Applied Energy 174 (2016) 256–274

Contents lists available at ScienceDirect

Applied Energy

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

Naturally comfortable and sustainable: Informed design guidance and performance labeling for passive commercial buildings in hot climates

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HIGHLIGHTS

- Parameters varied in building energy simulations to assess adaptive comfort impacts.
- Building size and internal gains were most important; envelope properties less so.
- Ceiling fans and night ventilation were effective, low-energy comfort interventions.
- A new metamodel can support building labeling program and provide design guidance.
- With informed design, comfort achievable in most of Brazil with no air conditioning.

ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 12 April 2016
Accepted 16 April 2016

Keywords:
Natural ventilation
Building energy simulation
Adaptive thermal comfort
Sensitivity analysis
Metamodel
Sustainable development

ABSTRACT

This work develops guidance and tools to understand the performance, improve the design, and simplify the evaluation of naturally ventilated low-rise commercial buildings in warm and hot climates. We conducted ~50,000 detailed energy and airflow simulations in 427 locations across Brazil, varying 55 parameters representing building morphology, fenestration, construction properties, internal gains, operating times, wind modifiers, flowpaths, window control, and soil traits. Comfort performance was quantified by the average annual fraction of occupied hours that exceeded the upper limit of an adaptive comfort zone, and investigated with sensitivity analysis and machine learning methods. Results indicated that, after climate, building size (both footprint area and number of stories) and internal gains were most influential and were positively associated with discomfort. Adding air movement with ceiling fans and providing for night ventilation both proved highly effective comfort interventions. Except for roof solar absorptance, opaque envelope changes, including increasing insulation or thermal mass, had only marginal impacts. A support vector regression metamodel, requiring 29 easily obtainable inputs plus a weather file, was fit to the simulation results and successfully validated ($R^2 = 0.97$). The metamodel was developed as a simplified compliance path for naturally ventilated buildings to enhance Brazil's commercial building performance labeling program, which, because it currently provides such a path only for air conditioned buildings, may discouraging decision-makers from considering even more efficient passive solutions. We use a case study to show how the metamodel, which we will distribute publicly, can also serve as a design tool, and demonstrate that modifying a small set of parameters can drastically improve thermal performance and achieve sustainable comfort in hot and warm climates.

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1. Introduction

The strong relations between countries' energy use or carbon footprint and both their per capita GDP [1] and human development index score [2], despite some quantitative uncertainty and substantial inter-country variability [3,4], raise a critical question: can development bring significant improvements in living standards without significant increases in energy consumption

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Abbreviations: AE95, 95th percentile absolute error; AFN, airflow network; AR, aspect ratio; CDD, cooling degree day; EH, exceedance hour; EHF, exceedance hour fraction; ELA, effective leakage area; ELPD, equipment and lighting power density; FPA, footprint (projected) area; GLM, generalized linear model; NVW, night ventilation window; PCA, principal component analysis; PI, prediction interval; PW, primary window; RMSE, root mean square error; SA, sensitivity analysis; SD, standard deviation; SHGC, solar heat gain coefficient; SRC, standardized regression coefficient; SVR, support vector regression; WWR, window-to-wall ratio.

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http://dx.doi.org/10.1016/j.apenergy.2016.04.081
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and carbon pollution? Globally, by 2040, at least 65% of the world's energy consumption is expected to be in developing countries [5]. Brazil, a newly industrialized economy, is a case in point. As of 2014, per capita carbon emissions were still low by developed standards—less than a sixth of those in the U.S. and a little over a third of those in the EU-28—but had risen 71% since 1990 (compared to declines of 16% and 27% in the U.S. and EU-28, respectively) [6]—and the largest driver has been increases in individuals' living standards [7].

In response, mitigation has been proposed on both the supply and demand side [8–11], emphasizing quality economic growth and energy efficiency as keys to sustainable development, echoing similar emphasis around the world [12,13]. In particular, the important role of buildings in total energy consumption and carbon emissions—about 40% globally [14,15]—has begun to be addressed in Brazil. Inmetro (the National Institute of Metrology, Quality and Technology), which had focused on energy efficiency standards for appliances since 1984, launched a whole-building energy efficiency labeling program for commercial and public buildings (RTQ-C) in 2009 and residences (RTQ-R) in 2010 [16,17]. The regulations, which classify buildings from "A" (most efficient) to "E," represented a major step forward for Brazilian building-sector energy conservation.

The commercial version, voluntary for private structures but mandatory for new government projects, is strongly oriented toward buildings with air conditioning. It ascribes 70% of total weight to factors related to mechanical system performance, for which there is a simplified calculation technique based on tabulated values and a linear regression metamodel [18]. The regulation does briefly address buildings without air conditioning, stipulating that the 70% of the score for thermal performance is to be based on the fraction of annual occupied hours that are outside of the comfort zone. (If the fraction is less than 0.20—i.e., 20% of occupied hours—the building's thermal performance is awarded an "A.") Unlike for air conditioned buildings, comfort *must* be calculated via energy simulation; there is no simplified calculation path. One goal of our work is to develop that needed path.

By creating a practical natural ventilation labeling path, we hope, in addition to strengthening and balancing the labeling program, to promote recognition of the validity of passive design options, which can dramatically reduce building energy use [14]. By its nature, harnessing wind and stack effects and careful passive design to maintain comfort with natural ventilation conserves more energy than the most advanced air conditioning efficiency improvements ever could. While natural ventilation is not appropriate for very noisy or polluted environments [19], and requires providing for sufficient occupant control [20] and air movement [21,22], it represents a crucial bioclimatic design strategy for Brazil [23] and beyond [24]. It also provides significant economic co-benefits and helps avert problems that can occur in conditioned buildings, including high concentrations of indoor pollutants like CO_2 [25], reduced productivity in offices [26,27] and less learning in schools [28,29], and an increase incidence of various acute health symptoms [30], including asthma exacerbations in schools [31].

While natural ventilation has enjoyed renewed interest in developed areas [32], it never went away in emerging countries like Brazil, where public buildings like schools often do not rely on mechanical cooling, and even many small commercial buildings have operable windows. Occupants of such naturally ventilated commercial buildings have generally been found to be quite comfortable [33], with thermal acceptability in the milder south of Brazil ranging from 14 to 24 °C [34,35] and in the hot northeast from about 24 to 32 °C [36]. Such broad ranges substantially conform to—indeed, are even somewhat broader than—the adaptive thermal comfort model of ASHRAE Standard 55-2013 [37], but would probably come as a surprise to practicing engineers in developed countries. One reason is that occupants habituated to air conditioning appear to have narrower thermal preferences and a greater desire for air conditioning, even when indoor conditions are broadly acceptable to those not accustomed—or addicted, as it has been called—to air conditioning [38]. Such acclimatization is exactly the type of change in expectations that, cumulatively, helps determine the strength of coupling between economic development and environmental impacts.

Constructing comfortable passive buildings, therefore, is not only about promoting the health and well-being of current occupants, but also reducing the likelihood they will (often justifiably) turn to air conditioning as living standards rise, potentially leading to a vicious circle of habituation and further increased consumption. This research contributes by significantly enhancing understanding of what characteristics affect comfort in passive commercial buildings. The first step was developing a comfort performance dataset by creating, simulating, and processing thousands of airflow/energy/comfort models with dozens of varying parameters. The second was applying statistical and machine learning techniques to develop both qualitative design guidance and a quantitative design tool, the latter of which can also provide the simplified calculation path for naturally ventilated structures needed for the RTQ-C commercial building labeling program.

The qualitative understanding was developed through an impact and sensitivity analysis (SA) of the energy simulation results. Applying SA to building energy simulations has been of much recent interest [39], with goals ranging from evaluating uncertainties in design parameters, material properties, and use patterns [40–42], to neglecting non-influential parameters [43], assessing operational strategies [44], and identifying favorable retrofit implementation scenarios [45]. The quantitative tool is a metamodel, or an empirical input–output relationship. Metamodeling, enabled by the spread of advances in machine learning, has also been a subject of significant recent interest in the building energy community [43,46–50]. Metamodels' computational speed makes them attractive if many simulations need to be run (e.g., for optimization), and their simplicity is suited to typical construction projects where having a detailed energy model built is cost prohibitive.

The novelty of this paper, therefore, consists not so much in the individual methods employed, but in the scope of processes and parameters considered, the comprehensiveness of the comfort performance dataset constructed, and the application, for the first time, of sensitivity analysis and metamodeling tools to such a dataset. The results are novel: simple lists of the most important building parameters affecting occupant comfort in naturally ventilated buildings in warm and hot climates, and a metamodel—which we will release for free public use—that enables, in only minutes of set-up and seconds of execution, case-specific assessment of design parameters' comfort impacts. Our hope is that informed design guidance (and, in Brazil, streamlined inclusion within the commercial building labeling scheme) can promote effective and comfortable passive buildings, both meeting and shaping expectations and long-term behavior, thereby preserving where appropriate the availability of a healthy, economical, sustainable, bioclimatic, and even stimulating [51] architectural solution.

2. Methods – comfort performance dataset

Our first objective was to create a large comfort performance dataset by varying building and site characteristics and calculating the impacts on thermal comfort. The core models for these calculations were EnergyPlus 8.3 for building thermo-energetic modeling [52], the multizone Airflow Network (AFN) model within

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