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Estimating the influence of occupant behavior on building heating and cooling energy in one simulation run

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HIGHLIGHTS

- The potential impact of OB on building performance must be assessed on a case-by-case basis.
- A method based on one simulation run provides significant estimate of potential OB impact.
- Impact indices can be used to take calculated risks for building energy performance contracting.

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ABSTRACT

Energy performance contracting (EPC) aims at guaranteeing a specified level of energy savings in the built environment for a client. Among the building energy performance uncertainties that hinder EPC, occupant behavior (OB) plays a major role. For this reason, energy service companies (ESCOs) may be interested in including OB-related clauses in their contracts. The inclusion of such a clause calls for an efficient, easy-to-implement method to provide a first estimate of the potential effect of various aspects of OB on building cooling and heating energy demand. In contrast with common sensitivity analysis approaches based on a high number of scenarios, a novel simulation method requiring only a single simulation run for both heating and cooling seasons is presented here. The estimate is provided by evaluating the newly developed impact indices (II) based on the results obtained by means of the simulation run. A set of 16 building variants differing in floor height, climate, construction vintage and equipment and lighting power density was investigated to test the method. All II were calculated for the 16 building variants. In order to verify their significance, the results of a one-at-a-time sensitivity analysis mimicking simplified variations in occupant behavior (OB) were plotted against the II. The R^2 values were above 0.9 when evaluating the effect of equipment use, lights use, and occupant presence, confirming the significance of the developed II. For blind use and temperature setpoint setting, the R^2 values were ca. 0.85. Subsequently, the method was applied to an existing office building in Delft, The Netherlands, to evaluate its potential for EPC. This study confirms the high variability of the effect of OB on heating and cooling energy demand according to the case at hand. The developed method is useful for practitioners to evaluate the potential effect of OB on a given design in a time-effective manner.

1. Introduction

Occupant behavior (OB) is commonly acknowledged to be one of the main causes of uncertainty in building energy performance [1–3]. Because of its intrinsic stochasticity and due to the difficulty in predicting how people will behave, OB is also among the unsolved problems of building performance simulation (BPS), and it is often mentioned as an important cause of the energy performance gap [4]. A clear understanding of building performance uncertainties is required when performing energy performance contracting (EPC), a financing method designed to promote energy efficient building commissioning. In EPC, an energy service company (ESCO) guarantees building energy savings to the customer. Energy intensive real estate is particularly attractive to ESCOs as it provides large savings potential. In this paper, we focus on office buildings as an example of energy intensive real estate. The companies issuing energy performance contracts are motivated to minimize the risk of not achieving the desired energy savings. For this reason, they must increase their current understanding of OB, among other uncertainties. OB cannot be generalized as a whole, as different aspects (e.g., the use of equipment or blinds operation) have entirely different triggers as well as different effects on the building's heat balance. Nevertheless, a number of studies show the combined effect of

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various aspects of OB on building energy performance [5–8]. An investigation of the impact of OB can be made with field studies or simulation-based studies. Field studies can be conducted by monitoring identical buildings, where the residents are the only variable (e.g., [8]), or by testing the effect of OB-related conservation measures (e.g., [9,10]). At the building level it is difficult to find identical commercial buildings, which are hence often researched in a parametric way (e.g., [11]), considering one OB aspect at the time, as well as their combined influence.

Hoyt et al. [12] studied the effect on energy consumption of reducing the heating setpoint and increasing the cooling setpoint. The Medium Office DOE reference model [13] was used by the authors as a case study and modeled in EnergyPlus, with two construction vintages (new construction and Post-1980 construction) and in 7 ASHRAE climate zones. According to their study, increasing the cooling setpoint from 22.2 °C to 25 °C results in an average of 29% cooling energy savings. Reducing the heating setpoint from 21.1 °C to 20 °C results in an average of 34% terminal heating energy savings. However, the results show a high variability across different building models and climates. Ghahramani et al. [14] also analyze the influence of temperature setpoint on the energy use of the DOE reference office buildings, considering three sizes, three construction categories and all United States climate zones. The authors discovered that for extreme temperatures (i.e., outside the range −20 to 30 °C), choosing the highest cooling setpoint for outdoor temperature above 30 °C, and the lowest heating setpoint for outdoor temperature below −20 °C, led to the lowest energy consumption, regardless of climate, size, or construction. Within the range of −20 to 30 °C, the optimal setpoint depends on the building size. Within a range of observed outdoor temperatures (9–14 °C for small buildings and 8–11 °C for medium buildings) the setpoint selection is negligible. Great variability in potential savings was observed in respect to climate, building size and construction. Lin and Hong [7] demonstrated that the effect on the energy use in a single-occupant office building of occupancy-controlled light, equipment, and HVAC operation, as well as temperature setpoint and cooling startup control, varies with the climate. Sun and Hong [15] implemented stochastic occupancy-related measures to a two-story office building modeled in EnergyPlus Version 8.4, and verified the impact that the measures had on the energy savings for the climates of Chicago, Fairbanks, Miami and San Francisco. Two standards, ASHRAE 90.1 – 1989 and 90.1 – 2010, were evaluated. The effect of single measures was shown to be highly dependent on building vintage and climate, while the overall savings of all measures were similar across vintages (27.9–40.5% in the four climates of vintage 1989, and 24.7–41.0% in vintage 2010). Azar and Menassa [16] perform a sensitivity analysis on the occupancy behavioral parameters of typical office buildings of different sizes and in different weather zones. The authors generally found a significant sensitivity, with values of the influence coefficient (IC) ratios (defined as the percentage change in output to the percentage change in input) of up to +1.0197. They conclude that the influence of various occupancy behavioral parameters varies according to size and weather conditions, with the highest sensitivity to be found when varying the heating temperature setpoint in small-size buildings located in US zone 2 Dry. Despite most authors found significant sensitivity of the investigated office buildings to OB, it is worth noting that the characteristics of occupant behavior can differ according to building type [17]. For example, in the residential sector the impact of different behaviors on energy use may be even higher. In fact, influential factors such as different age, function and socio-economic status, may play an important role in adding diversity to energy-related behaviors [6].

All mentioned studies investigated the effect of OB by means of one-at-a-time (OAT) sensitivity analysis or with global sensitivity analysis supported by statistical methods (e.g., [14]) for sampling and ranking. The common conclusion to be drawn is that the effect of various aspects of OB depends on climate, building size, building vintage, etc. and general guidelines suitable for practitioners cannot be derived. The available methods to define the potential influence of OB on building performance are complex and time-consuming, as they require the formulation of a high number of scenarios. As such, they are not feasible for companies seeking to efficiently quantify the OB-related risks of performing EPC. Moreover, most available methods do not provide information on the specific contribution of different aspects of OB, which could be helpful for ESCOs. There lacks an effective way to find information about potential OB-related performance uncertainties which also offers insights on predominant OB aspects (which could be specifically regulated by means of clauses in the contracts). This study seeks to fill this gap and to provide practitioners with an effective, efficient method to estimate the potential influence of various aspects of OB (i.e., blinds operation, equipment and lights use, people presence and temperature setpoint setting) on building cooling and heating energy demand.

We build up on and improve the common practice of simulation use in companies by proposing a one-simulation-run approach. In fact, performing sensitivity or uncertainty analysis typically requires a high number of simulations (or scenarios), a practice which may not be feasible for companies for time and cost reasons. The here proposed method consists of a number of indicators (impact indices) that allow to quantify the influence of various aspects of OB without requiring the formulation of scenarios, but instead using the already available information provided by one simulation run. The indicators are developed in the form of ratios among the various contributors of the building energy balance which were obtained by the simulation run. The paper is structured as follows: first, the impact indices are defined (Section 2). Secondly, 16 building variants are introduced and the methodological steps to acquire and test the indices are presented (Section 3). Then, results concerning impact indices and their test are obtained and discussed (Section 4). An existing building is used as a case study to assess the applicability of the proposed method to EPC (Section 5). Finally, conclusions are given in Section 6.

2. Impact indices definition

The impact indices are simple indicators that allow to estimate the effect of OB on heating and cooling energy demand. In this study, impact indices are developed for blind use, equipment and light use, occupants' presence (Section 2.1) and setting of temperature setpoints (Section 2.2).

2.1. Impact indices for blind, equipment, light use and occupant's presence

The impact indices for blinds, equipment, light use and occupant presence are all developed in a similar manner. The indices' definition is based on the building heat balance and borrows from the concept of skin-load dominated buildings vs. internal-load dominated buildings. Simply put, the heat balance of skin-load dominated buildings is more likely to be highly affected e.g. by blind use, which directly affects the thermal resistance of the façade, while a variation in internal loads is expected to only have a marginal effect. Instead, the amount and distribution of internal loads is especially critical in internal-load dominated buildings. BPS tools calculate, alongside heat gains from people, lighting, equipment, windows, interzone air flow, and infiltration, also the effect of the walls, floors and ceilings/roof to the zone, and the impact of the delay between heat gains/losses and loads on the HVAC equipment serving the zone [19]. Hence, assuming that no cooling occurs during the heating season, the heat balance can be written as

$$Q_{NH} = (Q_{L,Win} + Q_{L,Int} + Q_{L,Inf} + Q_{L,Op}) - (Q_{G,People} + Q_{G,Lights} + Q_{G,Eq} + Q_{G,Win} + Q_{G,Int} + Q_{G,Inf} + Q_{G,Op}), \quad (1)$$

where Q_{NH} is the HVAC input sensible heating [J], $Q_{L,Win}, Q_{L,Int}, Q_{L,Inf}, Q_{L,Op}$ [J] is the heat removal due to conduction and radiation through windows, interzone air transfer, infiltration,