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A review of simulation-based urban form generation and optimization for energy-driven urban design

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A B S T R A C T

This paper first defines the concept of energy-driven urban design. It aims to reveal synergies and trade-offs that may arise while designing urban areas for better energy performance. To facilitate urban planners and designers tackle these problems at the early stage of their work, this paper proposes the idea of simulation-based urban form generation and optimization modeling. It connects parametric models of urban form generation to an optimization engine coupled with a widely available program of energy systems.

To build up the model of simulation-based urban form generation and optimization modeling, this paper reviews the state-of-the-art of simulation-based design generation and optimization modeling and discusses its application on energy-driven urban design at the district scale. The paper compares the main generative methods and presents their limitations and advantages to aid energy-driven urban design. For the urban form generation modeling, the paper also reviews the most relevant approaches to urban morphology. These approaches help to define the urban elements for the urban form generation.

Most of the existing design generation and optimization models are observed to consist of a workflow, a generative method, and a series of generation constraints. Based on this, the paper proposes a model of simulation-based urban form generation and optimization modeling for energy-driven urban design. The model consists of a workflow with three steps, a collection step, the generation step, and the optimization step. The constraints yet need to be defined. At the district scale, the model also has to work at an appropriate resolution and precision.

Contents

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1. Introduction

54% of the world's population lived in urban areas in 2014, and the number is expected to hit 66% by 2050 [1]. With the current prevailing population growth and urbanization rate, by 2030, the global urban area will triple, compared to that of the beginning of the Twentieth Century [2]. Cities consume around three-quarters of global primary energy and account for nearly 60% of the world's greenhouse gas emissions [3]. How the urban areas are built has a substantial impact on the urban energy performance of the present and the future [4]. In recent years, urban energy studies started to embrace the tendencies to focus on the intermediate scale between the city scale and the building scale [5], namely the district scale. Urban design and sometimes urban planning work on this scale, in the process of urban development. In other words, energy considerations are better and effective to be considered at the beginning of an urban development process [6].

Recent attempts to incorporate energy considerations into urban planning and design have been made. Fonseca et al. [7] created four different plausible urban transformation design scenarios of a small site in Zug, Switzerland, to find out the best zoning strategy of the four. Though the design team was comprised of experts like architects, urban designers, engineers, the four scenarios have been intuitively produced. However, new patterns of development and technology render the traditional intuitive methods of designers not adequate to manage the interdependencies between various aspects of urban form and energy systems [8]. Optimization modeling is a promising method of minimum energy benchmarking for a new urban development [9]. A computationally optimized design solution can be very different from and much more energy efficient than those based on the designer's subjective intuition [10].

Simulation-based optimization modeling is an efficient way to meet several stringent requirements of high-performance building design [11]. Combining a simulation program with an algorithmic optimization engine has become popular since the late 2000s [11]. The results of building simulation programs serve as the optimization's objective function. Likewise, beyond a single building, simulation-based optimization can be applied to the district scale when coupling with an urban energy simulation program. Besides, since nothing has been formed yet at the beginning stage of urban planning, this urban energy simulation program and the optimization engine require to be connected with a parametric model of urban form generation.

This paper reviews the state-of-the-art of the research and knowledge on design generation modeling, urban morphology, and optimization methods for urban form optimization modeling. Consequently, the review is structured in three parts. After defining the terminologies relevant for setting up the concept of energy-driven urban design in Section 2, we review the existing models of design generation modeling, their workflows, and the generative design methods in Section 3, relevant approaches to urban morphology in Section 4 and approaches to urban form optimization in Section 5. As a synthesis of the reviews, Section 6 proposes a new approach towards energy-driven urban design. Section 7 contains the summary and future research outlook.

2. Definitions

In the following section, we define relevant aspects and terminology to set the stage for the proposal of energy-driven urban design.

2.1. Urban morphology and urban form

Urban morphology connects the technological aspect with the formal and various other aspects of cities [12]. Marshall and Çalişkan [13] summarized the definitions of urban morphology in different research contexts. This paper adopts the most basic definitions by Cowan [14], Lozano [15] and the International Seminar on Urban Morphology [16] – urban morphology is "the study of the physical urban form" and the various factors (e.g. the people and the process) that govern and influence form".

In this paper, by urban form, besides physical geometries, we also refer to the urban program and open spaces. The links between urban form and building energy performance have been established at the district scale [17]–[26]. These links mainly affect the energy performance through manipulating the physical geometries for lower operational energy demand. However, there is a lack of the knowledge of the interdependencies between urban form and energy systems.

Some energy technologies have enabled new possibilities of the urban form. For example, a district cooling system can free the building rooftops for more architectural design options, like an infinity pool or a sky garden. Vice versa, to maximize the energy performance, some energy technologies enforce some specific requirements (e.g. density, building program) on the urban form. Moreover, building rooftops and façades can be equipped with solar panels for in-city energy generation. The layout and heights of buildings may affect the mutual shading and further influence the solar-harvesting potential. Some studies have discussed such interdependencies between building programs [27], density [28] and urban energy supply infrastructures.

2.2. Urban energy system

The definition of urban energy system has constantly been evolving. In *Urban Energy Systems*, based on Jaccard's 2005