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

Citation for published version (APA):

DOI:
10.1016/j.apenergy.2018.03.108

Document status and date:
Published: 01/08/2018

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 01. Nov. 2019
Estimating the influence of occupant behavior on building heating and cooling energy in one simulation run

Isabella Gaetani⁎, Pieter-Jan Hoes, Jan L.M. Hensen

Building Physics and Services, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

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.

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 R² 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 R² 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

⁎ Corresponding author.
E-mail address: i.i.gaetani@tue.nl (I. Gaetani).

https://doi.org/10.1016/j.apenergy.2018.03.108
Received 10 October 2017; Received in revised form 6 February 2018; Accepted 26 March 2018
Available online 26 April 2018
0306-2619/ © 2018 Elsevier Ltd. All rights reserved.
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 7 ASHRAE 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 [13] 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 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

\[
Q_{NH} = (Q_{L,win} + Q_{L,inf} + Q_{L,op}) - (Q_{\text{people}} + Q_{L,inf} + Q_{L,inf}) + Q_{L,win} + Q_{L,inf} + Q_{L,op},
\]

(1)

where \(Q_{NH}\) is the HVAC input sensible heating [J], \(Q_{L,win}\), \(Q_{L,inf}, Q_{L,op}\) [J] is the heat removal due to conduction and radiation through windows, interzone air transfer, infiltration,
In order to evaluate the potential effect of blinds, equipment, light use and occupants’ presence during the heating season, the following impact indices are developed:

\[
I_{\text{blinds, }H} = \frac{Q_{\text{losses, Tot}} - (Q_{\text{gains, Tot}} - Q_{\text{W}})}{Q_{\text{NH}}} - 1 \\
I_{\text{equipment, }H} = \frac{Q_{\text{losses, Tot}} - (Q_{\text{gains, Tot}} - Q_{\text{Eq}})}{Q_{\text{NH}}} - 1 \\
I_{\text{lights, }H} = \frac{Q_{\text{losses, Tot}} - (Q_{\text{gains, Tot}} - Q_{\text{Lights}})}{Q_{\text{NH}}} - 1 \\
I_{\text{presence, }H} = \frac{Q_{\text{losses, Tot}} - (Q_{\text{gains, Tot}} - Q_{\text{People}})}{Q_{\text{NH}}} - 1
\]

The impact indices aim to quantify the weight of a given source of heat gain within the heat balance. For example, in \( I_{\text{equipment, }H} \), the heat gains due to equipment are subtracted from the total heat gains contributing to the heating load. If the equipment heat gains represented \(0\)% of the total heat gains, the ratio \( \frac{Q_{\text{losses, Tot}} - (Q_{\text{gains, Tot}} - Q_{\text{Eq}})}{Q_{\text{NH}}} \) would be \(1\), and the resulting impact index would be \(0\). The higher the specific impact index, the more likely blinds, equipment, light use or occupants’ presence are to have an impact on the building heating energy use. The term \(-1\) is added to allow comparison with the impact indices developed for cooling, which are presented hereafter. Hence, the minimum value of the impact index is \(0\), which would occur if a type of behavior has no potential influence.

Similar to the heating season, the heat balance in the cooling season can be written as

\[
Q_{\text{NC}} = Q_{\text{gains, Tot}} - Q_{\text{losses, Tot}}
\]

from which, dividing both terms by \(Q_{\text{NC}}\),

\[
1 = \frac{Q_{\text{gains, Tot}} - Q_{\text{losses, Tot}}}{Q_{\text{NC}}}
\]

Hence, the impact indices for blinds, equipment, light use or occupants’ presence in the cooling season are defined as follows:

\[
I_{\text{blinds, }C} = 1 - \frac{(Q_{\text{gains, Tot}} - Q_{\text{W}}) - Q_{\text{losses, Tot}}}{Q_{\text{NC}}} \\
I_{\text{equipment, }C} = 1 - \frac{(Q_{\text{gains, Tot}} - Q_{\text{Eq}}) - Q_{\text{losses, Tot}}}{Q_{\text{NC}}} \\
I_{\text{lights, }C} = 1 - \frac{(Q_{\text{gains, Tot}} - Q_{\text{Lights}}) - Q_{\text{losses, Tot}}}{Q_{\text{NC}}} \\
I_{\text{presence, }C} = 1 - \frac{(Q_{\text{gains, Tot}} - Q_{\text{People}}) - Q_{\text{losses, Tot}}}{Q_{\text{NC}}}
\]

where the term \((1 - \cdot)\) allows for a comparison with the impact indices developed for heating. Also in this case, the higher the impact index, the more likely is the considered component to have an impact on the building cooling energy use. The minimum possible value of these impact indices is \(0\). Values higher than \(1\) indicate that the second term of the equation is negative, i.e. the total heat losses are greater than the total heat gains minus the heat gains from the considered source. It is important to note two simplifications related to the proposed formulas: i) the impact indices are based on the components of the building sensitive heat load, hence the results should be carefully considered in presence of significant latent loads; ii) heat gains do not entirely contribute to reducing the heating demand or increasing the cooling demand; for example, for buildings characterized by particularly high gains/losses ratios and low time-constant (i.e. for those cases where the utilized gains are suspected to be extremely low) it is advised to perform a OAT sensitivity analysis as the resulting impact index could be over estimating the potential effect of OB. One method to calculate the share of a given heat gain that is indeed used to reduce heating or to increase cooling demand would be to compare the results to those obtained setting the heat gain of interest to zero.

### 2.2. Impact indices for temperature setpoint

An evaluation of the impact of setting the temperature setpoint calls for a different methodological approach. Here, the building energy signature is evaluated when the system is active during the heating and cooling season. The \(\Delta T\) between outdoor and indoor temperature is reported on the x-axis, with the underlying assumption that if the cooling or heating energy of a building is highly correlated with the \(\Delta T\),

---

**Fig. 1.** A building whose cooling energy use is barely correlated to the \(\Delta T\) between outdoor and indoor temperature (left), vs. a building which shows high correlation (right).
then the building is sensitive to the temperature setpoint, and vice versa. The \( R^2 \) values and the slope of the equation approximating the data points are then analyzed and the results are used to create the impact index. Fig. 1 is an illustrative example of how the total cooling energy use over the season of two buildings can be differently correlated to the \( \Delta T \) between outdoor and indoor temperature. In Fig. 1 (right) the temperature setpoint setting is expected to have a higher impact on the cooling energy use than in Fig. 1 (left). The data is derived from two of the buildings presented in Section 3. However, the purpose of Fig. 1 is purely illustrative.

It is important to note that, because of their intrinsic nature, impact indices for blinds, equipment, light use and occupants’ presence evaluate the relative effect (expressed in percentage variation) on heating and cooling energy use of the mentioned aspects of OB. Instead, the impact index for temperature setpoint evaluates the correlation between energy’s absolute value and \( \Delta T \).

3. Computation and evaluation of the proposed impact indices

A virtual experiment was developed to evaluate the reliability of the newly proposed impact indices. The test was performed on 16 building variants in two locations (described in Section 3.1). The methodological steps followed to obtain the indices and evaluate whether they are meaningful are illustrated in Section 3.2.

3.1. Description of the virtual experiment

A six-story office building with dimensions of \( 24 \times 16 \times 18 \text{ m}^3 \) was modeled in EnergyPlus Version 8.3 and used for the virtual experiment. Each floor of the building comprises 12 office rooms with dimensions of \( 3.4 \times 6.1 \times 2.7 \text{ m}^3 \) and two service rooms, aligned on the northern and southern sides of a corridor (Fig. 2). Large windows of \( 2.4 \times 1.2 \text{ m}^2 \) are situated on the external walls of the office rooms.

The building is occupied according to ASHRAE Standard 90.1 schedules [20]. Heating and cooling are provided by means of an ideal system, which keeps the indoor temperature within the setpoint limits (\( T_{\text{sp, heating}} = 21^\circ\text{C} \) and \( T_{\text{sp, cooling}} = 24^\circ\text{C} \)) between 7 am and 10 pm during weekdays, and between 7 am and 6 pm on Saturdays. During the remaining hours, temperature setbacks are set at 15.6 \(^\circ\text{C}\) and 26.7 \(^\circ\text{C}\) for heating and cooling season, respectively. In order to study the influence of OB on a larger set of buildings, 16 building variants were modeled. The variants include two floor heights (III and VI floor), as well as two...
construction types, two climates and two extreme values of equipment power density (EPD) and light power density (LPD). Table 1 illustrates the characteristics of the investigated building variants.

3.2. Impact indices computation and evaluation

Before evaluating the impact indices, the building variants’ energy end uses must be analyzed by means of a preliminary simulation run. This step is essential to understand whether a building variant requires further study of the effects of OB on heating and cooling energy. In fact, it is possible that heating and/or cooling energy represent only a negligible share of the building’s total energy consumption; in which case – if the simulation purpose is an assessment of the impact of OB on the overall building energy performance – this investigation is not prioritized. If heating and/or cooling represent a significant share of the total energy consumption, the length of the heating and/or cooling seasons are also assessed for each building variant. A number of methods are available in literature to perform this operation [18]. For the case at hand, using a seasonal definition according to climate alone would compromise the scope of the study, as building and operation parameters play a significant role in defining heating and cooling seasons. Hence, it is proposed to also use a preliminary year-long simulation to obtain specific heating and cooling seasons for the investigated building(s).

The impact indices are evaluated to estimate the potential effect of various aspects of OB on heating and cooling energy by means of a single simulation run. The one-at-a-time sensitivity analysis is carried out in this study to evaluate whether the developed impact indices yielded significant results. The one-at-a-time sensitivity analysis is performed in a simplified manner by modifying OB-related parameters as shown in Table 2. Blinds are operated according to façade orientation; in particular, they are lowered in the East façade between 6 am and 2 pm, in the South façade between 9 am and 6 pm, and in the West façade between 1 pm and 9 pm. The blinds are modeled as roller blinds.
having a thickness of 0.01 m, a conductivity of 1 W/mK, and a solar transmittance of 0.05. The amendments presented in Table 2 are for illustrative purposes; the actual variation in OB may differ significantly according to the specific case and designated use of the building.

4. Impact indices computation and evaluation results and remarks

4.1. Energy end uses analysis

First, the energy end uses were analyzed for the 16 building variants. Fig. 3 reports the absolute value of total primary energy consumption for each variant, as well as the share of energy used for lights, equipment, cooling and heating. The primary energy consumption of the 16 building variants is within the range of 199.1 GJ (AMS1) – 825.3 GJ (AMS8). It is important to note that heating and cooling supplied by the ideal system are considered as district heating and cooling within EnergyPlus. The primary energy is calculated from the site energy with the standard EnergyPlus conversion factors (i.e., 3.167, 1.056, and 3.613 for electricity, district cooling and district heating, respectively).

Heating and cooling energy use were considered relevant if they represented > 5% of the total primary energy use. Hence, the impact of

Table 3
Impact indices results for all investigated building variants and aspects of OB.

<table>
<thead>
<tr>
<th>Building ID</th>
<th>II Equipment</th>
<th>II Lights</th>
<th>II Presence</th>
<th>II Blinds</th>
<th>II Tsp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>AMS1</td>
<td>0.76</td>
<td>1.09</td>
<td>0.52</td>
<td>0.74</td>
<td>0.27</td>
</tr>
<tr>
<td>AMS2</td>
<td>1.11</td>
<td>–</td>
<td>0.76</td>
<td>–</td>
<td>0.13</td>
</tr>
<tr>
<td>AMS3</td>
<td>0.89</td>
<td>0.45</td>
<td>0.61</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>AMS4</td>
<td>1.10</td>
<td>2.81</td>
<td>0.75</td>
<td>1.91</td>
<td>0.13</td>
</tr>
<tr>
<td>AMS5</td>
<td>–</td>
<td>0.15</td>
<td>–</td>
<td>0.10</td>
<td>–</td>
</tr>
<tr>
<td>AMS6</td>
<td>1.10</td>
<td>0.61</td>
<td>0.75</td>
<td>0.41</td>
<td>0.13</td>
</tr>
<tr>
<td>AMS7</td>
<td>–</td>
<td>0.13</td>
<td>–</td>
<td>0.09</td>
<td>–</td>
</tr>
<tr>
<td>AMS8</td>
<td>–</td>
<td>0.45</td>
<td>–</td>
<td>0.31</td>
<td>–</td>
</tr>
<tr>
<td>ROM1</td>
<td>0.46</td>
<td>–</td>
<td>0.31</td>
<td>–</td>
<td>0.16</td>
</tr>
<tr>
<td>ROM2</td>
<td>0.69</td>
<td>–</td>
<td>0.47</td>
<td>–</td>
<td>0.08</td>
</tr>
<tr>
<td>ROM3</td>
<td>0.37</td>
<td>0.95</td>
<td>0.25</td>
<td>0.64</td>
<td>0.13</td>
</tr>
<tr>
<td>ROM4</td>
<td>0.83</td>
<td>–</td>
<td>0.57</td>
<td>–</td>
<td>0.10</td>
</tr>
<tr>
<td>ROM5</td>
<td>0.22</td>
<td>0.31</td>
<td>0.15</td>
<td>0.21</td>
<td>0.08</td>
</tr>
<tr>
<td>ROM6</td>
<td>0.51</td>
<td>1.63</td>
<td>0.35</td>
<td>1.11</td>
<td>0.06</td>
</tr>
<tr>
<td>ROM7</td>
<td>0.22</td>
<td>0.23</td>
<td>0.15</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>ROM8</td>
<td>0.51</td>
<td>1.12</td>
<td>0.35</td>
<td>0.76</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Fig. 4. Influence of changing the temperature setpoint on heating energy (AMS7).

Table 4
OAT sensitivity analysis results: mean values of absolute energy variations.

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Effect of equipment [%]</th>
<th>Effect of lights [%]</th>
<th>Effect of presence [%]</th>
<th>Effect of blinds [%]</th>
<th>Effect of Tsp [GJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>AMS1</td>
<td>24%</td>
<td>33%</td>
<td>16%</td>
<td>22%</td>
<td>13%</td>
</tr>
<tr>
<td>AMS2</td>
<td>36%</td>
<td>–</td>
<td>26%</td>
<td>–</td>
<td>7%</td>
</tr>
<tr>
<td>AMS3</td>
<td>24%</td>
<td>15%</td>
<td>17%</td>
<td>10%</td>
<td>14%</td>
</tr>
<tr>
<td>AMS4</td>
<td>40%</td>
<td>61%</td>
<td>29%</td>
<td>37%</td>
<td>8%</td>
</tr>
<tr>
<td>AMS5</td>
<td>–</td>
<td>6%</td>
<td>–</td>
<td>4%</td>
<td>–</td>
</tr>
<tr>
<td>AMS6</td>
<td>27%</td>
<td>20%</td>
<td>20%</td>
<td>13%</td>
<td>5%</td>
</tr>
<tr>
<td>AMS7</td>
<td>–</td>
<td>5%</td>
<td>–</td>
<td>3%</td>
<td>–</td>
</tr>
<tr>
<td>AMS8</td>
<td>–</td>
<td>16%</td>
<td>–</td>
<td>10%</td>
<td>–</td>
</tr>
<tr>
<td>ROM1</td>
<td>15%</td>
<td>–</td>
<td>10%</td>
<td>–</td>
<td>8%</td>
</tr>
<tr>
<td>ROM2</td>
<td>25%</td>
<td>–</td>
<td>17%</td>
<td>–</td>
<td>5%</td>
</tr>
<tr>
<td>ROM3</td>
<td>12%</td>
<td>24%</td>
<td>9%</td>
<td>18%</td>
<td>7%</td>
</tr>
<tr>
<td>ROM4</td>
<td>26%</td>
<td>–</td>
<td>18%</td>
<td>–</td>
<td>5%</td>
</tr>
<tr>
<td>ROM5</td>
<td>6%</td>
<td>8%</td>
<td>4%</td>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>ROM6</td>
<td>16%</td>
<td>30%</td>
<td>11%</td>
<td>19%</td>
<td>3%</td>
</tr>
<tr>
<td>ROM7</td>
<td>6%</td>
<td>7%</td>
<td>4%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>ROM8</td>
<td>15%</td>
<td>24%</td>
<td>10%</td>
<td>15%</td>
<td>3%</td>
</tr>
</tbody>
</table>

First, the energy end uses were analyzed for the 16 building variants. Fig. 3 reports the absolute value of total primary energy consumption for each variant, as well as the share of energy used for lights, equipment, cooling and heating. The primary energy consumption of the 16 building variants is within the range of 199.1 GJ (AMS1) – 825.3 GJ (AMS8). It is important to note that heating and cooling supplied by the ideal system are considered as district heating and cooling within EnergyPlus. The primary energy is calculated from the site energy with the standard EnergyPlus conversion factors (i.e., 3.167, 1.056, and 3.613 for electricity, district cooling and district heating, respectively).

Heating and cooling energy use were considered relevant if they represented > 5% of the total primary energy use. Hence, the impact of
OB on heating energy was evaluated for all variants except AMS2, ROM1, ROM2, ROM4; the impact of OB on cooling energy was evaluated for all variants except AMS5, AMS7, and AMS8. The results concerning the length of the heating and/or cooling season for the various buildings are reported in Appendix A.

4.2. Impact indices computation

The impact indices for heating and cooling were calculated for each building variant following the approach presented in Sections 2.1 and 2.2. The impact indices for blinds were calculated only with respect to cooling energy use, as blind use is here considered for thermal purposes only, rather than also for visual purposes. Table 3 contains all impact indices results.

Generally speaking, Table 3 shows a high variability of impact indices according to building vintage, climate, considered aspect of OB and performance indicator of interest. For example, the impact indices describing the effect of equipment on cooling energy use are higher in Amsterdam, where summers are milder, than in Rome, where most of the cooling load is likely related to weather conditions. A varied effect of OB on the analyzed building variants is hence expected.

4.3. One-at-a-time sensitivity analysis test

As mentioned earlier, the one-at-a-time (OAT) sensitivity analysis is used in the reliability test of the presented approach. The effect of applying the variations presented in Table 2 to heating and cooling energy is considered to be the ground truth, or the actual influence that different aspects of (simplified) OB have on heating and cooling energy. An example of the results obtained by means of the OAT sensitivity analysis is reported in Fig. 4.

Fig. 4 shows that applying the changes presented in Table 2 results in a positive and negative variation of the energy use if compared to the base case. For example, increasing the heating temperature setpoint of AMS7 by 1 °C results in a 9% increase of the heating energy (i.e. 14.33 GJ), while decreasing it by 1 °C reduces the heating energy by 9% (or 13.05 GJ). Likewise, decreasing e.g. the EPD is expected to have an increasing effect on the heating energy, while decreasing the EPD should have the contrary effect. For the sake of simplicity, all results of the OAT analysis are reported in Table 4 as mean values of the absolute increase/decrease in energy resulting from the OB variations (in the example case, corresponding to [13.69] GJ). The effect of applying blinds is reported solely as energy reduction as it is only calculated for cooling energy (and the blinds have a beneficial effect on cooling energy use, as expected).

Table 4 shows that the effect of changing the EPD by ±50% causes a relative variation in cooling energy of 6% (ROM5) to 40% (AMS4). ROMS is a skin-load dominated building, where heating and cooling together cover 67% of the primary energy use, while AMS4 is an internal load dominated building (heating + cooling = 20% of the total primary energy use). The relative variation of heating energy is 6% (AMS5) – 61% (AMS4). Instead, changing by ±50% the LPD has a 4–29% effect on cooling and 3% – 37% effect on heating. Presence has a smaller influence on cooling and heating, causing a variation of 3–14% and 2–14%, respectively. The maximum cooling reduction due to blind use is registered in ROM5 (−36%), while the minimum occurs in AMS2 and ROM4 (−6%). In absolute terms, the temperature setpoint has a higher effect on buildings characterized by a low thermal insulation. In particular, the largest effect of varying the cooling setpoint occurs in ROM5 – ROM8, while a variation in heating setpoint has most influence in AMS5 – AMS8.

In order to determine whether the impact indices led to a satisfactory estimation of the potential impact of OB, the impact indices results are plotted against those obtained by means of the OAT analysis for each aspect of OB (cooling and heating energy need are shown separately) (see Figs. 5–9).

The impact indices, calculated by means of a single simulation run, have a significant correlation with the results of the OAT sensitivity analysis. In particular, the R² values for both heating and cooling reliability test with regard to equipment use, light use and people presence were always > 90%. This outcome reveals that >90% of the effect on cooling and heating energy due to variations in the mentioned aspects of OB can be explained by the impact indices. When analyzing the effect of blind use and temperature setpoints, approximately 85% of the variations could be explained. These results demonstrate how a method based on a single simulation run can yield significant estimates of the potential effect of equipment use, light use, blind use, occupant presence and setting of the temperature setpoint on heating and cooling energy.

A number of simplifications made in this study ought to be pointed out: (i) the considered building variants are purposely extreme variations (e.g., EPD and LPD = 16.14 W/m² may not be representative of common office buildings); (ii) the aspects of OB are modeled as static variations rather than stochastic implementations of occupants’ diversity; the variations presented in Table 2 are intentionally exaggerated for the purposes of this study; (iii) the choice of supplying energy by means of an ideal system could correspond to the initial phases of the building design, but is not representative of a more advanced stage. Nevertheless, the proposed initial screening method proved to be efficient and effective in providing information about the potential effect of a number of OB aspects on heating and cooling energy demand. Among the envisioned applications of the method is investigating OB-related risks for EPC. For this reason, in Section 5 the method is applied to an office building for which it was required to assess the potential for EPC.

5. Illustrative application

5.1. The building

An office building in Delft, the Netherlands is used as an illustrative application of the aforementioned methodology. The building is part of a project that has an interest in understanding the OB-related risks associated to (heating and cooling) EPC. Firstly, the aim of the project is to assess buildings’ potential for EPC. If the analysis shows high potential for EPC (i.e., relatively low influence of OB), the ESCO involved is still interested in understanding whether further clauses should be applied in the EP contract for specific aspects of OB on a monthly basis.

5.1.1. Building characteristics

The building was built in 2001, consists of three floors, has dimensions of 39 × 29 × 9 m³ (W × L × H) and a gross floor area of 2040 m². At present, the building is used as semi-open office spaces and flexible workspaces, with occupation hours of 7:30 am–7 pm during weekdays only. There is an atrium spanning over the three floors which functions as common space, and a restaurant for the employees. Fig. 10 gives an impression of the double façade and atrium of the building, as well as a typical floor plan. Automatically controlled sun shading devices are incorporated on the inside of the outer façade for the eastern, southern and western sides of the building to prevent overheating during the summer. For as the thermal characteristics, the external walls, ground floor, and roof R-value is 3.0 m² K/W, while the windows’ U-value is 1.2 W/m² K. The building has Dutch Energy Label A and Energy Index (EI) = 0.96.

The indoor climate of the office is controlled by two air handling units (AHUs): one for the offices, which controls both supply and
Fig. 5. II reliability test: comparison with OAT sensitivity analysis results for the impact of equipment use on cooling (left) and heating (right) energy. Each dot represents a building variant.

Fig. 6. II reliability test: comparison with OAT sensitivity analysis results for the impact of lights use on cooling (left) and heating (right) energy.

Fig. 7. II reliability test: comparison with OAT sensitivity analysis results for the impact of people density on cooling (left) and heating (right) energy.
exhaust air, and one for the restaurant/atrium, which controls only the supply air of the restaurant. The building has a gas-fired boiler and a fully-electric cooling machine. The AHU of the office spaces also has a rotary heat/cold exchanger with an efficiency of around 72%, according to the technical specifications. The AHUs are also used for night ventilation during the summer to cool the building. The operational hours of night ventilation are between 01:00 am and 06:00 am during weekdays, and always on during the weekend. The outdoor air itself is used for night ventilation. The general system properties are specified in Table 5.

5.1.2. Occupant-related characteristics

Sun shading and climate installations are centrally controlled; hence people do not directly interact with them. Conversely, occupants trigger the occupancy-dependent lighting in office spaces and restrooms, and have a direct influence on the amount of equipment (two computer screens, a keyboard, and a computer mouse) which is used in the approximately 80 workspaces in the building. Moreover, people (may) have an impact on the thermal status of the building by means of their metabolic rate. While operable windows and internal blinds are present throughout the building, they are seldom operated by the occupants. Hence, it was decided to focus the subsequent analysis on the effect of occupant presence, equipment and light use on energy demand for heating and cooling. Hereunder, the analysis is reported for heating only, which represents 20% of the building’s total primary energy consumption, while electricity use for cooling is only about 5%. Heating is used throughout the year except between the months of Jun-Aug.

5.2. Impact indices evaluation and validation

A model of the building was developed in EnergyPlus Version 8.7; the model was representative of the building energy behavior both in terms of aggregated yearly results for electricity and heating use (Fig. 11) and of hourly electricity profiles (Fig. 12).

The impact indices for heating were calculated as in Section 2.1, and are reported in Fig. 13. It can be noticed how the whole building impact of each OB aspect is rather low, reaching a peak of 0.40 for light use. It is expected that an II of 0.40 corresponds to a heating energy demand variation of ca. 10–15% if the LPD is varied by ± 50%. A lower impact on the heating energy demand is expected for OB-related equipment use and occupant presence. It is interesting to note how the total equipment use has a very high impact index, while the potential impact is substantially decreased when looking at OB-related equipment use. The added value of calculating II for each zone is dual: on one hand, it provides an indication that different modeling complexity levels may be needed to represent OB for different zones, on the other hand it could provide insights into the appropriate placing and installing of OB-related monitoring sensors.

In order to verify the results obtained by means of the II, an OAT sensitivity analysis increasing and decreasing presence, LPD and EPD by 50% was carried out. The sensitivity analysis was performed in respect to gas use for heating, as that was the PI of interest for the ESCO. The results are reported in Fig. 14. As expected, changing the LPD by ± 50% causes the maximum variation in the output (ca. 10–15%), followed by OB-related EPD and occupant presence.
5.3. Monthly analysis

As mentioned, one of the aims of the project is to understand whether to incorporate guidelines/clauses in the EP contract for occupants on how to operate the building on a monthly basis. For this reason, it seems relevant to calculate II for the selected aspects of OB for each month. The months Jun-Aug are omitted, as during that period no heating occurs. The results of this analysis are reported in Fig. 15.

Fig. 15 shows what appears to be an inversely proportional relationship between the effect of OB and weather. In fact, the II increase for all three considered OB aspects as the weather conditions become milder (up to May-September), and decrease again with the arrival of winter months. This result confirms the well-established hypothesis that the relative impact of OB is more important for buildings which are less affected by the outdoor environment. Hence, a similar observation can be made on a seasonal/monthly basis.

However, it is important to note that the II give an indication of the relative potential impact of OB. In other words, they quantify the % variation of a performance indicator related to its absolute value. As we expect the absolute heating energy demand to be higher during the colder months, the II presented in Fig. 15 do not directly provide information about the actual amount of gas that could be consumed because of OB in absolute terms. Fig. 16 shows both the absolute monthly variation in gas use and the relative monthly variation when varying the LPD by ± 50%. The relative variation follows the trend indicated by the II in Fig. 15. Instead, the absolute variation shows that the “riskiest” months are March and December. August and September, despite presenting a high II (and therefore a high relative variation) are characterized by the lowest absolute variation. This example clearly shows the importance of considering both absolute and relative variations when dealing with sensitivity analysis.

For the investigated building, historical data about the gas use during the last years was available. Fig. 17 confirms that the yearly variation in gas use was not significant, and mostly imputable to differences in weather conditions, here quantified by means of the Heating Degree Days (HDD) indicator, rather than OB. For this building, it is hence possible to issue EP contracts with a low risk-factor. If the clients are interested in absolute gas use variation, it is advisable to include clauses about lights use for the months of March, April, and Oct-Dec. However, the necessity of including such clauses should depend on the required tolerance, as well as on the assessment of actual lighting use variability.

6. Conclusions

A novel method was proposed to estimate the potential effect of various OB aspects on heating and cooling energy demand. The method consists of a number of newly proposed impact indices, which can be obtained with one simulation run and are based on the building heat balance. This process is very efficient compared with formulating and simulating a high number of scenarios, a method commonly employed to evaluate a simulation’s output sensitivity to input perturbations. A reliability testing process confirmed that the impact indices are able to explain 85% to 95% of the variations of heating and cooling energy demand observed as a consequence of deviations in light use, equipment use, occupant presence, blind use and temperature setpoint.
potential applications of this method are varied, spanning from EPC, to modeling complexity selection in BPS for different aspects of OB, to efficient placing of OB-related sensors. The impact indices were calculated for an existing office building to show how the method can be used for real applications, and the results rapidly confirmed the potential for a low-risk application of EPC in the investigated building. Buildings’ energy performance clearly depends on OB, but the sensitivity is influenced by a high number of factors, as highlighted both in field and simulation studies. To the best knowledge of the authors, this research is a first example in seeking to respond to the need for an efficient and effective method to quickly establish the potential influence of various aspects of OB on buildings’ cooling and heating energy demand. This methodology is based on the relative importance of the different contributors to the building heat balance and is hence applicable to buildings with diverse uses.
Acknowledgements

The authors would like to thank Bas Giskes for his help with the work related to the existing building. The financial support of PIT/VABI, the SPARK consortium and TKI EnerGO TRECO-office is greatly appreciated. The authors’ involvement in IEA-EBC Annex 66 (Definition and Simulation of Occupant Behavior in Buildings) is acknowledged.

Appendix A. Lengths of heating and cooling season

<table>
<thead>
<tr>
<th>Building ID</th>
<th>Heating season</th>
<th>Cooling season</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS1</td>
<td>1/01 – 30/04</td>
<td>9/10 – 31/12</td>
</tr>
<tr>
<td>AMS2</td>
<td>–</td>
<td>1/01 – 31/12</td>
</tr>
<tr>
<td>AMS3</td>
<td>1/01 – 31/05</td>
<td>1/10 – 31/12</td>
</tr>
<tr>
<td>AMS4</td>
<td>1/01 – 31/03</td>
<td>21/10 – 31/12</td>
</tr>
<tr>
<td>AMS5</td>
<td>1/01 – 31/05</td>
<td>1/09 – 31/12</td>
</tr>
<tr>
<td>AMS6</td>
<td>1/01 – 23/05</td>
<td>1/09 – 31/12</td>
</tr>
<tr>
<td>AMS7</td>
<td>1/01 – 30/06</td>
<td>1/09 – 31/12</td>
</tr>
<tr>
<td>AMS8</td>
<td>1/01 – 23/05</td>
<td>1/09 – 31/12</td>
</tr>
<tr>
<td>ROM1</td>
<td>–</td>
<td>1/02 – 23/12</td>
</tr>
</tbody>
</table>

Fig. 16. Monthly absolute and relative variation in gas use when varying the LPD by ± 50%.

Fig. 17. Observed yearly variation in gas use (2014 was omitted due to lack of data).
References


