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Evaluating approaches for district-wide energy model calibration considering the Urban Heat Island effect

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HIGHLIGHTS

- Evaluation of the impact of the urban context via district-scale modelling and inverse parameter estimation (calibration).
- Automated calibration process for 56 buildings in a representative district in Abu Dhabi.
- A straightforward methodology to calibrate a large number of buildings, considering the urban microclimate condition.
- Informs city planners, energy engineers, and governmental agencies on building energy efficiency and UHI intensity.

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ABSTRACT

Over the past decade, the building energy research community has increasingly focused on urban-scale models. The shortcomings of analyzing isolated buildings in an urban context are well-known and far from negligible, mainly due to the inability to account for Urban Heat Island (UHI), shading from neighboring obstructions, and obstructed wind flow. The aim of this paper is to evaluate the impact of the urban context via urban-scale modelling and inverse parameter estimation (calibration) using metered building energy consumption. We describe an automated calibration process for modelling 56 buildings in a representative district in downtown Abu Dhabi (UAE), where a detailed energy audit was conducted with data from 2008 to 2010. Since the urban ambient air temperature could differ significantly from the reference rural air temperature used in most building simulations, the calibration procedure will also consider this UHI effect. Two main approaches of district-wide energy model calibration are proposed using a genetic algorithm and compared to a baseline case where UHI is not considered. The first approach estimates seven building-related parameters together with four microclimate-related variables (describing annual average and seasonal variation of the UHI effect on both air temperature and humidity). The second one uses the Urban Weather Generator (UWG) to pre-process the urban EPW file, thereby reducing the number of the parameters to be estimated. In addition, two approaches are investigated for the calculation of the ASHRAE Guideline 14 calibration error metrics (CvRMSE and NMBE). One approach is to look at the whole district as one aggregate building, while the other, introduced for the first time herein, consists in deriving the weighted-average of the error of each building. The main contribution of this study is to provide simultaneous calibration for multiple buildings in the same district—and subject to the same UHI intensity. Hence, the UHI intensity (urban-rural temperature/humidity differential) is estimated alongside other calibration parameters. For the weighted average approach, CvRMSE found is between 19.09% and 19.40%, while NMBE is between 16.24% and 16.39%. For the aggregated building, CvRMSE is between 2.71% and 4.04%, while NMBE is between 1.95% and 2.35%.

1. Introduction

The rapid development and growth of urban areas has caused significant impacts on the built environment. One of the consequences is the Urban Heat Island (UHI) phenomenon, which has been studied and quantified throughout the world in cities with various morphologies and climates. This phenomenon is a major determinant of the urban microclimate and influences, sometimes significantly, the indoor space conditioning energy use in buildings.

Physics-based building energy models (BEM) have been used

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extensively in research and engineering for the estimation of heating/cooling energy demand. BEMs take into account various heat exchanges that may occur within the building and between the building and its immediate environment. BEM parameters are often derived from design specifications. Commonly used BEM software engines include DOE-2, EnergyPlus, and TRNSYS.

In the case of existing buildings with a recorded history of operation, a calibration process can be conducted to better estimate uncertain BEM parameters. Calibration can be either manual or automated. The goal of calibration is to reduce the discrepancy between model outputs (e.g. simulated building energy consumption) and measurements extracted from real buildings (e.g., utility meters). Once the model is properly calibrated, it could potentially allow for building performance evaluations under different conditions, enabling the comparison of alternative design options and retrofit scenarios.

However, one recognized obstacle is that the current BEM practice rarely incorporates the specific urban microclimatic characteristics. In the quasi totality of cases, buildings are simulated in isolation without any surrounding buildings and 'rural' environment is assumed. The weather files used in simulations are usually extracted from local airport weather stations. This study proposes several adaptations to the common practice in order to model and calibrate BEMs considering the urban microclimate at a district level.

We modelled a district in downtown Abu Dhabi (UAE) composed of 67 buildings for which relatively detailed information was gathered in the course of an energy audit conducted in 2011. We investigate two novel district-wide calibration approaches that incorporate the UHI effect and compare to a more conventional calibration with rural weather. The first proposed approach uses an urban energy model wherein the urban-rural temperature/humidity differential due to UHI will be estimated during the calibration process together with the building-related properties. The second proposed approach involves a pre-processing of the reference rural weather data using the Urban Weather Generator (UWG) [1] before the calibration process. The latter, then, only tunes the building-related parameters.

The main novelty of this study, therefore, is that it proposes a district-wide energy model calibration procedure accounting for the UHI. Through the introduction of new error metrics similar to those set forth in ASHRAE Guideline 14, the calibration attempts to simultaneously minimize the global district level modelling error and the building level modelling error.

2. Literature review

2.1. Urban Heat Island

The Urban Heat Island (UHI) effect has been observed in many cities worldwide. It is a complex phenomenon that results in urban temperatures that are, in average, higher than surrounding rural areas. The UHI is caused by several factors, including increased absorption of the short-wave radiation (from reduced solar reflectance of urban surfaces), increased sensible heat storage (in urban structures), generation of anthropogenic heat (mainly from air-conditioning system heat rejection and motorized vehicles), reduced evapotranspiration (due to the lack of vegetation in urban areas), reduced sensible heat losses (due to reduced wind speeds in urban canyons), etc. [2]. In general, there is a growing concern about the UHI effect, especially during the summer when outdoor air temperatures are considerably higher and heat waves may endanger public health and aggravate air pollution. Furthermore, the UHI impacts the building indoor space conditioning load [3]. To quantify these impacts, one simple indicator is the Urban Heat Island (UHI) intensity, usually defined as the temperature difference between the urban area and surrounding rural area. Distinct climates and levels of urbanization tend to present different UHI intensities [4].

In order to mitigate the UHI effect, Rosenfeld, et al. [5] explored solutions at building and city scales, including cool (reflective) surfaces, tree shading, and district cooling. The study highlighted the potential for energy savings, especially with the use of cool surfaces that can be implemented at low cost. Furthermore, specific attention was drawn to policies and standards to motivate the implementation of new technologies and reduce CO_2 emissions. Rizwan et al. [4] compiled different works of mitigation strategies and reported the resulting temperature reduction and savings. The studies mainly include increase of vegetation, reduction of anthropogenic heat, increase of shading, cool roofs, and humidification. Rossi et al. [6] investigated the use of reflective surfaces and concluded that it could reduce radiative effects, especially in areas with buildings in close proximity. Santamouris [7] studied reflective and green roofs as mitigation levers for heat islands, considering the limitation of this solution for high-rise buildings, but highlighting the potential for latent heat losses. The author concluded that the reflective roofs gain advantage in sunny climates, while vegetation presents higher benefits in colder climates.

2.2. Energy modelling

2.2.1. Building energy model (BEM)

A typical building energy model (BEM) is a white-box engineering model used for estimating real or proposed building thermal behavior. A series of detailed calculations is conducted by the model, based on a large amount of information such as building characteristics, climate conditions, and activity schedules [8]. The high input uncertainty, quite common given the level of detail required, often leads to lower accuracy of the simulated output. Furthermore, developing a reliable model is a long-term process that requires a high level of expertise. That is why simplified models are often used and it is up to an expert modeler to decide which assumptions and simplifications should be made [9]. Sensitivity analysis is thus recommended to understand how certain variables affect the building performance [10]. Applications of BEM include:

- Testing of new technologies, estimating savings and potential for retrofits, such as green roofs [11]or thermochromic glazing [12],
- Parametric analysis to test feasibility, cost-benefit, and design option for a real project [13],
- Verifying compliance for certifications, such as the LEED, BREEAM (UK), Green Star (Australia), Estidama (Abu Dhabi, UAE), etc. [14],
- Estimating more suitable solutions for different regions and climates [15],
- Research or consultancy work for design, retrofits, operation, and commissioning [14],
- Generation of life cycle cost (LCC) and life cycle analysis (LCA), as well as measurement and verification (M&V) [13].

2.2.2. Urban energy model (UEM)

Energy system modelling has been well explored at the building level. Over the past four decades, we have achieved significant progress in modelling the heat and mass flows entering or leaving buildings to the point where, given reasonably comprehensive input data, most simulation engines can predict future energy use of standard constructions with acceptable accuracy. However, the study of the UHI requires the use of neighborhood-to-city scale urban energy models (UEMs).

The BEMs usually run simulations under isolated conditions (no shading effect from adjacent buildings) and consider that rural weather conditions, uniformly distributed around the envelope, prevail. The latest UEMs have been created as adaptations to traditional BEM software and are able to model, to varying degrees, the interactions between the building, occupant, and environment [16].

Pisello et al. [17] considered inter-building effect to study how they influence the accuracy of building energy performance evaluations. They concluded that, when evaluating the energy performance of a single building, the special relationship with surrounding buildings should be taken into account. Martin et al. [18] coupled an urban