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# Application of users' light-switch stochastic models to dynamic energy simulation

V. Camisassi<sup>1</sup>, V. Fabi<sup>1</sup>, RK. Andersen<sup>2</sup>, SP. Corgnati<sup>1</sup>

<sup>(1)</sup>TEBE Research Group, Department of Energetics, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

<sup>(2)</sup>ICIEE, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé Building 402, 2800 Kgs. Lyngby, Denmark.

## 1. ABSTRACT

The design of an innovative building should include building overall energy flows estimation. They are principally related to main six influencing factors (IEA-ECB Annex 53): climate, building envelope and equipment, operation and maintenance, occupant behaviour and indoor environment conditions. Consequently, energy-related occupant behaviour should be taken into account by energy simulation software. Previous researches (Bourgeois et al. 2006, Buso 2012, Fabi 2012) already revealed the differences in terms of energy loads between considering occupants' behaviour as stochastic processes rather than deterministic inputs, due to the uncertain nature of human behaviour. In this paper, new stochastic models of users' interaction with artificial lighting systems are developed and implemented in the energy simulation software IDA ICE. They were developed from field measurements in an office building in Prague. The aim is to evaluate the impact of a user's switching action over whole building energy consumption. Indeed, it is interesting not only to see the variance related to electric energy consumption, but the overall effect on a building's energy load.

**Keywords:** Lightswitching behaviour, stochastic models, energy simulation

## 2. INTRODUCTION

To predict better building energy consumption, as well as, occupant necessity in term of comfort, human interaction with building and its systems needs further investigations. Several experts from branches of study that vary from philosophy, social studies to more technical and scientific areas, tackle the uncertainty and differences of human behaviour. Building science undertook this effort observing reality. Researchers try to reproduce, as well as, forecast behaviours developing stochastic model, through statistical and random processes, based on environmental conditions. Different models and observations were carried out on how people interact with buildings adjusting blinds, opening or closing windows, changing temperature set point, switching on and off the light (Parys, 2011). These studies were undertaken through the implementation in energy simulation software of several occupant behaviour models. Fabi (2012) implemented, on the simulation software IDA ICE, stochastic models for window controls in residential buildings. Buso (2012) considered human uncertain interaction with shading devices and window operation in office buildings. Bourgeois et al. (2006) assessed the total energy impact of occupant behaviour in relation to lighting systems using Reinhart's light-switch 2002 model (Reinhart, 2004) inside the sub-hourly occupancy control enabled on ESP-r. In fact, the most well-known and utilized stochastic model of occupant behaviour over artificial lighting system was developed by Reinhart in 2002. This study takes into account findings from different studies and it was firstly implemented in the lighting analysis software DAYSIM and online software light-switch Wizard. Here, occupants' behaviour toward manual

lighting operational system in office buildings is modelled in order to expand the knowledge on which indoor and outdoor environmental conditions influence peoples' behaviour as well as to predict their impact on electric energy usage in buildings. In fact, the development of this work is to implement part of the models built in energy simulation software in order to achieve predictions of possible energy consumptions, which take into consideration the uncertainty of user actions. The models were built over field measurements recorded from an office building in Prague.

In this paper, firstly the light-switch 2002 developed by Reinhart is displayed, since it represents the principal reference in literature, then the method of implementation is illustrated along with its differences with the previous one.

## 2.1 People actions upon artificial lighting in simulation software

Even if ESP-r includes Hunt's stochastic algorithm for manual light-switch, the most known and used algorithm for artificial lighting is the one developed by Reinhart (2004). This study was first implemented in the daylight simulation program DAYSIM and the online tool light-switch Wizard. Then, other researchers incorporated this algorithm into whole-building energy simulation programs: Bourgeois (2006) included this algorithm into his Sub-Hourly Occupancy Control (SHOCC) enabled on ESP-r; Daum and Morel (2009) used it on IDA ICE in order to assess the total energy impact of manual and optimized blind controls with different lighting schedules.

Reinhart proposed a manual stochastic lighting and deterministic blind control algorithm based on a recent review, made by himself and Voss (2003), on a section of studies made in Canada, Japan, Germany, the UK and the United States. The figure below illustrates in detail how the Lightswitch-2002 algorithm processes every 5-min: illuminance and occupancy are the input data. The occupancy is simulated with an adapted version of Newsham's stochastic model (Reinhart, 2001). At each time-step the electric lighting and blind status are set according to the outcome of the loop illustrated. The coloured parts of the graph represent the stochastic model used to infer the switching probability: the red part represents switch on at arrival and it is employed twice; the green part represents the switch on during the presence; the blue part represents switch off at departure.

In processing the model, it is possible to choose between 4 types of occupants (Fig. 2), depending on their attitude towards operating blinds and windows. Two users are distinguished for lighting in this model:

- Users who paid more attention to the indoor lighting conditions and used the artificial lighting system in relation to daylight availability on the work plan. In particular, in this case, he included the probability inferred by Hunt (1979) concerning the switch on action on arrival, and the one inferred by Pigg et al. (1996) for the switch off, and, eventually, his own study for the intermediate switch on probability.
- Users who do not care about daylight and continually use artificial lighting.

The stochastic models for the first user type ran through random processes while the latter is represented as deterministic factor.

For the blinds instead, he inserted one automated and two manual blind control strategies. An automated blind control if blinds are completely lowered when incoming direct solar irradiance reaches more than  $50\text{W/m}^2$  over the work plan while the blinds are fully opened otherwise. A dynamic manual blind control if blinds are completely lowered when incoming direct solar irradiance above  $50\text{W/m}^2$  superscripts the work plan and fully re-opened just once a day in the

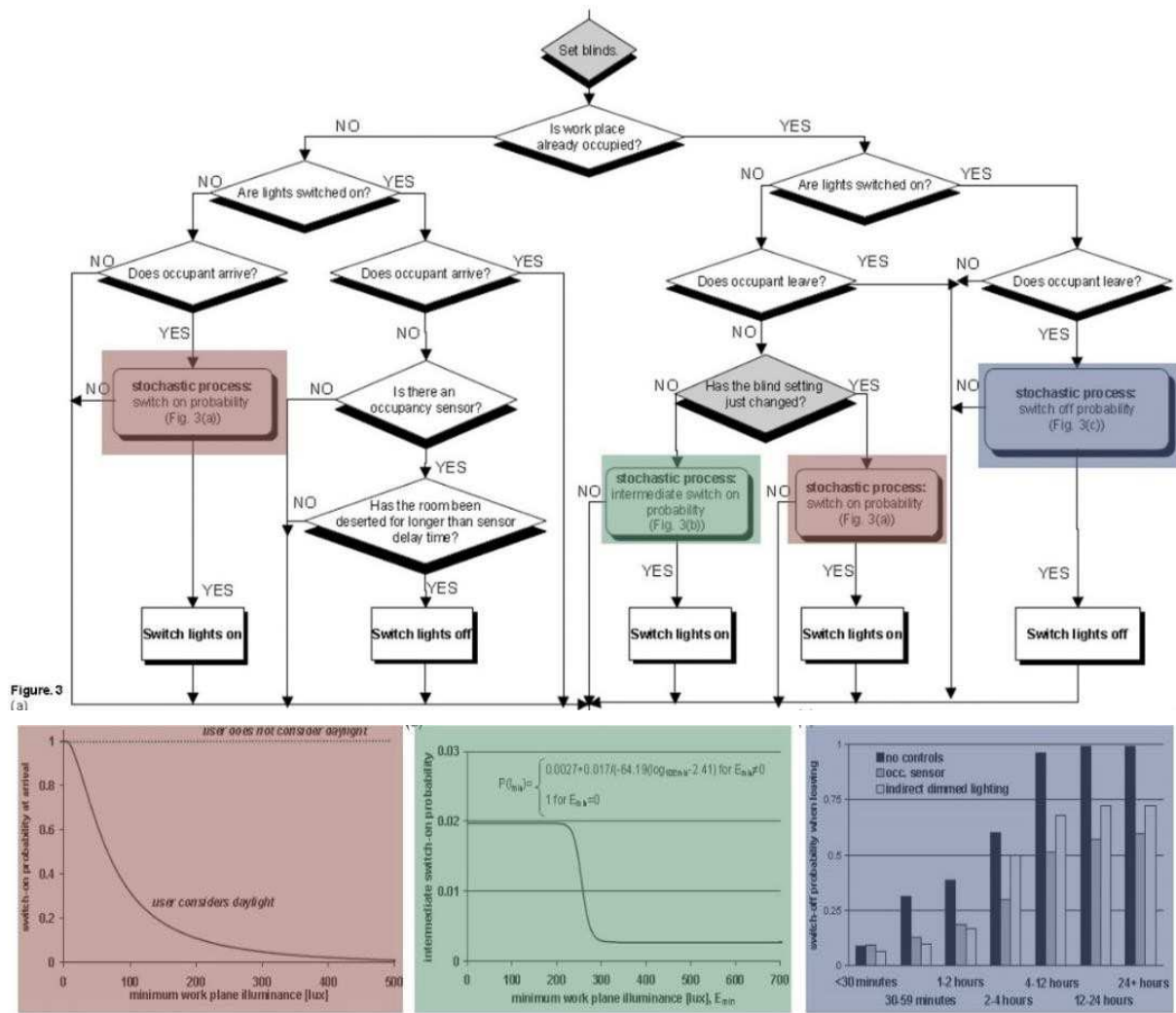


Figure 1: Light-switch 2002 algorithm

morning upon arrival. Moreover a static manual blind control is taken into account if blinds are always entirely lowered.

As we can see from the algorithm represented in Fig.1, the lighting system is directly interrelated with the blinds' setting. However, the blinds' position is deterministically treated, even if it is based on assumptions made after a review of field observations.

user $DdBd^*$	The user controls the lighting system with sensitivity to ambient daylight conditions and uses the blinds on a daily basis
user $DiBd$	The user controls the lighting system independent of ambient daylight conditions and uses the blinds on a daily basis
user $DdBs$	The user controls the lighting system with sensitivity to ambient daylight conditions and keeps the blinds permanently lowered with a slat angle of $75^\circ$ .
user $DiBs$	The user controls the lighting system independent of ambient daylight conditions and keeps the blinds permanently lowered with a slat angle of $75^\circ$ .

\* $Dd$ : Daylight dependant lighting use;  $Di$ : Daylight independent lighting use;  $Bs$ : Blinds static;  $Bd$ : Blinds dynamic.

Figure 2: User types described by Light-switch 2002.

### 3. CASE STUDY

Data on how people interact with artificial lighting in real life are needed in order to develop a stochastic model on how light switch's operations are carried out by occupants. In this study the data are collected within the framework of the European project "Clear-up".

Its aim is the development of new technological solutions, based on the integration of new building technologies along with control strategies, in order to optimize the energy efficiency and indoor quality of existing buildings, while also stressing the importance of their affordability and user-handiness. To achieve results, several tests on real building have been carried out. The data, used to model occupant behaviour, were measured at the Czech Technical University (CTU) Civil Engineering Faculty Building in Prague. It is a typical example of 1970's architecture, a sixteen-storey building, which has a centralized heating and ventilation system but it is characterized by poor thermal insulation and no air conditioning and no building management system (It has actually just been refurbished in July 2013.)



*Figure 3: Building's localization and views.*

The Clear-up team instrumented for measurements eight almost identical offices, located on the second floor, and provided them with an “active” management system. They are 5 m x 3 m in size with a floor to ceiling height of 3.3 m. There is just one insulated external wall, facing South-West, with two windows 1.5 m x 1.6 m, while the others walls separate each room from the others and the corridor.

The following variables were organized together with a common time step of 5 minutes. Indoor environment:

- Air temperature [ $^{\circ}\text{C}$ ]
- Relative Humidity [%]
- VOC concentration [ppm]
- Illuminance in the middle of the room(depth) [lux]
- Illuminance on the desk [lux]
- Illuminance at the window [lux]
- Illuminance ratio depth/window [-]
- Illuminance ration depth/desk [-]
- Blind position [%]
- Operating state of ceiling luminaire [0/1]
- Operating state of standing lamp [0/1]
- Door contact [0/1]
- Window contact [0/1]
- Ceiling luminaire switch [0/1]
- Standing lamp switch [0/1]
- Moment of presence [arrival/intermediate/departure]

Outdoor environment:

- Air temperature [ $^{\circ}\text{C}$ ]
- Relative Humidity [%]

- Vertical illuminance on the façade [lux]
- Horizontal illuminance [lux]
- Wind velocity [m/s]
- CO2 concentration [ppm]
- VOC concentration [ppm]
- Sun elevation [°]
- Azimut [°]
- Rain detector [0/1]

### 3.1 Models development

Multivariate logistic regression with interactions between selected variables was used to infer the probability of a light switching on and off event. The method relies on the probability function described on equation 1. The models predict the probability of an action (switching on or switching off) using equation 1, where  $p$  is the probability of switching on/off the light,  $a$  and  $b_n$  are the coefficients in the tables presented in figure 4 and  $x_n$  are the associated variables (temperature, CO2 concentration etc.). Moreover, this equation takes into account the interactions between variables by adding interaction terms to the model.

$$\log\left(\frac{p}{1-p}\right) = a + b_1 \cdot x_1 + b_2 \cdot x_2 + \dots + b_n \cdot x_n + c_{12} \cdot x_1 \cdot x_2 + c_{13} \cdot x_1 \cdot x_3 + \dots \quad (1)$$

The models are described in the following figure (Figure 4).

SWITCH ON MODEL for IDA ICE				IDA ICE SWITCH OFF MODEL			
UNITED DATABASE	Variables	Moment of presence	Estimates	ACTIVE		Estimate	
		Intercept - Active user	Arrival		4.3337	Intercept	-0.5068
			Departure		0.6414	illuminance_Depth	-0.0053
	Intermediate		2.7841	Azimut	0.0053		
	Intercept - Passive user	Arrival	1.4181	PASSIVE	Intercept (arrival)	-13.3400	
		Departure	-2.2742		Departure	0.7955	
		Intermediate	-0.1315		Intermediate	-0.9821	
	Illuminance_window [log +1]		Illuminance_window [log]		-0.3234		
	illuminance_Depth		Room temperature		0.6324		
	Room temperature		illuminance_Depth		-0.0011		
Elevation							

Figure 4: Stochastic model, based on logistic regression, to implement on IDA ICE

For example, the probability of switch on actions during occupants' periods of arrival could be inferred using the following logistic regression function:

$$\log\frac{p}{1-p} = 1.42 - 0.22 \log(E_{v,w} + 1) + 1.8 \cdot 10^{-3} E_{mr} - 0.26 T_r - 4.2 \cdot 10^{-2} Elevation \quad (2)$$

Where  $E_{v,w}$  represents the variable illuminance at the window,  $E_{mr}$  the illuminance in the middle of the room and  $T_r$  the room temperature.

It is possible to see that, in order to formulate the equation, type of user as well as the moment of the presence were specified since the intercept values depend upon these factors as figure 4 describes. It is evident that the equation does not present interactions among variables and its simplicity is useful for its final implementation in simulation software.

The switch-off models were inferred from active and passive databases. The probability of turning off the light for active users does not display the moment of presence as a factor and always results higher than the one inferred from passive occupants.

#### 4. SOFTWARE IMPLEMENTATION

The stochastic models inferred from field measurement in the office building of the Czech Technical University (CTU), Civil Engineering Faculty in Prague (paper II) were implemented in the simulation software IDA ICE.

IDA ICE is a whole-building simulation software for thermal indoor climate and energy consumption, developed by EQUA. The first version, made in 1998, was originally elaborated at the Royal Institute of Technology in Stockholm (KTH) and at the Helsinki University of Technology.

Its strength lies in the fact that it is an equation based modelling tool which uses the formal languages Modelica or Neutral Model Formal. For this reason it is user friendly and, with its expert interface (Fig. 4), allows quick expansion with the addition of new mathematical equation. Fabi (2013), D'Oca (2012) and Buso (2012) already implemented different stochastic models in IDA ICE to predict occupant actions over several building system in both residential and office buildings. In this work the expert edition of the latest version 4.5.1 was used.

It was decided to use as a reference building the construction where the measures were recorded. This choice was taken in order to not disregard the overall applicability of the illustrative model in the general context of office building, but it is necessary to assess it firstly on its original context in order to evaluate the differences between the deterministic approach and the stochastic one in building energy simulation. Specifically, an office of the Micro-environmental and Building Services Engineering Department of the CTU university in Prague was modelled on IDA ICE.

In particular the location, orientation and building envelope characteristics were set in accordance to the real construction. The office, 5 m x 3 m, is at the second floor of the sixteen-storey building, the floor to ceiling height is 3.3 m and it was provide with two south-west facing windows of 1.4m x 1.6 m.

Since it is a typical example of 1970's architecture, it could be assumed that it was predominantly made by concrete with poor insulation level and thermal bridge prevention. However, the model was implemented with the Vacuum Insulated Panel that were added to the external wall from the inside in order to carry out other experiments connected to the European Clear-up project, that aim to the development of new technological solutions in order to optimize the energy efficiency and indoor quality of existing buildings. The thermal transmittances adopted are described in the following figure (Figure 5).

Construction	U [W/m <sup>2</sup> .K]	Construction	U [W/m <sup>2</sup> .K]
Insulated perimeter wall	0.15	Interior wall	2.55
Window	4.10	Partition wall	2.00
Floor	0.85	Door	3.50
Ceiling	0.85		

Figure 5: Stochastic model, based on logistic regression, to implement on IDA ICE.

During the measurement period, the building was provided with diverse control strategies for the heating as well as for mechanical ventilation systems. In this modelling, the air change flow rate was fixed to 30 m<sup>3</sup>/h, which represents the basic operational state of the system. The thermal zone was equipped with 2 waterborne radiators with constant heating set-point of 21°C,

in accordance to the comfort category I for cellular offices described in Standard EN 15251:2006.

The office was provided with an additional standard cooling device, having set-point of 25.5°C (Standard EN 15251:2006), in order to evaluate also how cooling and heating loads varies in relation to the stochastic and deterministic approach for simulating artificial lighting use. Indeed, it was already proved how, in general, the use of artificial lighting effects not only the electrical energy consumption but also the heating and cooling demands. The boiler operational schedule was set always on while chiller's operational time was adopted almost to users' occupancy from 9.00 to 18.00 during working days. Specifically, the occupancy schedule was set from 9.00 to 12.00 in the morning and 13.00 to 18.00 in the afternoon in the attempt to better replicate the occupancy resulted from measurements. The artificial lighting system was composed by six sources with an emitted power for unit of 35 W, a luminous efficacy of 80 lm/W and it was scheduled as the occupant presence. The emitted heat for the equipment was set 15 W/m<sup>2</sup> following the setting described by TEBE research group for the office reference building (Buso, 2012). Only internal blinds were considered in the model and they were included with a deterministic control strategy based on sun and occupant's schedule. In particular blinds were disposed to be fully lowered when incoming direct solar irradiance is above 50W/m<sup>2</sup>.

## 5. RESULTS

The energy loads obtained from deterministic simulation are displayed first. In particular, two outputs characterized by different controls of lighting are stressed:

1. Lights are always set on during occupancy presence (Figure 6)
2. Ideally controlled lighting use: lights are turned on if the daylight level at the work plan is lower than 100 lux, while they are automatically switched off when it is higher than 500 lux (Figure 7)

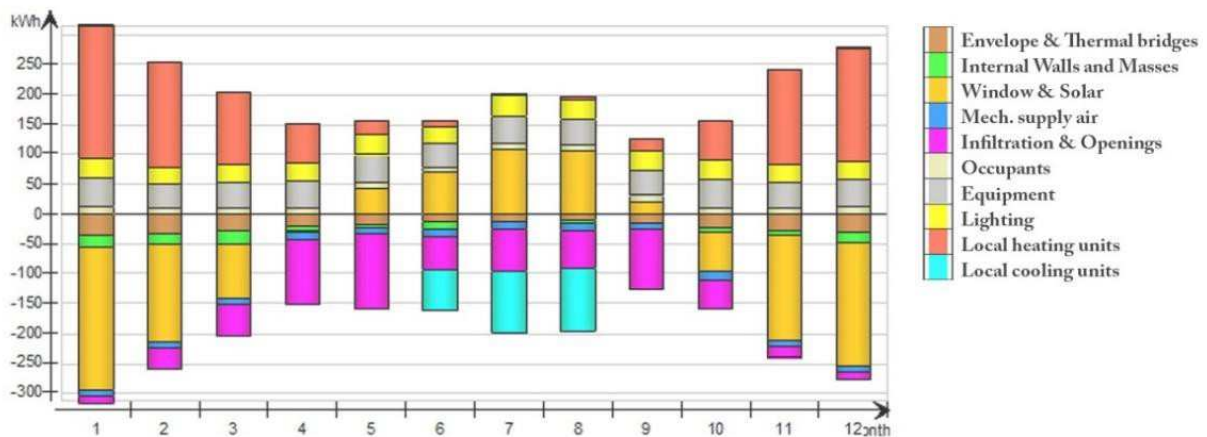


Figure 6: Output graph of IDA ICE describing energy balance on yearly base with a constant use of lighting during occupancy



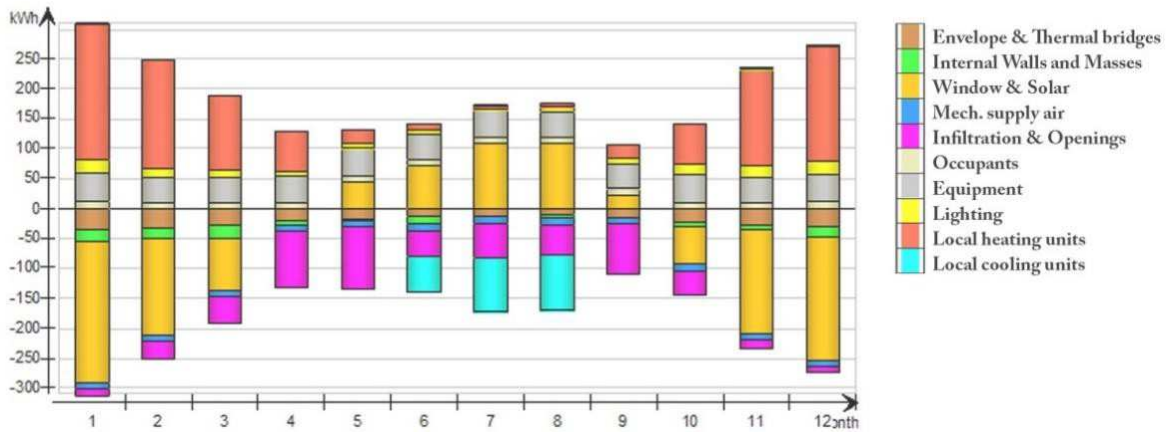


Figure 7: Output graph of IDA ICE describing energy balance on yearly base with a lighting use dependent on daylight level.

This setting, even if it considers two values highlighted by Reinhart (2001) and Hunt (1979) has turning points for people actions, still represents a deterministic input and of course it is strictly related by the blinds position. It reproduces the operation of an automatic controller. From these two settings it emerges already the range between what it is supposed to be an ideal control and a pessimistic option. However it does not depict a high difference between heating and cooling loads.

### 5.1 Stochastic algorithm implementation

The models described in the previous tables (figure 4) were implemented on IDA ICE following a similar algorithm used by Valentina Fabi (2013).

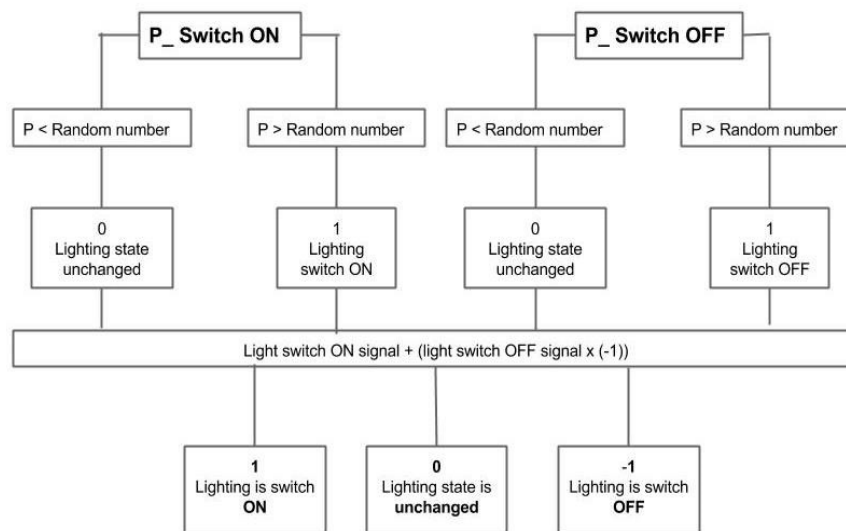


Figure 8: Algorithm for the implementation in IDA ICE

The logistic regression model for switching on and off the lights could be directly inserted in IDA ICE thanks to its equation-based modelling system. All the variables needed were connected to those corresponding in the simulation program, for example the room temperature was directly inserted as a continuous input for the logistic function. In order to distinguish among arrival, intermediate and departure period a schedule was introduced.

Given the probability outcome, it is compared to a random number in order to get the deterministic signal, for example a P value higher than the random number will give as output 1 (switch on). Then the signals are checked through a simple equation in order to make sure that a switch-on signal is not given at the same time of a switch-off one. Finally the control is given. The algorithm loop for every time step and since there are two types of users the algorithm was applied twice.

## 6. DISCUSSION AND CONCLUSION

From the implementation carried on so far, general limitations could be outlined in order to suggest improvements in its implementation for further researches on energy consumption related to artificial lighting. Moreover, a general comparison with the light-switch 2002 model along with its results' review is undertaken in order to emphasize the importance of how a stochastic models of occupants' behaviour related to artificial lighting could affect energy consumption.

Actually, two main limitations of the implementation can be recorded. Firstly, the occupancy has been scheduled deterministically and even if the switching actions will take place randomly according to the logistic function, the fixed schedule influenced the probability since the moment of presence is introduced as drivers: in the first 15 minutes of presence there is a higher probability that the light will be turned on and in this case, the 15 minutes are fixed from 6:00 to 6:15 in the morning. Furthermore, all the variables presented in the statistical results were related to their correspondence in the simulations software, but for some of them approximations were made. The lux levels measured in the middle of the room were included as illuminance at the desk. For what concern the illuminance values recorded at the window, the software's corresponding variable took into account the blinds since the lux level is evaluated behind the shading; consequently, within this implementation, the simulation can be run only without considering blinds. Another loop in order to solve this situation should be added with the perspective to combine this model with a stochastic model for shading control.

Reinhart's model and the stochastic model presented in this paper differ even if they got the same long-term aim to develop a more reliable users' action control strategy in energy simulation.

First of all, Reinhart developed a model with a higher level of applicability. It is already implemented in several simulation software and used by designers. It is based on a review of field studies and only considered the main drivers gathered: moment of users' presence; duration of absence time; daylight illuminance at the work plan.

Its use already highlights how actual electric lighting energy demand in an office is closely associated with the occupant's user type (Reinhart, 2004): it varies between 10 and 39 kWh/m<sup>2</sup>/year depending if active or passive users is considered. Bourgeois et al. (2006) showed a similar discrepancy and furthermore, they also evaluated how much impact there is on heating and cooling energy loads.

The results support the general knowledge that reduction in lighting use will create, not with a linear proportion, a reduction in cooling loads while increase heating needs. On the other hand, they also underlined how the presence of a switch off sensor could imply a reduction in energy consumption of 20 % since the probability to turn off the lights spontaneously is very low. Nevertheless, despite its recognised relevance, in this model the majority of users' profiles are still fixed. Only one light switch profile is based on the stochastic approach and its definition is strictly related to the blinds' positions that are set deterministically. As Reinhart stressed the underlying behavioural patterns still represent a "preliminary" option.

The data collected in Prague inferred models that do not highlight interrelation between blind state and user interaction with the lighting system. Consequently, simulation does not integrate lighting and shading system patterns.

It could be assumed that the use of these models will determine even lower energy consumption than the one evaluated by light-switch 2002 since the probability of switching the light on is so infrequent. However, probably also in this case the addition of an occupancy-sensing switching OFF system could produce lower energy consumption.

Nevertheless, undoubtedly the two new models do not reflect all possible users' behaviour in relation to lighting system and its uncertainties. They are based upon the observation of only few users and, even if they have been called active and passive, in general, they could be seen as different hints of a single user type: people not so used to operate actions over the light system.

The differences between all the models highlights how interaction between users and artificial lighting is strictly related to the users themselves and probably to some circumstantial aspects that the models do not consider in their implementation for example seating orientation and controls' location. In particular, the new models' accuracy is decrease by the presence of a floor standing lamp.

For all the above-mentioned aspects, it becomes even more relevant the stochastic approach proposed by Fabi (2013) and Corgnati et al. (2006). It implies a probabilistic approach for the evaluation of both input and output parameters, due to the variability and unpredictability related to the whole building operation. The result of the design process should not be a single value, but the probability to fulfil a certain performance. Concerning human behaviour, the probabilistic output could be evaluated considering several user types, defined by different stochastic processes, for each interaction between occupants and building systems.

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