Building and Environment 115 (2017) 269–280

Contents lists available at ScienceDirect

Building and Environment

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

Tree shade coverage optimization in an urban residential environment

Qunshan Zhao [a, *], Elizabeth A. Wentz [a], Alan T. Murray [b]

[a] Center for Geographical Information Science, School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85287-5302, USA
[b] Department of Geography, University of California at Santa Barbara, Santa Barbara, CA 93106, USA

ARTICLE INFO

Article history:
Received 4 November 2016
Received in revised form
16 January 2017
Accepted 31 January 2017
Available online 2 February 2017

Keywords:
Tree shade coverage
Spatial optimization
Location modeling
Solar insolation
GIS

ABSTRACT

Shade provided by trees, shrubs and other vegetation serves as a natural umbrella to mitigate insolation absorbed by features of the urban environment, especially building structures. For a desert community, tree shade is a valuable asset, contributing to energy conservation efforts, improving home values, enabling cost savings, and promoting enhanced health and well-being. Therefore, maximizing tree shade coverage is an important component in creating an eco-friendly and sustainable urban environment. Strategic placement of trees enhances tree shade coverage of buildings. This paper details an optimization method to simultaneously maximize tree shade coverage on building facades and open structures and to minimize shade coverage on building rooftops in a 3-dimensional environment. This method integrates geographic information systems and spatial optimization approaches for placing trees that provide the greatest potential benefit to a building. A residential area in Tempe, Arizona is utilized to demonstrate the capabilities of the method. The optimization results show that two trees can provide up to 22.20 m^2 shade coverage at 12:00 across a 54 m^2 south-facing facade. This research offers a method to help homeowners, urban planners, and policy makers to quantitatively evaluate shade coverage from trees for building structures in a residential environment.

1. Introduction

The urban heat island (UHI) is the consequence of the thermal properties of the urban fabric that results in higher temperatures in urban areas compared to the surrounding rural areas [1–3]. The UHI exacerbates heat waves during the summer, increases energy consumption, and more importantly, increases the risk of heat-related morbidity and mortality, especially for the elderly, children, and disadvantaged groups [4–7]. Well-known UHI mitigation methods rely on increased vegetation such as shading impervious surfaces through increased tree coverage, building urban parks with lawns and water ponds, and adding green roofs or cool roofs on residential and commercial buildings [8–15]. In this research, we focus on the strategic planning of shade trees in residential areas, which has been shown to provide significant energy and long-term cost savings, to enhance the environmental quality of the urban ecosystem, and to promote a range of human health benefits [8,16–18]. Intuitively, the benefits of shade are best realized when trees are located on the sunward facing facade of buildings such as the west and southwest of a building for regions in the northern hemisphere. A simple method to create ample shade involves planting as many trees as possible on these sides of the building. This approach, however, is impractical because of the financial cost of trees as well as water restrictions in many water regulated communities [19]. Similarly, excessive shading reduces the possibility of retaining exposed residential rooftops for placing electricity-generating solar panels [20–23]. So while existing research provides a general guideline on where to locate residential trees, they fail to consider the position of windows and doors, residential landscape siting restrictions, and the rooftop solar energy loss from shade coverage [24–28]. The challenge, however, is achieving the maximum benefits of shade at the individual building structure level with a more quantitative method, something that is not fully understood [29,30].

The goal of this research is to consider where to optimally and precisely locate shade trees on a residential parcel such that: a) the shading of facade, windows, and doors of home structures is maximized and rooftop shade is minimized; b) the shade from trees to the surrounding structures is considered; and c) spatial optimization is creatively used to find the best tree locations quantitatively in 3-dimensional (3D) environment. The study is limited to the shade coverage provided by trees and does not

* Corresponding author.
E-mail addresses: qszhao@asu.edu (Q. Zhao), wentz@asu.edu (E.A. Wentz), amurray@ucsb.edu (A.T. Murray).

http://dx.doi.org/10.1016/j.buildenv.2017.01.036

consider the dynamics of sensible and latent heat flux that occurs through evapotranspiration, diurnal variations in insolation, and seasonality. While limited in scope, we believe this approach provides an effective strategy for maximizing the shade of trees on residential structures. We therefore present a 3D spatial optimization model that identifies optimal tree locations for residential structures by integrating geographic information systems (GIS) with spatial optimization methods to solve this problem as a mathematical model. We demonstrate the method on a residential neighborhood in the greater Phoenix metropolitan area of Arizona, where tree shade coverage, water conservation, and solar energy potential are critical because of the hot and dry conditions.

2. Literature review

The study described here draws upon literature examining residential tree shade and spatial optimization in 3D environment. From the residential tree shade literature, research shows that west and east tree shade outside of house open structures provide the optimal cooling effects and energy reduction on residential homes [25]. The 3D spatial optimization literature guides the research on how to extend the 2-dimensional (2D) maximum coverage location problem into the 3D space [31]. The following sections elaborate on these bodies of work.

2.1. Impact of tree shade

Existing research on the impact of tree shade on home structures associates tree shade with energy use savings in a single-family house setting. Larger energy savings, up to 54% in some studies [27], are found with trees located on the west side of a home, followed by trees on the east or southwest [24,25]. These conclusions are similar across different northern hemisphere climate zones where both heating and cooling conditions are considered. For example, Hwang et al. [26] evaluated the tree shade effects from a single tree to a single family house during the cooling and heating season at both northern (Minneapolis and Indianapolis) and lower latitude (Charlotte and Orlando) locations. Using the distance between the tree and the building through eight cardinal (E, S, W, N) and inter-cardinal points (NE, SE, SW, NW), they show that trees on the west and east side of the house provided more energy conservation than those on the south side during the summer followed by the southeast or southwest.

The beneficial relationship between tree shade and energy is well established but there are only general guidelines on tree placement strategies and the optimal number of trees. Tree placement strategies emphasize cardinal direction with precision only specified at the inter-cardinal level [26] and without incorporating the distance from the home structure. This type of information is limited when it is infeasible to plant trees in specific cardinal directions. Furthermore, the distance trees are planted from the house structure, independent of the directionality, can further impact the area tree shade on a facade. Similarly, the number of planted trees is understudied, with most research focusing on the impact of a single tree. The starting point for these issues is research such as Simpson & McPherson [24], McPherson et al. [25], Calcerano & Martinelli [28], Huang et al. [32], and Akbari & Taha [33], who examined shading effects on different tree heights, multiple story buildings, and number of trees. Results are consistent with prior research showing optimal tree placement for energy savings is the east and west side of the buildings. These studies offer a broader range of design considerations, but they still do not consider the relationship to neighboring houses, the open features on the building facade, and a potential for rooftop solar panels.

Design considerations for tree placement additionally need to consider the relationship to nearby buildings, additional shade for windows and doors, and rooftop exposure for solar panel installations. There are two considerations for nearby buildings and tree placement. Nearby buildings, depending on distance, can simultaneously provide shade as well as receive shade from target building trees, although little research has examined this dual relationship. Also missing from the literature is tree placement to maximize shade on windows and doors. Windows and doors have less heat-insulation comparing to facades, so shading the windows by trees or other nearby structures will provide significant energy saving to the household comparing to facade [34]. On the other hand, residential building rooftops are the preferred location for photovoltaic solar panels to generate electricity from direct solar radiation, shown in multiple geographic locations [35]. Tree canopy coverage and shade will significantly reduce the photovoltaic efficiency of solar panels [20,21,23].

2.2. Spatial optimization in 3D

A challenge in maximizing shade coverage is that the buildings and trees are 3D objects, where the comparative location of the trees, roof, facade, doors and windows are important components for insolation remediation. Many real world facility location modeling problems have service coverage in the 3D environment such as camera surveillance or Wi-Fi connection services [31,36,37]. Nevertheless, existing facility location modeling problems are mostly abstracted and formulated in the 2D environment, such as the location set covering problem (LSCP) and the maximal covering location problem (MCLP) [38,39]. To manage the 3D space, these 3D coverage problems were simplified into 2D environment to ease the formulation and solution of the facility location problems [40]. Because of the dimensional simplification, the reliability and accuracy of optimal facility locations were unavoidably lost projecting from a 3D to a 2D environment.

With the development of 3D computational tools, several attempts have been made to appropriately formulate and solve the facility location modeling problems in the 3D environment [31]. Some of this has taken place through a 2.5D surface, such as digital elevation model (DEM), by using a visibility analysis or viewshed analysis [41]. Goodchild & Lee [42] utilized visibility analysis to locate the minimum number of viewpoints to observe the entire DEM surface, or to locate a fixed number of viewpoints to maximize the overall visible area on the DEM. This research extended the concept of set-covering problems to the topographic surface, and viewshed analysis was used to derive coverage on the DEM surface rather than the 2D planar surface. However, DEM is not a real 3D surface and the coverage derivation by visibility analysis required extensive computation. These limitations make it difficult to use their method to obtain the optimal coverage in a true 3D environment. To overcome the computational inefficiency, Kim et al. [43] extended Goodchild and Lee's research by only utilizing terrain features (peak, pass and pit) as candidate viewpoints to acquire the maximal coverage with given number of viewpoints. Their method solved the problems faster and overcame the computational difficulty, but they used the same viewshed method to derive the coverage in 2.5D. Murray et al. [44] found optimal security sensor placements in a 3D university environment utilizing the MCLP and the backup coverage location problem with visibility analysis. They considered the 3D building blocking effects in the coverage derivation process, but the coverage was only derived on the ground surface and did not consider the coverage on campus building facades. Most recently, Bao et al. [45] applied viewshed analysis to derive the watchtower coverage on the DEM, and integrated LSCP and MCLP solutions to determine the optimal watchtower locations for forest fire monitoring. To simplify the coverage representation,