PLEA SANTIAGO 2022 Will Cities Survive? Green Infrastructure to reduce cooling loads and heat stress in Mediterranean Climates. A building simulation and machine learning approach

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Green Infrastructure to reduce cooling loads and heat stress in Mediterranean Climates.
A building simulation and machine learning approach.

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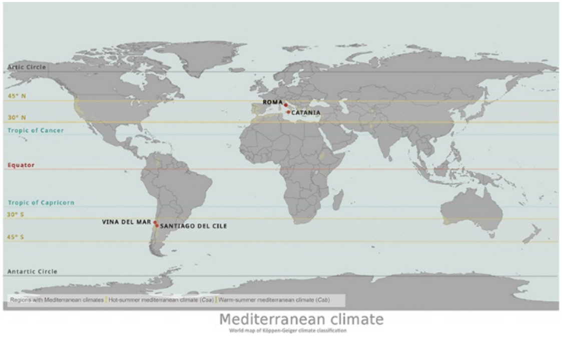
ABSTRACT: Climate change impact on cities and urban warming due to anthropogenic effects are urgent problems to be solved. Among the most beneficious strategies to reduce those impacts we can account the development of green infrastructures in cities, a kind of intervention that assure both mitigation of global warming by reducing greenhouse gases emissions, and adaptation to warmer urban environments. This work presents a building simulation and machine learning methodology to estimate the energy and comfort-related benefits that can be obtained by using a green infrastructure to shadow buildings' façades and roofs. We used previously developed simulation models to test the energy savings provided by different types of trees planted to produce shadows on buildings. Then, we tested different algorithms to predict using a machine learning approach the saving that can be obtained in different buildings-trees contexts for the cities of Catania, Rome, Santiago de Chile and Viña del Mar. Results show that the saving obtained is in the range 5-60%, mainly depending on the number of façade shadowed and on the specie of trees; and the prediction accuracy of machine learning process is over 90% for a binary classification (energy saving > 15% or <15%).

KEYWORDS: Urban Heat Island, Urban Climate, Green Infrastructure, Building Performance Simulation, Machine Learning

1. INTRODUCTION

During the last decades, global warming and land use change have intensified the urban heat stress condition, affecting energy loads of buildings and both indoor and outdoor thermal conditions. The problem is so deep that in 2021 the world experimented the record temperatures of 48.5 Celsius degrees in Canada during the summer and peaks of 29 Celsius degrees in central Chile in the middle of the winter season. Scientific community is agreeing that urgent measures should be taken to mitigate the global warming and the urban heat island (UHI) phenomenon. At the same time, there is an urgent need to develop adaptation strategies to face warmer environments, including nature-based solutions to restore ecological services in cities and reduce the probability of heat stress under heat waves [1]. Green Infrastructure (GI) is a strategy to achieve these goals, and has more benefits such as CO_2 sequestration, reduction of flood damages, visual and acoustical better environment, biodiversity development. Many authors assessed in the past the possible reduction in UHI intensity provided by trees and vegetal surfaces [2-3]. The influence of trees on indoor thermal environment has also been assessed by various studies [4-5]. In previous works, authors established a strategy to simulate not only theoretical solutions, but real configurations of trees-buildings relations, depending on availability of space in case studies sectors placed in Mediterranean climates [6]. Mediterranean climates are normally located between 30 and 45 degrees of latitude in both hemispheres, covering the Mediterranean Sea basin, the South and North America Pacific coasts, and small parts of Australia and South Africa (figure 1) [7].

Figure 1:
Mediterranean climates and cities considered in this study



Machine learning (ML), a branch of artificial intelligence that learn from a set of data to do a prediction or a classification of new configurations performance, has been used to predict the energy loads reduction in summer and the indoor heat stress probability, with the objective to help urban planners in deciding where to place the GI considering the global cost-benefits results [8].

In this work, the methodology developed in previous works is applied to the cases of Rome, Catania, Santiago de Chile and Viña del Mar, evaluating the capability of GI to reduce cooling loads and indoor heat stress as well as the accuracy of ML process to predict the results for new cases.

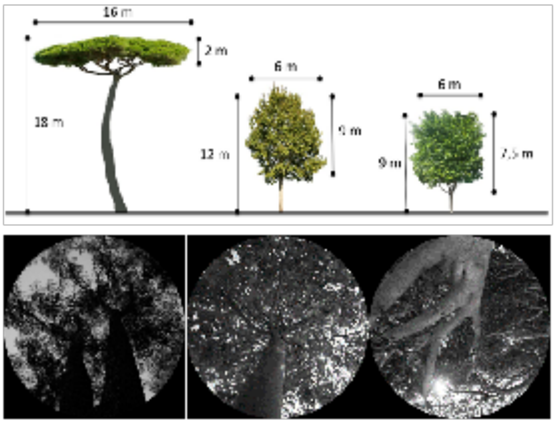
2. METHODOLOGY

To establish the capability of a GI to reduce cooling loads and heat stress probability, we followed a three steps methodology. Firstly, some real case studies has been considered (Catania, Roma, Santiago de Chile, and Viña del Mar) and a classification of effective building-trees configurations has been obtained. This process includes the identification of typical urban morphologies and buildings' shapes and design of linear GI configurations to be placed to an appropriate distance from the building's façades.

Secondly, the interaction building-trees has been modelled by using shadow masks in TRNSYS Studio version 17. The trees are represented as simplified solar shadow elements with a permeability to sunlight obtained by field assessment using fish-eye images and Gap Light Analyzer (GLA) software to process the radiation data [9]. Finally, a set of simulations was run out to obtain the base case (without trees) and the configuration performance. Buildings were modelled in TRANSBUILD type of TRNSYS and simulation was run with TRNSYS Studio.

Once obtained the simulation results, a ML technique was developed to predict the cooling load and the probability of heat stress occurrence for new configurations. We tested different algorithms to obtain two different classifications: one with a single value (15% energy saving and heat stress probability reduction) and the other with a five categories strategy to indicate the estimated amount of reduction obtained with the GI.

Figure 2:
Trees' morphology and solar permeability



Simulations were done in Mediterranean climates, characterized by slightly different behaviour determined by latitude and coast distance: Catania (Mediterranean semi-arid, on the Mediterranean Sea), Rome (Mediterranean, at 20 km from the Mediterranean Sea), Santiago de Chile (Mediterranean-continental, at 100 km from the Pacific Ocean), and Valparaiso-Viña del Mar (Mediterranean semi-arid, on the Pacific Ocean).

Weather files for selected locations have been obtained from the webpage climate.onebuilding.org [10,11] and modified by using Urban Weather Generator (UWG) tool to consider the urban heat island effect of the sectors. UWG tool was developed by Bueno et al. [12] and updated several times to improve accuracy of the prediction [13,14]. It was tested in different climates [15,16,17] locations and permits to realize parametric studies on the influence of urban form on microclimate.

UWG needs for many inputs for running. Most important are: inputs on urban morphology (as built up area, façade to site ratio, average building height, green areas, albedo values for all surfaces, anthropogenic heat production in the urban sector). Here we focused on morphological parameters to generate the representative urban weather file. Anthropogenic heat and albedo values have been left as a fixed value across the cases.

Urban heat island intensity has been found to be higher in Santiago than in the other cases. The phenomenon is positive at night and slightly negative during the day. Table 1 resumes the parameters values used for UWG simulations and table 2 shows the max and min values of UHI intensity for all locations.

Table 1:
Parameters used in UWG simulation

Location	Built Area	Fac. ratio	H (m)	Green Area
Tor Bella Monaca	0.11	2.64	24	0.25
Casale Caletto	0.12	0.62	15	0.08
Trimesteri Etneo	0.19	0.88	12	0.05
Les Condes	0.15	0.73	15	0.27
Benidorm	0.07	0.36	12	0.24

Table 2:
UHI intensity for locations studied

Location	Max UHI	Min UHI
Tor Bella Monaca	3.7	-1.0
Casale Caletto	2.4	0.6
Trimesteri Etneo	2.8	-1.1
Les Condes	6.1	-1.5
Benidorm	2.0	-0.4

2.1 Selection of urban compounds

Urban compounds to be studied were selected among urban development sectors since the ’60 decade until today in Rome (Tor Bella Monaca and Casale Caletto), Catania (Tremesteri Etneo), Santiago de Chile (Las Condes) and Viña del Mar (Benidorm). The analysis conducted on the sectors leaded to the selection of 40 specific configurations, considering the availability of space to plant trees, the building morphology and the green areas already present in the sector (figures 3-7).

Figure 3:
Casale Caletto compound and configurations analysed

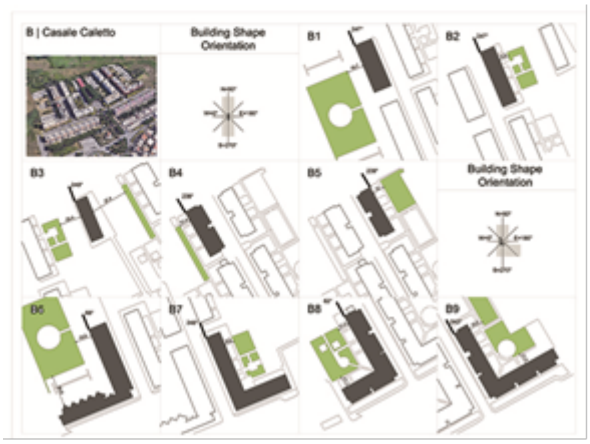


Figure 4:
Benidorm compound and configurations analysed

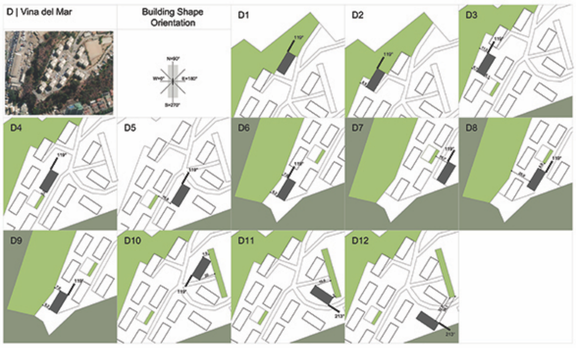


Figure 5:
Las Condes compound and configurations analysed

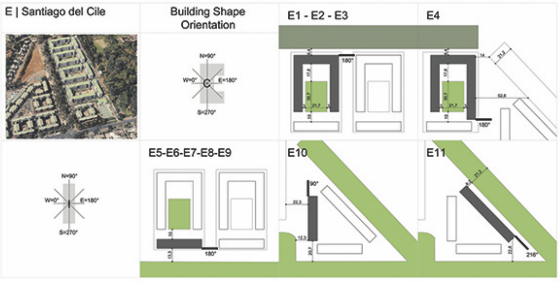


Figure 6:
Tor Bella Monaca compound and configurations analysed

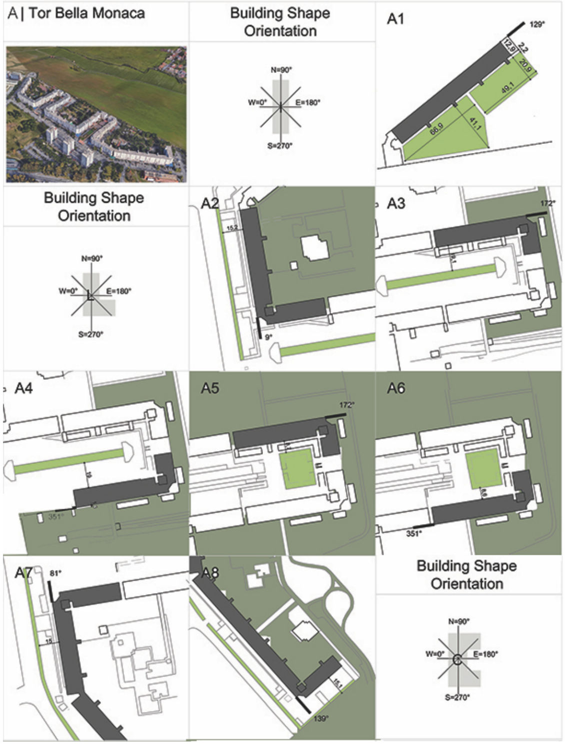
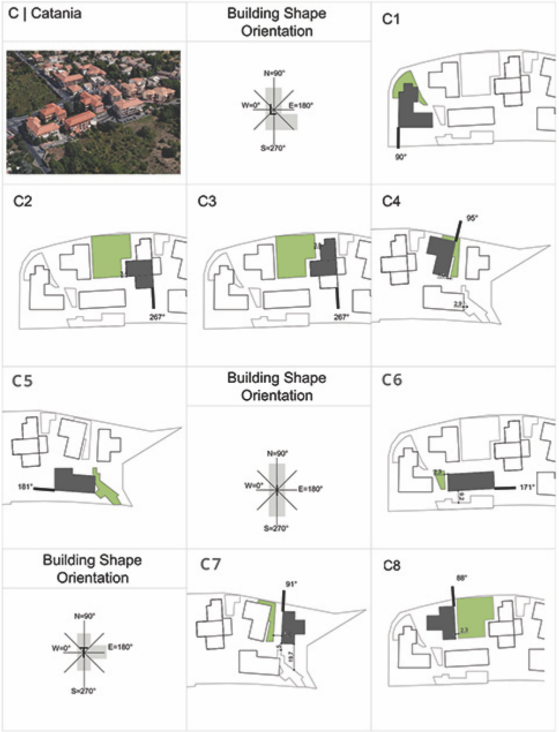


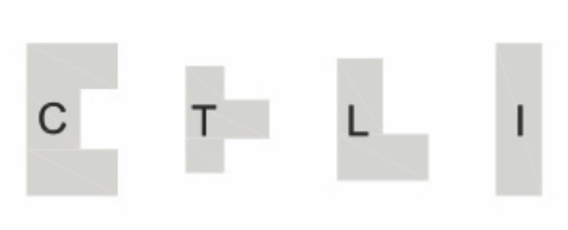
Figure 7:
Trimesteri Etneo compound and configurations analysed



2.2 Simulations of cooling loads

To simulate the cooling loads, buildings of selected compounds were firstly grouped in standard types by plan shape. We used “T”, “C”, “L” and “I” typical shapes. Each shape has its standardized dimensions and internal distributions. Figure 8 shows the plan shape of typical buildings.

Figure 8:
Standard building shapes considered in this study



Simulations consider standard materials used in Mediterranean climates, with solar absorptions and thermal transmittances for walls and roofs resumed in table 3. Windows to wall ratio depends on the building form, as shown in table 4. For all cases, radiation control was considered to simulate the use of blinds or other internal system. Table 5 shows operational settings used.

Table 3:
Envelope values for all buildings

Element	Construction	Thermal transmittance (W/m^{2}K)	Solar absorption or g-value windows
Walls	Bricks - XPS	0.56	0.60
Flat roofs	Conc. - XPS	0.32	0.60
Windows	Alum. single	5.80	0.86

Table 4:
Windows to wall ratios for building tyipes

Shape	Floor surface	Window/wall ratio main fac	Window/wall ratio other
I	480 m^2	20%	7%
C	800 m^2	20%	20%
T	400 m^2	20%	15%
L	528 m^2	20%	20%

Table 5:
Operational settings used in the study

Description	Schedule or control	Value
Light gains	18-22 h	5 W/m^2
Cooling set point	0-24 h	26 ˚C
People	0-24 h	1 met
Occupancy	0-24 h	50 m^2/p
Solar shading open	120 W/m^2	1.0
Solar shading closed	140 W/m^2	0.4

In TRNSYS, shadows are simulated as geometrical masks obtained by projecting the inclination angle for minimum and maximum solar incidence on each floor. The point to see the sky or the tree was set into the middle of the façade (figure 9). Equations (1)-(6) show the calculation procedure to obtain the inclination angles.

$$\boldsymbol{\alpha_{min} = arctan\frac{a_{min}}{b}} \qquad (1)$$

$$\boldsymbol{\alpha_{max} = arctan\frac{a_{max}}{c}} \qquad (2)$$

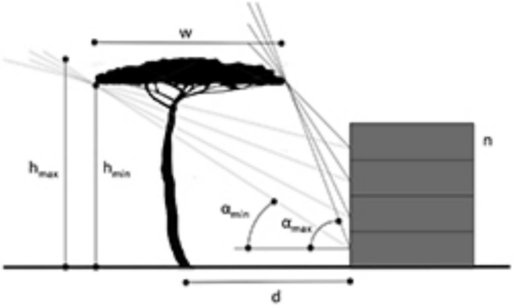
$$\boldsymbol{a_{\min(n)} = h_{min} - [1.5 + 3 \times (n-1)]} \qquad (3)$$

$$\boldsymbol{a_{\max(n)} = h_{max} - [1.5 + 3 \times (n-1)]} \qquad (4)$$

$$\boldsymbol{b = d + \frac{w}{2}} \qquad (5)$$

$$\boldsymbol{c = d - \frac{w}{2}} \qquad (6)$$

Figure 9:
Shadow mask calculation



2.3 Machine Learning

Once obtained simulation results, a machine learning strategy was developed to predict, based on certain numbers of predictors, the final cooling load reduction that can be reached by planning trees in a determined configuration. As a continuous prediction of cooling load is difficult to be obtained, we developed a classification method to divide the configurations in categories. In a first attempt, we used a 15% of reduction in cooling load as the threshold value to be used. In a more interesting attempt, we established five ranges: very low saving (0-5%), low saving (5-15%), medium saving (15-25%), high saving (25-35%) and very high saving (more than 35%). We used different algorithms to predict the results: Loess, Random Forst, KNN, GLM and a combination (ensemble) of all them. Respect to predictors, we used: climate classification, type of urban environment, altitude, latitude, sea distance, number of floors, number of façades on shadow, plan shape, orientation, distance, and tree species.

3. RESULTS

Simulation results show that the energy savings that can be reached in summertime are in a range 2-60%. Figure 9 resumes the values for 120 simulations (40 representative configurations, 3 species of trees). Figure 10 shows the average savings obtained by location, divided by tree species.

Figure 9:
Base case and improved case (with trees) cooling loads

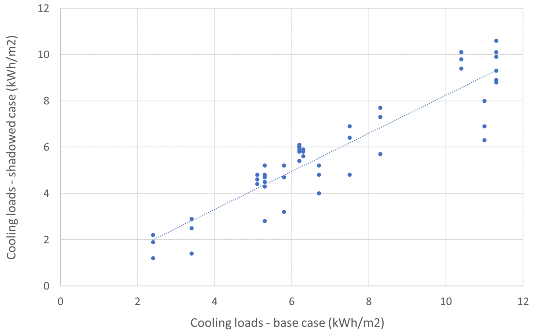
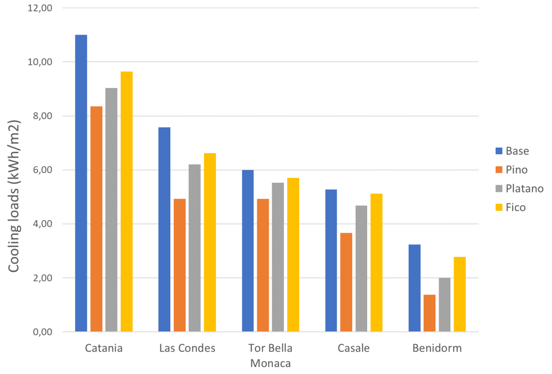


Figure 10:
Average cooling loads by location and tree specie



Looking at figure 10, it is immediate to notice that Benidorm has a summertime energy demand quite lower than other cases, around 2-3 kWh/m^2. In the sectors of Rome, cooling loads of the base case are around 5-6 kWh/m^2 year, while in Santiago loads are around 6-8 kWh/m^2 year. The hottest location is Catania, with summer cooling loads of 10-11 kWh/m^2. Influence of Pacific Ocean's breeze and latitude are the most relevant factors for this.

If the savings over 45% belongs to the case of Benidorm, where cooling loads are low even without shading, the range 2-45% apply to all studied cases. There is a big difference among 2% or 45% of cooling load reduction. So, it is interesting to understand which are the most influencing factors that explain these results.

Among the cases studied, Tor Bella Monaca is clearly the case more difficult to be shadowed. This is obvious because of the number of floors (8) of buildings in this sector, compared with the others (5-4 floors). West façades are confirmed as important façades to be shadowed, and "I" buildings are detected as easier to be shadowed respect other shapes buildings. The case of Santiago is particularly interesting because of the UHI intensity of the sector.

Green infrastructure can be used as a mitigation/adaptation strategy to reduce the impact of urban heat in the city. Table 6 resumes the number of cases analysed and the performance achieved in a 5-categories classification.

Table 6:
Classification of cooling reduction in 5 categories

Location	Very low	Low	Medium	High	Very high
Bella Monaca	3	7	1	0	1
Casale	2	14	8	0	6
Trimesteri	1	5	3	1	2
Les Condes	0	11	5	9	5
Benidorm	0	2	12	10	12
TOTAL CASES	6	39	29	20	26

More than the half of cases have a result higher than 15% reduction in cooling loads, confirming the findings of previous studies [18]. More than one third of the cases present a saving higher than 25% of cooling loads reduction. This allows stakeholders to invest in green infrastructure projects, whit a return of investment guaranteed in a relatively short time lapse.

Machine learning resulted to be quite accurate, achieving the extraordinary result of a 96% of accuracy in a binary categorization process. While a 5-categories classification is required, the accuracy is quite lower but still acceptable for the ensemble of algorithms (75%).

Among algorithms, best results are achieved by the ensemble and by random forest procedure. Random forest is particularly interesting because the output information includes the priority of predictors, putting in evidence that the number of façades on shadow is the key factor to predict the performance. This result is perfectly in accordance with previous studies [19] and with our interpretation of simulation results. The algorithm used the predictor "number of façades on shadow" in the first places of the decision tree, followed by "tree specie", "distance from the sea", "altitude", and "distance from the façade".

4. CONCLUSION

This paper showed how the development of a green infrastructure can help to prevent overheating in buildings and to reduce energy use for cooling during summertime in Mediterranean climates. This benefit must be accounted in a general analysis to establish the convenience to plant trees in urban environments. Green areas has certainly some costs, due to maintenance, water consumption and the process of planting, however the benefits in terms of several ecosystem services provided to the inhabitants shows that the development of a green infrastructure is almost always convenient.

Building performance simulation can be used as a part of the cost-benefit accounting in establishing where to place a green intervention. Machine learning processes can be useful to reduce time to be spent in simulations, allowing technicians to quickly obtain a first assessment of the convenience of the trees under an energy use point of view.

Future works will regard the simulation of different macroclimatic locations, where other factors take more importance: seasonality, heating loads increase, water needs for trees, among others.

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