Automation in Construction 69 (2016) 131–150

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

An evolutionary approach for 3D architectural space layout design exploration

Ipek Gürsel Dino

Middle East Technical University, Department of Architecture, Universiteler Mah., Dumlupinar Bulvari, No:1, 06800 Ankara, Turkey

ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 24 April 2016
Accepted 22 May 2016
Available online 24 June 2016

Keywords:
Design exploration
Evolutionary algorithms
Architectural space layout design

ABSTRACT

This work introduces Evolutionary Architectural Space layout Explorer (EASE), a design tool that facilitates the optimization of 3D space layouts. EASE addresses architectural design exploration and the need to attend to many alternatives simultaneously in layout design. For this, we use evolutionary optimization to find a balance between divergent exploration and convergent exploitation. EASE comprises a novel sub-heuristic that constructs valid spatial layouts, a mathematical framework to quantify the satisfaction of constraints, and evolutionary operators to improve alternative layouts' fitness. We test EASE on the design of a library building. We evaluate EASE's performance for different building forms and different evolutionary algorithm parameters. The results suggest that EASE can generate valid layouts, quantify the constraints' degree of satisfaction and find a number of optimal layout solutions. The layouts that EASE generates are intended not as end results but design artifacts that provide insight into the solution space for further exploration.

1. Introduction

Space layout design (SLD) is one of the key phases of architectural design, which comprises decisions regarding the search for an optimal spatial configuration that satisfies a set of constraints. It is also a complex problem due to the subjective and fuzzy nature of dependencies, the difficulties in quantifying solution quality and its discontinuous and multimodal design space [29]. SLD typically is manually conducted. However, due to the vast number of alternatives, alternative configurations cannot be systematically explored by hand.

Computation-aided design optimization can support SLD by the automated generation, manipulation and evaluation of design alternatives. This way, rational decision-making based on quantitative criteria can be facilitated towards well-performing design solutions. At the same time, creative design problems are said to resist being solved to optimality by deterministic methods, as there is no complete understanding of the problem structure at the outset of the design process and the relationship between the design variables and objective function(s) is not clear. This mismatch between rational methods of exploitation and creative acts of design synthesis is a major hindrance to the effective implementation of optimization in early design. Moreover, it is generally accepted that layout problems are NP-complete, and their time complexity is upper-bounded by exponential functions. This means that such problems cannot be solved with definite optimality in a reasonable amount of time. Therefore, the focus should be the formulation of efficient heuristics that seek for near-optimal solutions. Evolutionary computing methods have the potential to tackle such complex design problems while expanding opportunities for emergence and creativity.

In our research, we address two distinguishing characteristics of architectural design and SLD. The first is the privilege that the architects place upon architectural form. Typically form addresses higher-order architectural qualities such as esthetics, meaning, context or performance, and therefore precedes the design of its layout configurations. The second characteristic is the importance of divergent thinking and working with multiple alternatives. Similarly in architectural design, architects explore not one but a number of design alternatives simultaneously until a complete understanding of the design context is attained. This means that SLD design tools should be able to deal with arbitrary building forms that architects propose. Quantitative exploration of the layout solutions of a number of different building forms can help benchmark them against each other and aid the selection of the most optimal building forms and layouts. Therefore, it is important to be able to operationalize a heuristic for SLD that tackles arbitrary building forms proposed by the architects.

This paper presents a novel approach to the multi-floor, unequal-area 3D space layout problem. Evolutionary Architectural Space layout Explorer (EASE) is a design tool that facilitates the generation and optimization of 3D space layouts. Within EASE, layouts are generated by a novel heuristics named Precedence-Based Layout Configuration Heuristics (P-LCH) that can satisfy hard constraints of space overlaps and empty areas. Generated layouts are evaluated by a number of constraints that quantify the size, geometry, placement and topology

E-mail address: ipekg@metu.edu.tr.

http://dx.doi.org/10.1016/j.autcon.2016.05.020
0926-5805/

relations. Evolutionary algorithms (EA) then facilitate the generate/evaluate cycle to improve individuals' fitness by crossover, mutation and repair operators. EASE is tested on a building design case using the form alternatives for a given architectural brief. We comparatively evaluate the layout performances of these forms based on empirical and quantitative data. We present metrics to describe different building forms to be able to find their correlations with constraints. Then we discuss the convergence characteristics of EASE. Finally, the effect of different EA parameters on the performance of EASE is investigated.

2. Concepts for sld support

2.1. Design tools for exploration and exploitation

Design is a creative activity that cannot be solved with certainty, as it resists definitive formulations and lacks objective evaluation criteria [42]. Where the cost of finding an optimal solution is high, designers search for "good enough" solutions that meet the minimum objectives, known as satisficing [48]. By nature, satisficing entails large design spaces and divergent exploration. As it aims to extend the boundary of a design situation to achieve a large and fruitful search space, divergent (exploratory) designer behavior is also associated with design creativity [30]. The ability to simultaneously attend to alternative design threads within such large search spaces is a measure of the frequency of creative leaps during conceptual design [7]. Conversely, *convergent* design narrows and intensifies search towards more promising areas. It invests only in areas of high opportunity through testing and validation. At this phase, uncertainties are resolved, objectives are agreed upon and design variables are identified.

Design is an interplay of *divergence* and *convergence*, where designers engage in a continuous cycle of broadening and narrowing the design space. Well-informed decision-making can be facilitated by equally encouraging creative variation and rational optimality. Such approaches need to generate and present feedback for a number of design alternatives by assessing the relative impact of design performance parameters. Such quantitative information can be used to compare or benchmark the quality of design alternatives.

2.2. Metaheuristics as design support

A common characteristic of creative, non-routine design is that neither an inherent solution structure nor an a priori problem formulation exists. During design, design formulations constantly change together with the designer's understanding of the problem. As requirements cannot be definitively and exhaustively defined, a direct operational strategy to find a good solution (heuristics) isn't available either. Metaheuristics are suitable for design, or "I know it when I see it" type of problems, as can evaluate a candidate solution once it is instantiated [37]. Metaheuristic methods comprise a class of upper-level approximate methods that aim efficient search space exploration within discontinuous, multimodal solution spaces.

Evolutionary algorithm (EA) is a metaheuristic method that uses principles of biological evolution, wherein successive generations of design instances evolve by means of recombination and mutation operators. As a high-level decision support technique, it can support multivariate design problems with multimodal and discontinuous design spaces [16]. We support that EA can address creative design by maintaining a balanced amount of divergence for novelty and convergence for utility. EA's micro-level bottom-up organizational principles can motivate macro-level creativity [46]. As such they can facilitate design experimentation and design discovery and eventually contribute to new architectural values that initially remain unnoticed and unexplored.

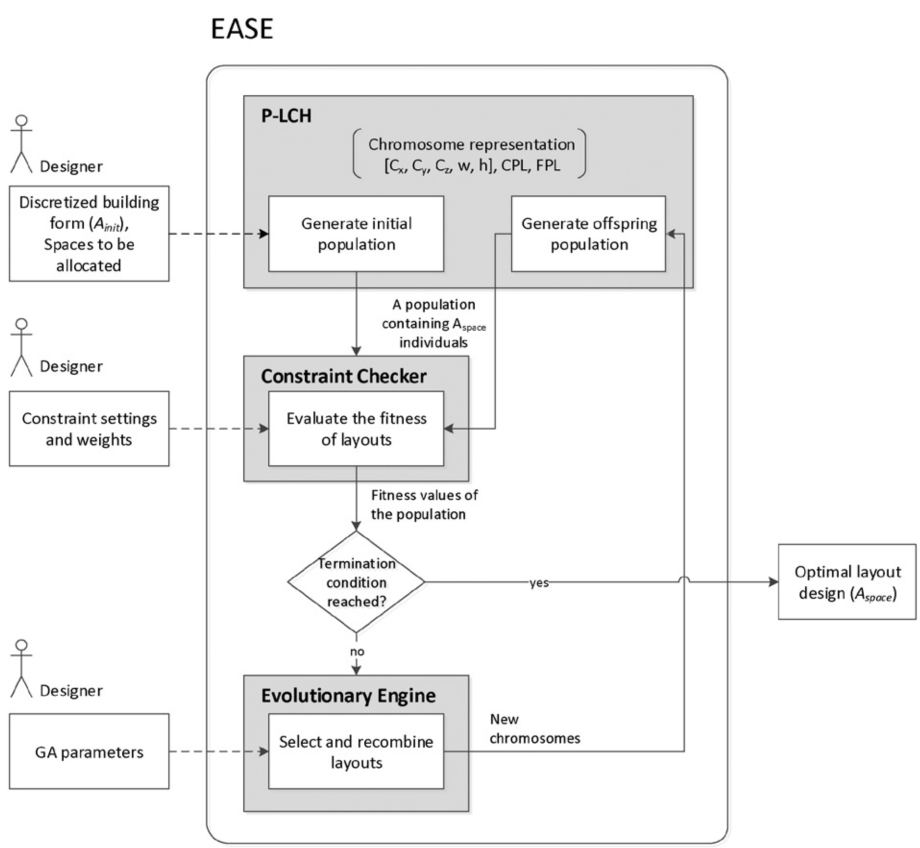

Fig. 1. EASE modules.