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Floor shape optimization for green building design

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Abstract

Shape is an important consideration in green building design due to its significant impact on energy performance and construction costs. This paper presents a methodology to optimize building shapes in plan using the genetic algorithm. The building footprint is represented by a multi-sided polygon. Different geometrical representations for a polygon are considered and evaluated in terms of their potential problems such as epistasis, which occurs when one gene pair masks or modifies the expression of other gene pairs, and encoding isomorphism, which occurs when chromosomes with different binary strings map to the same solution in the design space. Two alternative representations are compared in terms of their impact on computational effectiveness and efficiency. An optimization model is established considering the shape-related variables and several other envelope-related design variables such as window ratios and overhangs. Life-cycle cost and life-cycle environmental impact are the two objective functions used to evaluate the performance of a green building design. A case study is presented where the shape of a typical floor of an office building defined by a pentagon is optimized with a multi-objective genetic algorithm.

Keywords: Building design; Genetic algorithms; Optimization; Shape representation; Sustainable development

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1. Introduction

The greatest opportunities for integrating "green" design strategies occur at the conceptual design stage. During this stage, many potential design alternatives are generated and their performance are roughly evaluated in order to select the most promising solutions [1,2]. The decisions made in the conceptual stage have tremendous impact on building performance in many aspects. For example, by changing design parameters such as shape, orientation, and envelope configuration, a high-quality designed building can consume 40% less energy than a low-quality designed one [3,4].

The building shape is one of the most important considerations in the conceptual stage of building design. Since the building shape determines the size and the orientation of the exterior envelope exposed to the outdoor environment, it can affect building performance in many aspects: energy efficiency, cost and aesthetics. Too often, however, decisions on the building shape are based on aesthetics only, which has the evident disadvantage of limiting the potential of performance improvement. Shape optimization can help overcome this disadvantage by exploring more design alternatives at the conceptual design stage for specific criteria such as environmental and economical performance.

There are a number of previous studies on building shape optimization. Rosenman and Gero [5] combined a design grammar and a genetic algorithm to evolve two-dimensional building plans. The whole building plan is constructed by sequentially applying the design grammar on building hierarchical elements including space units, rooms

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and zones. Caldas [6] proposed a system for the generation and optimization of three-dimensional architectural forms to satisfy two performance criteria: maximum daylighting use and minimum operating energy consumption. Different building architectural forms were created by altering the dimensions of spatial elements while keeping a predefined configuration. Chouchoulas [7] developed a prototype using the design grammar approach for three-dimensional shape generation. In that prototype, a circulation unit and an apartment unit are the two fundamental shapes from which the morphology of an apartment building was constructed and optimized with a genetic algorithm. All three studies presented above adopted the part-whole approach in that they determine the building shape from its spatial elements. This part-whole approach is capable of defining a wide range of shapes, some of which may be innovative solutions for a design problem. However, as noted by Caldas [6], energy simulation programs require information about the adjacencies between spaces, and this information might be difficult to extract from a building shape generated with the part-whole approach. In contrast, the whole-part approach defines a building shape by its external boundaries and represents its internal spatial elements implicitly [8]. Because the whole-part approach can easily describe the building geometry for energy simulation programs, it is adopted in several optimization studies on energy performance. A few studies [9,10] assumed a rectangular building plan and optimized its geometry via aspect ratio. Jedrzejuk and Marks [11] optimized a building with a symmetrical octagonal plan by chamfering a rectangle. Wang et al. [12] considered both L-shape and rectangular shape in the optimization of a green building design. All these previous studies using the whole-part approach are limited to simple shapes that cannot be easily generalized to more complex ones. Moreover, since these shapes are heavily constrained, some more promising shapes may be precluded from the design space right from the start.

This paper proposes to use a generalized polygon representation for building footprint optimization considering two conflicting criteria: minimum life-cycle cost and minimum life-cycle environmental impact. The paper is organized as follows. Two alternative methods for representing the building footprint are discussed in the next section. The optimization problem is presented in Section 3 with its variables, objective functions and constraints. This is followed by a description of the multi-objective genetic algorithm used to solve the optimization problem. A case study is presented in Section 5 for comparing the considered representation techniques and demonstrating the application of genetic algorithms in shape optimization with conflicting criteria. This paper ends with some concluding remarks and suggestions for future work.

2. Shape representation

In this research, the building footprint is defined as a simple n-sided polygon with no intersection of non-consecutive edges. This geometrical shape is selected because most energy simulation programs used to estimate building energy consumption model exterior walls as line segments. The polygon provides a basis to consider more complicated building shapes in the future since a curve can be approximated with line segments. It is also reasonable to limit the scope to simple polygons since buildings do not have boundaries that intersect.

For a given area, an n-sided polygon can be defined based on different representations such as the length-angle representation, the length-bearing representation, and the Cartesian or Polar coordinates representation. These representations are discussed in this section with an emphasis on their potential encoding problems in genetic algorithms.

2.1. Length-angle representation

Since a polygon is made up of a number of sequential line segments (i.e., edges), it is intuitive to represent a polygon with the length of each edge and the angle between every two adjacent edges. Thus, given an area S, an n-sided polygon can be established with the following procedure, as illustrated in Fig. 1:

- From an initial point P_1, the coordinates of the endpoint P_2 of the first edge can be determined from its length a_1 and the building orientation α. The alignment of the first edge is selected here as the reference direction, called building north. This reference direction is necessary in energy simulation programs to describe the geometry of a building. Thus, the building orientation is defined as the angle α between the true north and the building north, clockwise being positive.
- The direction of the ith edge is determined by the angle θ_{i-1}, measured counter clockwise from the previous edge. Note that the angle θ_{i-1} is an interior angle if the vertices are arranged in a clockwise order; otherwise,

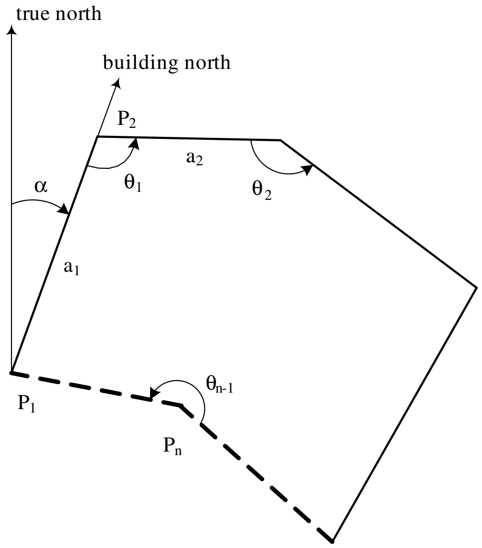

Fig. 1. Length-angle representation of a polygon.