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Adding advanced behavioural models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control

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Abstract

Behavioural models derived from on-going field studies can provide the basis for predicting personal action taken to adjust lighting levels, remedy direct glare, and save energy in response to physical conditions. Enabling these behavioural models in advanced lighting simulation programs, such as DAYSIM and the Lightswitch Wizard, allows for a more realistic estimate of lighting use under dynamic conditions. The current downside of these approaches is that the whole building energy impact of manual changes in blind settings and lighting use, including its effect on heating and cooling requirements, is not considered. A sub-hourly occupancy-based control model (SHOCC), which enables advanced behavioural models within whole building energy simulation, is presented. The considered behavioural models are the Lightswitch2002 algorithms for manual and automated light and blind control, while the investigated whole building energy simulation program is ESP-r.

The enhanced functionality is demonstrated through annual energy simulations aiming at quantifying the total energy impact of manual control over lights and window blinds. Results show that building occupants that actively seek daylighting rather than systematically relying on artificial lighting can reduce overall primary energy expenditure by more than 40%, when compared to occupants who rely on constant artificial lighting. This underlines the importance of defining suitable reference cases for benchmarking the performance of automated lighting controls. Results also show that, depending on the proportion of buildings occupants that actively seek out daylighting, reduced lighting use through automated control may not always produce anticipated savings in primary energy for indoor climate control. In some cases, reduced lighting use is shown to even increase primary energy expenditure for indoor climate control, trimming down initial primary energy savings in lighting alone. This reveals the superiority of integrated design approaches over simpler daylighting guidelines or rules of thumb.

Keywords: Energy simulation; Daylighting; Lighting controls; User behavioural models

1. Introduction

Recent advances in daylighting and lighting control modelling include the development of advanced behavioural models in response to short term changes in luminous conditions in buildings. The integration of the Lightswitch2002 behavioural algorithms in the online design support tool Lightswitch Wizard [1] and the expert daylighting analysis software DAYSIM [2], allows for a more realistic estimate of lighting use under dynamic conditions [3]. The current downside of these approaches is that the whole building energy impact of manual changes in blind settings and lighting use is not considered. Enabling advanced behavioural models in whole-building energy programs would provide greater simulation accuracy in estimating heating and cooling requirements and coincident peak electricity demands, key variables in assessing the cost-effectiveness and sustainability of related strategies and technologies.

The paper first provides an overview of the Lightswitch2002 user behavioural model. Current approaches to modelling building occupants and personal control in energy simulation are reviewed as a preface to the introduction of a sub-hourly occupancy-based control model (SHOCC) which integrates advanced behavioural models in whole building energy simulation programs, such as ESP-r. The enhanced functionality is demonstrated through annual energy simulations in a private office. Results are analysed and discussed as an exercise on how to assess the overall energy impact of manual light and blind control compared to automated lighting controls.

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2. The Lightswitch2002 algorithms: an example of advanced behavioural models

Existing methods of modelling personal blind and light control are reviewed by Reinhart [3]. The findings point out that blind control models are often based on invariable thresholds, such as static visual glare or overheating criteria, while lighting systems in reference cases are commonly assumed to be switched on during occupied hours. In 1979, Hunt [4] introduced one of the first field-based stochastic models to calculate the likelihood of switching on lights upon arrival. In 1995, Newsham et al. [5] put forth Lightswitch, a field-based stochastic model to predict arrival, departure and temporary absenteeism of individuals in office environments. The model was later used to estimate savings in lighting use from occupancy-sensors. Based strictly on field evidence, either from previously published surveys or from original investigations, as well as Newsham et al.'s original Lightswitch model, Reinhart derived the stochastic Lightswitch2002 algorithms to predict dynamic personal response and control of lights and blinds [3]. Occupant responses are adapted to various lighting control options, from manual ON/OFF switching to various combinations of dimming and occupancy-sensing technology.

One key concept of the Lightswitch2002 algorithms is the categorization of building occupants as either *active* or *passive* daylighting users. Reinhart defines an *active* user as someone who *actively* seeks daylighting rather than systematically relying on artificial lighting as would a *passive* user. Similarly, an *active* window blind user is someone who rearranges blind settings on a daily basis to maximize daylight availability – although visual glare will trigger blind occlusion – while a *passive* blind user permanently arranges blind settings to exclude daylight. It is generally hypothesized that a *passive* blind user is also a *passive* light user, as continuous blind occlusion implies a greater reliance on artificial lighting to provide adequate desk level illuminance. Yet there is no field evidence to support the hypothesis that an *active* blind user is necessarily an *active* light user, i.e. it is quite possible that occupants may arrange blind settings to provide access to outside views, all the while relying on continuous artificial lighting. The increased likelihood of visual glare – as occurring in south-facing rather than in north-facing rooms – is often cited in the literature as a determinant in the proportion of *active* versus *passive* users, yet it remains unclear why these *active*/*passive* distributions are observed to be skewed to one side or the other, i.e. some studies report a high proportion of *passive* users in a given building, while others report a high proportion of *active* users.

By enabling the Lightswitch2002 algorithms within DAYSIM, a Radiance-based [2] daylighting simulation method, Reinhart demonstrated the impact of manual control on predicted electric lighting energy requirements. Reinhart concluded that users seeking daylighting by *actively* controlling both blinds and lights provide the greatest savings in artificial lighting use, while lighting consumption associated to *passive* users is more closely associated to that of continuous artificial lighting use. Given the limited knowledge of the distribution of *active* versus *passive* users in buildings, the energy impact of manual control in lighting may be best represented as a range of possibilities between two extremes: reduced lighting use from *active* manual control on one hand, and continuous lighting use on the other. The current shortcoming of DAYSIM and the Lightswitch Wizard is that the whole building energy impact of manual lighting control, e.g. on heating and cooling requirements, is not considered. While it is obvious that reduced lighting use through personal control will lower cooling loads in office environments, just how much remains difficult to estimate without proper assessment methods. Enabling advanced behavioural models in whole building energy simulation becomes the desired next step.

3. Current approaches in modelling occupancy in energy simulation

A complete review of existing approaches in energy simulation to modelling occupants, their mobility and the influence they exert on energy use is beyond the scope of this paper. Nonetheless, a few widespread approaches are presented, followed by an overview of behavioural modelling techniques available within the ESP-r system [6].

3.1. Diversity profiles

A widely used technique in energy simulation is to model the influence of occupants through diversity factors, a solution passed down from the previous generation of hourly simulation programs. Diversity factors are numbers between zero and one, and are used as multipliers of some user-defined maximum load, e.g. occupants, lighting, and equipment. Load variability, due to absenteeism or power management features of IT equipment, is ordinarily defined by associating different sets of 24-h diversity factors, or diversity profiles, for weekdays, weekends, holidays, etc. Many energy standards and codes either provide, or refer to, typical diversity profiles for performance-based compliance demonstrations [7,8]. Abushakra et al. [9] provide an overview of existing methods for deriving diversity profiles.

Recent developments in this area include findings from the ASHRAE Research Project 1093 [10]. The goal of this project was to compile a library of schedules and diversity factors based on measured electricity use data for energy simulations and peak cooling load calculations in office buildings. This research project derived multiple sets of diversity factors from measured lighting and receptacle loads in 32 office buildings [11]. Occupancy was not monitored under RP-1093, yet another study from Claridge and Abushakra [12] established a strong correlation between observed occupancy levels and lighting loads, suggesting that valid occupancy diversity profiles may be derived from lighting diversity profiles using linear regression.

Diversity profiles are often adequate as average input data models for large, core zones containing multiple spaces. If lighting and office equipment use in a given building is considered predictable for a given set of day-types, e.g. if their use is independent of weather patterns, then the technique is often quite valid. One significant shortcoming of the RP-1093 diversity profiles, or any other similarly derived data for that matter, is that they are derived independently of meteorological data. This may be a valid assumption when considering core zones, but hardly so for perimeter spaces: for a given occupancy pattern and daylight illuminances, two differently oriented perimeter zones will clearly possess very distinct lighting loads if manual and/or automated control are available. Correlating occupancy from these lighting profiles would lead to obvious errors.

Yet as many North American buildings have very low envelope-to-floor area ratios, these errors are considered by some to be minor and applying diversity profiles, including those for occupancy, derived from monitored core zone lighting use may be considered acceptable. In cases where greater envelope-to-floor area ratios are found, or even in some cases where there are no core zones at all, the use of generic diversity profiles becomes difficult to justify. This would certainly be the case for building designs aiming at high daylight autonomy levels and/or offering outside views to most occupants, such as prescribed by certain daylighting design guides, required by related standards [13,14], or recommended by green building rating systems such as LEED [15].

Other studies have shown that the use of hourly diversity profiles can lead to considerable errors when applying control strategies that are sensitive to short-term variations in occupancy. This consideration fuelled the original Lightswitch model, whose outputs were adapted diversity profiles for DOE-2.1_E [16]. Degelman [17] also suggested that fixed lighting profiles generate misleading information when occupancy-sensing lighting controls are used, and put forth a Monte Carlo approach to space occupancy prediction based on survey statistics. Keith [18] demonstrated how average profiles lead to overestimations of electrical energy savings and demand reduction through occupancy-sensing controls, which in turn lead to underestimations of heating loads for various U.S. locations. Keith proposed an on-line, field-based tool modifying standard DOE-2.1_E weekly profiles by introducing *peak-days*, thereby enhancing monthly peak demand estimations without increasing simulated energy use.

The aforementioned studies focus on improving occupancy prediction to better assess the energy savings from occupancy sensors, but fail to address the lingering misconception in energy simulation that occupants are, in Newsham's words, "fixed metabolic heat generators passively experiencing the indoor environment" [19]. Occupants instead respond to various, often sudden environmental stimuli, triggering abrupt manual changes in window blind settings and artificial light use, in turn affecting electrical energy use and demand. This restates the necessity of introducing valid behavioural models to predict occupant perception and response to environmental stimuli.

3.2. Behavioural modelling in ESP-r

Within ESP-r [6], a building comprises a collection of interacting technical domains, each solved by exploiting the specific nature of the underlying physical and mathematical theories [20]. A few notable, typically coupled, domains include natural illuminance prediction, building thermal processes, intra-room airflow, and electrical demand and embedded power systems. Clarke [21] describes the approaches taken to solve the governing equations, while preserving domain interaction.

Occupant effects in ESP-r are often simply modelled as casual gains, defined within ESP-r as 24-h load profiles expressed in W or W/m^2; a variant of the diversity profile approach presented earlier. Within each technical domain, a number of controls can be enabled to dynamically adjust certain component definitions during simulation. These controls are often used to emulate personal control. Examples include mimicking blind/shutter control by dynamically substituting transparent surface optical properties, or reproducing operable window closure by adjusting the area of a crack component within an airflow network. Certain component changes will affect the system more globally than others. For example, blind/shutter control enabled during the solar calculations will influence the sensed illuminance in the daylighting calculations, which can in turn affect the lighting load on the electrical network and how power is used from embedded renewable components, if such systems are defined.

Almost all control laws in ESP-r use static thresholds as triggering mechanisms, a significant limitation in behavioural modelling as suggested by Reinhart [3]. As an exception to this rule, ESP-r includes the original Hunt stochastic algorithm for manually switching on lights [4]. However, unlike the Lightswitch2002 algorithms, ESP-r's Hunt algorithm may not be combined with other control laws, such as dimming or occupancy-sensing control.

Bookkeeping arises as a major challenge in regards to occupancy-related input and control in ESP-r, or in any other advanced simulation package for that matter. In ESP-r, each control law provides its own definitions for describing occupancy, whether by specifying arrival and departure times in Hunt's algorithm or by setting a temporal window when control is enabled, e.g. 08:00–17:00 h. Considerable effort can be required to harmonize casual gain definitions and control law definitions to ensure, for instance, that metabolic heat from occupants is indeed injected simultaneously when personal computers are operated, when lights are turned on, when windows are opened, etc. The potential for incorrect data specification increases with the number of zones, occupants, nested domains and enabled control laws. Clearly, a more robust solution is desired.

4. Sub-hourly occupancy-based control

SHOCC has been developed to integrate advanced, sub-hourly occupancy-based control within whole building energy simulation programs. Its design rejects the traditional concept of merely modelling the state of clustered objects rather than the individual objects themselves. For instance, rather than tracking lumped heat injections from a group of occupants or a set of personal computers, SHOCC instead tracks individual instances of occupants and occupant-controlled objects, the state of which depends on personal mobility and control. Most of the functionality needed for tracking occupant-controlled objects, whether through simple control laws or advanced behavioural algorithms, is common to most models. For instance, knowing the current number of individuals within a space at any given time and how long it is been since the last occupant left are both useful for any occupant-based control model, whether it is for lighting, ventilation, or IT equipment use. Individuals, lighting fixtures, or IT equipment can be grouped into clusters to facilitate data sharing and common functionality, such as scheduling and control. An example of an appropriate population clustering scheme for population would be differentiating students from teachers within classrooms. Another would be to differentiate between overhead from task lighting.

SHOCC objects populate SHOCC spaces, which together constitute building thermal zones within a SHOCC project. Rather than burdening current whole building energy simulation programs with the additional required functionality, which can spread over many technical domains, SHOCC is instead designed as a self-contained simulation module concerned with all building occupant related events in a building. As such, SHOCC can be integrated within different whole building energy simulation programs with few very changes in either application. High-level libraries constitute the basic building blocks of advanced controls in SHOCC, such as occupancy-sensing controls, advanced power management (APM) profiles [22], and even advanced behavioural models: the Lightswitch2002 algorithms, for instance, are enabled in SHOCC as one of the few self-contained control libraries.

It is a straightforward exercise in SHOCC to differentiate between user groups, as well as individuals within groups, when it comes to attributing control over specific entities. A number of automated attribution control tools are available in SHOCC to facilitate this task. For instance, in the case of a school computer laboratory, it is matter of choosing the right input keyword if overhead lighting is to be controlled by *anyone* occupying the laboratory, whether students or teachers, rather than teachers alone. Similarly, control over individual PCs in the laboratory can be automatically attributed to *every* single student arriving in the laboratory at different instances during the day, and as such plug loads in the laboratory will vary according to short term changes in occupancy.

5. Enabling sub-hourly occupancy-based control within ESP-r

At the early stages of a design, it is typical to rely on basic definitions, such as lighting diversity profiles, when running ESP-r. As the design evolves, and more information becomes available, it then becomes possible to override these definitions by enabling more complex calculation methods. For instance, ESP-r's advanced daylighting methods are designed to override lighting diversity profiles. SHOCC works much in the same way within ESP-r yet rather than being constrained to a specific domain, it operates independently to ESP-r as an external library, *handshaking* with the latter only when necessary.

At every time step (time t, time $t + \mathrm{d}t$, etc.), the ESP-r simulator sequentially updates boundary conditions for each technical domain, computes new domain solutions, and moves on to solve the next domain equations, often sending the preceding solutions as boundary conditions for the next set of domain equations to solve. This process is repeated until the end of the simulation. Pertaining to lighting control, the status of each transparent surface, i.e. open/drawn blinds, is determined during the solar calculations; which becomes input for natural illuminance calculations, required to set lighting output during casual gain computations. Data are passed from one domain to another by directly accessing global data structures.

Once enabled, SHOCC updates specific boundary conditions within ESP-r targeted technical domains when requested. First, ESP-r calls SHOCC directly to update the status of its own internal representations of occupants, such as daily arrivals and departures and short-term mobility at every time step. Then SHOCC is called to update and retrieve only specific bits of information useful to a given technical domain. For instance, SHOCC is called during the casual gain calculations a first time to update the status of its own internal representations of IT equipment and lighting systems, and then called a second time to return the summed heat injections and/or electrical loads of these systems for ESP-r's own computations. Data exchange between ESP-r technical domains – at least data associated to occupants – is no longer done directly, but rather via SHOCC. The advantage of the latter approach is that data pertaining to occupants (e.g. mobility, behavioural control) are no longer spread throughout ESP-r's technical domains but concentrated within SHOCC, minimizing the aforementioned risk of incorrect data specification. As SHOCC is fully expandable, this approach offers a high degree of resolution for populating a building model without this becoming cumbersome for energy simulation programs. Only a dozen essential function calls to SHOCC are embedded within ESP-r's simulator and targeted technical domains. The past and current status of SHOCC entities are kept in memory at all times, so for instance if a SHOCC lighting fixture is left on during a weekend, then ESP-r will continually retrieve the nominal output of that fixture as a casual gain, at least until a SHOCC occupant finally switches it off. A more detailed description of SHOCC is given in the principal author's doctoral thesis [23].

6. The total energy impact of introducing advanced behavioural modelling

6.1. Scope of the investigation

The impact of introducing manual light switching, dimming and occupancy-sensing control in whole building energy simulation is demonstrated through a series of ESP-r/SHOCC/Lightswitch2002 simulations. The chosen test case is a single occupancy perimeter office. Three control options are investigated:

- *Constant*: Continuous overhead lighting use during occupied hours; no blind control.
- *Manual*: *Active* manual ON/OFF light switching; *active* manual blind control.
- *Automated*: *Active* manual ON/OFF light switching with ideal photocell-based dimming and occupancy-sensing OFF switching; *active* manual blind control.

The first option, considered to be the most energy intensive lighting approach, is a common assumption made in energy simulation practice. As discussed previously, this hypothesis may be adequate for core zones but its use for perimeter zones tends to yield unrealistic results if daylighting control is considered, e.g. manual and/or automated. This first option also assumes that shading devices are not available—or rather that the impact of drawn interior blinds on solar gains is not so significant when they occlude high-performance windows. Indeed, within the scope of this study, preliminary simulations reveal that the selected interior shading device, once drawn over the selected high-performance window, has little impact on absorbed solar gains within the occupied space. The secondary solar heat rejection capability of the same interior shades would likely be more important when drawn over a more conventional window, but this goes beyond the intended scope of this paper.

The second option relies on the Lightswitch2002 behavioural models for manual light switching and blind control, considering an *active* light and blind user. As presented previously, *active* user behaviour is considered to be the most energy efficient with regards to daylighting. The increase in artificial lighting use once shades are drawn, due to the reduced overall visual transmittance, is found to be a much more significant factor in total energy expenditure than the relatively small difference in absorbed solar gains in the office. *Manual* light and blind control are assumed to go hand in hand within the scope of this investigation, providing a more realistic assessment of occupant response to lighting conditions.

The third option is considered as the most energy efficient combination of personal and automated control [3]. *Manual* control is considered by the Illuminating Engineering Society of North America (IESNA) as ‘‘the most common practice and should function as a reference system, relative to which energy savings of automated lighting controls should be expressed’’ [24]. Depending on which reference system is chosen, *constant* or *manual*, the relative energy savings from *automated* lighting control could vary greatly. In addition to *manual* light switching and blind control, the *automated* case includes occupancy sensors to switch off artificial lighting after an absence of more than 5 min, and ideal photocell dimming control modulating artificial lighting output to match a desired 500 lx at desk level, down to 10% of lighting output. Artificial lighting is completely switched off if daylight provides at least 600 lx for more than 15 min.

6.2. Model description and simulation parameters

The office’s south facing wall is in contact with the outdoor environment, while interior partitions, ceiling and floor are considered to be in an adiabatic state with similar indoor conditions. A cross-section of the office is provided in Fig. 1.

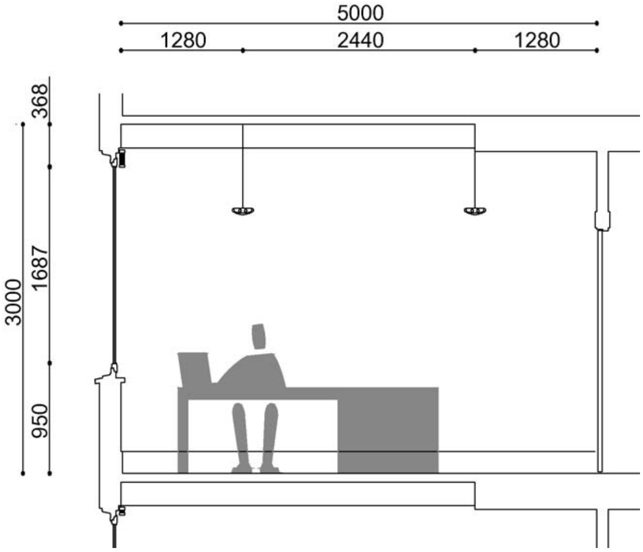

Fig. 1. Cross-section of the modelled test office.

Although access to outside views in office environments is rarely regulated, and specifically not in Canada, the south facing wall integrates a wood-framed, insulated double glazing unit (DGU), with size and placement (e.g. height from floor, width) matching the prescriptive requirements of the German standard DIN 5035 [25]. This is an attempt to fix the window’s geometry within the scope of this study, regardless of office lighting/climate-control energy use. The DGU consists of a high-performance, spectrally selective low-e coating on the interior face of the outer pane. Window occlusion is provided by means of a diffuse roller shade. The DGU’s direct normal visual transmittance (VT) is 69% when the shade is retracted, and drops to 15% when the shade is drawn. ESP-r-driven, Radiance-based daylight coefficient sets [26,27] are produced for both cases when the window shade is either retracted or drawn, using the respective visual transmittances as input to the radiance built-in *transmissivity* function. Alternate shade positions, e.g. drawn or retracted based on SHOCC output, are selected at run-time within ESP-r by choosing either optical data sets illustrated in Fig. 2a and b for thermal calculations, which are output of the WIS program [28], and by selecting the appropriate daylight coefficient set. All multilayered constructions conform to prescriptive requirements of the Model National Energy Code of Canada for Buildings [8] and the Regulation Respecting Energy Conservation in New Buildings in Quebec [29]. A more detailed description of multilayered constructions is provided in Table 1.

In all simulated cases, a SHOCC individual occupies the space on weekdays, typically arriving at 08:30 h and then leaving at 17:00 h, with lunch and morning/afternoon breaks splitting the time spent in the office cell into four equal shifts. Although this weekly schedule is applied for the whole year, stochastic variations in daily occupancy patterns add realism to the simulation, as calculated based on the Lightswitch2002 occupancy predictor. The individual’s presence produces

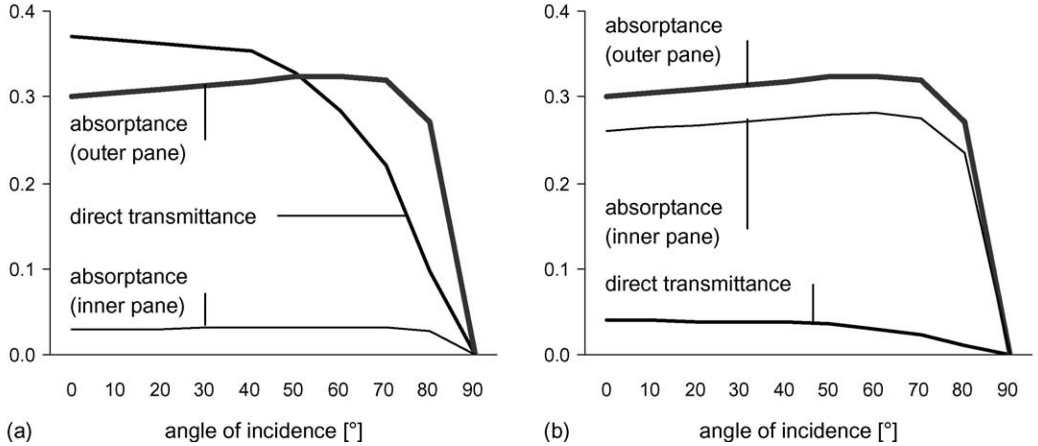

Fig. 2. (a) Direct solar transmittances and pane absorptances for the double glazing unit, when shades are retracted and (b) when shades are drawn.

metabolic heat injections in the office (29 W convective; 44 W radiative; 47 W latent), and also triggers the use of a laptop computer, which in turn injects additional convective and radiant heat in the office (30 W convective; 10 W radiative). When left unused, the laptop powers down to factory-set rates (down to 50% of nominal output after 10 min; 10% after 20 min; 0% after 30 min). As scheduling is the same in all simulated cases, annual heat injections from the individual and the laptop would remain equally constant, e.g. an average annual metabolic heat injection of 128.4 kWh in the sensible range, an average annual injection of 72.0 kWh for the laptop.

The study specifically targets loads directly influencing the luminous and thermal conditions within the office. This includes energy required for operational tasks, e.g. overhead lighting and the laptop, as well as heating and cooling requirements, with respective constant setpoints set at 21 and 24 °C. Space heating is provided locally through a hot-water baseboard system, while cooling is provided through a local AC unit. All other loads, such as the energy required for primary air conditioning, hot water heating, IT servers, elevators, etc., are not simulated and therefore are not accounted for in the results. The thermal balance of the space is nonetheless influenced by the primary air delivery, which is set at a rate of 10 L/s (weekdays, from 07:00 to 20:00 h) at a constant 21 °C, which is indicative of a dedicated outdoor air delivery approach. Background infiltration is set at a constant air change rate of 0.25 L/s/m^2 of building envelope area. Overhead lighting is provided through fluorescent fixtures, with a nominal lighting power density of 15 W/m^2.

All simulations are carried out using a 5-min time-step; a suitable frequency to capture short-term occupancy patterns and dynamic responses to luminous conditions. All three control options are investigated for two locations: Quebec City, Canada (heating dominant) and Rome, Italy (cooling dominant).

Table 1
Multilayered constructions of outside and inside walls, and floor-to-ceiling assembly

Assembly	Material description	Thickness (mm)
Outside wall	Wood siding	19
	Air	19
	Mineral fiber insulation	38
	Gypsum plasterboard	13
	Mineral fiber insulation[a]	75
	Gypsum plasterboard	13
	Air	19
	Off-white gypsum plasterboard	13
Inside walls	Off-white gypsum plasterboard	13
	Mineral fiber insulation[a]	75
	Off-white gypsum plasterboard	13
Floor-to-ceiling	Rubber tile	03
	Light mix concrete	50
	Plywood	16
	Air	19
	White gypsum plasterboard	13

[a] Insulation filling 38 × 89 @ 406 mm wood stud cavity. Thickness adjusted to account for thermal bridging.

7. Results

Annual energy loads are presented in Fig. 3 for Rome, and in Fig. 4 for Quebec.

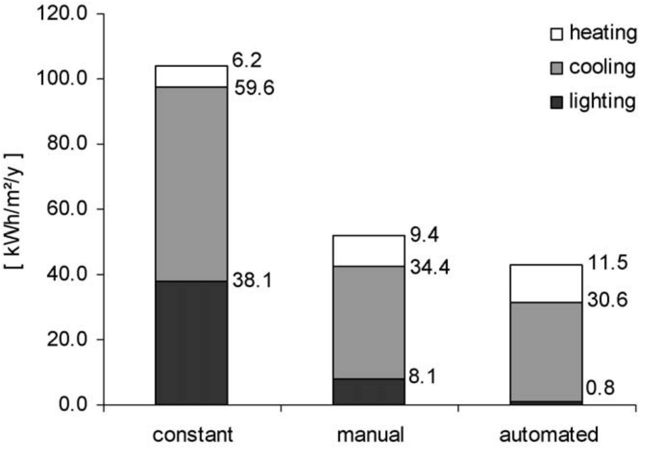

Fig. 3. Annual energy loads for lighting, cooling, and heating (kWh/m^2/year), for various lighting control options in Rome.

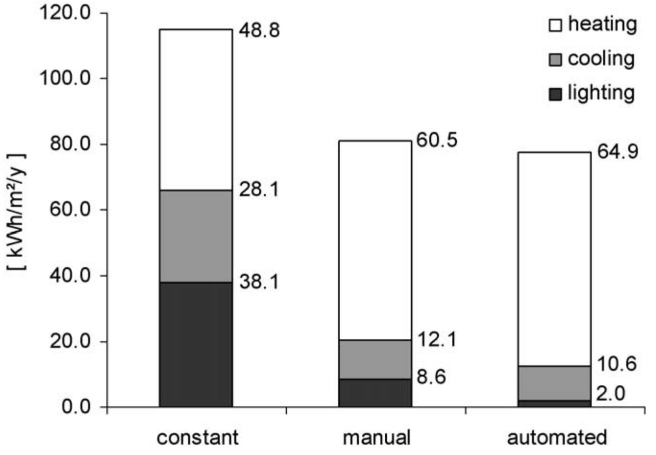

Fig. 4. Annual energy loads for lighting, cooling, and heating (kWh/m^2/year), for various lighting control options in Quebec.

7.1. Lighting

As *constant* lighting output is predefined independently of meteorological boundary conditions, e.g. natural illuminance available in the room, annual lighting loads are set equal for both climates, representing 38.1 kWh/m^2/year. *Manual* control over lights and blinds, simulated through the SHOCC-enabled Lightswitch2002 behavioural models, produce annual reductions in lighting loads of 79% in Rome and 77% in Quebec. Once *automated* lighting control is provided in addition to *manual* control, annual reductions in lighting loads reach 98% in Rome and 95% in Quebec. Under both *manual* and *automated* control options, savings are greater in Rome than in Quebec given the greater daylight availability.

If energy savings from *automated* lighting controls are to be expressed as relative to some previously-defined reference case, as suggested by IESNA guidelines, then results in both figures clearly underline just how significant the selection of the reference case may be in this instance, as both *manual* control and *constant* lighting use are often considered as valid choices in simulation. If lighting use associated to *passive* users can be considered as being similar to *constant* lighting use, then the difference between *constant* and *manual* lighting use, as shown by the results, provides an indication of the significance of the often-unknown distribution of *active* versus *passive* users in a building.

7.2. Cooling

Cooling loads, i.e. energy extracted to maintain office indoor temperatures below defined setpoints, are strongly affected by *constant* lighting use in Rome and Quebec. Once *manual* control is enabled, annual reductions in cooling loads are in the order of 42% in Rome, and 57% in Quebec. Once *automated* controls are added, annual reductions in cooling loads are further increased, just as for lighting loads, to a total of 49% in Rome and 62% in Quebec. Results support general knowledge that any reduction in lighting use will in turn reduce cooling loads; amplifying the initial savings in lighting use alone. This amplification is well supported here, independently of meteorological boundary conditions. By comparing annual reductions in lighting loads stemming from both *automated* and *manual* control, to related annual reductions in cooling loads, it is obvious that this amplification is not linear: a one watt reduction in lighting use does not produce a one watt reduction in cooling. A*utomated* control, when applied in Rome, reduces annual lighting loads by an additional 7.3 kWh/m^2, while the related additional reduction in annual cooling loads is only 3.8 kWh/m^2; approximately half. For Quebec, the effect is even smaller with an annual additional 6.6 kWh/m^2 reduction in lighting only producing an additional 1.5 kWh/m^2 reduction in cooling; less than a quarter. This illustrates the constant influence of environmental boundary conditions on indoor temperatures, e.g. excess solar gains, regardless of any changes in internal loads.

7.3. Heating

A portion of the estimated reduction in annual lighting use effectively reduces cooling loads, as discussed in the preceding section. The remaining portion is either influencing the extent of the free-running period for the investigated office, i.e. when neither cooling nor heating are required to maintain indoor temperatures within defined setpoints, or otherwise producing an increase in annual heating loads. The latter is observed for both locations. This reiterates the general understanding that internal loads are sometimes, in a way, *useful* in compensating heat loss through the building envelope.

Just as with cooling, the influence of reduced lighting use on heating loads is not linear. Applying *automated* lighting control in Quebec produces an additional 6.6 kWh/m^2 reduction in annual lighting use when compared to *manual* control alone, while the related additional increase in annual heating loads is only 4.4 kWh/m^2. A similar observation is made for Rome. This equally constitutes a reminder of the constant influence of environmental boundary conditions on heating loads, notably during times when internal loads are negligible, e.g. on cold nights.

7.4. Primary energy

The preceding analysis confirms that the overall benefits of reduced lighting use can hardly be assessed on lighting reductions alone. Although reduced lighting use systematically lowers cooling loads, heating loads increase by the same token. In addition, the impact of reduced lighting use on required energy for indoor climate control is not linear. Total primary energy requirements, defined as the sum of primary energy requirements for lighting, cooling, and heating, are estimated for each simulated case, providing a single metric to compare the performance of different lighting control for different locations. Within the context of this study, a three-to-one primary-to-secondary electricity conversion factor from fossil fuels is assumed, while a global transportation and distribution loss of 90% is assumed for fossil fuel for heating. At the building level, mechanical cooling is provided with a

Table 2
Annual secondary and primary energy requirements for Rome

	Lighting control options		
	Constant	Manual	Automated
Energy loads (kWh/m^2/year)[a]			
Lighting	38.1	8.1	0.8
Cooling	59.6	34.4	30.6
Heating	6.2	9.4	11.5
Energy requirements (kWh/m^2/year)[b]			
Lighting (efficiency of 100%)	38.1	8.1	0.8
Cooling (CoP of 3)	19.9	11.5	10.2
Heating (efficiency of 85%)	7.3	11.1	13.5
Primary energy requirements (kWh/m^2/year)[c]			
Lighting (conversion efficiency of 33%)	114.3	24.3	2.4
Cooling (conversion efficiency of 33%)	59.6	34.4	30.6
Heating (total losses of 10%)	8.1	12.3	15.0

[a] Energy needed to perform each task, e.g. energy needed to extract excess heat from the occupied zone to maintain indoor temperature below a defined setpoint.

[b] Required energy to operate each system, e.g. required electricity to operate air conditioning units.

[c] Required primary energy for production, transportation and distribution of secondary energy for each system, e.g. required primary energy to deliver the required electricity to operate air conditioning units.

Table 3
Annual secondary and primary energy requirements for Quebec

	Lighting control options		
	Constant	Manual	Automated
Energy loads (kWh/m^2/year)[a]			
Lighting	38.1	8.6	2.0
Cooling	28.1	12.1	10.6
Heating	48.8	60.5	64.9
Energy requirements (kWh/m^2/year)[b]			
Lighting (efficiency of 100%)	38.1	8.6	2.0
Cooling (CoP of 3)	9.4	4.0	3.5
Heating (efficiency of 85%)	57.4	71.2	76.4
Primary energy requirements (kWh/m^2/year)[c]			
Lighting (conversion efficiency of 33%)	114.3	25.8	6.0
Cooling (conversion efficiency of 33%)	28.1	12.1	10.6
Heating (total losses of 10%)	63.8	79.1	84.8

[a] Energy needed to perform each task, e.g. energy needed to extract excess heat from the occupied zone to maintain indoor temperature below a defined setpoint.

[b] Required energy to operate each system, e.g. required electricity to operate air conditioning units.

[c] Required primary energy for production, transportation and distribution of secondary energy for each system, e.g. required primary energy to deliver the required electricity to operate air conditioning units.

coefficient of performance (CoP) of 3, heating is provided with an efficiency of 85%, and lighting efficiency is assumed to be 100%. This conversion of lighting, cooling, and heating loads to primary energy requirements is detailed in Tables 2 and 3. Figs. 5 and 6 show the resulting annual primary energy requirements for all three control options, when applied in Rome and Quebec, respectively.

Under *constant* use, lighting energy overwhelms total primary energy requirements, comprising more than 60% of total requirements for both locations. Once *manual* lighting and blind control is enabled, total annual primary energy requirements are reduced by 60% for Rome, and 43% for Quebec. The differences in total primary energy expenditure between *constant* and *manual* control reiterate the significance of selecting suitable reference cases against which should be compared the relative performance of *automated* lighting control, and underline the significance of the *active*/*passive* user distribution in building populations.

When *automated* control is applied in Rome in addition to *manual* control alone, total primary energy savings in lighting are estimated at 21.9 kWh/m^2/year. This constitutes a reduction in cooling primary energy requirements of 3.8 kWh/m^2/year, while primary energy for heating increases by 2.7 kWh/m^2; a net reduction of 1.1 kWh/m^2/year. In other words, the initial estimated reduction in annual primary energy requirements for lighting, resulting from the introduction of *automated* lighting control, is amplified by approximately 5%, due to an overall reduction in primary energy requirements for indoor climate control.

When the same strategy is applied in Quebec, the additional annual primary energy reduction in lighting is estimated at 19.8 kWh/m^2. Similarly, primary energy for cooling incrementally drops by 1.5 kWh/m^2, while primary energy for heating increases by 5.7 kWh/m^2; a net increase of 4.2 kWh/m^2/year. In this instance, the initial estimated reduction in annual primary energy requirements for lighting, resulting from the introduction of *automated* lighting control, are no longer amplified but trimmed down by approximately 20%, due to the overall

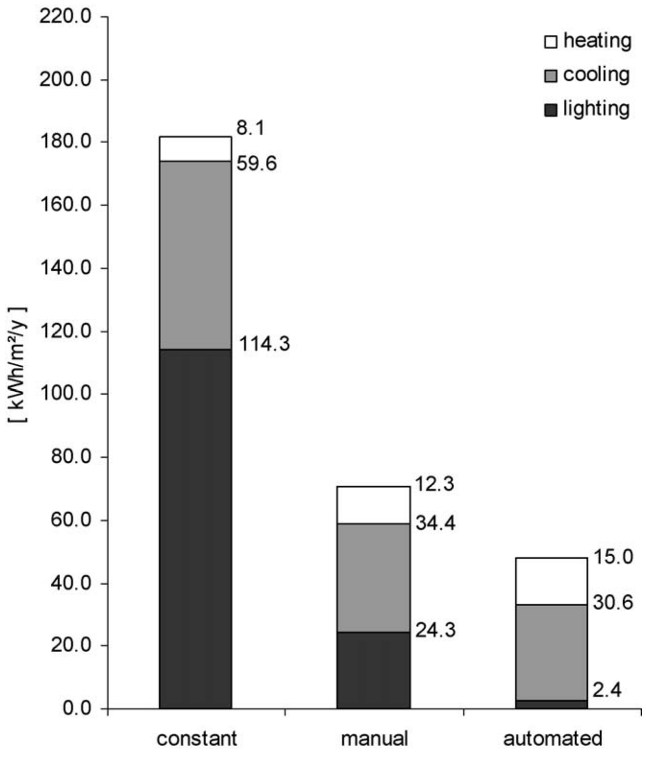

Fig. 5. Annual primary energy requirements for lighting, cooling, and heating (kWh/m^2/year), for various lighting control options in Rome.

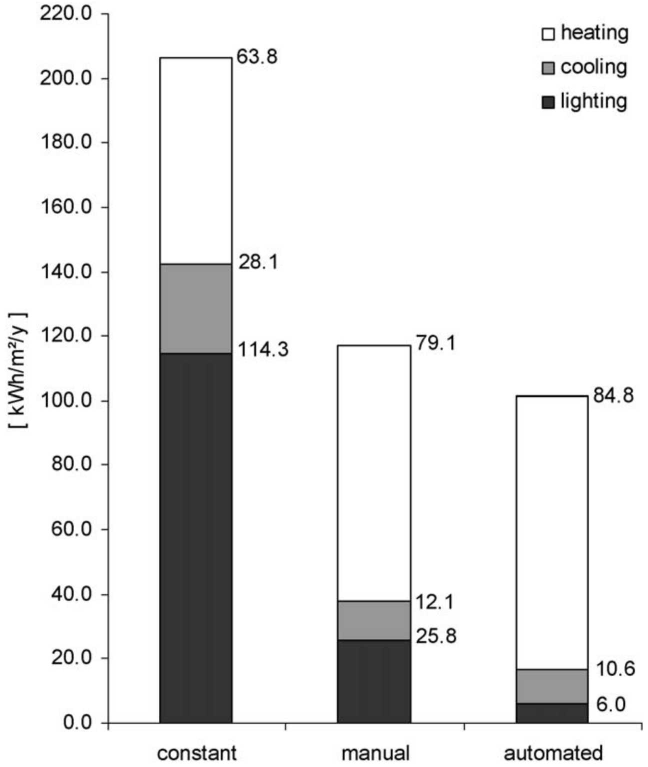

Fig. 6. Annual primary energy requirements for lighting, cooling, and heating (kWh/m^2/year), for various lighting control options in Quebec.

increase in primary energy requirements for indoor climate control.

The preceding results certainly highly depend on a location's primary energy mix and building system efficiencies. For instance in Quebec, most of the electricity used in buildings is generated through hydroelectricity, with different conversion factors than with fossil fuel power generation [30]. In addition, electric-resistance heating is widely used in buildings in Quebec for HVAC reheat applications (heating coils) and zone requirements (baseboards heaters), which imply different system efficiencies that would significantly affect the resulting total primary energy savings linked to lighting technology. This would also be the case if heating loads were to be met by local, ground-coupled heat exchangers on a water loop. The argument to be made is that primary energy savings stemming from advanced lighting technology can hardly be estimated in isolation of indoor climate control strategies and system efficiencies, as well as a location's primary energy mix, supporting the need for integrated simulation.

8. Summary

The paper introduces SHOCC, a sub-hourly occupancy-based control model which renders advanced behavioural models, such as the Lightswitch2002 algorithms, operational within whole building energy simulation programs such as ESP-r. The enhanced functionality is demonstrated through annual energy simulations aiming at quantifying the total energy impact of manual control over lights and window blinds. Results show that building occupants that actively seek daylighting rather than systematically relying on artificial lighting can reduce overall primary energy expenditure in the perimeter zone by more than 40%, when compared to constant artificial lighting use. This underlines the importance of defining suitable reference cases for benchmarking the performance of automated lighting controls. Results also show that, depending on the proportion of buildings occupants that actively seek out daylighting, reduced lighting use through automated control may not always produce anticipated savings in primary energy for indoor climate control. In some cases, reduced lighting use is shown to even increase primary energy expenditure for indoor climate control, trimming down initial primary energy savings in lighting alone. This finding reveals the superiority of fully integrated simulation approaches over qualitative guidelines for advanced lighting design solutions.

9. Outlook

Advanced behavioural models have been demonstrated to be quite accurate, certainly under previously investigated conditions. Yet their widespread use in simulation is somewhat thwarted by the strong dependency on detailed population data, such as past and current room occupancies and vacancies, as well as behaviour. The only current method of providing this information in SHOCC is through the Lightswitch2002 population predictor, which requires detailed input of mean arrival and departure times, average time taken for meals, etc. While the technique is quite suitable for routine occupancy patterns, i.e. a single occupancy office or a classroom, it may be unsuitable to tackle the increasingly complex occupancy patterns found in many environments. For instance, white collar workers increasingly tend to stray away from the traditional 9-to-5/5-day work week. In addition, there is limited knowledge on how people perceive and control their environment in space types other than single offices. This is certainly the case for open plan office environments where perception of personal control and social interactions are much more complex. More field studies are required for such contexts.

The current ESP-r/SHOCC/Lightswitch2002 integration will be matured and expanded within the coming years. Remaining key tasks are to better predict occupant mobility, generalize existing user behaviour models for building types other than single offices and to apply the methodology to advanced solar shading devices such as external venetian blinds, split blinds, etc. The approach will be further implemented into the online Lightswitch Wizard interface to make fully integrated lighting simulations accessible to the design community at large. All of these simulation improvements and technology transfer activities will have the common goal of promoting an occupancy-centred approach to building design.

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