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Improving thermal performance of automatically generated floor plans using a geometric variable sequential optimization procedure

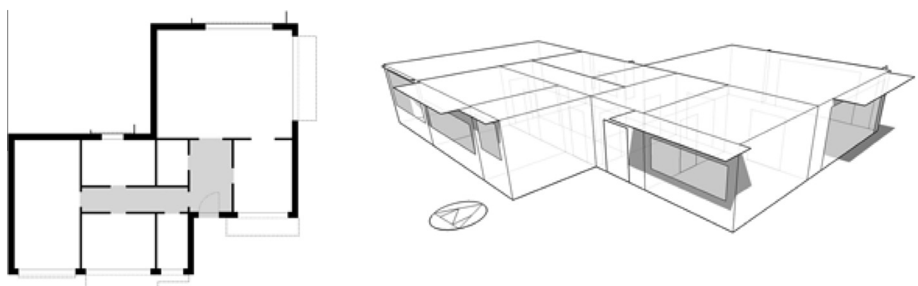
Eugénio Rodrigues [a,b,*], Adélio Rodrigues Gaspar [a], Álvaro Gomes [b]

[a] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal
[b] INESCC, Department of Electrical and Computer Engineering, University of Coimbra Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal

HIGHLIGHTS

- Alternative floor plans are automatically generated, assessed and optimized.
- Geometric variable sequential optimization is used.
- Thermal performance assessment is carried out with dynamic simulation.
- A case study for a family house, with one and two-level floor plans, is presented.
- Algorithm performance and case study results are analyzed.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an approach for the optimization of floor plan designs. These are generated using a hybrid evolutionary approach, which produces alternative designs according to the user's preferences and requirements. Once generated, an optimization algorithm is used to improve the thermal performance of each solution. The algorithm evaluates each possible transformation for several design variables in each floor plan, such as floor plan orientation and reflection, window orientation and size, overhang size, fin size, and wall translation. A geometric variable sequential optimization procedure is used to satisfy the user's design strategy.

A case study of a single-family house is carried out, where two design sets, with 12 alternative solutions each, are generated, assessed, and optimized according to thermal performance criteria. The results demonstrate that the thermal performance of the floor plans may improve by up to 41% for single-level solutions and 54% for two-level designs. When comparing solutions within each design set, the floor plan design which ranks first is 33% and 29% better than the worst design, in the first and second design set respectively.

1. Introduction

Architects need task oriented design tools embedded with dynamic simulation programs to inform and to help improve the performance of a building design. Not only should these tools meet the architec's design needs but also they should not increase the difficulty of an already complex design process. The operating agents of the IEA-SHC Task 41 – Solar Energy and Architecture carried out an international survey to determine the need to improve current technologies or tools for the design of low-energy buildings. The results suggest that there is a need to develop more user-friendly tools that are capable of taking the requirements and specifications of different design phases into consideration [1].

* Corresponding author at: ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal.
E-mail address: eugenio.rodrigues@gmail.com (E. Rodrigues).

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One of the first and foremost design phases performed by architects is space planning. The process consists of two stages where practitioners search for a distribution layout which accommodates preferences until the final design emerges. In the initial stage (analysis) information and data about the design program is gathered; the equipment needed for each room is listed; functionality and requirements are determined and constraints are identified. In the latter stage (synthesis), several sub-tasks are carried out which include setting up the design program in topological diagrams; sketching prototypical plans for each room; block planning; and drawing floor plans.

The use of computers to speed up the drawing process and to help architects cope with a much larger set of objectives has been a computational problem since the 1960s. Existing automated procedures are able to allocate rooms/spaces within a building boundary [2], partition the building boundary [3], assign functional unit areas to known area [4], or establish some kind of hierarchical relation between elements [5]. Some researchers have also included energy/thermal performance objectives in the generation criteria [2,6]. However, the mentioned procedures consisted of simplified static estimation and floor plan generation approaches which have never been coupled to dynamic simulation, even though the idea had been previously proposed [7]. By linking dynamic simulation to the automated generation of floor plan algorithms it is possible not only to globally evaluate and rank different design solutions, but also to provide the architect with detailed information on the performance of each space, allowing them to make judicious decisions. The design decisions in the space planning stage may significantly contribute towards the thermal performance of the building as the arrangement of the rooms affects the position and size of windows, building orientation and shape. Nonetheless researchers have hitherto focused their attention either on the improvement of some aspect of the building's design solution (mainly related to the constructive system and materials) or on the development of graphical interfaces for decision support tools [8]. These however, do not tackle the architect's need to compare the performance of alternative competitive designs with meaningful and clear results [1]. Some of the aspects used in the optimization procedures are constructive system specifications and a few geometric variables. The most common optimization procedures are population-based search techniques, which are computationally demanding and time consuming when linked to dynamic simulation [9]. These issues have lead researchers to either simplify the simulation model (treating the whole building as a single thermal zone), or reduce the number of design variables, or still adjust the algorithm parameters to reduce the number of simulations with consequent loss of algorithmic efficiency [9].

Stevanović [10] presents a long review of several approaches that use dynamic simulation for the optimization of passive solar strategies. Research focus has been mainly on the improvement of constructive systems [11], the selection of material type [11,12], the configuration of layers [12,13] and respective thicknesses [11,14–16], shading mechanisms [17,18], windows specifications [18–21], and building form [22,23] and orientation [18].

Caldas [20] used a Genetic Algorithm (GA) and a thermal analysis procedure to optimize window size according to thermal and lighting criteria. Wright et al. [19] used an NSGA-II algorithm to perform a multi-objective optimization of the position of several cellular windows with overhangs in a façade. The purpose was to minimize capital cost and energy use. Nguyen and Reiter [24] used a simplified zone design optimization that used GenOpt to minimize construction costs, thermal discomfort, and operative costs.

Yi and Malkawi [22] Tuhus-Dubrow and Krarti [23] developed a GA to optimize a building's form according to energy consumption and life cycle costs. Kämpf and Robinson [25] used a multi-objective optimization for urban form improvement. Shi [16] implemented a GA design optimization environment to search for the best insulation strategy to minimize the space-conditioning load and insulation usage of an office building. Rapone and Saro [21] used a population-based probabilistic algorithm to optimize a building façade according to energy efficiency and comfort criteria. The design variables were glass type, percentage of glazed surface, and depth and spacing of louvers. A simulation-based multi-objective optimization scheme was developed by Asadi et al. [11] with TRNSYS, GenOpt, and Tchebycheff optimization technique for defining building retrofit strategies, in particular the best combination of window type, solar collector type, roof and exterior wall insulation materials.

When developing tools for architects, it is pertinent to take into consideration their working needs by using task-oriented energy performance tools; the importance of helping them to make informed building performance decisions; and the benefits of automated generative design methods to speed up the design process. For these reasons, an approach that automatically generates several alternative floor plan designs, assesses their thermal performance, and optimizes their performance by changing a set of geometric design variables is presented. It considers alternative floor plans solutions that have different space arrangements but which satisfy the same preferences and requirements that were set in the design program. The floor plans are generated using a hybrid evolutionary strategy technique named Evolutionary Program for the Space Allocation Problem (EPSAP) [26–30]. These floor plans are then assessed and optimized for their thermal performance using a Floor plan Performance Optimization Program (FPOP) algorithm, which consists of a design variable sequential optimization conforming to thermal performance criteria. Specific design variable operators are used sequentially according to the user's design strategy. The design variables available to the user are floor plan orientation and reflection, window orientation and size, overhang size, fin size, and wall translation. The FPOP optimizes EPSAP's generated designs either by using gradient descent technique or by testing all admissible variable values with its operators. This significantly reduces the computational time in comparison to population-based approaches, in an architectural design stage where fast prototyping is important. The EPSAP and FPOP algorithms allow the architect to create, compare and improve alternative floor plans. Practitioners may screen these alternative solutions and select which should be further developed in the following stages of the architectural design process.

The paper is divided into four sections. In this first section, the background on building optimization approaches is presented. The second section describes the automated procedure of generating floor plans and the algorithm for optimization of those designs. The third section presents a case study of a single-family house where the presented solutions and the algorithm performance is analyzed. Finally the conclusions are made in the fourth section.

2. Optimization of floor plan designs

The approach consists in improving the thermal behavior of automatically generated floor plans using a geometric variable sequential optimization procedure. Each variable has its own specific operator, which will carry out geometric transformations to the floor plan design with the purpose of improving the thermal performance. The floor plans are initially created according to the user's preferences and requirements (geometric and topological) using EPSAP algorithm [26–30]. After, a subset of the floor plans (the fittest or user selected) are assessed and entered in an optimization procedure to improve the thermal performance criteria using FPOP algorithm, which will be described in detail in following subsections.