A simulation method for estimating the influence of occupant behavior on building heating and cooling energy

Isabella Gaetani [a,*], Pieter-Jan Hoes [a], Jan L. M. Hensen [a]

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

[*] *Corresponding author. Tel.: +31 402472571. E-mail address: i.i.gaetani@tue.nl (I. Gaetani).*

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. In contrast with common sensitivity analysis approaches based on a high number of scenarios, a 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 indexes (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 validate 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 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.

Keywords:

Occupant behavior modeling; sensitivity analysis; performance contracting

Highlights

1. Introduction

Occupant behavior (OB) is commonly acknowledged to be one of the main causes of uncertainty in building energy performance [1,2]. 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 [3]. Energy performance contracting (EPC) is a financing method in which an energy service company (ESCO) guarantees building energy savings to the customer. The companies issuing EPCs, therefore, are motivated to minimize the risk of not achieving the desired energy savings. For this reason, it is necessary to increase our current understanding of the energy performance gap and of the influence of OB on building energy consumption. However, 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 various aspects of OB on building energy performance [4–7]. These studies are mostly experimental studies, and show variable effects according to the investigated case. Instead, simulation studies tend to be parametric, and consider one aspect at the time, as well as their combined influence.

Hoyt et al. [8] studied the effect on energy consumption of reducing the heating setpoint and increasing the cooling setpoint. The Medium Office DOE reference model [9] 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. [10] 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 setpoint for outdoor temperature above 30 °C, and the lowest 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 [6] 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 [11] implemented stochastic occupancy-related measures to a two-story office building modeled in EnergyPlus Version 8.4, and verified the impact 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 [12] 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.

All mentioned studies investigated the effect of occupant behavior by means of one-at-a-time (OAT) sensitivity analysis or with global sensitivity analysis supported by statistical methods (e.g., [10]) 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. The lack of generalizability and the requirement to formulate scenarios renders it difficult to acquire knowledge from the results of a limited amount of publications. In the current situation, it is difficult for practitioners to perform EPC in a time-efficient, risk-free manner. Moreover, ESCOs do not have information on the specific contribution of different aspects of OB, and hence cannot include OB-related clauses in the contracts to minimize their risk.

To overcome these issues, we propose a one-simulation-run approach to effectively 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 use. The method consists of a number of indicators (impact indexes) that allow the influence of various aspects of OB to be quantified without requiring the formulation of scenarios. First, the impact indexes are defined (Section 2). Secondly, the 16 building variants are introduced and the methodological steps to acquire and test the indexes' significance are presented (Section 3). Then, results concerning impact indexes and their validation 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 indexes definition

The impact indexes are simple indicators that allow the effect of OB on heating and cooling energy use to be estimated. In this study, impact indexes 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 indexes for blind, equipment, light use and occupant's presence

The impact indexes for blinds, equipment, light use and occupant presence are all developed in a similar manner. The indexes' 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. ISO 13790 [13] proposes a quasi-steady state building energy calculation method (to be used for long calculation periods such as seasons), whereby the energy need for space heating for each calculation period is $Q_{NH} = Q_{L,H} - \eta_{G,H} \cdot Q_{G,H}$, where Q_{NH} is the building energy need for heating [J], $Q_{L,H}$ is the total heat transfer for the heating mode [J], $\eta_{G,H}$ is the dimensionless gain utilization factor [-], and $Q_{G,H}$ are the total heat sources for the heating mode. The need for space cooling is defined as $Q_{NC} = Q_{G,C} - \eta_{L,C} \cdot Q_{L,C}$, where Q_{NC} is the building energy need for cooling [J], $Q_{G,C}$ is the total heat transfer for the cooling mode [J], $\eta_{G,H}$ is the dimensionless utilization factor for heat losses [-], and $Q_{L,C}$ is the total heat transfer for the cooling mode. The utilization factors are functions of the gain-loss ratio and the thermal inertia of a building. The use of dynamic simulation removes the need for the utilization factors, as BPS tools calculate, alongside heat gains from people, lighting, equipment, windows, interzone air flow, and infiltration, as well as 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 [14]. Hence, assuming that no cooling occurs during the heating season, the heat balance can be written as

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

where Q_{NH} is the HVAC input sensible heating [J], $Q_{L,Eq}, Q_{L,Win}, Q_{L,Int}, Q_{L,Inf}, Q_{L,Op}$ [J] is the heat removal due to conduction and radiation through windows, interzone air transfer, infiltration, conduction of opaque surfaces and other, and $Q_{G,People}, Q_{G,Lights}, Q_{G,Eq}, Q_{G,Win}, Q_{G,Int}, Q_{G,Inf}, Q_{G,Op}$ is the heat addition due to people, lights, equipment, conduction and radiation through windows, interzone air transfer, infiltration, conduction of opaque surfaces and other. The terms $(Q_{L,Eq} + Q_{L,Win} + Q_{L,Int} + Q_{L,Inf} + Q_{L,Op})$ and $(Q_{G,People} + Q_{G,Lights} + Q_{G,Eq} + Q_{G,Win} + Q_{G,Int} + Q_{G,Inf} + Q_{G,Op})$ can be written as $Q_{Losses,Tot}$ and $Q_{Gains,Tot}$, respectively. Equation (1) can be simplified by dividing both terms for Q_{NH} as

$$1 = \frac{Q_{Losses,Tot} - Q_{Gains,Tot}}{Q_{NH}} \quad (2)$$

In order to evaluate the potential effect of blinds, equipment, light use and occupants' presence during the heating season, the following impact indexes are developed

$$II_{blinds,H} = \frac{Q_{Losses,Tot} - (Q_{Gains,Tot} - Q_{G,Win})}{Q_{NH}} - 1 \quad (3)$$

$$II_{equipment,H} = \frac{Q_{Losses,Tot} - (Q_{Gains,Tot} - Q_{G,Eq})}{Q_{NH}} - 1 \quad (4)$$

$$II_{lights,H} = \frac{Q_{Losses,Tot} - (Q_{Gains,Tot} - Q_{G,Lights})}{Q_{NH}} - 1 \quad (5)$$

$$II_{presence,H} = \frac{Q_{Losses,Tot} - (Q_{Gains,Tot} - Q_{G,People})}{Q_{NH}} - 1 \quad (6)$$

The impact indexes aim to quantify the weight of a given source of heat gain within the heat balance. For example, in $II_{equipment,H}$, the heat gains due to equipment are subtracted from the total heat gains contributing to the heating load. If the heat gains represented 0% of the total heat gains, the ratio 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 indexes 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

$$Q_{NC} = Q_{Gains,Tot} - Q_{Losses,Tot} \quad (7)$$

from which, dividing both terms by Q_{NC},

$$1 = \frac{Q_{Gains,Tot} - Q_{Losses,Tot}}{Q_{NC}}. \quad (8)$$

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

$$II_{blinds,C} = 1 - \frac{(Q_{Gains,Tot} - Q_{G,Win}) - Q_{Losses,Tot}}{Q_{NC}} \quad (9)$$

$$II_{equipment,C} = 1 - \frac{(Q_{Gains,Tot} - Q_{G,Eq}) - Q_{Losses,Tot}}{Q_{NC}} \quad (10)$$

$$II_{lights,C} = 1 - \frac{(Q_{Gains,Tot} - Q_{G,Lights}) - Q_{Losses,Tot}}{Q_{NC}} \quad (11)$$

$$II_{presence,C} = 1 - \frac{(Q_{Gains,Tot} - Q_{G,People}) - Q_{Losses,Tot}}{Q_{NC}} \quad (12)$$

where the term (1 –) allows for a comparison with the impact indexes developed for heating. Also in this case, the higher the impact index, the more likely blinds, equipment, light use or occupants' presence will have an impact on the building cooling energy use. The minimum possible value of these impact indexes 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.

2.2 Impact indexes 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 ΔT 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 ΔT, 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. 2 shows an example of two buildings with a cooling energy use differently correlated to the ΔT between outdoor and indoor temperature. In Fig. 2 (right) the temperature setpoint setting is expected to have a higher impact on the cooling energy use than in Fig. 2 (left).

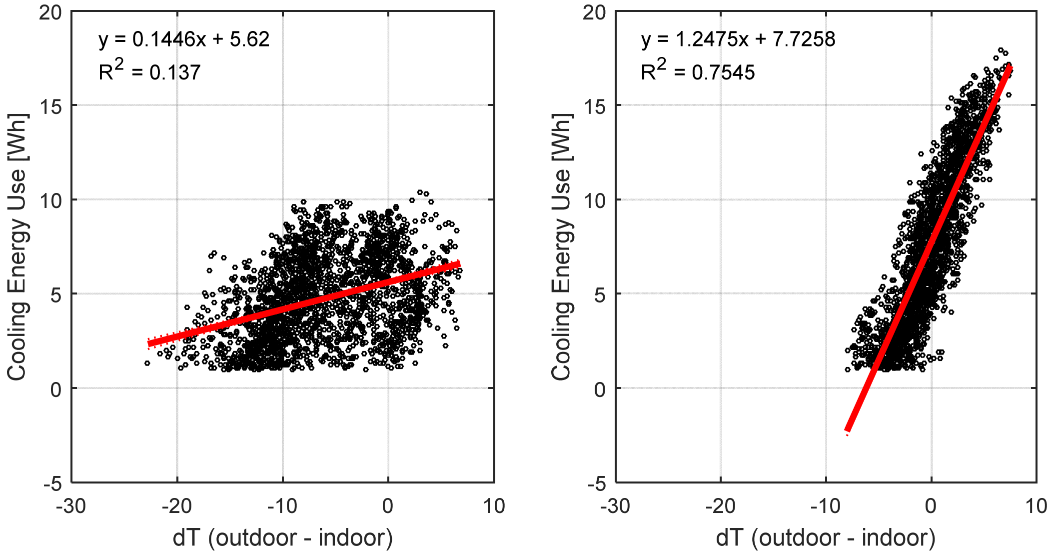

Fig. 2: A building whose cooling energy use is barely correlated to the ΔT between outdoor and indoor temperature (left), vs. a building which shows high correlation (right)

It is important to note that, because of their intrinsic nature, impact indexes 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 ΔT.

3. **Evaluation and validation of the proposed impact indexes**

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

3.1 Description of the validation test

A six-story office building with dimensions of 24 x 16 x 18 m³ 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 x 6.1 x 2.7 m³ and two service rooms, aligned on the northern and southern sides of a corridor (Fig. 1). Large windows of 2.4 x 1.2 m² are situated on the external walls of the office rooms.

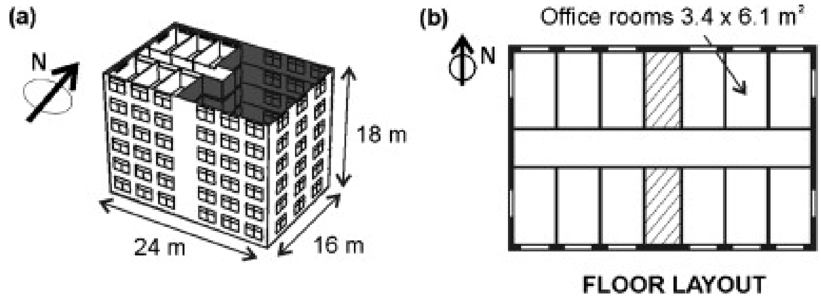

Fig. 1: Building geometry (a) and plan of a typical floor layout (b) (in white the occupied zones)

The building is occupied according to ASHRAE Standard 90.1 schedules [15]. Heating and cooling are provided by means of an ideal system, which keeps the indoor temperature within the setpoint limits ($T_{sp,\ heating}$ = 21ºC and $T_{sp,\ cooling}$ = 24ºC) 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 ºC and 26.7 ºC for heating and cooling season, respectively. In order to study the influence of occupant behavior 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.

Table 1: Characteristics of the investigated building variations

			Thermal insulation				Power Density	
Building ID	Climate	Floor	Wall R-value [m^2K/W]	Window U-value [W/m^2K]	g-value [-]	Visual Transmittance [-]	Lights [W/m^2]	Equipment [W/m^2]
AMS1	Amsterdam	III	4	1.1	0.29	0.48	5.38	5.38
AMS2	Amsterdam	III	4	1.1	0.29	0.48	16.14	16.14
AMS3	Amsterdam	VI	1.3	3	0.73	0.75	5.38	5.38
AMS4	Amsterdam	VI	1.3	3	0.73	0.75	16.14	16.14
AMS5	Amsterdam	III	4	1.1	0.29	0.48	5.38	5.38
AMS6	Amsterdam	III	4	1.1	0.29	0.48	16.14	16.14
AMS7	Amsterdam	VI	1.3	3	0.73	0.75	5.38	5.38
AMS8	Amsterdam	VI	1.3	3	0.73	0.75	16.14	16.14
ROM1	Rome	III	4	1.1	0.29	0.48	5.38	5.38
ROM2	Rome	III	4	1.1	0.29	0.48	16.14	16.14
ROM3	Rome	VI	1.3	3	0.73	0.75	5.38	5.38
ROM4	Rome	VI	1.3	3	0.73	0.75	16.14	16.14
ROM5	Rome	III	4	1.1	0.29	0.48	5.38	5.38
ROM6	Rome	III	4	1.1	0.29	0.48	16.14	16.14
ROM7	Rome	VI	1.3	3	0.73	0.75	5.38	5.38
ROM8	Rome	VI	1.3	3	0.73	0.75	16.14	16.14

3.2 Impact indexes evaluation and validation

Before evaluating the impact indexes, 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 [13]. 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 indexes 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 as a validation to evaluate whether the developed impact indexes 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 3. 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.

Table 3: Amendments made to operation parameters to perform one-at-a-time sensitivity analysis

Operation parameters	**Amendment made**
$T_{sp,\ heating}$ [°C]	±1ºC
$T_{sp,\ cooling}$ [°C]	±1ºC
Equipment Power Density (EPD) [W/m^2]	±50%
Lighting Power Density (LPD) [W/m^2]	±50%
Occupancy Rate [people/office]	±50%
Blinds Use	Closed according to façade orientation

4. Impact Indexes validation 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).

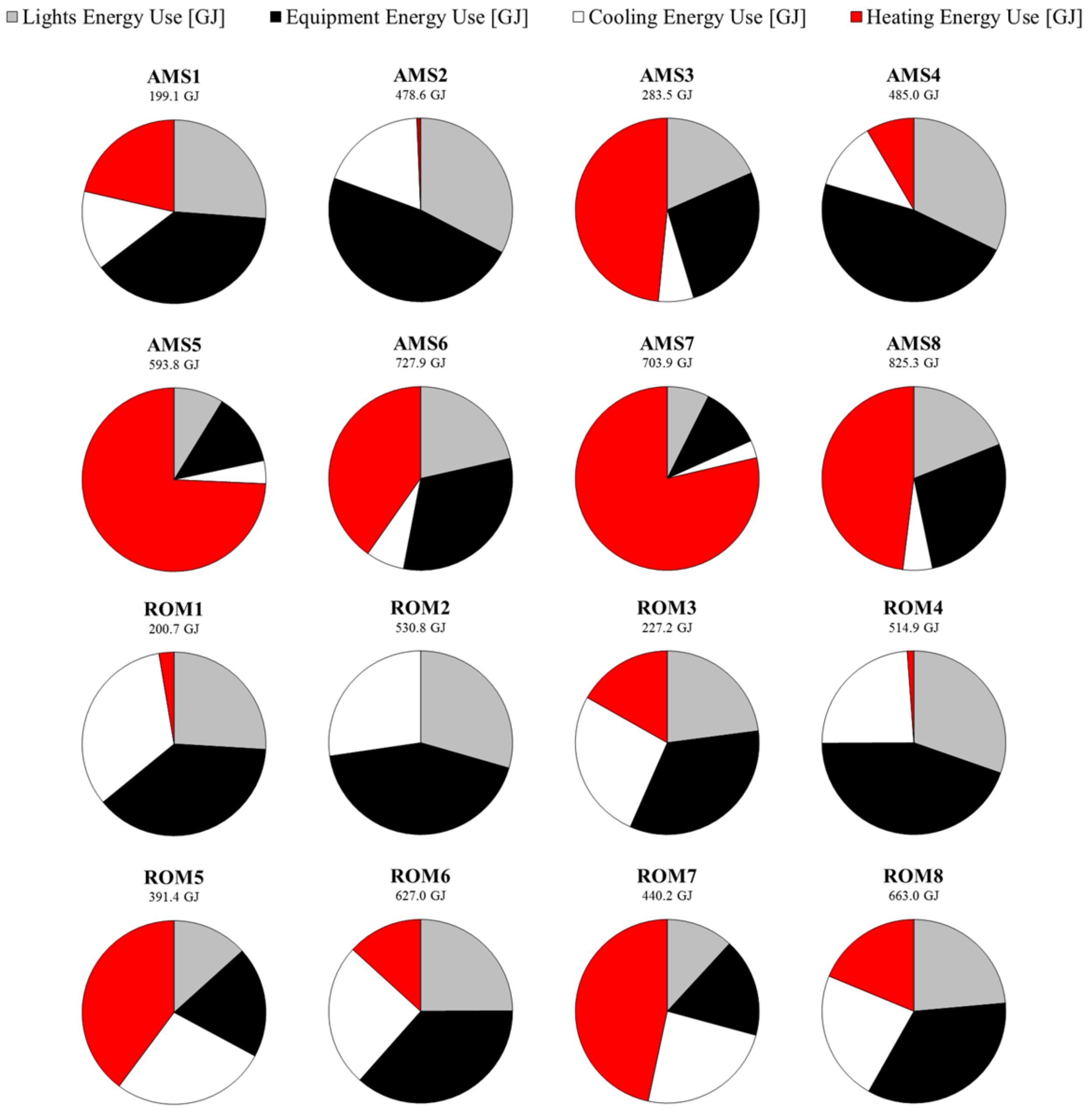

Fig. 3: Total primary energy use [GJ] and energy end uses of the 16 building variants

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 Calculated impact indexes

The impact indexes for heating and cooling were calculated for each building variant following the approach presented in Sections 2.1 and 2.2. The impact indexes 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 4 contains all impact indexes results.

Table 4: Impact indexes results for all investigated building variants and aspects of OB

Building ID	II Equipment		II Lights		II Presence		II Blinds	II Tsp	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Cooling	Heating
AMS1	0.76	1.09	0.52	0.74	0.27	0.42	1.15	0.48	0.13
AMS2	1.11	-	0.76	-	0.13	-	0.44	0.58	-
AMS3	0.89	0.45	0.61	0.31	0.32	0.18	1.51	0.47	0.29
AMS4	1.10	2.81	0.75	1.91	0.13	0.33	0.57	0.53	0.07
AMS5	-	0.15	-	0.10	-	0.06	-	-	0.58
AMS6	1.10	0.61	0.75	0.41	0.13	0.08	1.66	0.63	0.48
AMS7	-	0.13	-	0.09	-	0.05	-	-	0.62
AMS8	-	0.45	-	0.31	-	0.06	-	-	0.53
ROM1	0.46	-	0.31	-	0.16	-	0.89	0.60	-
ROM2	0.69	-	0.47	-	0.08	-	0.43	0.57	-
ROM3	0.37	0.95	0.25	0.64	0.13	0.36	0.79	0.14	0.31
ROM4	0.83	-	0.57	-	0.10	-	0.52	0.66	-
ROM5	0.22	0.31	0.15	0.21	0.08	0.12	1.29	0.75	0.51
ROM6	0.51	1.63	0.35	1.11	0.06	0.18	0.95	0.72	0.31
ROM7	0.22	0.23	0.15	0.16	0.08	0.09	1.27	0.72	0.54
ROM8	0.51	1.12	0.35	0.76	0.06	0.13	0.97	0.72	0.38

Generally speaking, Table 4 shows a high variability of impact indexes according to building vintage, climate, considered aspect of OB and performance indicator of interest. For example, the impact indexes 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 validation

As mentioned earlier, the one-at-a-time (OAT) sensitivity analysis is used in the validation test of the presented approach. The effect of applying the variations presented in Table 3 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.

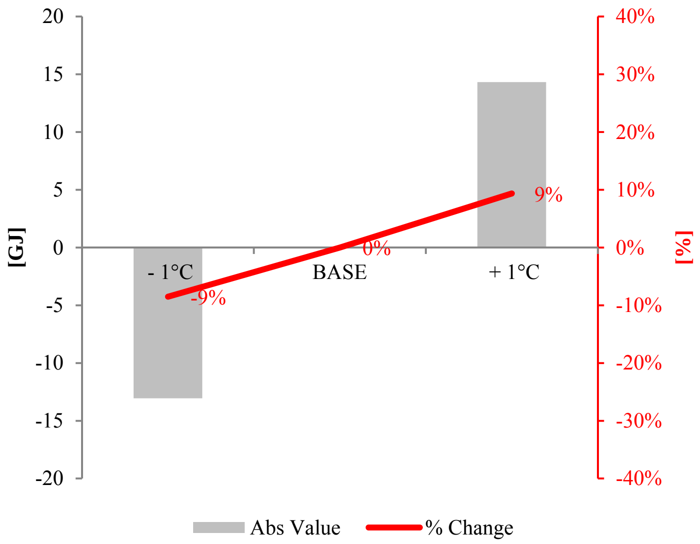

Fig. 4: Influence of changing the temperature setpoint on heating energy (AMS7)

Fig. 4 shows that applying the changes presented in Table 3 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 5 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 5: OAT sensitivity analysis results: mean values of absolute energy variations

Effect of Equipment [%]	Effect of Lights [%]	Effect of Presence [%]	Effect of	Effect of Tsp [GJ]

							Blinds [%]		
Building ID	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Cooling	Heating
AMS1	24%	33%	16%	22%	13%	14%	-16%	3.39	2.58
AMS2	36%	-	26%	-	7%	-	-6%	5.50	-
AMS3	24%	15%	17%	10%	14%	6%	-16%	3.46	5.29
AMS4	40%	61%	29%	37%	8%	6%	-7%	6.39	3.27
AMS5	-	6%	-	4%	-	2%	-	-	11.93
AMS6	27%	20%	20%	13%	5%	3%	-41%	8.13	9.94
AMS7	-	5%	-	3%	-	2%	-	-	13.69
AMS8	-	16%	-	10%	-	2%	-	-	11.71
ROM1	15%	-	10%	-	8%	-	-12%	8.13	-
ROM2	25%	-	17%	-	5%	-	-6%	4.99	-
ROM3	12%	24%	9%	18%	7%	11%	-10%	5.64	3.03
ROM4	26%	-	18%	-	5%	-	-6%	7.48	-
ROM5	6%	9%	4%	6%	3%	4%	-36%	11.49	7.43
ROM6	16%	30%	11%	19%	3%	4%	-28%	13.69	5.46
ROM7	6%	7%	4%	5%	3%	3%	-33%	12.08	8.66
ROM8	15%	24%	10%	15%	3%	3%	-26%	14.25	6.78

Table 5 shows that the effect of changing the EPD by ±50% causes a relative variation in cooling energy of 6% (ROM5) to 40% (AMS4). ROM5 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 indexes led to a satisfactory estimation of the potential impact of OB, the impact indexes 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).

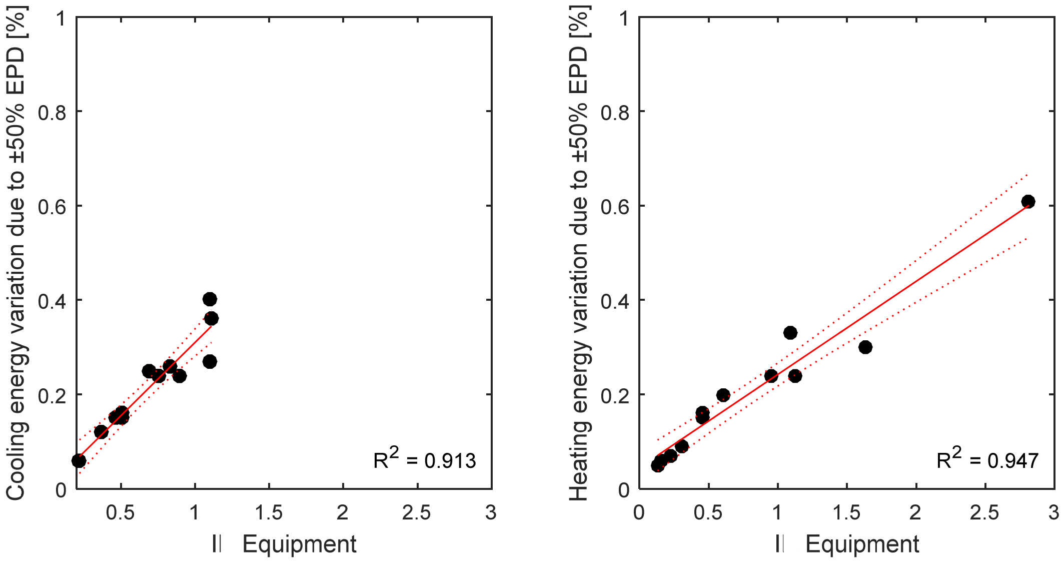

Fig. 5: II validation: comparison with OAT sensitivity analysis results for the impact of equipment use on cooling (left) and heating (right) energy. Each dot represents a building variant

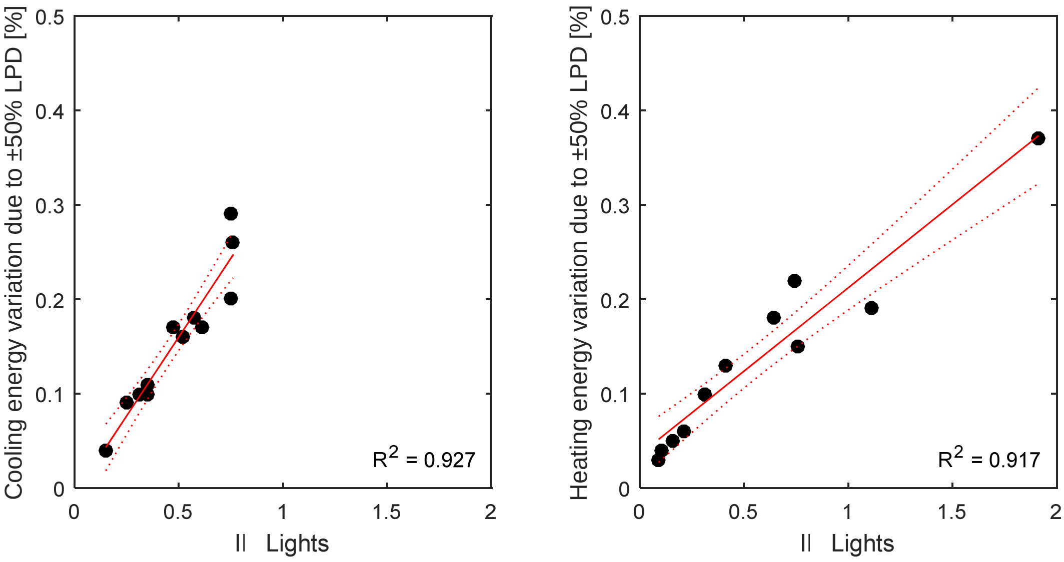

Fig. 6: II validation: comparison with OAT sensitivity analysis results for the impact of lights use on cooling (left) and heating (right) energy

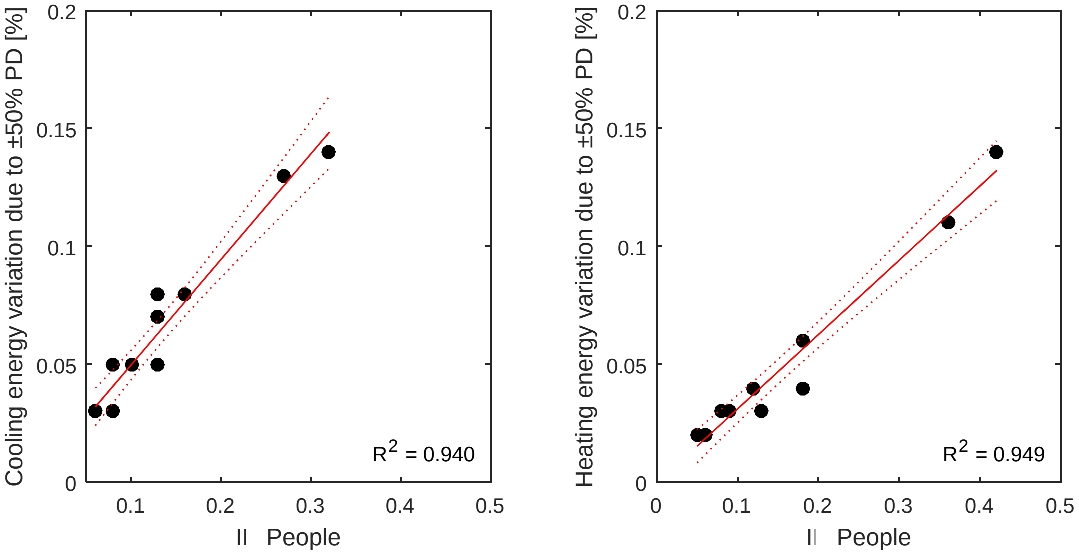

Fig. 7: II validation: comparison with OAT sensitivity analysis results for the impact of people density on cooling (left) and heating (right) energy

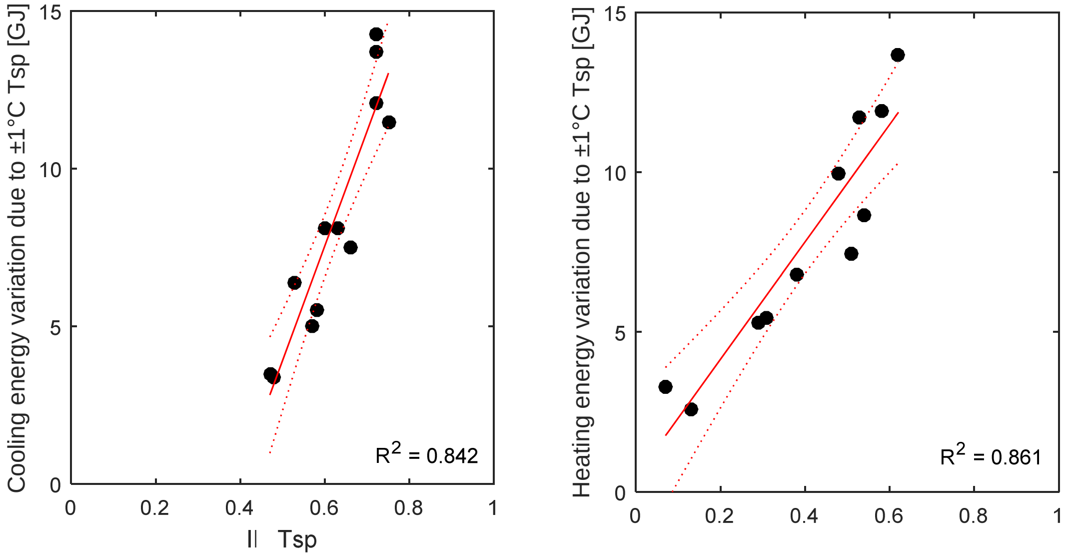

Fig. 7: II validation: comparison with OAT sensitivity analysis results for the impact of temperature setpoint on cooling (left) and heating (right) energy

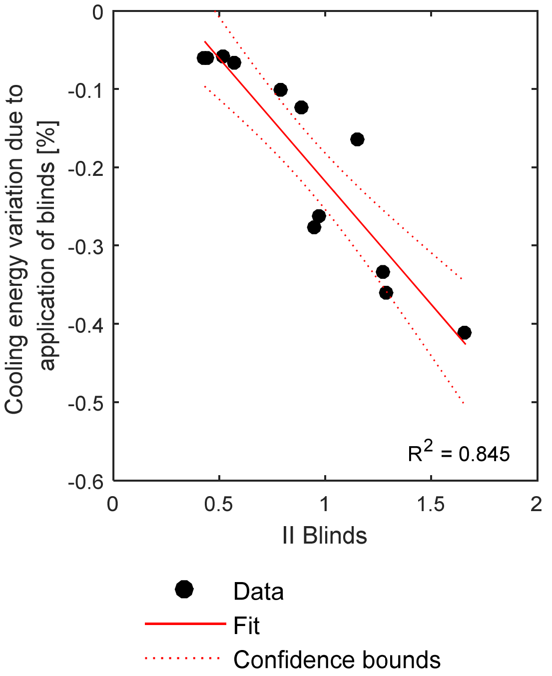

Fig. 8: II validation: comparison with OAT sensitivity analysis results for the impact of applying the blinds on cooling energy

The impact indexes, calculated by means of a single simulation run, have a significant correlation with the results of the OAT sensitivity analysis. In particular, the R^2 values for both heating and cooling validation 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 indexes. 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/m^2 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 3 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 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. One of the main envisioned applications of the method is investigating OB-related risks for energy performance contracts.

For this reason, in Section 5 the method is applied to an office building for which it was required to assess the potential for energy performance contracting.

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 associates 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 x 29 x 9 m^3 (W x L x H) and a gross floor area of 2040 m^2. 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. Figure 9 gives an impression of the double façade and atrium of the building, a typical floor plan and the location/orientation of the building. 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. As for the thermal characteristics, the external walls, ground floor, and roof R-value is 3.0 m^2K/W, while the windows' U-value is 1.2 W/m^2K. The building has Dutch Energy Label A and Energy Index (EI) = 0.96.

Figure 9: Façade of the office (left), impression of the atrium (middle), and plan of the second floor (right)

The indoor climate of the office is controlled by two air handling units (AHUs): one for the offices, which controls both supply and 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 6.

Table 6: General system properties of the ABT office in Delft

General system properties	
AHU offices	122 kW heating, 71.4 kW cooling Airflow: 4.06 m^3/s
Rotary heat/ cold exchanger (AHU offices)	Efficiency = ca. 72 %
AHU restaurant (only supply)	23 kW heating, 9.2 kW cooling Airflow: 0.42 m^3/s
Boiler capacity	HR, 160 kW Efficiency = 0.975
Cooling machine	105.9 kW
Post heaters	14 kW per post heater
Energy generation	PV panels
Set point temperature HVAC	22.5 °C
HVAC control	Centrally/automatically

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 gas consumption for heating and electricity consumption for cooling. Hereunder, the analysis is reported for gas use 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 Indexes evaluation and validation

A model of the building was developed in EnergyPlus Version 8.7; the impact indexes for gas consumption for heating were calculated as in Section 2.1, and are reported in Fig. 10. 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 gas consumption variation of ca. 10-15% if the LPD is varied by ±50%. A lower impact on the gas consumption 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 for different zones, on the other hand it could provide insights into the appropriate placing and installing of OB-related monitoring sensors.

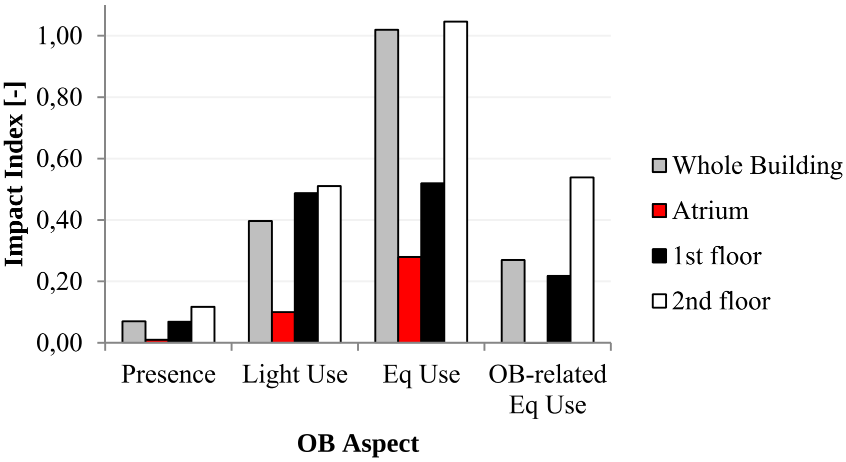

Figure 10: Yearly Impact Indexes for presence, light use, equipment use and OB-related equipment use for whole building and each separate zone

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 results are reported in Fig. 11. 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.

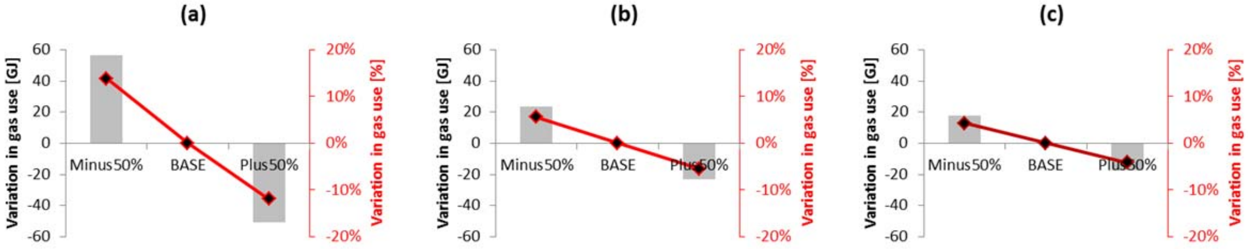

Figure 11: OAT sensitivity analysis. Absolute and % gas use variation resulting from increasing/decreasing LPD (a), OB-related EPD (b), and presence (c) by 50%

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 omitted, as during that period the cooling needs exceed the heating needs, and the heat gains become significant, nullifying the hypothesis made while developing II for heating that heat gains should be insignificant in relation to heat losses. The results of this analysis are reported in Fig. 12.

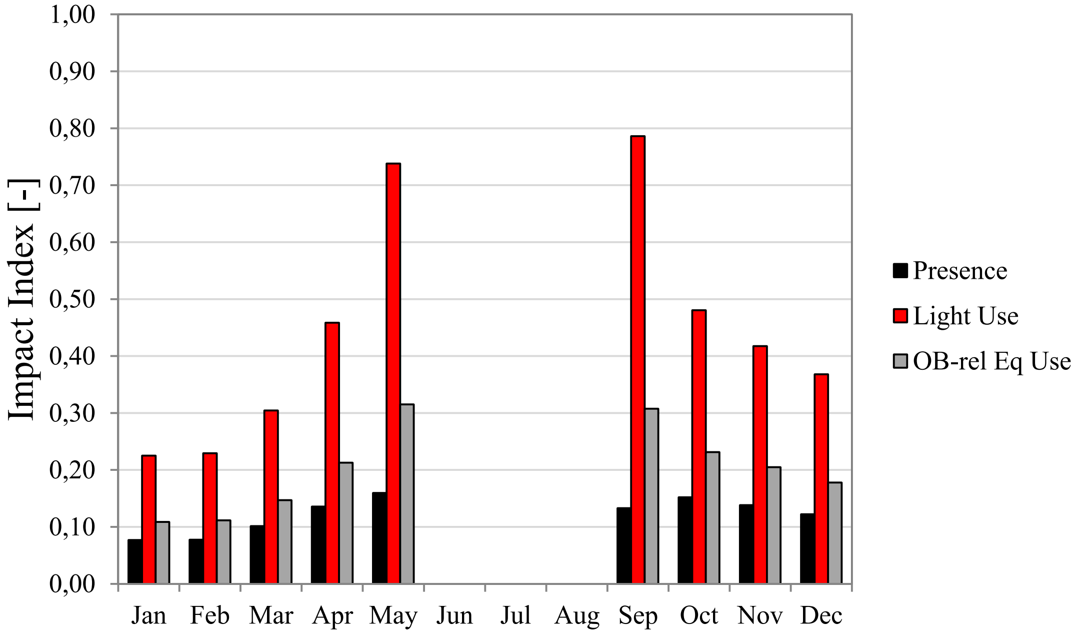

Figure 12: Monthly Impact Indexes for occupant presence, light use, equipment use and OB-related equipment use for the whole building

Fig. 12 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 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 (in this case, gas consumption) related to its absolute value. As we expect the absolute gas consumption to be higher during the colder months, the II presented in Fig. 12 do not directly provide information about the actual amount of gas that could be consumed because of OB in absolute terms. Fig. 13 shows both the absolute monthly variation in gas consumption and the relative monthly variation when varying the LPD by ±50%. The relative variation follows the trend indicated by the II in Fig. 12. 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.

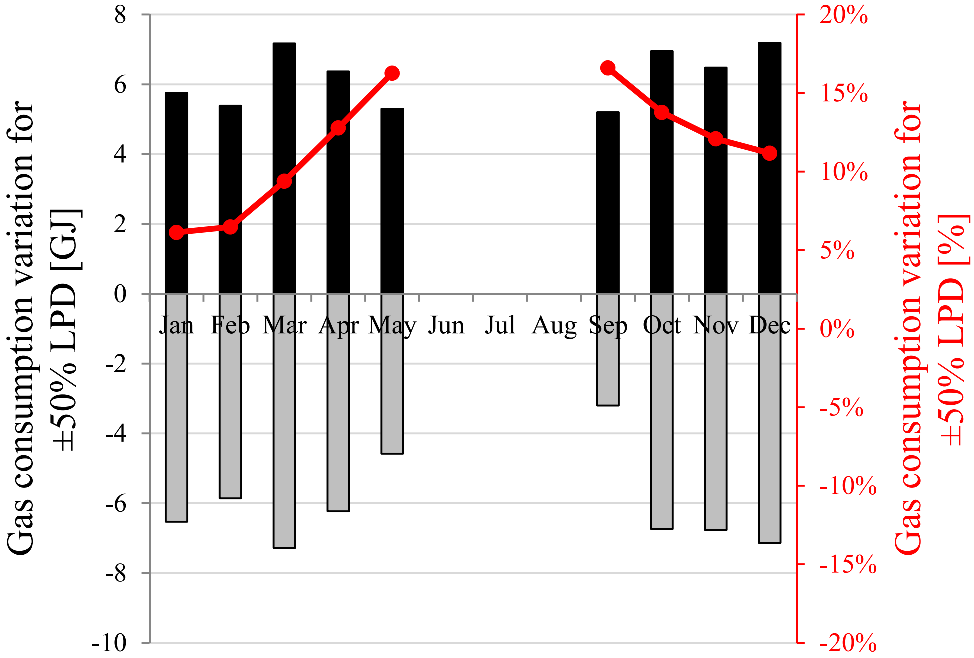

Figure 13: Monthly absolute and relative variation in gas consumption when varying the LPD by ±50%

For the investigated building, historical data about the gas consumption during the last years was available. Fig. 14 confirms that the yearly variation in gas consumption 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 performance contracts with a low risk-factor. If the clients are interested in absolute gas consumption variation, it is advisable to include clauses about lights energy 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.

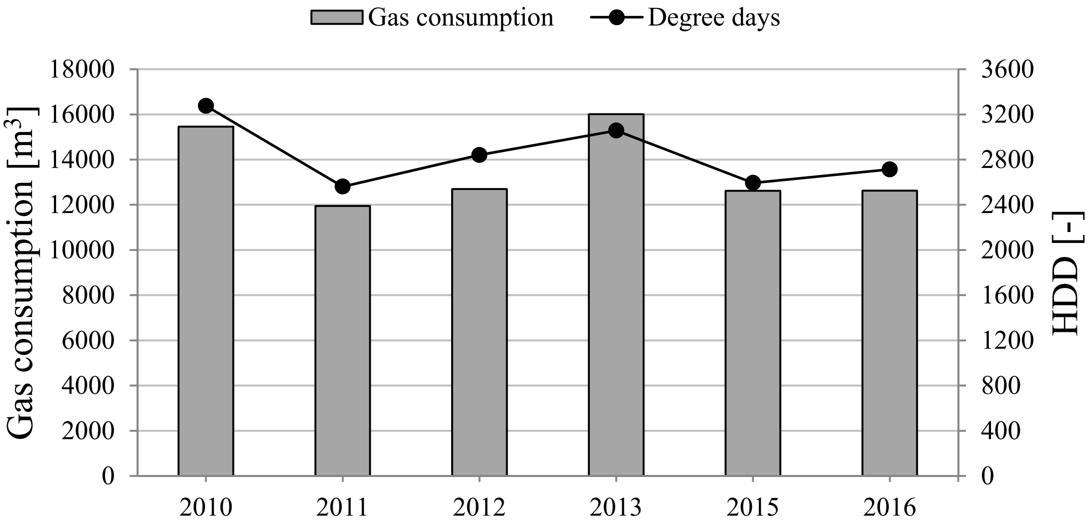

Figure 14: Observed yearly variation in gas consumption (2014 was omitted due to lack of data)

6. Conclusions

A method was proposed to estimate the potential effect of a number of OB aspects on heating and cooling energy use. The method consists of a number of newly proposed impact indexes, which can be obtained with one simulation run. This process is highly 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 simplified validation process confirmed that the impact indexes are able to explain 85% to 95% of the variations of heating and cooling energy use observed as a consequence of deviations in light use, equipment use, occupant presence, blind use and temperature setpoint. The potential applications of this method are varied, spanning from energy performance contracting, to modeling selection for different aspects of OB, to efficient placing of OB-related sensors. The impact indexes were calculated for an existing building and rapidly confirmed the potential for a low-risk application of energy performance contracting. 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. This research seeks 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 use.

References

[1] P. Hoes, J.L.M. Hensen, M.G.L.C. Loomans, B. de Vries, D. Bourgeois, User behavior in whole building simulation, Energy Build. 41 (2009) 295–302. doi:10.1016/j.enbuild.2008.09.008.

[2] C.M. Clevenger, J. Haymaker, The impact of the building occupant on energy modeling simulations, in: Jt. Int. Conf. Comput. Decis. Mak. Civ. Build. Eng. Montr. Canada, Citeseer, 2006: pp. 1–10.

[3] C. van Dronkelaar, M. Dowson, E. Burman, C. Spataru, D. Mumovic, A Review of the Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings, Front. Mech. Eng. 1 (2016) 1–14. doi:10.3389/fmech.2015.00017.

[4] G. Branco, B. Lachal, P. Gallinelli, W. Weber, Predicted versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data, Energy Build. 36 (2004) 543–555.

[5] O. Guerra Santin, L. Itard, H. Visscher, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy Build. 41 (2009) 1223–1232.

[6] H.W. Lin, T. Hong, On variations of space-heating energy use in office buildings, Appl. Energy. 111 (2013) 515–528. doi:10.1016/j.apenergy.2013.05.040.

[7] R.K. Andersen, The influence of occupants ’ behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments, in: 2012: pp. 18–20.

[8] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings, Build. Environ. 88 (2014) 89–96. doi:10.1016/j.buildenv.2014.09.010.

[9] U.S. Department of Energy (DOE), Commercial reference buildings, (n.d.). http://energy.gov/eere/buildings/commercial-reference-buildings.

[10] A. Ghahramani, K. Zhang, K. Dutta, Z. Yang, B. Becerik-Gerber, Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings, Appl. Energy. 165 (2016) 930–942. doi:10.1016/j.apenergy.2015.12.115.

[11] K. Sun, T. Hong, A Simulation Approach to Estimate Energy Savings Potential of Occupant Behavior Measures, Energy Build. 136 (2016) (Article in press). doi:10.1016/j.enbuild.2016.12.010.

[12] E. Azar, C.C. Menassa, A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings, Energy Build. 55 (2012) 841–853. doi:10.1016/j.enbuild.2012.10.002.

[13] International Organization for Standardization, ISO 13790: Thermal performance of buildings — Calculation of

energy use for space heating and cooling, Int. Organ. (2005) 106.

[14] EnergyPlus, EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations, 2012.

[15] ASHRAE, ANSI/ASHRAE/IESNA Standard 90.1-2013: Energy standard for buildings except for low-rise residential buildings, 2013.

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

Building ID	Heating season	Cooling season
AMS1	1/01 – 30/04 | 9/10 – 31/12	1/05 – 8/10
AMS2	-	1/01 – 31/12
AMS3	1/01 – 31/05 | 1/10 – 31/12	1/06 – 30/09
AMS4	1/01 – 31/03 | 21/10 – 31/12	1/04 – 20/10
AMS5	1/01 – 31/05 | 1/09 – 31/12	-
AMS6	1/01 – 23/05 | 1/09 – 31/12	24/05 – 31/08
AMS7	1/01 – 30/06 | 1/09 – 31/12	-
AMS8	1/01 – 23/05 | 1/09 – 31/12	-
ROM1	-	1/02 – 23/12
ROM2	-	1/01 – 31/12
ROM3	1/01 – 31/03 | 1/11 – 31/12	1/04 – 31/10
ROM4	-	1/01 – 31/12
ROM5	1/01 – 31/03 | 27/10 – 31/12	1/04 – 26/10
ROM6	1/01 – 30/04 | 27/10 – 31/12	1/05 – 26/10
ROM7	1/01 – 30/04 | 14/10 – 31/12	1/05 – 13/10
ROM8	1/01 – 30/04 | 14/10 – 31/12	1/05 – 13/10