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Occupant behaviour and the potential of automating lighting control in terms of energy consumption – is there a link for residential buildings?

L Van Thillo[1], S Verbeke[1,2] and A Audenaert[1]

[1]Energy and Materials in Infrastructure and Buildings (EMIB), University of Antwerp, Faculty of Applied Engineering, Groenenborgerlaan 171, 2020 Antwerp, Belgium
[2]Unit Smart Energy and Built Environment, VITO, Boeretang 200, 2400 Mol, Belgium

lotte.vanthillo@uantwerpen.be

Abstract. The implementation of occupancy-controlled and daylighting-dimmed lighting systems has an impact on the energy consumption of residential buildings. The BAC factor method of EN ISO 52120-1 estimates that 8% of the lighting energy can be saved compared to conventional manual control. However, it is assumed that their ability to potentially lower the lighting energy consumption is strongly related to external factors, such as the extent of daylight entrance and the behaviour of the inhabitants. By means of simulations in EnergyPlus, the performances of automated and manual lighting control are compared for an apartment and semi-detached building located in Brussels (Belgium) with variation in the occupant behaviour and orientation.

It appears that an automated lighting control including 0-100% dimmer reduces the lighting energy demand for all investigated cases with savings up to 38.4%, whereas a similar control without dimmer does not necessarily reduce the lighting electricity demand. However, the results show a considerable variation, making prediction methods as the BAC factor method highly inaccurate. The actual relative energy performance depends on the automation system, type of building, orientation and occupant behaviour (i.e. number of inhabitants and occupancy rate). Hereby, the number of inhabitants has the most considerable impact on the relative energy performances with differences up to 50%, while the occupancy rate shows a significant correlation, especially for low numbers of inhabitants.

1. Introduction

While automated lighting controls are already widespread in non-residential buildings for decades, their popularity in residential buildings only started to increase more recently. In general, it is assumed that the lighting energy consumption reduces by introducing occupancy-based and daylight-linked control systems. However, automating the lighting control in residential buildings can also result in an increase of the lighting energy consumption [1]. The BAC (Building Automation and Control) factor method of EN ISO 52120-1 fixes the electricity reduction at 8% for automated control compared to traditional manual lighting control, whereas scientific papers report lighting energy savings up to 34% and increases up to 10% [1–5]. Moreover, a reduction of the lighting energy consumption does not necessarily cause a decrease of the total energy demand as the production of internal heat gains reduces [5,6].

It appears that the actual impact of advanced lighting control systems shows a considerable spread. This is caused by variation in parameters related to the building design (e.g. window-to-wall ratio (WWR), g-value), installation characteristics (e.g. location of sensors, settings), occupant behaviour (e.g. comfort perception, presence) and other contextual factors (e.g. shading and daylight availability) [6]. This paper will focus on the impact of influencing parameters related to the occupant behaviour. Generally, it seems that occupancy and daylight sensing controls have the highest potential with infrequently and unpredictably occupation, whereas the number of residents has only a minor effect [1,6–8]. In several cases, a linear correlation between the occupancy rate and lighting energy reduction can be found, while others show no relation at all [4,9,10]. Furthermore, the illuminance levels are related to the residents' activity patterns and user comfort perception [11]. These settings, as well as the time delay settings, have a major impact on the absolute and relative lighting energy consumption [1].

The representation of the manual control behaviour is one of the challenges in energy performance simulations. Nowadays, the reported energy savings refer to various baseline scenarios, often making unrealistic assumptions such as lighting that is continuously switched on or ignoring presence of daylight [1,7,12]. In fact, manual control is driven by interactions between circumstances and variables, including residents' occupation, type of room, preferred illuminance levels and degree of fatigue [11]. For office buildings, several researchers have already proposed probabilistic switching patterns to include this unpredictability such as Hunt's probability function and Lightswitch-2002 [13,14]. In this regard, the probability that employees switch the lighting is correlated with external factors as the illuminance on the working space and their movements in continuously occupied spaces, whereas this probability is mainly influenced by the daylight availability in intermittently occupied spaces [15].

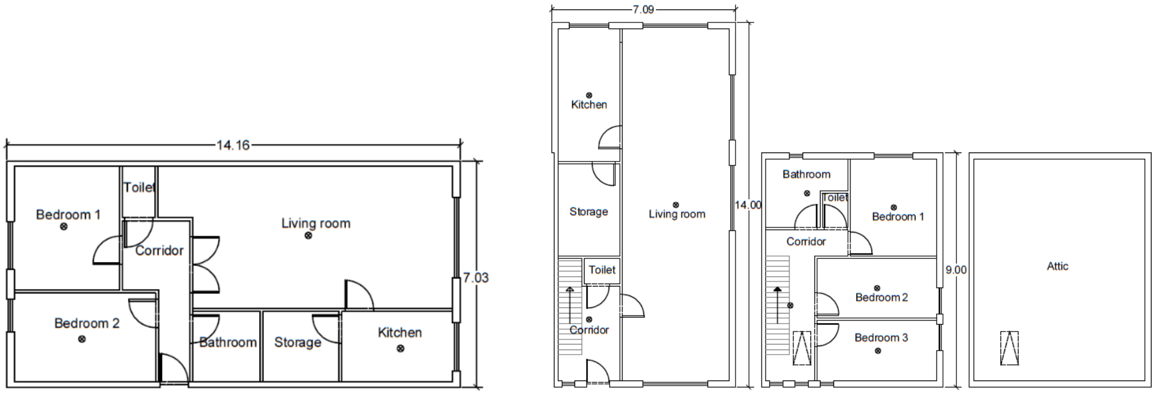
This paper explores the relation between the occupant behaviour and the consequences in relative energy consumption when automating the lighting control in residential buildings. The impact is investigated for two different case studies, an apartment and a semi-detached building, located in Belgium. Hereby, a simplified probabilistic control algorithm is proposed to represent the unpredictability of the manual switching behaviour.

2. Research method

The performances of manual and automated lighting control are investigated for one to four residents and three variations of household compositions and their routines. Furthermore, this influence is examined for four orientations of the case studies. To evaluate the impact of occupant behaviour, the performances of the different scenarios should be investigated in similar conditions. Therefore, building energy performance simulations are used to calculate the absolute energy consumptions. More specifically, the heating and lighting energy consumption are simulated in EnergyPlus (version 9.6.0) over a year with time steps of two minutes.

2.1. Building model

For this paper, two different residential building models are proposed: a unit in an apartment building and a semi-detached building, both located in Brussels (Belgium). Their design and thermal characteristics are based on Belgian buildings of about 30 years old [16]. The apartment consists of eight rooms (i.e. a living room, a kitchen, two bedrooms, a bathroom, a toilet, a storage/technical room and a corridor), whereas the semi-detached building additionally includes a third bedroom, a second toilet and an unheated attic (see figure 1). In the building energy performance simulation software, each room is modelled as a separate thermal zone.



(a) (b)

Figure 1. Design of the (a) apartment and (b) semi-detached building. In the remaining of the paper, the reported orientation refers to the direction that the wall on the upside of the figure is pointing. Furthermore, the locations where the daylighting illuminance is calculated, are indicated with ●. In general, these correspond to the middle point of the room.

The main living rooms of both case studies have windows through which daylight can enter the room. Hereby, it is assumed that none of the windows is located in the shadow of a surrounding construction so that the natural lighting is optimally utilized. To meet the remaining lighting requirements, all rooms are equipped with an artificial lighting installation with an efficacy of 102 lm/W [17]. Table 1 gives an overview of the lighting sources per room (adopted from [18]). Furthermore, a simplified ideal heating system is included to calculate the heating demand of the building. It is assumed that all the rooms are continuously heated at 20°C. The climate data for Brussels is adopted from the International Weather for Energy Calculations (IWEC) and the simulated energy consumption of each building design is calibrated with the consumption of Belgium households.

Table 1. Overview of installed artificial lighting and window area per room.

	Artificial lighting		Window area (m^2)	
	Illuminance (lux)	Power (W/m^2)	Apartment	Semi-detached building
Living	500	4.90	5.25	14.250
Kitchen	200	1.96	1.80	1.80
Bathroom	300	2.94	-	1.05
Toilet	50	0.49	-	-
Bedroom 1	100	0.98	1.58	1.58
Bedroom 2	500	4.90	1.05	1.05
Bedroom 3	500	4.90	-[a]	1.65
Storage	200	1.96	-	3.15
Corridor	100	0.98	-	-

[a] The apartment only contains two bedrooms.

2.2. *Occupant behaviour*

Probabilistic occupant behaviour patterns are included to simulate the unpredictability of the residents. In this study, the occupancy and activity model of Aerts is applied as it represents Belgians' residential behaviour [19]. In the used variant, the stochastic relations are defined with data from the Time Use Survey (TUS) of 2013. In general, this model generates the state and activity of each occupant stochastically per time step and afterwards, their position in the building is assigned [20]. However, these patterns only include the presence in frequently and long-occupied rooms. Therefore, the lighting requirements for passages and toilet visits are separately defined. Furthermore, these patterns take into account the local Daylight saving time.

Multiple of these occupancy patterns are simulated per building design to include variety of the household composition. The family that lives in the 2-bedroom apartment consists of one to three members and the semi-detached house is occupied by one to four people. For each number of inhabitants, three variations of occupancy routines are simulated.

2.3. Lighting control

The lighting system is controlled on three different manners: manually with switches per room and by two automatic systems: a presence-controlled system and a system that includes an additional daylight-linked dimmer. To determine the need for artificial lighting, the daylighting illuminance per room is calculated in the middle of each room (indicated with a ● in Figure 1). Furthermore, it is assumed that there is only one light circuit per room.

2.3.1. Manual lighting control. The manual lighting control system tries to reflect the human imperfections, especially when it comes to switching off the lighting. Therefore, the required minimum illuminance per room and per time step is defined in relation to the ongoing activity. An overview of these illuminance thresholds is given in table 2. It is assumed that the occupants switch on the lighting when they experience visual discomfort, i.e. if the daylight availability does not longer meet these minimum levels (adopted from [18]). On the other hand, the lighting will not always be turned off if there is sufficient daylight available or when the occupant leaves the room. These uncertainties are modelled in a probabilistic way: chances for forgetting to switch off the lighting when leaving the room, when going to sleep and when the daylight illuminance exceeds the threshold are introduced. In this study, they are fixed at respectively 5%, 2.5% and 10%. Furthermore, it is assumed that the occupants do not turn off the lighting in a room when they will return within 20 minutes.

Due to the application of a stochastic control algorithm, each simulation results in a slightly different outcome. Consequently, the anticipated energy consumption is an interval instead of a single value. In order to represent this variation, the results as presented here are an average of three separate simulations of the manual control.

2.3.2. Automated lighting control. Occupancy and daylight detection sensors with perfect operation are modelled to automatically switch the lighting. In general, the lighting is on when there is someone present in the room and the natural illuminance does not exceed the defined threshold. As the automated lighting cannot distinguish the different minimum values in relation to the activity, the level per room is defined as the maximum of the required lighting levels (see table 2). Furthermore, a time delay (i.e. the time interval before the lighting switches off after the latest movement is detected) per room is set. These settings are here fixed at two minutes for rooms with a short presence (i.e. storage and corridor), four minutes for the bedrooms and six minutes for the remaining rooms.

In this study, the performances of two automated control systems are compared with manual control. The first control system only switches the lighting, whereas the second control also includes a continuous dimmer with a range of 0-100%.

Table 2. Overview of the minimum illuminance levels (lux) for manual and automated control (adopted from [18]).

	Living	Kitchen	Bathroom	Bedroom 1	Bedroom 2/3	Corridor
Manual	Focus 500 Cleaning 200 Other 50	Cooking 200 Other 50	50	50	Focus 500 Other 50	50
Automated	200/500[a]	200	50	50	500	50

[a] depends on the activities of the occupants in the living room.

3. Results and discussion

3.1. Effects on lighting energy consumption

In general, the implementation of an automated control system including dimmer results in an energy reduction between 8.2% and 38.4% for the investigated cases, whereas the simplified automated control does not necessarily results in a reduction of the lighting energy consumption for the investigated cases (see figure 2). More specific, it appears that the variant without dimmer can consumes up to 41.2% more lighting energy than the manual on/off switches, while other cases result in energy savings up to 26.7%.

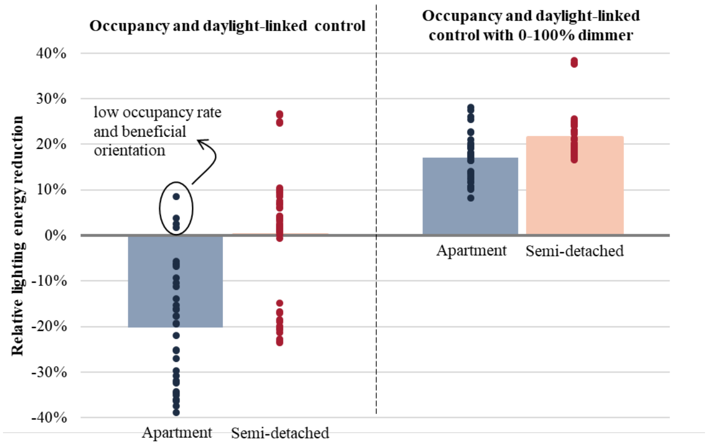


Figure 2. The automated lighting control including dimmer has a considerable potential to lower the energy consumption, whereas the variant without dimmer not always consumes less lighting energy than the manual switches. In general, these control systems achieve higher energy reductions in the semi-detached building compared to the apartment, but the investigated variants show a wide range.

On average, automating the lighting control results in an increase of the energy consumption with 20.3% in the apartment, while it has on average no effect (i.e. a reduction of 0.1%) in the semi-detached building. On the other hand, the control system with dimmer function causes an average decrease of respectively 17.1% and 21.6%. It seems that both control algorithms have a higher potential in the semi-detached building compared to the apartment.

However, the impact of the automated control algorithm shows a considerable variation for the investigated scenarios of each building design. Moreover, these results show a substantial difference with the corresponding BAC factor (i.e. 8%). It can consequently be concluded that a single value to predict the energy performances is highly inaccurate and additional characteristics of the building context and its occupants should be considered to properly evaluate the impact of automated lighting control systems.

3.1.1. Impact of the orientation. The orientation of the building influences the potential of automated lighting control in both building designs. For the apartment, a pairwise Wilcoxon signed-rank test (significance level of 0.05) shows that the average relative energy savings for the automated control without dimmer are slightly different for the four investigated orientations, whereas the variant with dimmer show no significant differences between an orientation of 90° and 180°. Similarly, the results for the semi-detached building slightly differ in relation to the orientation for the automated control without dimmer except for an orientation of 90° and 180°, whereas this influence cannot be detected when an automated control with dimmer is implemented.

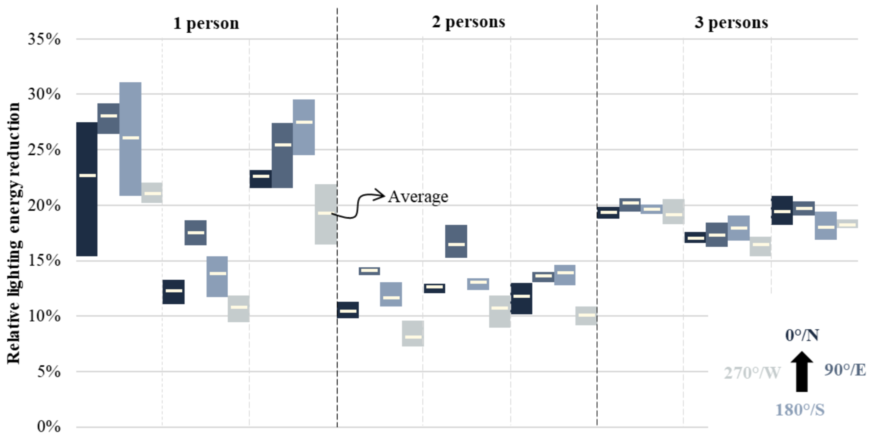


Figure 3. The relative energy reductions of an automated lighting control including 0-100% dimmer compared to manual switches are influenced by the orientation of the apartment. Orientations 90° and 180° show slightly higher energy reductions on average than orientations 0° and 270°.

The different orientations show variations up to 20.7% and 8.2% on average for the apartment and 6.5% and 3.9% on average for the semi-detached building, respectively for the automated control without and with dimmer, for the same occupant behaviour. The main rooms of the apartment only have one window, while the living room of the semi-detached building has daylight entrance in three orientations. Furthermore, it can be concluded that an orientation of 90° or 180° results in higher energy savings on average (see figure 3 for the automated control with dimmer in the apartment). This corresponds to a south and west orientation of the windows in the living room and kitchen for the apartment and consequently, a maximised usage of natural lighting.

3.1.2. Impact of the occupant behaviour. The impact of the occupant behaviour is investigated taking into account the impact of the orientation. Firstly, it can be concluded that the number of inhabitants influences the attainable energy savings and the variation in results. This parameter results in differences in the relative energy consumption up to 50.3% and 21.7% for both automated controls.

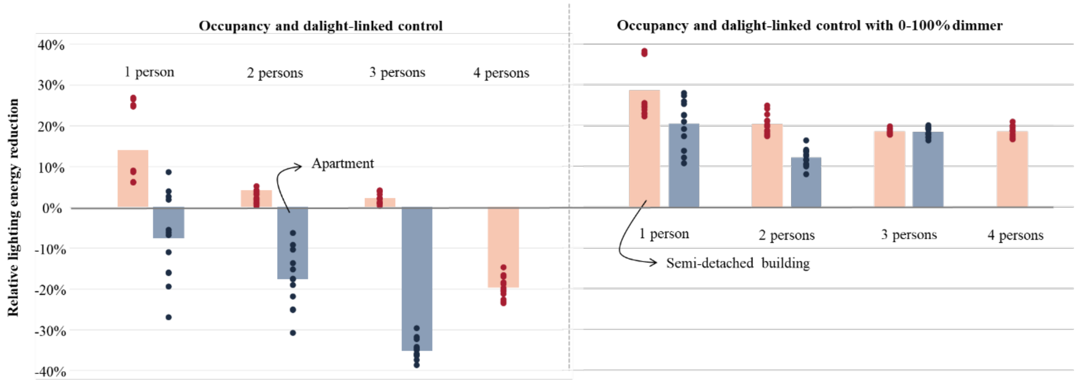


Figure 4. The relative impact of automated lighting systems is influenced by the number of inhabitants. The highest energy reductions are achieved for one-person households, while the range of results narrows with the increase of the number of occupants.

Figure 4 shows that a one-person household can achieve the highest energy savings by installing an automated control. This potential strongly reduces when the family consists of multiple members since the rooms are then more regularly occupied. This implies that the inhabitants notice faster that the lighting is unnecessary on. A Wilcoxon rank-sum test (significance level of 0.05) showed that the potential is considerably lower for a two-person household, whereas there is no significant difference between a one- and three-person household for implementing an automated control with dimmer in the apartment due to the variation in the results of a single occupant. For the semi-detached building, the conclusion is slightly different: the automated control system has the highest impact in the one-person household, followed by a two- and three-person household for the automated control without dimmer. The lowest impact is found for a family of four members, whereas no significant differences between two, three and four member families are detected for the automated control with 0-100% dimmer.

The variation in results between the scenarios decreases with an increasing number of occupants. These differences can partially be attributed to variation in the occupancy rate, especially for low numbers of inhabitants. Despite the small test sample, the relative energy savings, caused by installing an daylight-linked control system, of a one- and two-person household in the apartment are correlated with the occupancy rate for the four orientations as can be seen on figure 5. In this respect, the results of a two and three person household show an inconsistency which is caused by a different usage of the second bedroom, namely as home office or as bedroom. For the semi-detached building, the relation between occupancy rate and relative energy savings can even be detected within a 0.05 significancy level for all investigated family compositions. Furthermore, it can be noticed that the number of occupants has a minor effect on the occupancy rate when there are multiple residents in the semi-detached building. This explains why, for more than two residents, no significant differences could be detected in relation to the number of inhabitants.

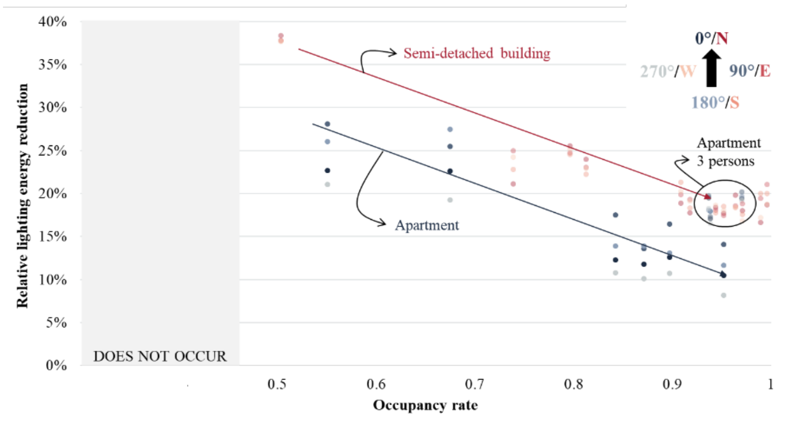


Figure 5. The impact of the automated lighting control inclusive dimmer is correlated with the occupancy rate and this for all orientations. As the occupancy rate increases, the potential of the automated control system decreases.

3.2. *Secondary effects*

Automating the lighting control does not only affect the lighting energy consumption, it also affects other building energy consumptions as the heating and cooling energy consumption. Relatively, the impact of the lighting control on the heating consumption can be neglected with changes of approximately 1%. As it can be expected, the extent of impact on the lighting and heating energy consumption are significantly correlated. More specific, a reduction of the lighting energy consumption causes an increase in the heating demand due to the decrease in associated heating gains. However, the produced heat is only partially useful so that the positive or negative impact on the lighting energy consumption is reflected in the total absolute energy demand.

4. Conclusion

This study investigated the potential of an automated lighting control system with and without 0-100% dimmer compared to traditional manual control in an apartment and semi-detached building. A probabilistic control algorithm is here introduced to represent the unpredictability and imperfections of manual switching behaviour. More specifically, chances for forgetting to turn off the lighting are assigned as well as a time span for short time absences during which the lighting stays on is included.

It is found that automating the lighting control system does not necessarily reduce the lighting and total energy consumption. In general, a control system with dimmer function has more potential to lower the lighting energy demand than a simple control based on presence and illuminance thresholds. This first type of control results in energy savings between 8.1% and 38.4%, whereas the latter control system can decrease the lighting electricity consumption with 26.7% and increase it up to 41.2%. Moreover, the secondary effects due to the changes in heat gains are neglectable since they only cause changes in the heating energy consumption of about 1%.

The results of the investigated cases show an enormous variation. Firstly, the building design influences the impact of smart lighting systems as higher energy reductions are found for the semi-detached building than for the apartment. Furthermore, the orientation also affects the performances: it is concluded that automated control systems have the most beneficial impact as the daylight availability in the main living rooms increases. Furthermore, the occupant behaviour has a significant influence on the relative impact. With differences up to more than 50% for various presence patterns, this is the most influential parameter of those examined. Two factors that characterize the occupant behaviour are here investigated: the number of inhabitants and the occupancy rate. The automated control systems have the most considerable impact on a one-person household. Nevertheless, the performances of small families strongly differ as a correlation with the occupancy rate was detected.

The results of this study show that simplified assessment methods as the BAC factor method are insufficiently accurate as the investigated cases differ up to 49.2%. Dynamic energy performance simulations demonstrate that the occupant behaviour, namely the number of inhabitants and occupancy rate, have a significant impact on the relative energy reductions. Moreover, the control algorithm, the type of building and orientation can also affect to varying extents the performances.

Although this study has been executed for Belgium, the literature review shows that similar trends can be expected to be found for other locations as well. However, the absolute and relative impact on the lighting energy consumption will strongly differ in relation to the daylight availability and should be further investigated.

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