Considering Occupant Behaviour in Building Energy Simulations along the Design Process: From a Semi-dynamic to a Dynamic Model

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Abstract

To reach the target of nearly Zero Energy Buildings (nZEBs), considering occupant behaviour is essential from the early design stage. This study proposes a design support tool for architects, which includes flexible and straightforward occupant behaviour modelling from the pre-design stage onwards. The tool uses a semi-dynamic model. The proposed tool can automatically export building characteristics and occupant behaviour to dynamic modelling for a more detailed assessment further on in the design process. The strength of the tool is its capacity of allowing a fast and consistent estimation with simple inputs of occupant behaviour. The tool is developed for Belgium, but the approach is valid for broader contexts.

Introduction

As the building sector has been well-known as a key sector to contribute to climate change (Boermans et al. 2011), the 2010 European Directive on the Energy Performance of Buildings Directive (EPBD) requires EU members to improve the energy efficiency of new buildings to achieve the target of nearly Zero Energy Buildings (nZEBs) by 2020 (EPBD recast 2010). Choices in the early design stage play a major role in the energy performance of buildings. Especially for small scale projects architects lack specialist's supports due to financial and time constraints.

Not only building design but also occupant behaviour influences energy consumption. Considering both aspects from the early design phase has a high impact on energy efficiency (Kohler and Moffatt 2003). In addition, as nowadays buildings are well insulated, the relative importance of occupant behaviour is increasing. The well-known gap between the predicted and actual performance of energy efficient buildings is partially caused by the lack of considering user patterns (Hauge et al. 2011). Building simulation tools used during the early design phase usually assume default values for occupant behaviour, not reflecting potential varieties (Yan et al. 2015).

This paper proposes a decision support tool for architects to design energy efficient residential buildings, including a variety of occupant behaviour situations. This tool is based on a semi-dynamic model and links to a dynamic model for more consistent simulations via EnergyPlus. The tool tries to solve the problem of communication between all stakeholders by visualisation of ideas and

simulation results (Attia et al. 2012; Miyamoto et al. 2015).

This paper is organised into five sections. The semi-dynamic estimation method and occupant behaviour modelling are described in section 2. Linking the tool to a dynamic model is demonstrated in section 3. The case study including the comparison between the proposed method and Energyplus simulation is described in section 4. Finally, conclusions are provided in section 5.

Semi-dynamic model

Dynamic Equivalent Heating Degree Day (dEHDD) method for prediction of annual energy demand

The proposed tool uses a refinement of the Equivalent Heating Degree Days (EHDD) method (Miyamoto et al. 2015). The Heating Degree Days (HDD) method predicts the yearly required energy for heating based on the number of days with a difference between the daily average outdoor and indoor temperature.

Figure 1: Representation of dEHDD for the temperate climate in Belgium and two different occupant behaviour profiles

The EHDD takes into account the free solar and internal heat gains in a static way by a fixed reduction of the HDD method (Diensten voor de programmering van het

wetenschapsbeleid 1984). In the dEHDD method, this reduction is calculated month by month for a better approximation of the solar gains and internal gains. As occupant behaviour and the resulting internal heat gains are the focus of this study, solar gains will be kept constant.

The outdoor temperature (T_e) is obtained via linear regression of monthly temperature during autumn, winter and spring in the Test Reference Year (Carlo Joyce Correna Roberto Lamberts 2005).

The approach can be represented in a graphical way (Fig.1) with horizontally the number of days of the heating season and vertically the temperature. Based on the HDD method, the heating season starts and stops when the outdoor temperature (T_e) is lower or higher than 15°C (T_{NH} : temperature of no more heating). In this study, solar gains are considered constant during the heating season. Depending on the losses via transmission and ventilation, the increase of the temperature by the heat gains (ΔT_{sum}) can be calculated:

$$\Delta T_{sum} = \frac{\Phi_{g,sum}}{h_T + h_V} \quad (1)$$

$$h_T = E \times U_m \quad (2)$$

$$h_V = V \times ACH \times \beta \times \rho \times C_p \times \frac{1}{3600} \quad (3)$$

With

- $\Phi_{g,sum}$: average heat gain rate (W)
- E : envelope surface (m^2)
- U_m : average heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$)
- V : building volume (m^3)
- ACH : air change per hour (1/h)
- β : volumetric coefficient ($= 0.95 \text{ m}^3/\text{m}^3$)
- ρ : density of air ($= 1.29 \text{ kg}/\text{m}^3$)
- C_p : specific heat capacity of air ($= 1006 \text{ J}/\text{kgK}$)

T_{NH} is calculated, considering the impact of the temperature setpoint (ΔT_{set}), internal gains from appliances (ΔT_{app}) and occupants (ΔT_{per}). The second temperature line (T_{WH}) is the increased indoor temperature, resulting from solar gains (ΔT_{sun}) when the building is not heated and not occupied. The number of dEHDDs is represented by the blue area in Fig.1.

Based on the dEHDD, annual energy demand per floor area (Q_E) is calculated (Miyamoto et al. 2015):

$$Q_E = H_t + H_v \quad (4)$$

$$H_t = \frac{h_T \times dEHDD \times 24 \times 3600}{3600 \times 1000 \times A_f} \quad (5)$$

$$H_v = \frac{h_V \times dEHDD \times 24}{3600 \times 1000 \times A_f} \quad (6)$$

With

- Q_E : annual energy demand per floor area ($\text{kWh}/\text{m}^2\text{year}$)
- H_t : annual transmission heat loss per floor area ($\text{kWh}/\text{m}^2\text{year}$)
- H_v : annual ventilation heat loss per floor area ($\text{kWh}/\text{m}^2\text{year}$)

- dEHDD: dynamic Equivalent Heating Degree Days (dayK/year)

Occupant behaviour modelling

Based on the dEHDD method, input parameters related to occupant behaviour are classified into four categories: (1) Temperature set-point (2) Occupancy and activity level (3) Usage of appliances and lighting and (4) Ventilation strategy. Simplified and user-friendly inputs are introduced in this model to describe occupant behaviour.

Set-point temperature

This early design tool considers one temperature (T_{season}) for the whole zone. In most Belgian houses, only some spaces are heated. Non-heated spaces receive heat from heated rooms. For the heated spaces, comfort is only required for specific periods of the day depending on the inhabitant's way of life. When the heating is off, space cools down depending on the insulation level, ventilation level, thermal capacity and remaining gains.

The tool requires the following inputs: (a) for both weekdays and weekend, indication of the hours when heating is required and desired temperature during these hours (non-grey cells, line by T_{com} in Fig.2) and (b) the percentage of heated floor area over the total floor area (R) (Fig.2). The seasonal average zone temperature (T_{season}) is calculated based on the following hypotheses.

- The hourly average temperature in the heated area (T_h) is equal to the comfort set-point temperature (T_{com}) during the heating "on". If the heating is "off" (T_{off}), the temperature will typically drop in winter.

$$T_h = \begin{cases} T_{com} \\ T_{off} \end{cases} \quad (7)$$

The average temperature in this "off" period depends on the balance between heat gains (by people, appliances and solar) and losses (transmission and ventilation) and the thermal capacity. In this study, a constant average thermal capacity is considered. Hence for a fixed volume, T_{off} is predicted by following linear-regression based on results of a dynamic simulation: (Eq.(8)).

$$T_{off} = (-2.47 \times ACH) - (0.28 \times i) + (0.015 \times Q_i) - (0.20 \times n) - (3.76 \times U_m) + 23.94 \quad (8)$$

Where

i : number of heating interruptions per day

Q_i : total heat gains (W)

n : non-heating hours per day (h)

This regression is built based on 288 combinations consisting of (1) three occupant schemes (family, elderly and young) regarding set-point temperature (Fig.3) and activity (Fig.6), (2) three values of ACH (0.26, 0.49 and 0.73 (1/h)) (3) 16 U-values ranging from 0.35 to 0.88 $\text{W}/\text{m}^2\text{K}$. Heat gains by people and appliances and ventilation rate are described in the following sections.

Weekend																										
Setpoint temperature	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	%Area	avg
Set-point temperature (Tcom)	off	off	off	off	off	off	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	off	50%	
Temp average heating area (Th)	19.8	19.8	19.8	19.8	19.8	19.8	19.8	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	19.8		
Temp average non heated area (Tnon)	11.9	11.9	11.9	11.9	11.9	11.9	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	11.9	50%	
Zone internal temperature (Tzone)	15.8	15.8	15.8	15.8	15.8	15.8	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	15.8		16.4
Weekdays																										
weekdays	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	%Area	avg
Set-point temperature (Tcom)	off	off	off	off	off	21	21	21	21	off	off	off	off	off	off	21	21	21	21	21	21	21	off	off	50%	
Temp average heating area (Th)	18.5	18.5	18.5	18.5	18.5	21.0	21.0	21.0	18.5	18.5	18.5	21.0	21.0	18.5	18.5	21.0	21.0	21.0	21.0	21.0	21.0	21.0	18.5	18.5		
Temp average non heated area (Tnon)	11.5	11.5	11.5	11.5	11.5	12.3	12.3	12.3	11.5	11.5	11.5	12.3	12.3	11.5	11.5	12.3	12.3	12.3	12.3	12.3	12.3	12.3	11.5	11.5	50%	
Zone internal temperature (Tzone)	15.0	15.0	15.0	15.0	15.0	16.7	16.7	16.7	15.0	15.0	15.0	16.7	16.7	15.0	15.0	16.7	16.7	16.7	16.7	16.7	16.7	16.7	15.0	15.0		15.8
Seasonal																										
Internal temperature	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	heated avg	days
weekend	15.8	15.8	15.8	15.8	15.8	15.8	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	15.8	16.4	2
weekday	15.0	15.0	15.0	15.0	15.0	16.7	16.7	16.7	15.0	15.0	15.0	16.7	16.7	15.0	15.0	16.7	16.7	16.7	16.7	16.7	16.7	16.7	15.0	15.0	15.8	5
																										16.0

Figure 2: The input and output parameters for set-point temperature schedules

Figure 3: Set-point temperature and heating-off schedule of three schemes for regression and case study

Figure 4: Probability plot of T_{off} between semi-dynamic model and E+ simulation

Figure 4 shows the comparison between T_{off} predicted by the proposed model and results of Energyplus simulations for newly generated combinations to test the regression function.

The average temperature in the non-heated area (T_{non}) is defined as follow:

$$T_{non} = T_o + \frac{T_h - T_o}{3} \quad (9)$$

Where T_o is average outside temperature during the heating season. T_o is based on the TRY (Carlo Joyce Correna Roberto Lamberts 2005).

- The weighted average determines the daily internal temperature (T_{zone}) over heated (T_h) and non-heated (T_{non}) floor area (Eq.10)

$$T_{zone} = \frac{\sum_{h=1}^{24} (T_h \times R) + \{T_{non} \times (1-R)\}}{24} \quad (10)$$

where R is the heated floor area as % of total floor area.

- The seasonal internal temperature (T_{season}) is the calculated average of T_{zone} (2/7 weekend, 5/7 weekday) (Eq.11).

$$T_{season} = \frac{T_{zone(weekday)} \times 5 + T_{zone(weekend)} \times 2}{7} \quad (11)$$

Occupancy and human activity

The occupant's body exchanges heat via convection, radiation, conduction, breathing, evaporation and sweating. Internal gains by people depend on his/her activity level (MET) and body surface (A). The activity level MET is the correction factor compared to "quietly sitting", which generates 58.15 W/m² per average body surface (1.8m² for an adult) (ASHRAE Standing Standard Project Committee 2008). Thus, internal gains by people (Φ_p) are calculated by Eq. (12).

$$\Phi_p = MET \times 58.15 \times A \times p \quad (12)$$

With

- p: number of inhabitants (p)

The tool requires to select an occupancy and activity level over 24 hours for both of a weekday and weekend (non-grey cells in Fig.5). Five activity levels are predefined to describe daily life in a dwelling (Table1). Based on this schedule, the average daily internal gains by the occupant(s) (Φ_p) are calculated. Figure 5 shows the daily occupancy and activity schedule. Average Φ_p can be based on predefined schedules or can be case specific.

Weekend																										
Internal gain by People	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	avrg/h	W/m²fl
Activity	sleep	sleep	sleep	sleep	sleep	sleep	light activity	light activity	Medium activity	Medium activity	Medium activity	Medium activity	light activity	light activity	light activity	light activity	Medium activity	Medium activity	light activity	light activity	Seated	Seated	sleep	sleep		
W/person	73.3	73.3	73.3	73.3	73.3	73.3	177.9	177.9	209.3	209.3	209.3	209.3	177.9	177.9	177.9	177.9	209.3	209.3	177.9	177.9	125.6	125.6	73.3	73.3	146.5	2.93
Weekdays																										
Internal gain by People	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	avrg/h	W/m²fl
Activity	sleep	sleep	sleep	sleep	sleep	sleep	light activity	light activity	away	away	away	away	away	away	away	away	away	Medium activity	light activity	light activity	light activity	Seated	Seated	sleep		
W/person	73.3	73.3	73.3	73.3	73.3	73.3	177.9	177.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	209.3	177.9	177.9	177.9	125.6	125.6	73.3	77.6	1.55
Seasonal																										
Internal gain by People	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Daily avg	days
weekend	73.3	73.3	73.3	73.3	73.3	73.3	177.9	177.9	209.3	209.3	209.3	209.3	177.9	177.9	177.9	177.9	209.3	209.3	177.9	177.9	125.6	125.6	73.3	73.3	146.5	2
weekday	73.3	73.3	73.3	73.3	73.3	73.3	177.9	177.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	209.3	177.9	177.9	177.9	125.6	125.6	73.3	77.6	5
																									97.32	1.9

Figure 5: The input and output parameters for occupant activity schedules

Figure 6: Occupant activity schedule of three example schemes for regression and case study

Table 1: List of human activity and metabolic rate

MET	sleep	seated	light activity	medium activity	hard activity
	0.7	1.2	1.7	2	3
W/person	73	126	178	209	314

Usage of appliances and lighting

In this study the most common appliances in households in Europe, such as domestic cooling appliances (fridge, freezer or combination of both), domestic laundry (washing machine and tumble dryer), domestic lighting, consumer electronics and small household equipment, are modelled (Department for Environment, Food and Rural Affairs 2009). The energy consumption by these appliances is determined by the electric power of each appliance and their total time in use. These days, for each type of appliance, various choices for energy efficiency are available on the market. In order to provide user-friendly input, the electric consumption power of each has to be selected from the classes A+++ to D which are elaborated based on the European Energy Label and real product data in the European market (Tompros et al. 2009). Time in use obviously depends on the individual lifestyle and the number of people who use the item, taking into account the simultaneous use of certain appliances by more than one person. Table 2 presents the consumption power of each appliance and the required input for the time in use.

The average heat gain of the heated zone by an appliance (Φ_A) is given as follows:

$$\Phi_A = u_A \times l_A \times f_A \times Q_A \times \frac{1000}{24 \times 365} \quad (13)$$

$$u_A = \begin{cases} 1, & \text{installed in a dwelling} \\ 0, & \text{not installed in a dwelling} \end{cases}$$

$$l_A = \begin{cases} 1, & \text{located in heated zone} \\ 0, & \text{located in non - heated zone} \end{cases}$$

With

- Φ_A : average heat gain rate (W)
- f_A : fraction of consumed energy dissipated to the environment as heat (%) (shown in Table 3) (Passive House Institute 2015)
- Q_A : consumed energy per year (kWh/year)

Table 2: List of consumption power levels and input for time in use of each appliance

Appliances	Consumption power	time in use
Fridge	A+++ to D (kWh/year)	24 hours/day
Freezer	A+++ to D (kWh/year)	24 hours/day
Combination	A+++ to D (kWh/year)	24 hours/day
Washing machine	A+++ to D (kWh/cycle)	cycle per week per person (c_{wp})
Tumble dryer	A+++ to D (kWh/cycle)	cycle per week per person (c_{wp})
Dish washer	A+++ to D (kWh/cycle)	cycle per week per person (c_{wp})
Cooking hubs	Type of hubs (kWh/hour)	hour per week per person (h_{wp})
Light	Average power (W)	hour per day per person (h_{dp})
Electronics	130W	1.5 hour per day person
Household Equipment	50kWh/year	-

Figure 7 shows the input and output parameters for the calculation of the internal heat gains by electric appliances and lights. Input parameters (non-grey background in Fig.7) are: installed or not, located in a heated area or non-heated area, equipment class (A+++ to

Area	100 m ²															
People	2 persons															
	Refrigerating appliances			Laundry												
	Fridge	Freezer	Combination	washing machine	spin dry process	tumble dryer	energy by evaporation	Dishwasher	Cooking hobs	Light	Electronic	Household equipment	auxiliary Power	Total		
Installation or not	installed	installed	not installed	installed	installed	installed	installed	installed	installed	installed						
Location: heated or non-heated area	heated area	heated area	heated area	heated area	heated area	heated area	heated area	heated area	heated area	heated area						
Type	-	-	-	-	-	Condenser	-	-	Electronic hob	-	-	-	-			
Energy consumption (level or kWh/year)	A++	A+	-	A+++	A	A+	Condenser	B	-	-	-	-	50			
kWh/cycle or hour	-	-	-	0.65	-	1.64	-	1.29	0.25	-	-	-	-			
spin speed (rpm)	-	-	-	-	800-1000	-	-	-	-	-	-	-	-			
residual moisture per rmd	-	-	-	-	68%	-	-	-	-	-	-	-	-			
correction for energy consumpt	-	-	-	-	0.975	-	-	-	-	-	-	-	-			
kwh/cycle(corrected)	-	-	-	-	-	-	-	-	-	-	-	-	-			
kg	-	-	-	6	6	6	6	-	-	-	-	-	-			
W	-	-	-	-	-	-	-	-	-	27	130	-	-			
number of light	-	-	-	-	-	-	-	-	-	5	-	-	-			
% of CFLs	-	-	-	-	-	-	-	-	-	30%	-	-	-			
% of LED	-	-	-	-	-	-	-	-	-	40%	-	-	-			
hour/person/day	-	-	-	-	-	-	-	-	-	1	1.5	-	-			
cycle(hours for cooking)/person/week	-	-	-	3	-	3	3	3	6	4	-	-	-			
h/person/year	-	-	-	156.43	-	156.43	156.43	156.43	312.86	365	547.50	-	-			
kWh/year	92.37	346.00	0.00	203.36	512.66	1150.69	403.59	156.43	96.73	142.35	100.00	-	-	2053.48	kWh/year	
Design level of appliance(W)	10.54	39.50	0.00	650.00	1638.65	-	-	1290.00	250.00	132.50	16.25	11.42	-			
% heat gain	100%	100%	100%	30%	70%	0%	30%	50%	100%	100%	100%	100%	-			
internal gain (W)	10.54	39.50	0.00	6.96	40.97	0.00	13.82	8.93	11.04	16.25	11.42	10.00	-	169.43	W	
% energy consumption	4%	17%	0%	10%	25%	56%	20%	8%	5%	7%	5%	0%	-	1.69	W/m ²	
% internal gain	6%	23%	0%	4%	0%	24%	0%	8%	5%	7%	10%	7%	6%			

Figure 7: The input and output parameters for appliances

Table 3: List of heat dissipation fraction

Refrigerating appliances			Washing machine			Energy by evaporation					Light				
Fridge	Freezer	Combination	washing process	spin dry process	tumble dryer	Convener	Vented	Hanging	Dishwasher	Cooking hobs	Incandescent	CFLs	LED	Electronic	Household equipment
100%	100%	100%	30%	30%	80%/70%	0%	-100%	-100%	30%	50%	100%	100%	100%	100%	100%

D) and usage hours or cycles per person in a week. Refrigerating appliances are used continuously over the year. The energy consumption (V_k) for refrigerating appliances is given in kWh/year, for other appliances in kWh/hour, kWh/cycle or W. The annual required energy (Q_A) in Eq.13 is calculated as follows:

- For appliances constantly running:

$$Q_A = V_k \quad (14)$$

- For dishwasher with estimated consumption per cycle per week per person (c_{wp}), Q_A is calculated as follows:

$$Q_A = V_k \times c_{wp} \times \frac{365}{7} \times p \quad (15)$$

- For the cooking hub with estimated consumption per hour per week per person (h_{wp}), Q_A is calculated as follows:

$$Q_A = V_k \times h_{wp} \times \frac{365}{7} \times p \quad (16)$$

- As the use of light-emitting diode (LED) lighting is widely replacing incandescent and fluorescent (CFL) lighting, mixed use of these lighting types is common in residential buildings (Richardson et al. 2009). The total number of lighting points (NLP), the % of CFL's (f_{CFL}) and LED's (f_{LED}) and the hours per day per person (h_{dp}) have to be input. Q_A is calculated as follows:

$$Q_A = NLP \times (15 \times f_{CFL} + 10 \times f_{LED} + 60 \times (1 - f_{CFL} - f_{LED})) \times h_{dp} \times 365 \times p \quad (17)$$

- For electronics with estimated consumption per hour per day per person (h_{dp}), Q_A is calculated as follows:

$$Q_A = V_k \times h_{dp} \times 365 \times p \times \frac{1}{1000} \quad (18)$$

- For small household equipment, the energy per year per person, Q_A is calculated as follows:

$$Q_A = V_k \times p \quad (19)$$

As shown in Figure 8, the laundry process is divided into three steps; (1) washing, (2) spinning and (3) drying.

- For each washing machine and tumble dryer with estimated cycles per week per person (c_{wp}), Q_A is calculated as in Eq.15.

Spin drying function is included in a washing machine based on EU Directive definition (EU Directive 2010). However, the remaining moisture content (RMC), which determines the energy impact of the drying process, is derived from the spinning performance.

The required energy is obtained by Equation (20). Evaporation energy (Φ_{evap}) depends on the RMC:

$$\Phi_{evap} = l_A \times V_e \times c_{wp} \times w \times RMC \times \frac{365}{7} \times p \times \frac{1000}{24 \times 365} \quad (20)$$

With

- V_e : evaporation energy for 1kg water (= 0.613kWh/kg) (Stamminger 2011)
- w : washing load size per cycle

Figure 8: Overview of the laundry process

After the spinning process, the RMC can be removed by a tumble dryer or by hanging. If the moisture is added to the heated space (tumble exhausted or hanging in a heated area, (a-2) and (b-1) in Fig.8), the evaporation energy has to be generated by the heating system and is subtracted from the internal gains released by the washing and drying equipment. Therefore, total internal gains by the laundry process (Φ_{Laun}) are calculated by Eq.21:

$$\Phi_{Laun} = \Phi_{wash} + \Phi_{dry} - \Phi_{evap} \quad (21)$$

This modelling of the laundry process except for the time in use leads to a total of 686 combinations.

Ventilation strategy

Indoor air change per hour (ACH) is the result of in/ex-filtration ($ACH_{In/ex}$) and ventilation (ACH_V). The EPB approach in Flanders estimates $ACH_{In/ex}$ and ACH_V as follows (Deurinck 2015):

$$ACH_{In/ex} = ACH50 \times \frac{V}{A_E} \times 0.04 \quad (22)$$

$$ACH_V = m \times (0.2 + 0.5 \times \exp(-(V/500))) \quad (23)$$

Where:

- ACH50: in/ex-filtration rate at 50Pa (fixed in this study to 0.5 (1/h))
- A_E : envelop area (m^2)
- V: building volume (m^3)
- m: correction coefficient

Figure 9: Building volume and ventilation rate

The value of the correction coefficient is defined between 1.0 and 1.5 by EPB regulation. However, the Flemish

Institute for Technological Research (VITO) measured in recent well-insulated buildings much lower ventilation rates (VITO et al. 2012). Hence, the correction coefficient can be selected as a value between 0.5 and 1.5 (Fig.9) in this model.

Link to dynamic model

A macro is developed to translate the input of the tool to an Input Definition File (IDF file) that can be used for dynamic energy simulations with the software EnergyPlus (U.S. Department of Energy) for more detailed assessments later on in the design process. The input parameters for the occupant behaviour are translated into more detailed schedules describe user behaviour for dynamic simulations (Fig.10). All other parameters, such as geometry, technical choice, and so on, are directly translated into an IDF file.

Figure 10: Representation of a two-day user behaviour schedule generated into E+ for a whole year

The model used for analysing the effect of occupant behaviour

Simulation model

As this research focuses on the impact of occupant behaviour, the geometry is fixed to a box building with one window and overhang on each façade and characteristics as summarised in Table 4. For all elements, the construction is fixed, leading to an average U_m of 0.37 W/m^2K . Table 5 summarises the parameters and the range considered for describing the occupant behaviour used to test simulations in this study. The tool allows to automatically generate all possible combinations (1152 in this case), estimate the energy consumption and generate the IDF files. Via an automatic procedure, Energyplus simulations are run and the results reported in addition to the results calculated by the early-design tool. A wider design space can easily be generated.

Figure 11: Building geometry

Table 4: Design space for the model

Building description	
Location	Brussels
Building typology	Box building (Fig.11)
facade	10m
depth	10m
storey height	3m
number of floors	1
orientation	0°(=North)
obstruction	No
North: window size	3m x 2m
East: window size	3m x 2m
South: window size	5m x 2m
West: window size	3m x 2m
North: overhang	1m
East: overhang	1m
South: overhang	1m
West: overhang	1m
Number of inhabitants	2
Zone	1
% of the heated area	100%
set-point temperature	Figure 3
activity level	Figure 6

Table 5: Parameters describing user behaviour

Parameters	Range	No. combi
set-point temperature & occupant activity	young, family, elderly (Fig.3,6)	3
Appliances class	A+++,A,D	3
Washing machine	1 or 3 cycle/week/person	2
Spin dry	NA (= washing machine)	1
Tumble dryer type	Condenser	1
Tumble dryer (cycle in use)	1 or 3 cycle/week/person	2
Dishwasher	1 or 3 cycle/week/person	2
Cooking hubs (cycle)	2 or 6 hours/week/person	2
Light (total number of bulbs)	5	1
Light (time in use)	1 or 4 (hors/day/person)	2
Light (bulbs choices)	0%-10% (CFLs)-90% (LED) 80%-10% (CFLs)-10% (LED)	2
ACH	0.26 or 0.49	2
Total combinations		1152

Comparison of the dEHDD and Energyplus simulations

Fig.12 illustrates the comparison between the dEHDD and Energyplus simulations. The energy consumption by the tool is from 4% less to 9% more than the dynamic simulations. As can be seen, three clusters are situated roughly on straight lines. The difference of these clusters depends on the set-point temperature and activity schedules summarised as “Family”, “Elderly” and

“Young” (Fig.3 and Fig.6). In other words, the proposed method slightly overestimates the energy demands, especially when the occupancy of the dwelling is low. Hence, the quick estimations by the proposed tool are in line with the EnergyPlus results. The dEHDD method and occupant behaviour modelling are quite consistent for early design phase on, and the method can be used to generate IDF files for a detailed design stage.

Figure 12: Comparison of annual energy demands between dEHDD and E+ simulation

Graphical representation of results of the described design space

Figure 13 presents selected results of combinations via parallel coordinates. In the same building, the heating energy demands including the different ventilation rates range from 33 kWh/m²year to 70 kWh/m²year (or from 1006 to 1768 dayK/year) only due to differences in occupant behaviour. The results confirm the hypothesis that varying occupant behaviour has enormous impacts on energy demand.

Conclusions

The advantages of the tool are: (1) fast and consistent simulations in the early design stage, (2) user-friendly input of occupant behaviour (3) interactive modelling of occupant behaviour, (4) supporting communications in a design process with the automatic translation of all inputs from the proposed tool to IDF file for Energyplus, (5) overview of the design space can be generated automatically and visualised via parallel coordinates.

This research can be applied to other contexts by using other climatic data. This study focuses on occupant behaviour, but the model allows a flexible way to change many more design parameters: geometry and technical choices.

Figure 13: Parallel coordinate of results with ACH=0.26

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