Buire site, which highlights the good results regarding the inherent potential of indirect mitigation of the cooling loads due to the UHI. Moreover, the cooling strategies were applied differently in both places Buire and Moncey, and EPI variations can be observed depending on these design options. The direct UHI mitigation is analyzed here through the degree-hour decrease. Absolute values are here in the same range for Buire and Moncey site. Degree-hours above 26°C converge to a same value near 1500°Ch, which corresponds to the meteorological data and a perfect UHI mitigation. However, the cooling strategies assessed with the ATMI index perform not in the same range as previously observed for the EPI index. In any place, the proposed increased albedo strategy seems rather better than the green strategy to reduce building energy demand (1.34% decrease over 0.7 for Buire and 5.5% decrease over 0.6 for Moncey) and ambient temperature (11.9% decrease over 5.7 for Buire and 5.9% decrease over 0.7 for Moncey). However, the number of treated surfaces is more important in the albedo strategy (all buildings and soils) than in the proposed green strategy (some roof and some soils). For the two places, the combined strategy is less efficient than the increased albedo strategy to reduce building energy demand and ambient temperature. For this latter case, surfaces with high albedo values are greened. Indeed, in Moncey case study, green roofs are less efficient than cool roofs (high albedo). In the Buire case study, the same results are observed with green places replacing high albedo pavements.

5. Conclusion

This study aimed to give an overview of the capabilities of a local UHI and a building energy simulation tool. Ten urban landscaping have been modeled to study district cooling strategies. The model has been used on two sites in existing district to highlight the possibilities of the proposed method. Results show that decrease due to the proposed greened scenario are lower than the results obtain for the increased albedo. Indeed, the design options were limited to the actual refurbishment possibilities of the district. Moreover, the direct impacts on UHI mitigation are higher regarding the absolute values of degree-hour decrease compared to the total cooling energy demand. For both sites, cooling strategies have a more direct impact to mitigate ambient temperature than building energy demand (4 to 25 more important). However, comparing absolute values is not relevant here, and *EPI* index as *ATMI* index could give a more objective value with a magnitude comparable for different districts and different weathers. As indexes defined in environmental regulations, *ATMI* and/or *EPI* indexes allow setting a performance level depending on case study itself. Moreover, ranking various strategies could be easier for a decision-maker with an index rather than absolute values that require a good technical knowledge of the context. However, various weighting factors could be introduced in the methodology such as environmental and economic costs. Finally, the definition of *EPI* and *ATMI* indexes is flexible and their use should be adapted in further studies. The computation of degree-hours to characterize the direct effects on UHI could be modified using pedestrian comfort indexes and other parameters (air velocity, humidity, and radiant temperature). These indexes can be also mapped on a district site to understand the spatial effects and considering a complete summer season. These mapped values, dependent of direct and indirect effects, could complete the analysis compared to the absolute values.

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