Available online at www.sciencedirect.com
ScienceDirect
Advanced Engineering Informatics 22 (2008) 59–70
ADVANCED ENGINEERING INFORMATICS
www.elsevier.com/locate/aei

Generation of energy-efficient architecture solutions applying GENE_ARCH: An evolution-based generative design system

Luisa Caldas

ICIST, Department of Civil Engineering and Architecture, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal

Received 1 December 2006; received in revised form 9 August 2007; accepted 17 August 2007

Abstract

As the field of design automation and generative design systems (GDS) evolve, more emphasis is placed on issues of design evaluation. This paper focus on the presentation of different applications of GENE_ARCH, an evolution-based GDS aimed at helping architects to achieve energy-efficient and sustainable architectural solutions. The system applies goal-oriented design, combining a genetic algorithm (GA) as the search engine, with the DOE2.1E building energy simulation software as the evaluation module. Design evaluation is based on energy spent for heating, cooling, ventilation and artificial lighting in the building, and on sustainability issues like greenhouse gas emissions associated with the embodied energy of construction materials. The GA can work either as a standard GA or as a Pareto GA, for multicriteria search and optimization. In order to provide a broad view of the capabilities of the software, different applications are discussed: (1) standard GA: testing and validating the software; (2) standard GA: incorporation of architecture design intentions, using a building by architect Alvaro Siza; (3) Pareto GA: choice of construction materials, considering cost, building energy use, and embodied energy; (4) Pareto GA: application to Siza's building, considering thermal and lighting behavior separately; (5) standard GA: shape generation with single objective function; (6) Pareto GA: shape generation with multicriteria evaluation; (7) Pareto GA: application to an urban and housing context. Overall conclusions from the different applications are discussed, as well as current challenges and limitations, and directions for further work.

Keywords: Genetic algorithms; Generative design systems; Pareto multicriteria optimization; Design automation; Sustainable construction; Bioclimatic architecture; Energy efficiency; Embodied energy; Life-cycle analysis

1. Introduction

GENE_ARCH is an evolution-based generative design system (GDS) that uses adaptation to shape architectural form [1]. It was developed to help architects in the creation of energy-efficient and sustainable architectural solutions, by using goal-oriented design, a method that allows to set goals for a building's performance, and have the computer search a given design space for architectural solutions that respond to those requirements. The system uses a Pareto genetic algorithm as a search engine, and the DOE2.1E building energy simulation software as the evaluation module (Fig. 1). One of the distinctive aspects of GENE_ARCH is that it generates complete building designs, both in terms of geometry, spatial layout and room characteristics, as in terms of construction materials, internal finishes, types and characteristics of window and glazing systems, and even mechanical and electrical installations. When a design is generated and evaluated by GENE_ARCH, it is a whole building entity that is being assessed, not an initial design concept or an abstract geometrical shape.

The fact that DOE2.1E is one of the most sophisticated building energy simulation programs in the market, also provides significant confidence in the results obtained by GENE_ARCH. For each of the thousands of alternative building solutions it creates in a typical run, a full

E-mail address: luisa@civil.ist.utl.pt

1474-0346/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.aei.2007.08.012

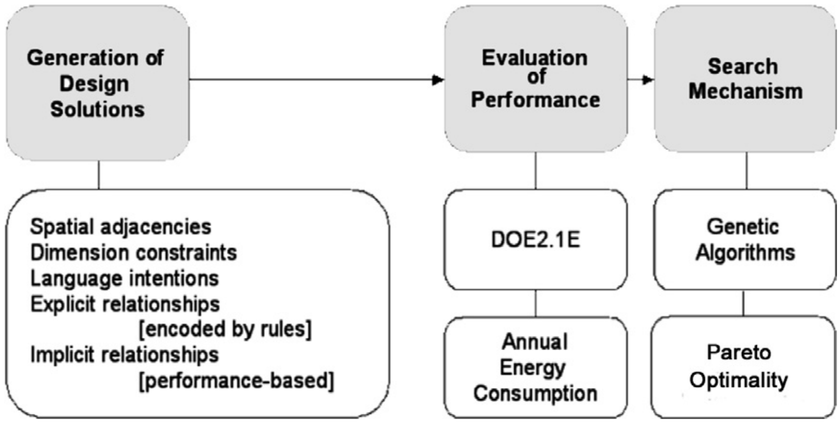

Fig. 1. GENE_ARCH's components.

DOE2.1E simulation is done, based on actual climatic data of the building's location and performed hourly for the whole year.

Other authors have explores the connection between building energy simulation and optimization systems. Bouchlaghen [2] developed a method coupling a simplified building thermal model with a non-random complex model as the optimization procedure. Wetter and Wright [3] and Wright et al. [4] developed tools and methods mostly focused on the energetic performance of HVAC and mechanical/electrical systems. Shea [5] used ant colony optimization to choose glass types for a paneled building envelope, considering daylighting and energy transmission by conduction. However, the issue of the generation of whole architectural solutions with the goal of energy conservation is not addressed by these authors.

Other studies in the literature provide important comparisons between search methods and algorithms. Elbeltagi et al. [6] compare five evolutionary-based optimization algorithms, to find that Particle Swarm Optimization provided the best results for their type of problem. Domer et al. [7] compared two stochastic search methods, simulated annealing (SA) and probabilistic global search Lausanne (PGSL) applied to structural shape control, and found that both performed well in the control of a tensegrity structure, although SA performed better for intermediate required accuracies, and PGSL did better for high and low ones, also requiring less control parameters. Caldas [1] compared SA and GA for a building design optimization problem, finding that GA's performed just marginally better for the problem under study. Garcia et al. [8] compared strategies for multiobjective evolutionary algorithm [MOEA] and worst-case combination evolution strategy (WCES), using Pareto fronts.

In the field of design generation and optimization, Svanerudh et al. [9] address some problems regarding the optimization of timber shear-wall design. In this case, the basic design is fixed, and the allowed geometric variations are limited. Elements are described as a kind of object prototypes, that can have pre-derived static normative knowledge and dynamic knowledge. Wang et al. [10] address issues of shape generation in buildings by establishing two opposing methods: the part-whole approach, and the whole-part approach. By adopting the latter, the building shape is defined by its external boundaries, and the internal spatial elements are represented implicitly. Although this method can capture an important design feature for energy efficiency, namely the form factor of the building, the lack of internal spatial information significantly constraints its usefulness, as it is known that the internal configuration and division of space also affects seriously the environmental performance of occupied buildings.

Hornby and Pollack [11] created generative representations for design automation using Lindenmayer systems, for static structures, 2D and 3D robotic structures, which, unlike a direct representation of a design, create a generative representation as an algorithm for creating a design. In this case, the data being optimized by the search algorithm is itself a program containing rules and program-like instructions for generating a design, also with a modular approach.

Couchoulas [12] presents an algorithmic method for conceptual architectural design combining shape grammars and genetic algorithms. The genetic algorithm is allowed to modify only the sequence of rules that are applied to generate a design, not the geometry of the design directly.

A GDS related to structural optimization was created by Shea [13], which combines shape grammars as a design method, simulated annealing as the optimization method, and finite elements analysis as the main structural evaluation procedure. The method is quite powerful and was applied to the design of various structures, like geodesic domes [14] and transmission towers [15]. The latter used structural topology and shape annealing (STSA) for the optimization of transmission tower design, including shape modification schemas.

In acoustical design, Monks et al. [16] used a combination of SA and steepest descent to optimize the acoustical performance of architectural spaces, using a combination of six acoustical measures. Variables used relate to physical characteristics of the space, like the tilt of reflectors and other room surfaces, and materials properties. Performance