ARTICLE IN PRESS

Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Exploring mutual shading and mutual reflection inter-building effects on building energy performance ☆

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HIGHLIGHTS

- Inter-Building Effects (IBEs) can influence a building's energy performance.
- We developed an approach to separately assess mutual shading and reflection.
- Cross-regional and real urban cases were studied using a dynamic simulation tool.
- We found shading IBE to impact building energy usage more than reflection IBE.
- The findings provide a more nuanced understanding of mutual building influences.

ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 29 October 2015
Accepted 30 October 2015
Available online xxxx

Keywords:
Building networks
Energy efficiency
Inter-building effects
Mutual reflection
Mutual shading
Simulation

ABSTRACT

The built environment contributes significantly to rapidly growing world energy expenditure and tighter spatial interrelationships can exacerbate this effect in cities. The concept of the Inter-Building Effect (IBE) was introduced to understand the complex mutual impact within spatially proximal buildings. Our research sought to develop a systematic approach to disaggregate and quantify the influence of mutual shading and mutual reflection within a network of buildings. We built an urban building network model and conducted cross-regional simulations under different climatological contexts by examining mutual shading only and mutual reflection only, respectively. We then expanded our investigation by examining two realistic urban contexts in Perugia, Italy. We found the shading effect played a more significant role in terms of impact on energy consumption. The results of the simulations in varying climatological contexts also revealed consistent trends of greater impact on the IBE for shading and reflection in warmer climatic cities. These findings expand and deepen our understanding of inter-building effects and may help in the search to minimize mutual influences between buildings that lead to increases in energy consumption in urban environments.

1. Introduction and background

Rapidly growing world energy expenditure has raised global concerns and became a central topic of research and public debate over the last several decades. Cities represent the highest concentration of energy use [1]. Buildings alone account for as much as 32% of total final energy consumption and nearly 40% of primary energy consumption [2]. To address building energy consumption, numerous research efforts have focused on how to achieve a more sustainable built environment from perspectives such as renewable energy [3,4], adaptive building envelopes and materials [5–7], occupant efficiency [8,9], advanced building information technologies [10,11] and building automation systems [12,13], sustainable rating strategies [14,15] and energy policies [16], among others. Urbanization—referred as the migration of rural dwellers toward towns, cities and megacities for the promise of a better life—is creating profound effects in the urban environment, including; the quality of urban air, urban temperature, energy consumption and water supply, pollution and waste products, loss of bio-diversity, conversion of agricultural to developed land, etc. [17]. A recent report from the United Nations projected the population in urban areas to reach 6.3 billion in 2050, 72% greater

☆ This paper was presented at the 7th International Conference on Applied Energy (ICAE2015), March 28–31, 2015, Abu Dhabi, UAE *(Original paper title: "Disaggregate Analysis of the Inter-Building Effect in a Dense Urban Context" and Paper No.: 334).*

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http://dx.doi.org/10.1016/j.apenergy.2015.10.170
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than the 3.6 billion urban dwellers in 2011 [18]. Urban built settings are evolving toward much tighter spatial interrelationships, which could exacerbate urban energy consumption, and also influence the surrounding microenvironment and microclimate. The motivation of this research is to examine and deepen our understanding of inter-building relationships in dense urban settings resulting from urbanization and the related impacts on building energy consumption.

Urban morphology—characterized by building density, size, height, orientation, and layout—causes considerable variations in the local environment. Urban microclimates affect a building's performance in terms of energy consumption and indoor living environment, while buildings affect the urban microclimate within their building networks [19–22]. Early research largely focused on the energy behavior attributed to individual buildings to understand and optimize the energy efficiency of an individual building by describing indoor thermal behavior, energy consumption, and building envelope features. However, to treat buildings as stand-alone entities does not accurately represent a building's energy performance since it does not consider the nearby buildings which could exert a mutual influence on thermal dynamics. One example is that reflective envelopes could reflect daylight to the neighboring buildings and surrounding areas and create problems such as glare and overheating, which may result in visual and thermal discomfort to building occupants [23]. Thus, building networks and urban street canopies should be taken into consideration, and have drawn attention by building researchers to holistically understand energy issues. He et al. [24] studied the impact of the local outdoor environment to building thermal–energy behavior, indicating that it is not sufficient enough to assess a building's energy dynamics solely based on building features. To evaluate solar rights and shading requirements in an urban environment, Shaviv and Yezioro [25] developed a CAD tool that can analyze the mutual shading between buildings and surrounding objects, such as trees, and it was later extended by Li and Wong [26] to study the daylighting and energy implications from nearby obstructing buildings. Golany [27] built upon this, bringing an urban design view of the relationship between urban design morphology and the thermal performance of the city concerning street orientation, building geometry and urban proportions. Taking the idea of urban design morphology to the next step, Conceição António et al. [28] proposed an approach on the optimal placement of buildings that favors the use of solar energy.

To understand the complex interactions within spatially proximal urban building networks, the concept of the Inter-Building Effect (IBE) has been introduced and further studied over the last several years [29–31]. Pisello et al. [30] employed IBE indexes to demonstrate the interrelationship between buildings within building networks which could result in substantial inaccuracies (up to 42% in summer, and up to 22% in winter) of energy consumption predictions for space heating and space cooling. The research also revealed that the buildings' energy performance can be significantly impacted by surrounding buildings through mutual reflection and mutual shading [30]. Thus, in order to accurately predict the energy performance of a single building, the IBE created by the spatially proximal buildings should be considered. IBE research was later expanded to examine primary lighting energy consumption using daylight analysis and through the use of empirical data for model calibration [29]. Higher values of the IBE indexes were found for the lighting energy consumption, indicating lighting is also impacted by surrounding buildings within inter-building contexts. With foreseeable urbanization in the next several decades, tighter spatial interrelationships between buildings in urban settings will exacerbate the IBE and this necessitates a more nuanced analysis of its effects. Although shading and reflection have been discussed as two essential components of the IBE [29,30], previous research has largely considered the IBE as a monolithic effect across building networks. More research is needed to disaggregate the impact in order to explore which factors may be largely dependent on the local climatic environment and which could be addressed separately through urban planning and building designs.

The research presented in this paper builds upon previous IBE efforts [29–31] concerning the study of energy and thermal behavior of buildings in a dense urban context to further analyze and understand the effect of mutual impact by the IBE in a micro-urban environment. Our objective is to develop a procedure to separately assess the complex interactions, i.e. mutual shading and mutual reflection, that make up the IBE. Through comparative simulation and analysis, we sought to disaggregate and quantify the influence of mutual shading and mutual reflection with respect to space heating, space cooling energy and lighting energy consumption within a network of buildings in urban contexts. The findings of a more nuanced analysis of IBE could lead to better understanding the inter-building thermal–energy relationship and lead solutions to mitigate the negative impact of the IBE in urban microenvironments.

2. Methodology

2.1. Simulating the IBE in a dynamic environment

Simulation tools offer powerful functionalities to predict and improve building energy consumption for both research and design purposes. Of current mainstream simulation environment and platforms, EnergyPlus [32], an energy analysis and thermal load simulation engine distributed by the U.S. Department of Energy, has become a popular building energy performance simulation tool owing to its sophisticated and validated functions. It was utilized for previous IBE research and dynamic building network analyses [29–31]. Early IBE simulation efforts were conducted based on a realistic physical urban block in New York State [30]. The research demonstrated that buildings could mutually influence the energy dynamics of near buildings, especially for cooling and heating, and cause substantial energy prediction inaccuracies over the course of a year. Later research further investigated the energy discrepancies in lighting and validated the IBE, as an important effect to be modeled in situations where buildings are surrounded by other nearby buildings [29]. Experiment and empirical data were used to calibrate and verify the simulation work.

Inherited from previous IBE research, we first developed a procedure to separately assess the shading effect and the reflection effect in EnergyPlus which is described in Section 2.2. With that, we built a hypothetical nine-building network model to analyze the thermal–energy behavior of the middle control building with combined IBE, IBE without shading, and IBE without reflection, respectively, under different climatological conditions. This is described in Section 2.3. We then examined two realistic urban dense contexts located in Perugia, Italy using the same procedure for this disaggregate analysis. This is described in Section 2.4.

2.2. Procedure for disaggregating shading and reflection from the IBE

Shading and reflection have been evidenced as major contributors that make up the IBE [29,30]. Therefore, we sought to develop a procedure to disaggregate mutual shading and mutual reflection and assess them separately in the numerical simulation and analysis. The control building was modeled with heat-transferring surfaces and its energy usage was monitored over the course of the simulation. Shading surfaces, an essential geometric element for shading and reflection in the EnergyPlus environment, were used