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Design and layout optimisation of a pair of buildings regarding their solar potential

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Abstract

Urban planners are often faced with the formulation of plans for multiple buildings, where they need to consider the available solar energy. Presented work tackles this problem using an evolution-based algorithm in combination with modelling of buildings within a real environment that was captured with laser-based LiDAR (Light Detection And Ranging) technology in order to optimise the design and layout of a pair of buildings regarding their solar potential. To solve the constrained optimisation problem the self-adaptive differential evolution (DE) is considered. The method was tested with a pair of rectangular buildings on a hilly LiDAR dataset, where the influence of shadowing between buildings and additional design parameters (the distance between buildings and orientation of the building pair) was analysed.

Keywords: *Solar potential, LiDAR, Buildings, Differential evolution*

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1. Introduction

Solar energy has an important role for the development of sustainable urban areas. Buildings are accounted for 40% of total European energy consumption and a considerable amount of carbon emissions (Parliament, 2010). With appropriate utilisation of solar energy and effective solar building design we can significantly reduce carbon emissions and maximise passive solar heating as well as electricity production. Hence, the layout of buildings within urban areas needs to be planned with the available solar energy in mind. This can be difficult for urban planners, especially when designing layouts of buildings in a real environment, where the availability of solar energy can be affected by many factors, such as shadowing from surroundings (e.g. man-made objects, vegetation or terrain), local climate and terrain topography. Difficulty increases with the number of buildings planned to be build. Before we can optimise more buildings, it is imperative to know how to optimise a single building regarding its solar potential.

In the past few years, several approaches have been developed for the optimisation of a solar building (Bizjak et al., 2015; Hachem et al., 2011a; Ouarghi and Krarti, 2006). When another building is considered, further factors need to be considered, such as mutual shadowing and relative position. Various studies have focused on optimising the design of residential neighbourhoods regarding the availability of solar energy at the urban scale. Some (Hachem et al., 2013, 2012, 2011b; Kanters and Horvat, 2012) manually inspected parameter space using predefined values, whilst others (Kämpf and Robinson, 2009; Kämpf et al., 2010) used automatic approach. None of them considered actual environment from real locations or focused on the layout of a pair of buildings.

Hachem et al. (Hachem et al., 2011b) developed a methodology for the investigation of the influence of two-storey housing units design parameters and neighbourhood patterns on the received solar irradiance. They investigated straight and curved roads as site layouts. Later they (Hachem et al., 2012) investigated solar

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potential and energy demand for heating and cooling of housing units. Their work continued in 2013 (Hachem et al., 2013) where previously developed methodologies were used to perform a parametric study to develop a design methodology for solar residential neighbourhoods based on an evaluation system that uses weighted objectives method. Kanters and Horvat (Kanters and Horvat, 2012) studied the impact of geometry form of urban blocks regarding the solar potential. Kampf and Robinson (Kämpf and Robinson, 2009) proposed a novel evolutionary approach for optimising the placement of buildings regarding the availability of solar irradiation. However, buildings' design was not considered. Kampf et al. (Kämpf et al., 2010) developed a multi-objective optimisation algorithm to optimise geometric parameters of building design on a range of urban typologies.

In this work we present a novel optimisation of the design and layout of a pair of buildings within LiDAR data and investigate the influence of geometrical design parameters of a pair of buildings on the received solar irradiance. To our knowledge, this is the first method for the optimisation of a pair of buildings to consider environment of real locations. Real environment is provided by LiDAR (Light Detection And Ranging) data. LiDAR is an active remote sensing technology that scans surface topographies and is normally mounted on an aircraft. The result of such scanning is an unstructured point cloud. As manual inspection of parameter space is exhausting, an evolutionary approach is used to perform the optimisation based on the methodology used in (Bizjak et al., 2015). The proposed method is therefore performed in two stages. In the first stage, user provides the footprint of a building model, which is then used as a base model for both buildings modelled within LiDAR data. During the second stage the pair of buildings is optimised with a modified self-adaptive differential evolution (DE) (Brest et al., 2006). The optimisation criterion is the cumulative estimation of solar potential (Lukač et al., 2013) of both buildings. Next to the design parameters of a single building model we consider the following optimisation parameters: the distance between the pair of buildings and orientation of the pair.

The paper is structured into four sections. The next section describes the proposed method. The third section presents the results and the last section concludes this paper.

2. Design and layout optimization of a pair of buildings

The following subsections describe the proposed method in detail. Subsection 2.1 details the method for the optimisation of a solar building, which is the base for the proposed method. The next subsection describes the design and layout optimisation of a pair of buildings.

2.1. Basic method for the optimisation of a solar building

The basic method's input is a classified LiDAR (Light Detection And Ranging) point cloud (see Fig 1a) that is arranged into a regular 2.5D grid, where each cell is defined by the height and classification of the highest point in the cell (Bizjak et al., 2015). The empty cells are interpolated with inverse distance weighting (IDW) method (Shepard, 1968). Points are classified as either building, ground or vegetation. The utilisation of LiDAR data enables us the optimisation within a real environment, where the influence of the local climate, terrain topography and shadowing from buildings and terrain are considered. Buildings are then modelled on the 2.5D grid, where the following design parameters are considered: position, rotation, facades' height, roof's height and roof's slope, as shown in Figure 1b. Buildings' position is bounded by an area of interest, which is defined as a user selected polygonal area on the grid. When modelling is completed, the building is rasterised into the 2.5D grid (see Figure 1c), where the highest point of the roof over each covered cell is considered. The cells of the rasterised building represent the input to the method for solar potential estimation (Bizjak et al., 2015), which is the considered optimisation criterion. An evolutionary approach is considered for the optimisation of a building model regarding the received solar potential, based on methodology used in (Bizjak et al., 2015). Evolutionary algorithms are inspired by biological evolution (Brest et al., 2006). One of them is differential evolution (DE) which is a direct parallel search method developed by Price and Storn (Storn and Price, 1997) that operates with P n-dimensional vectors $x_{i,G}; i = 1, \dots, P$ as a population throughout the optimisation for each generation G. Each vector goes through mutation, crossover and selection operations in a single generation G. During the mutation and crossover new candidates are generated, while selection regulates which vector survives the current generation. The decision regarding which candidate is selected is based on the estimation of solar potential which is described in the next section.

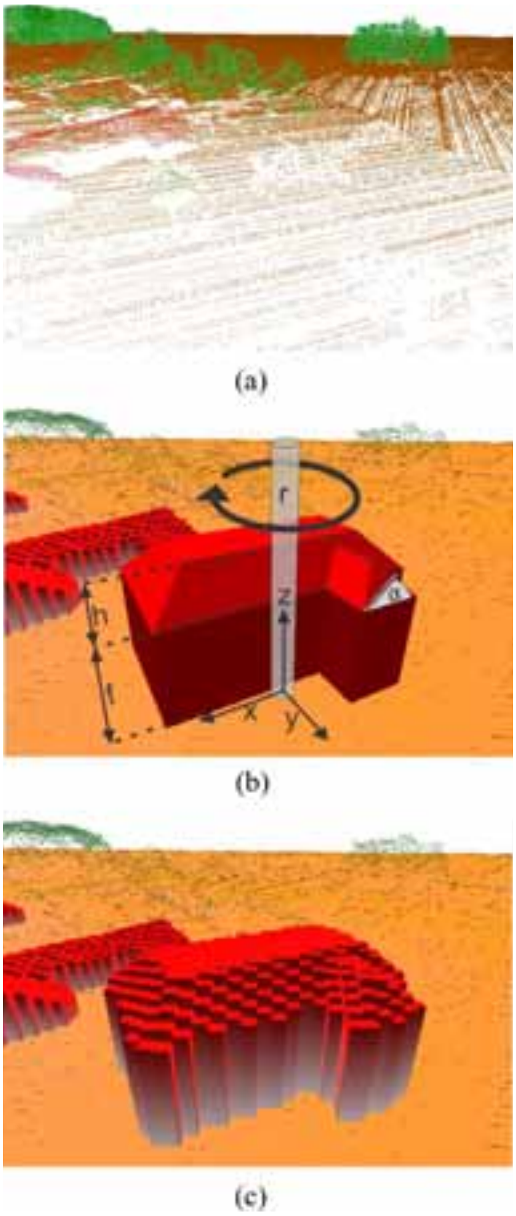


Figure 1: (a) Classified LiDAR point cloud; Building model on a 2.5D grid with the following building design parameters: r-rotation axis, f – facades' height, α – roof's slope and h – roof's height; (c) Cells of the rasterised building (Bizjak et al., 2015).

2.2. Building pair's solar potential maximisation

The optimisation method in (Bizjak et al., 2015) focuses only on the design of a single building, which is why this paper proposes a novel extension to the method's capabilities to assess the optimal design and layout of a pair of buildings. With an additional building, the influence of shadowing between buildings and the placement of a pair of buildings on a user defined area of interest can be estimated, in order to maximise the received solar irradiance. This is performed by introducing additional design parameters: the orientation γ of the pair of buildings and the distance d between the pair. The pair of identical buildings is parallel for any orientation angle. Two types of layouts of a building pair are considered. For the first layout type, the buildings lie on two parallel lines (see Figure 2a and equation 2) and for the other the buildings lie on the same line (see Figure 2b and equation 1). The lines for the layouts are defined as follows:

$$y = \tan(\gamma)\, x + y_P - \tan(\gamma)\, x_P \qquad \text{(eq. 1)}$$

$$y = \tan(\gamma)\,x + y_P - \tan(\gamma)\,x_P \pm \frac{\left(\frac{d+w}{2}\right)}{\cos\gamma} \qquad \text{(eq. 2)},$$

where $P(x_P, y_P)$ is the center point of the area of interest and w is the width of the building. Moreover, buildings can be mirrored over y-axis before rotated.

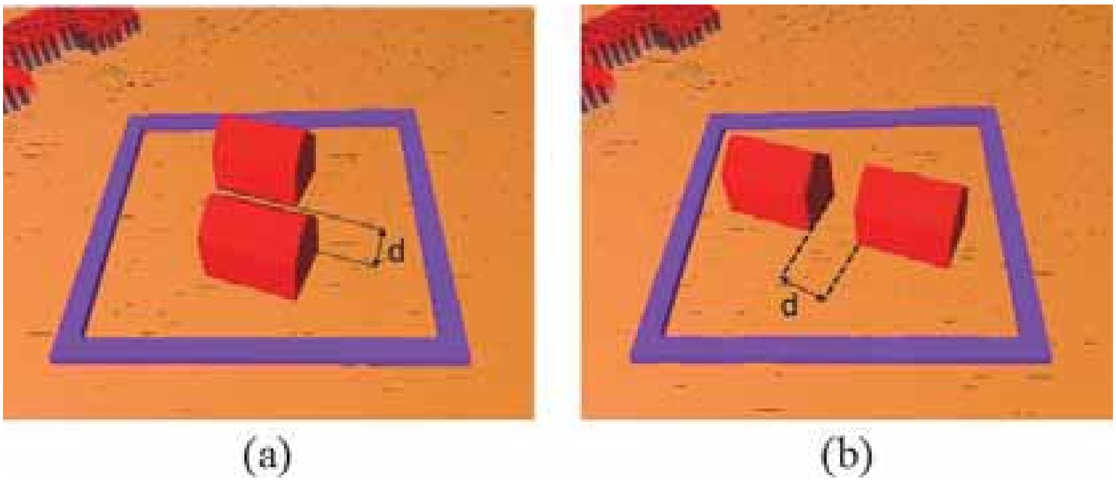


Figure 2: Two types of layout with orientation angle at 20°, where (a) buildings lie on two parallel lines and (b) buildings lie on the same line. The distance between buildings is defined by d.

The final model of the pair of buildings is rasterized into 2.5D grid by the rasterization of each individual building (see Figure 1c). The cells of both buildings are considered as input to the method for solar potential estimation (Lukač et al., 2013), that operates with the 2.5D grid that was generated with LiDAR data. Solar potential is roughly calculated as follows:

- Calculation of a normal vector for each building's cell.
- Time and location dependent terrestrial irradiance is calculated using cell's aspect and slope angles (Duffie and Beckman, 2006) together with long-term on-site diffuse and global solar irradiance measurements.
- The solar potential of a cell at a given time is defined as:

  $$I_c = I_{c_b}(1 - S_c) + I_{c_d}\left[\frac{\text{kWh}}{\text{m}^2}\right], \qquad \text{(eq. 3)}$$

  where I_{c_b} and I_{c_d} are the terrestrial direct and diffuse irradiances of a given cell, whilst $S_c \in [0,1]$ is the shadowing coefficient that affects the direct irradiance.
- I_c is considered between sunrise T_{sr} and sunset T_{ss} with the fixed time-step to estimate the daily solar insolation:

  $$J_c = \int_{T_{sr}}^{T_{ss}} I_c(t)dt\left[\frac{\text{kWh}}{\text{m}^2}\right]. \qquad \text{(eq. 4)}$$
- The solar potential is defined as an average daily insolation throughout the year (Lukač et al., 2013).
- The average amount of the daily solar energy the pair of buildings receives is the result of the fitness function. It is calculated as the sum of the solar potential of the pair's cells.

During the optimisation the initial population is not randomly generated over the parameter space only for the roof slope and the pair of building's orientation parameters. For these two parameters a simple heuristic is used, where the initial population is generated in Gaussian distribution with its peak at the expected value (Bizjak et al., 2015). Optimal roof slope is expected to be approximately at the location's latitude, whilst for the orientation most roof surfaces of the pair are assumed to be oriented towards equator. Figure 3 presents the workflow of the upgraded method.

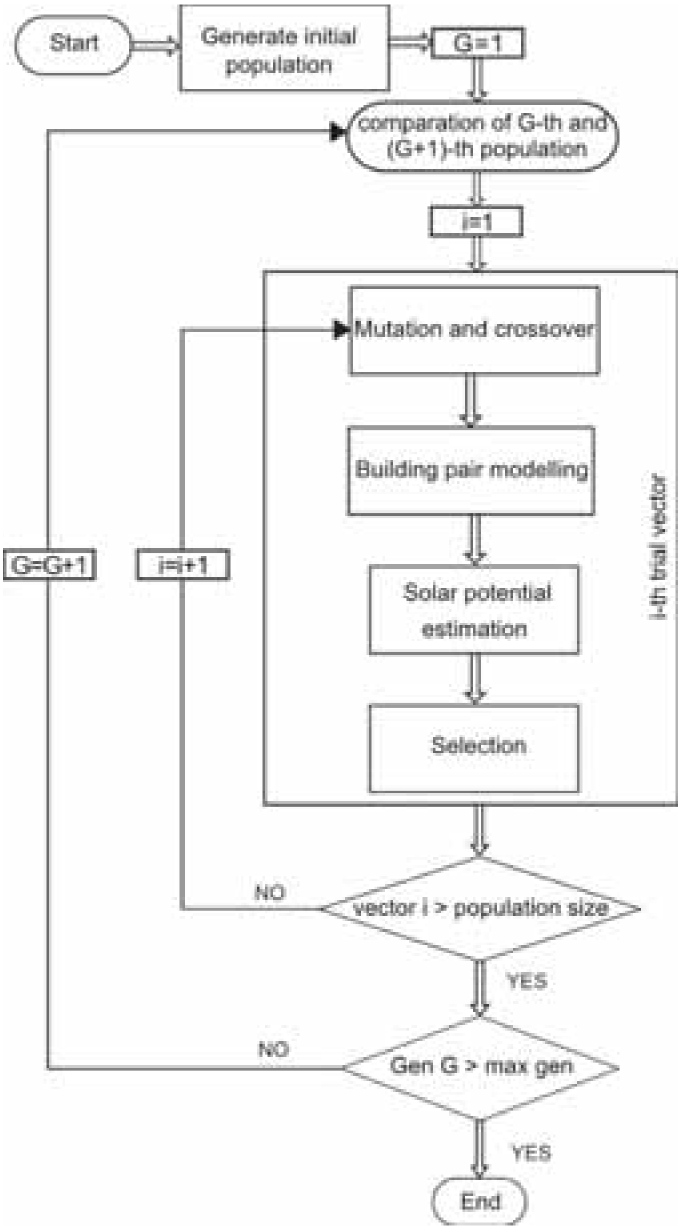


Figure 3: Workflow of the proposed method.

3. Results and discussion

The experiments were performed on two LiDAR datasets, one that represents a hilly landscape (located at 46° 37' 0.61" N, 15° 52' 37.59" E) and the other a flat landscape (46° 35' 59.43" N, 16° 13' 25.89" E) as can be seen in Figure 4. Testing was performed at a specified location on each dataset using a building in rectangular or L shape as a base for the optimisation of the pair. For the calculation of terrestrial irradiance of each pair of buildings candidate the average measurements from the closest meteorological station over the previous decade were used. The population size P for DE was set to 80 and the *DE/best/1/bin* strategy was considered, as proposed in (Bizjak et al., 2015).

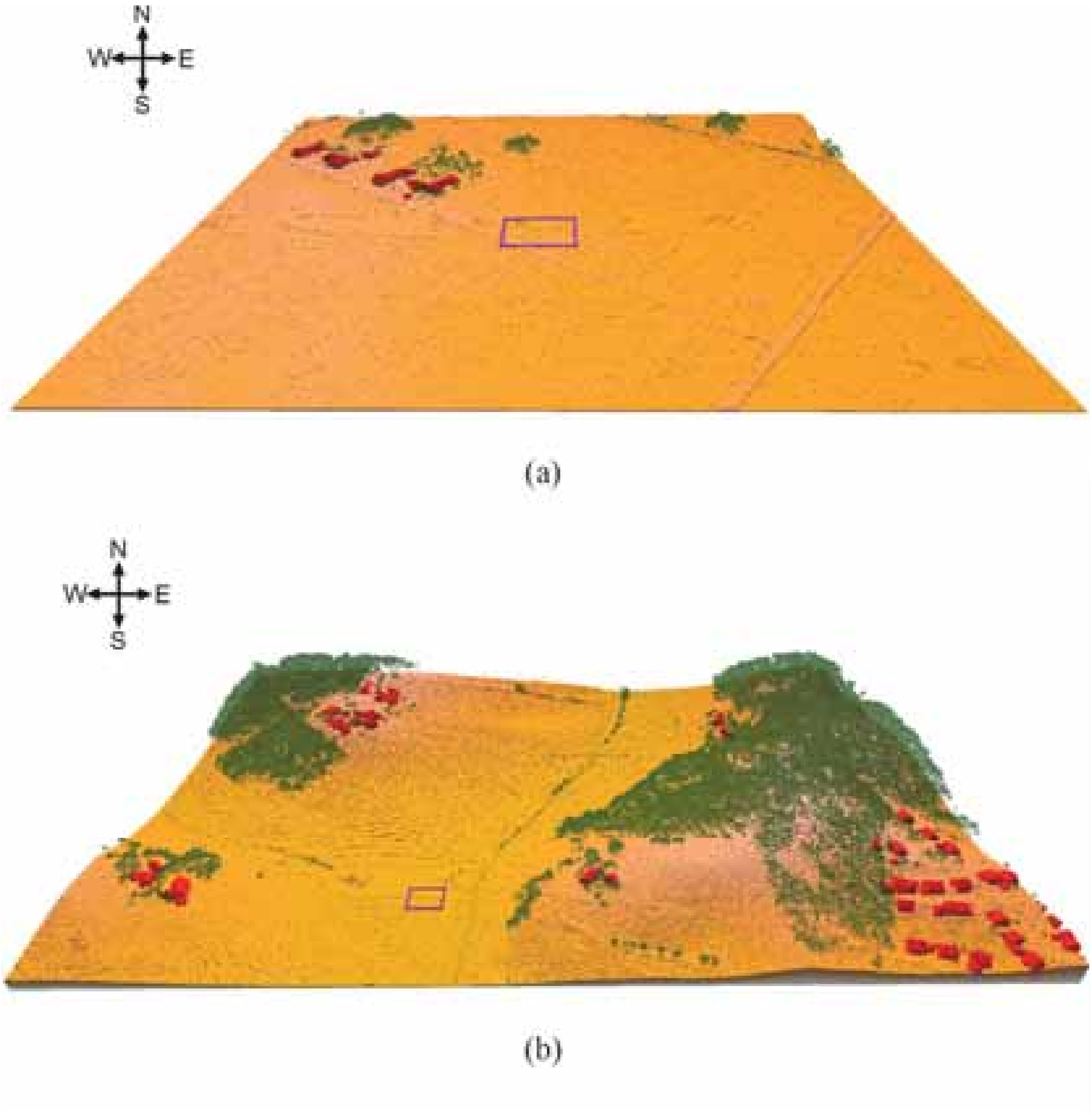
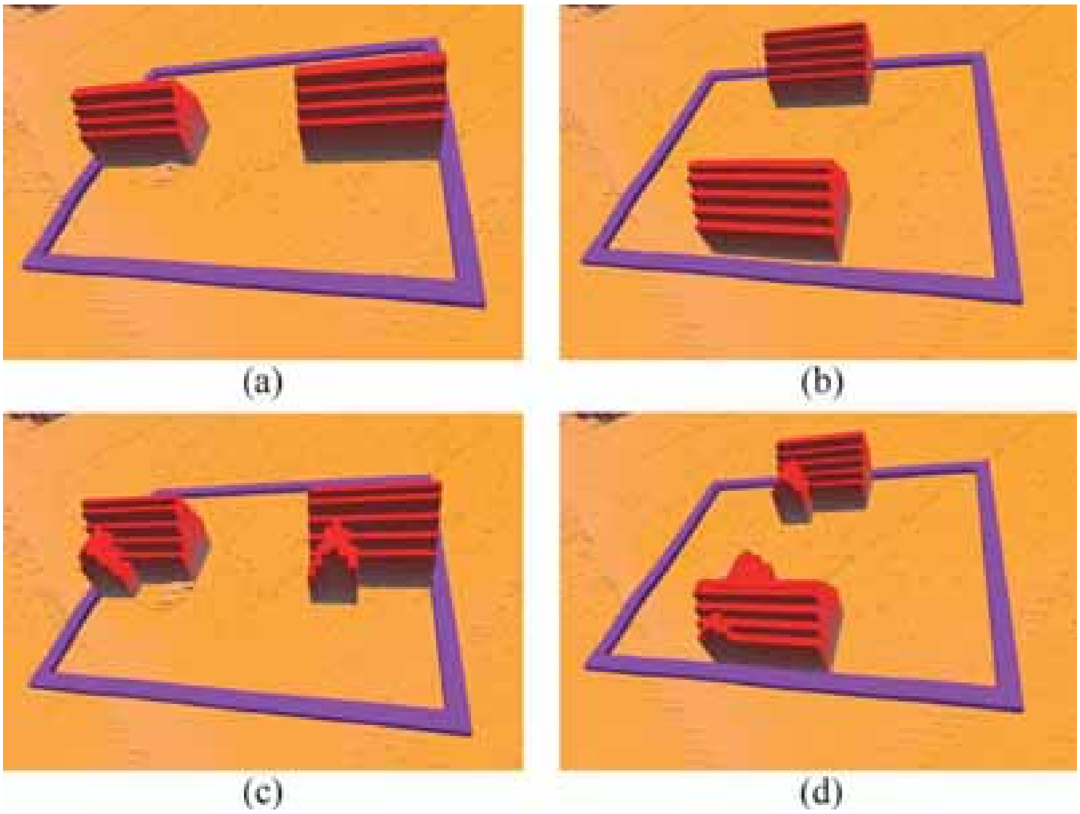


Figure 4: Flat (a) and hilly (b) LiDAR datasets with designated area of interest (purple rectangle).

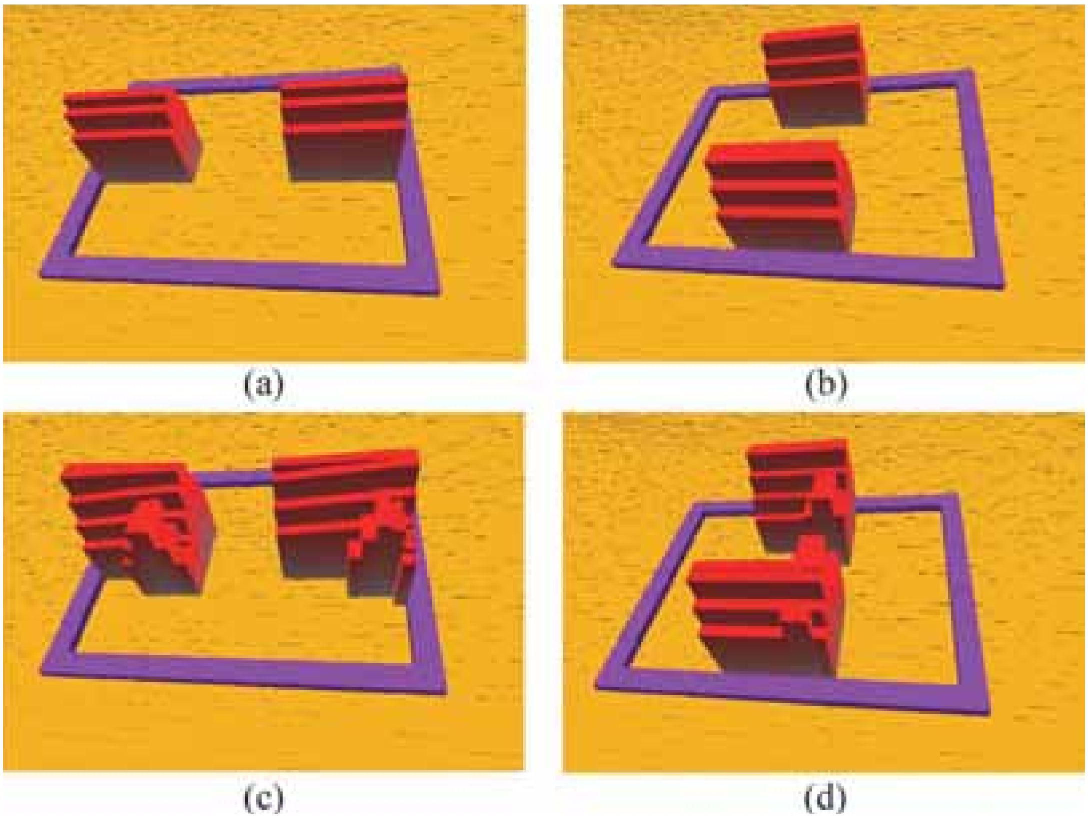
The results of the optimisation for all combinations of layouts and datasets are presented in Figures 5 and 6. Figure 5 shows the optimised pairs of buildings on the flat LiDAR dataset. The buildings' roofs were sloped on average at 46° (±2°). Buildings' height varied for each pair, which is caused by the lack of shadowing from surroundings. The optimal orientation of both layouts for all pairs of buildings was on an east-west axis, where the most exposed roof surfaces were facing equator. The distance between the buildings was the maximum possible distance within the considered area for both layouts. This is a natural consequence of decreased shadowing between buildings as the distance increases.

Figure 6 presents the optimised pairs of buildings on the hilly LiDAR dataset. The buildings' roofs were sloped on average at 45° (±1°). The difference in slope is caused by different topography and geographic location of each dataset. Buildings' height was maximal, which is a consequence of shadowing from the hill. Higher building means lower shadowing and therefore better fitness. The optimal orientation of building pairs was on an east-west axis for all cases except for L-buildings on the same line (see figure 6c). The building pair was oriented 2° from the east-west axis. This occurred due to internal shadowing, which happens when a building's cell is shadowed by another cell from the building. The distance between buildings was maximum on this dataset as well.



(a) (b) (c) (d)

Figure 5: Results of the optimisation for buildings on the same line (a,c) and buildings on two parallel lines (b,d). Area of interest is located at a 2.5D grid generated from the flat LiDAR dataset (see Figure 4a).



(a) (b) (c) (d)

Figure 6: Results of the optimisation for buildings on the same line (a,c) and buildings on two parallel lines (b,d). Area of interest is located at a 2.5D grid generated from the hilly LiDAR dataset (see Figure 4b).

4. Conclusion

This paper presented a novel method for the design and layout optimisation of a pair of buildings regarding the received solar potential. The optimisation was achieved with a modified self-adaptive differential evolution. For each candidate, a pair of buildings was modelled and assessed regarding solar potential. The solar potential estimation considers shadowing from surrounding obstacles within real data and local climate. The results suggest, that the method successfully optimises a pair of buildings, where the distance between the buildings is maximal. To our knowledge, this is the first method that tackles the optimisation of two buildings within LiDAR data regarding solar potential.

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