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Numerical optimisation through dynamic simulation of the position of trees around a stand-alone building to reduce cooling energy consumption

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ABSTRACT

Numerical optimisation through dynamic simulation should consider the influence of urban microclimate on the energy balance of buildings, to reduce the energy consumption of the residential sector, even if a full interaction of the two different simulative resolutions is still under development. The current study employs free software readily available and widespread in professional practice to explore the currently available possibilities to analyse the dynamic interaction between microclimate and building. It combines dynamic simulation, parametric design and genetic algorithms to identify the optimal position of trees around a 1-floor and a 2-floors building, located in Rome, as a function of the maximum reduction in energy consumption for cooling during summer season (from 21st June to 22nd September), taking into account only the shading effect of trees. The results confirm the significant influence of vegetation's shading effect for energy savings: energy consumption in the 1-floor building decreases from 11.1% for the 1-tree configuration up to 44.4% for the 5-trees configuration; in the 2-floors building, the reduction goes from 12.8% up to 48.5%. For each configuration, the optimised positions generally favour the east and west sides. The optimised positions of the first two trees have a paramount effect on energy consumption reduction, above 20% in both models, while there is a sharp decrease in energy consumption reduction between 2-trees configurations and 3-trees configurations.

1. Introduction

Rational use of energy in the building sector represents a relevant issue for the sustainable regeneration of European cities, as the existing building stock in Europe accounts for over 40% of the global demand of primary energy [1]. The significance of energy consumption for cooling is expanding, following an increase of air conditioning plants installed and cooled floor area in the EU by more than 50 times, from 1990 to 2015 [2,3].

Strategic decisions on the early stages of the design process have a notable impact on buildings' overall energy performances. During initial phases, numerical simulations can therefore represent a key tool to improve energy efficiency, providing a simplified model of the building behaviour, reduced to a certain level of abstraction [4–6]. There is a strong trend in contemporary architecture integrating numerical simulation to parametric design, which is based on design variants connected to each other through mathematical relationships [7]. In fact, parametric simulation considerably extends the possibility for sensitivity analysis of the energy performances of single or grouped variants, because a massive number of alternatives can be obtained modifying the mathematical relationships defining each variant [8,9]. However, this approach can drastically increase model complexity and calculation time [10]. In order to restrain these limitations, the use of optimisation algorithms in the building simulation process is rapidly increasing [11]. Optimisation algorithms explore alternatives with the highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones. In building performance simulation, finding the global optimal solution can often be impracticable, due to the nature of the problem or the simulation programme used [12]. Nevertheless, available local optima, which are optimal within a neighbouring set of candidate solutions, are still considered an improvement over non optimisation [13]. Moreover, a series of local optima allow the designer the freedom to choose from a range of energy efficient alternatives, which may be more or less functional in relation to other factors involved in the decision-making process [14]. Among the optimisation algorithms, the genetic algorithms or evolutionary algorithms

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(GA) are a class of mathematical optimisations that mimics natural biological evolution and utilises the process of inheritance, mutation, selection and crossover to determine the best solution [15]. The base principle of GA consists in involving a population of candidate solutions, called *individuals*, through generations, to fit the most a given objective [16,17]. These algorithms can efficiently handle non-linear problems with discontinuities and many local minima and are mostly used for global searching [13,18,19].

Numerous simulation studies [13] have focused on the energy efficiency of buildings and HVAC systems, to optimise their overall performances for heating, cooling and lighting. They mostly considered buildings as self defined entities, underestimating the influence of surrounding urban elements on the energy transfer and airflow movements through the envelope [20,21]. This simplification partly depends on technical difficulties, still present in simulating the building in its microclimate at different model scales resolutions [22–24]. However, within the Urban Canopy Layer (UCL), which approximately extend from the ground to the rooftops of buildings [25], there is an interrelation between indoor and outdoor thermo-hygrometric conditions, as urban design factors have a substantial effect on microclimate, which reflects on the building energy balance and energy consumptions [23]. Urban geometry (i.e., the shape and position of buildings), urban materials and natural elements, such as water and vegetation, together with anthropogenic heat, affect short and long-wave radiation fluxes and air movements, shadowing direct solar radiation from building envelopes and modifying the heat exchange between building surfaces [26–30].

Following these assumptions, recently more and more studies are concentrating on the effect of urban microclimate on building energy consumptions during summer for different climates, focusing on the shading effect of urban geometry to restrict solar access on the building envelope. In fact, solar access has a very high influence even on limited spatial variations, as it causes a pattern of shaded–unshaded surfaces with highly variable temperatures [31]. Bouyer et al. [23] analysed the influence of microclimatic context on building performances, concluding that solar irradiance is the most influent parameter on the building energy consumption. Similarly, comparing the space cooling and heating demands for a stand-alone building and buildings in an urban street canyon for the city of Basel, Allegrini et al. [24] highlighted the relevance of radiation exchange between neighbouring building surfaces. According to Ali-Toudert [32], for both mid-latitude and sub-tropical locations, the internal cooling needs of a single building decrease with the reduction of street height/width ratio. Krüger [33] corroborated these findings for hot-arid climate, observing a significant drop in energy demand for air-conditioning for deeper street canyons, consistent with results for thermal loads on pedestrians in the street. Lam et al. [34] remarked a 14% reduction of cooling demand for the shaded building for peak design conditions, simulating the energy performance of the same building in an open field and in an urban environment with shade from the surrounding constructions.

Another urban design parameter that has a significant impact on solar access, especially for stand-alone buildings in low-density areas, is vegetation [20]. Trees have a very complex physical behaviour, which can reduce building cooling load in summer, both directly and indirectly. Their main direct effect is the reduction of short and long-wave radiation fluxes through the envelope by shading. Sunshine radiation transmission through a tree canopy depends on the shape, dimension and Leaf Area Density (LAD) of the single plant, i.e. the portion of leaf surface in m^2 within a m^3 of air; at any rate, during summer, between 10% and 30% of sun energy generally reaches the base of a tree [35]. Indirectly, trees lower the dry-bulb air temperatures and increase latent cooling due to the addition of moisture to the air through evapotranspiration processes, which are the sum of evaporation and plant transpiration [36–38]. Moreover, a notable fraction of solar energy is absorbed by the leaves for photosynthesis, without increasing their surface temperature [35]. However, there are also drawbacks in the use of plants for passive cooling of buildings: they can reduce air infiltration by modifying wind speed and direction and they can limit nocturnal thermal losses, blocking outgoing long-wave radiation fluxes with large canopies [39].

Several empirical studies demonstrated the impact of trees on outdoor microclimate for different climates [40–44]. Few researches monitored their quantitative effect on indoor thermo-hygrometric conditions and energy savings [45,46], but simulation analysis are scarce, due to the above-quoted difficulty of simulating the building in its microclimate and the specific vegetation behaviour [47,48].

Following these lines of research, the aims of the present study are to:

- integrate the simulation scales of building and its outdoor microclimate, to perform a numerical assessment of the influence of tree shading to reduce the building energy consumption for cooling;
- couple dynamic multizonal simulation, parametric design and genetic algorithms to determine the optimised positions of trees around the building to maximise energy savings.

2. Methods

2.1. Used simulation tools

The current study employs free software readily available and widespread in professional practice to explore the currently available possibilities to analyse the dynamic interaction between microclimate and building. The software used for the simulation analysis is *EnergyPlus*™, which is one of the most commonly used for building thermal dynamic analysis and is particularly suited for optimisation studies, thanks to the text-based format of inputs and outputs that facilitates coupling [13]. We perform energy consumption calculations by modelling cooling loads with the ideal HVAC, in order to avoid complex input data, which have minor importance in the early design stage. The problem at hand is represented by a rather simplified model, with a single thermal zone and reduced input data, allowing the process of a large number of design alternatives on a standard personal computer [14].

The chosen energy modelling type is connected, through the 3D graphic software *Rhinoceros*™, its parametric design plug-in *Grasshopper*™ and the plug-ins *Honeybee*™ and *Ladybug*™ [49], to the *Grasshopper*™ in-built GA optimisation algorithm *Galapagos*™ [16], as in previous studies [50–52]. The joint use of *Rhinoceros*™ and *Grasshopper*™ befits the task of exploring simulation alternatives, thanks to their ease of use, speed of processing and level of diffusion, which allows designers with no formal scripting experience to quickly generate parametric forms [7].

Within *Galapagos*™ GA, it is possible to define a fitness function that either minimises or maximise a single or a group of variants; the algorithm explores a population of individuals, represented by design alternatives, mating and selecting them in order to find local or global optima solutions. The mechanism for the selection of individuals is the *biased selection*, where the chance of mating increases as the fitness increases. The in-breeding factor (i.e., the distance of the mates used for the coupling algorithm) is 75%, to guarantee mate variety and limit incompatibility. The mechanism of gene transmission to the offspring is the *blend coalescence* mechanism, which computes new values for genes averaging the values of both parents, adding a blending preference based on relative fitness. To