Energy and Buildings 85 (2014) 473–482

Contents lists available at ScienceDirect

Energy and Buildings

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

Optimization of a free-form building shape to minimize external thermal load using genetic algorithm

Jeong-Tak Jin [1], Jae-Weon Jeong [2,*]

[1] Woowon Mechanical & Environmental Engineers, Sillim-Dong, Gwanak-Gu, Seoul, 151-904, Republic of Korea
[2] Division of Architectural Engineering, College of Engineering, Hanyang University, Seoul 133-791, Republic of Korea

ARTICLE INFO

Article history:
Received 10 September 2014
Accepted 30 September 2014
Available online 13 October 2014

Keywords:
Parametric design method
Free-form building
Genetic algorithm
Building envelope optimization

ABSTRACT

This study aimed to propose an optimization process for a free-form building shape in terms of the thermal load characteristic in the early design stage. Geometric modeling of a model free-form building was performed using a parametric design method with Rhinoceros. The model free-form building's surface was divided into finite elements by generating a mesh using Grasshopper, which is an add-in program of Rhinoceros. Geometric information was extracted from each finite element and used to estimate the heat gain and loss characteristics of the whole free-form building. A free-form building shape optimization process was proposed based on the genetic algorithm (GA). Its applicability was demonstrated by deriving the optimized shape of the model free-form building for various climate zones. Established models that returned the thermal characteristics of a free-form building were used as objective functions, which are critical in the GA optimization process. The results showed that the proposed process could rapidly predict and optimize the variation of the heat gain and loss characteristics that was caused by changing the building shape.

1. Introduction

To conserve energy and reduce greenhouse gas emissions in the building sector, rapid prediction and optimization of building energy performance during the early design phase is vital for the whole building design process. Free-form building design is not an exception; prediction and optimization of free-form building designs is however challenging in terms of energy performance compared to that of conventional buildings, because of their irregular footprints and free-curved shapes. Free-form buildings generally do not have a simple geometry with mathematical representations [1]. Due to this inherent characteristic of the free-form design, a lot of effort is required to quantitatively identify and optimize the thermal characteristic of a free-form building using the established design tools that are commonly used in the early stage of the free-form design process.

The thermal characteristics of a given free-form building can be predicted by one of the following three approaches [2]: dynamic simulation, steady-state estimation, or statistical approaches. Relatively accurate prediction may be possible with dynamic simulation by entering detailed information on the building's components. However, for successful simulation this method may require a high level of experience, a complete set of input data, and time and effort. Consequently, dynamic simulation may not be appropriate to use during the early design stage [3,4]. The steady-state estimation method may also be used to predict the thermal performance of a free-form building. It uses established methods [5–8] that determine heat gains and losses through building components based on the thermal properties of the building envelopes and climatic conditions. However, this method also requires significant time and effort and may sacrifice the level of accuracy.

The statistical approach uses a thermal performance prediction model derived from statistical regression analysis of the thermal behavior data of a building acquired from actual measurements or dynamic simulations [9–16]. If the regression model can ensure high reliability, it may provide prompt and reliable thermal characteristic predictions during the early design phase [17]. Recently, polynomial functions have been proposed that return the ratios of the envelope heat loss, heat gain, and solar heat gain of a free-form building with respect to a conventional building [18]. They were derived by statistically analyzing the thermal load data acquired from numerous dynamic simulations of various free-form buildings in five different climate zones. These polynomials may be used during the early design phase for rapid prediction and/or to optimize a free-form building's thermal performance.

* Corresponding author. Tel.: +82 2 2220 2370; fax: +82 2 2220 1945.
E-mail address: jjwarc@hanyang.ac.kr (J.-W. Jeong).

http://dx.doi.org/10.1016/j.enbuild.2014.09.080
0378-7788/

A free-form building's shape also affects its thermal performance and can be optimized for better thermal performance than the initial design. This is commonly overlooked by architects because of the lack of shape optimization tools and/or processes that are applicable to free-form building design. Established research on building shape optimization can be found in the open literature. Tuhus-Dubrow and Krarti [19] optimized residential building shapes and envelope materials using a genetic algorithm (GA). Their research was however limited to small-scale residential buildings with typical footprint shapes, such as the L, T, H, U, cross, and trapezoid. Yi and Malkawi [20,21] also optimized the envelope shape using a GA. Their research suggested interlocking and data transfer between the existing computer-aided design software and the energy analysis program during the optimization process. This was however still difficult and not effective to use during the early design phase of a free-form building with complex geometry.

The present study therefore suggested a rapid optimization process for an energy efficient free-form building shape that could be applied in the early design stage. The established models for the rapid prediction of the thermal performance of a free-form building proposed by Jin et al. [18] were implemented in the optimization process based on a GA. The proposed free-form building shape optimization process can be performed in well-known free-form building design programs and their add-in software, such as Rhinoceros, Grasshopper, and Galapagos, without interlocking with existing detailed energy simulation programs.

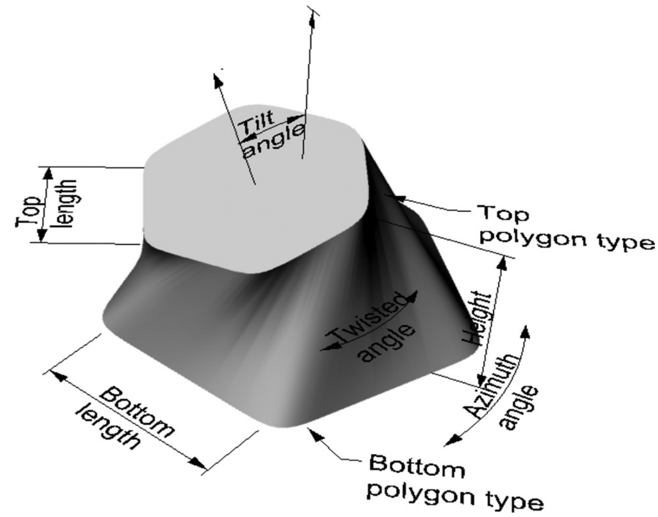

Fig. 1. The initial free-form building model.

2. Free-form building shape optimization process

2.1. Model free-form building

To demonstrate the possibility of free-form building shape optimization for thermal performance, a model free-form building was generated by following the conventional parametric design method. The non-uniform rational B-spline (NURBS)-based three-dimensional design program Rhinoceros and its add-in software Grasshopper were used to design the model free-form building.

In free-form building design, architects can define or change the shape of the building mass rapidly and automatically by modifying the values of design parameters that affect the building shape (i.e., parametric design). This method may also enable designers to explain their design process more clearly based on quantitative or qualitative changes of the parameters used in their designs [22].

There are three types of design parameters that define a building shape:

- *Static parameters* (fixed at a constant value);
- *Dynamic parameters* (changing within a range specified by a designer); and
- *Dependent parameters* (determined by the values of static and dynamic parameters).

For example, when a 20-story building with a 3 m floor height is designed, the floor height is the static design parameter and the number of stories the dynamic design parameter. The dependent parameter is the total height of the building determined by multiplying the floor height by the number of stories.

The model free-form building designed in this study had a polygonal footprint at the bottom and top surfaces (Fig. 2). The top length, bottom length, and height of the building were selected as design parameters. Additionally, to consider the envelope components with various azimuth and tilt angles that characterize the free-form building, the tilt angle formed by normal vectors from the roof and the bottom surfaces, twisted angles of the roof and the bottom surfaces, and the azimuth angle of the building were also considered as design parameters. Consequently, eight design parameters were used to generate various free-form shapes.

Table 1 summarizes the design values of the eight parameters defining the initial shape of the model free-form building (Fig. 1) and indicates the range of each parameter. The five parameters (top polygon, top length, tilt angle, twisted angle, and azimuth angle) were set as dynamic parameters that varied freely within the given ranges. The parameters defining the footprint of the building (bottom polygon and bottom length) were considered static parameters.

To maintain the building size with varying dynamic parameters, the building height was considered as a dependent parameter that was determined to maintain the building's volume at 1600 m^3. The window-to-wall ratio was assumed as a design constraint in the model free-form building and set to 30%. The overall heat transfer coefficients (*U*-values) of the model building envelope components were selected based on established building energy code [23]: 0.2 $W/m^2\,{}^\circ C$ for the roof, 0.36 $W/m^2\,{}^\circ C$ for the external wall, and 2.07 $W/m^2\,{}^\circ C$ for the window. The solar heat gain coefficient (*g*-value) of the window, which affected the solar heat gain in the model building, was set to 0.613 [2]. Because compliance of the model free-form building to a certain building energy code was not a critical factor for the introduction of the proposed shape optimization process, pre-defined envelope thermal properties of the model building were maintained throughout this study.

In the parametric design process that is commonly used in free-form design, architects select the design parameters they want to vary to generate their own free-form shape and define the range of variation or constraint of each selected parameter. Architects vary their selected parameter values within pre-defined ranges until they obtain a shape that meets their aesthetic and functional preferences. The building size and design parameters to be varied are the designer's choice. The proposed approach is not limited to a certain building size and design parameters. The parameters and ranges shown in Table 1 were just for the model free-form building designed by following the parametric design process and do not represent the scope of the proposed methodology. The building size and design parameters and their varying ranges depend on design projects and are not limited by the proposed optimization process.