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Evolutionary-driven search for solar building models using LiDAR data

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ABSTRACT

The search for solar buildings is one of the primary challenges in urban planning, especially when developing self-sustainable cities. This work uses an evolutionary approach for finding the optimal building model based on airborne Light Detection And Ranging (LiDAR) laser-scanned data, regarding solar potential. The method considers self-adaptive differential evolution for solving the constrained optimisation problem. In the experiments, the effect of different buildings' layouts and design parameters were analysed regarding solar irradiance. Rectangular, T and L-shaped buildings were considered with various design parameters: position, building rotation, facades' height, roof's height and slope. The experiments confirmed that the method can efficiently find the solar building design with maximum solar potential within constrained optimisation space.

1. Introduction

Solar energy is one of the most available renewable and clean types of energy [1]. Nonetheless, its great potential for electrical energy generation remains widely unutilised. In order to develop low energy buildings for self-sustainable cities, reduce carbon emissions or maximise passive solar heating, it is vital to know how to maximise solar energy utilisation. Solar energy is normally actively converted into electricity using photovoltaic (PV) systems. Since the recent development of cheaper and more efficient PV modules [2,3], these systems have received significant positive attention. They are commonly installed on buildings' roofs, where it is generally considered that a surface oriented towards the Equator with a tilt angle equal to a location's latitude is optimal for solar energy utilisation [4]. However, this is often not the case due to local climatic conditions [5] and the influence of shadowing from terrain and man-made objects that decrease the received irradiance. Therefore, the optimal slope and orientation of a PV system attached onto a building's surface presents an optimisation issue for investors, as well as for architects, urban planners and civil engineers who want to assess the solar energy potential of rooftops, renewable energy integration into buildings and the carbon footprint of buildings.

Over recent years several methods have been developed in order to address this issue by modelling solar irradiance on a given surface. This is an increasing problem for energy-efficient building design and for finding the most suitable building's surfaces for PV systems' placements. Some studies [6–8] only consider self-shadowing and not the shadowing from surroundings. This is evident when considering the modelling of buildings within urban areas, where solar radiation obstructions are more common [9]. With the advancement of remote sensing technologies, such as Light Detection And Ranging (LiDAR), new methods have been developed for buildings' irradiance modelling and for estimating the solar potential of buildings' roofs [10]. LiDAR is an active remote sensing technology that can be mounted on an aircraft in order to scan the Earth's surface using laser pulses. The resulting LiDAR data is presented as an unstructured set of 3D points (i.e. point cloud).

Various studies have been conducted in the search for the most efficient solar building design. Most methods [11,6–8,12–14] consider a selected range of parameters (e.g. predetermined roofs' slopes). Others [15–18] have considered automatic approaches that are presented as optimisation problems. This is generally solved by evolutionary-driven algorithms. Hachem et al. [7] performed a parametric investigation of building design regarding solar potential. In another study [6], the authors developed a methodology of neighbourhood design that included streets' and different buildings' shapes, and their positions in order to avoid mutual shading. Furthermore, they used this methodology for evaluating the energy supply for neighbourhoods housing [8]. Energy demand was compared with the solar potential of different neighbourhoods by considering heating and cooling requirements. Kämpf et al. [16] presented a new evolutionary algorithm for optimising solar irradiation availability. Its performance was compared with several related evolutionary algorithms, including DE. They searched for optimal positions for multiple buildings but did not consider their

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Nomenclature

$\vec{x}$	population vector
f	fitness function
H_i	upper bound
I_c	solar potential for a cell at a given time
I_g	global solar irradiance
I_{c_b}	terrestrial direct irradiance of a given cell
I_{c_d}	terrestrial diffuse irradiance of a given cell
J_c	daily solar insolation of a given cell
L_i	lower bound
Mi	i-th location at mountainous LiDAR dataset
S_c	shadowing coefficient
Ui	i-th location at urban LiDAR dataset
x_i	i-th element of the population vector $\vec{x}$

Abbreviations

CR	crossover rate
DE	differential evolution
F	amplification factor of the difference vector
G	generation
IDW	inverse distance weighting
LiDAR	light detection and ranging
P	population size
PV	photovoltaic
SPA	solar positional algorithm

design. Moreover, Kämpf et al. [17] presented a new methodology for optimising building and urban geometric forms for the utilisation of solar irradiation. Kämpf et al. [18] proposed an alternative evolutionary algorithm, a multi-objective optimiser, in order to optimise several parameters, such as building's height, roof's height and its orientation. The main objective was to maximise available solar irradiation for new urban forms. Ouarghi and Krarti [15] presented the optimisation of an office building's shape regarding energy and construction costs using a genetic algorithm and an artificial neural network. Esch et al. [12] studied the influence of street and building design parameters such as street width, orientation and building's envelope design regarding the received solar energy. Ling et al. [11] investigated the effect of the geometric shape and orientation of high-rise buildings in order to minimise solar irradiation. Hwang et al. [13] examined the maximisation of solar irradiation utilisation for high-rise buildings with installed PV systems. In their study they analysed the effects of the inclination and direction of PV systems, as well as the distance to the module length ratio. Roohollahi et al. [19] inspected solar energy gain on seven 3D geometries during different months of the year. Kanters and Wall [14] studied the effect of various building blocks' design including urban density on the received solar radiation. To our knowledge none of these methods have considered LiDAR data in order to estimate solar efficient buildings.

Several methods have been developed for solar radiation modelling [20] that mainly differentiate on the estimation of the diffuse irradiance. During recent years, a number of methods for solar potential estimation have been developed that consider topography from LiDAR data [21–29,10,30–32]. With the advancement of remote sensing technologies and evolutionary computing, new methods can be developed for solving the irradiance optimisation problem regarding building design, by considering real data.

This paper presents a novel optimisation of a building model using LiDAR data, in order to maximise a building's received solar irradiance by finding the most solar-efficient design. The usage of LiDAR data allows us to perform the search for optimal solar building within a real urban environment, where several optimisation constraints (e.g. shadowing from buildings and terrain, local climate, and terrain topography) are considered. The real environment, provided by LiDAR data, presents a difficult problem when searching for global optimum regarding solar potential, as there are many factors that affect it. Moreover, the optimisation of a building's model is a high-dimensional problem with multiple parameters to be considered, where manual inspection would be exhausting. Although many other optimisation algorithms could be used, DE (differential evolution) [33] was selected, as it is an evolutionary method for finding global optimum within a reasonable time even when the problem space is large and contains many local extremes. The presented method consists of two core stages. During the first stage the user provides a specific building model that is integrated into existing LiDAR data. During the second stage the optimisation problem is solved by using self-adaptive DE [34]. This method considers the following optimisation parameters for building modelling: orientation, height, location and roof's height and slope. The maximisation criterion is the estimated solar irradiance [10] based on shadowing from surrounding objects, terrain and vegetation, as well the local climate conditions that are captured by the long-term diffuse and global on-site irradiance measurements using a pyranometer.

The paper is structured into 4 sections. The next section describes the proposed method for optimising solar building design. The results of the experiments are presented in Section 3. The last section concludes this paper.

2. Method for modelling solar-efficient buildings

The proposed method is described in detail in the following subsections. Section 2.1 presents parameter-based building modelling, whilst Section 2.2 describes the used evolutionary approach. The approach is based on the self-adaptive DE with heuristics that speed-up the search for the most solar efficient building model within the constrained solution space.

2.1. Building modelling within LiDAR data

The method's input is the georeferenced LiDAR point cloud, where each point is classified as either building, terrain or vegetation [35–37], as shown in Fig. 1a. Firstly, the point cloud is arranged into a regular 2.5D grid. In order to improve the accuracy of the solar potential estimation for each building, the empty cells (i.e. without points) are interpolated using the inverse distance weighting (IDW) method [38]. The height of each cell is defined by the highest point of the point cloud's subset located within the given cell. Fig. 1b shows the 2.5D grid together with a polygonal building model.

A user-defined building is interactively modelled in two steps. Firstly, the user imports a 3D building model, which is then converted into virtual 2.5D blocks that define the building's shape from the top-down perspective. The width and length of a block are defined as a multiple of the grid's resolution. The building's shape from this perspective remains constant throughout the optimisation process. In the next step all blocks are normalised and placed at the same height as the lowest block in order to embed the building onto the surface. The rest of the building's design is defined by several key parameters: position, building rotation, facades' height, roof's height (i.e. vertical distance from walls to the ridge) and slope, as shown in Fig. 1b. The building's position is within the area of interest for the building's location. The area of interest is defined as a polygonal area on the grid selected by the user. The building's rotation is considered around the centre of its bounding box. The roof's height allows alternation of the rooftop design from the ridged to a flat horizontal surface at a given roof height. The roof's