Daylight harvesting: a multivariate regression linear model for predicting the impact on lighting, cooling and heating

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Abstract

On a worldwide scale lighting accounts for 20% to 50% of buildings' energy use [1] and 19% of the global electricity consumption [2], and therefore represents a key opportunity for energy efficiency efforts in different countries due to its relevant impact and often short payback periods of investments. Among the various strategies developed to foster efficient lighting, daylight harvesting (i.e. the deployment of controls to reduce electric lighting based on available daylight in interior spaces) in combination with dynamic daylighting devices (i.e. windows and skylights able to modify their Visible Light Transmittance and Solar Heat Gain Coefficient) has shown dramatic potential for energy savings, peak electricity demand reduction and occupant visual comfort improvement.

This paper is focused on daylight harvesting implementations utilizing fenestration systems that incorporate dynamic components, such as electrochromic glazing and operable louvers, assessing their impact on building energy performance and occupant visual comfort through advanced modeling techniques based on the EnergyPlus simulation engine. EnergyPlus is used in combination with the Building Controls Virtual Test Bed (BCVTB), which supports simulation of multiple fenestration and electric lighting control strategies, based on occupancy/vacancy and daylight availability. Results show dramatic savings potential on electric lighting (35-41%) and cooling (16-29%) loads, but also potential for significant increase in heating loads, especially in heating-dominated climates.

Since case-by-case simulation is often not affordable for real buildings, parametric simulations are performed varying the values of key design and context parameters in JEPlus and the results are used to develop a linear multivariate regression model for predicting the impact of daylight harvesting strategies on electric lighting, cooling and heating loads as functions of a limited set of input parameters. This approach proves to be very useful for order-of-magnitude estimation of building energy requirements during the early, schematic phases of building design, as well as high-level analyses for investment and policy making goals. The approach is very suitable for the development of a quick and easy-to-use tool for such purposes.

1. Introduction

1.1 Literature review

Daylight harvesting and electrochromic technologies have been widely studied by the "Windows and Daylighting" group at Lawrence Berkeley National Laboratory since their first appearance in the 1980s. In an extensive simulation work published in 2004, DOE-2.1E [3] is used to simulate the effect of lighting and fenestration controls on the annual energy balance of a three-story commercial building in five different US climates [4]: results show 10-24% savings in all climates compared to a baseline case with ASHRAE 90.1-1999 compliant windows with no daylighting controls and 0.30 WWR (Window-to-Wall Ratio). Electrochromic glazing generate 5-9% additional savings in South perimeter zones over lighting controls compared to low-E spectrally selective glazing, and 5% in the other zones in most climates.

The Pacific Northwest National Laboratory performed a similar study using EnergyPlus v3.0, evaluating the addition of electric lighting controls and electrochromic glazing to an ASHRAE 90.1 baseline case for small and medium office buildings [5]. Results, averaged for Northern and Southern climates, show total savings of 3-6% for the small office case, and 4-5% for the medium office case.

1.2 Motivation and method

The aim of the present study is to assess the potential impact of electric lighting and fenestration controls on commercial buildings energy consumption (lighting, cooling and heating) and to develop a linear regression model able to predict this impact quickly and easily through a limited set of input values for key design and context parameters, thus avoiding the need for time-consuming case-by-case detailed simulations that are not attractive during initial, schematic design decisions on fenestration and electric lighting.

The first part of the paper is focused on simulations performed with EnergyPlus at different levels of complexity to assess the impact of daylight harvesting strategies in different climates. Initial simulations are focused on a very small space with a single skylight, aiming at exploring the complexity and effectiveness of the simulation approach. After successfully configuring the approach itself, further simulations are performed using US Department of Energy (DOE) validated building models and realistic control algorithms implemented in the Building Controls Virtual Test Bed (BCVTB).

The second part of the paper is focused on the development of a multivariate linear regression model based on multiple JEPlus parametric simulations for key design (fenestration and lighting controls) and context (US locations) variables to characterize the model at its partial derivatives, i.e. to understand how each variable defining initial building conditions influences the impact of energy efficiency strategies on annual building energy performance.

1.3 Simulation toolkit

Annual energy simulations of the dynamic fenestration and electric lighting systems are performed using the EnergyPlus v7.1 software environment [6].

Custom control algorithms for electrochromic glazing management are implemented using the EnergyPlus external interface and the Building Controls Virtual Test Bed v1.1 software [7].

Parametric simulations in EnergyPlus are automated using the JAVA shell JEPlus v1.3 [8].

This state-of-the-art toolkit allows a more innovative and reliable simulating approach in comparison to what can be found in the literature studies dealing with the topic.

2. Simulation

2.1 Simple office space with skylight

The first goal of this effort is to assess the complexity and effectiveness of simulating the impact of dynamic glazing and electric lighting controls on building energy consumption in different climates, considering a simple 25 m^2 small office space with a single skylight (Skylight-to-Roof Ratio = 0.04), and the following features (Fig. 4):

- ASHRAE 90.1-2004 construction and skylight for three US climates: Phoenix, AZ (US climate zone 2), Baltimore, MD (US climate zone 4) and Minneapolis, MN (US climate zone 6).
- Fluorescent lighting at 10.8 W/m^2, dimmable in power from 20% to 100%.
- Two illuminance control points at the centre of space: one at 0.8 m from floor and one right under the skylight.
- Ideal loads simplification for HVAC system: a COP of 4 is used to translate cooling into electricity load.
- Skylight simulated as a double-glazing window, with very thin translucent internal layer to diffuse the transmitted daylight.
- The electrochromic glazing effect is simulated as “switchable glazing” using the EnergyPlus “MeetDaylightIlluminanceSetPoint” function.

  When dynamic glazing is simulated, the ASHRAE compliant external layer is replaced by a theoretical glazing switching between a clear state (VLT=SHGC=1) and a fully tinted state (VLT=SHGC=0) in a continuous mode. For simplicity, it is assumed that the values of Visible Light Transmittance (VLT) and Solar Heat Gain Coefficient (SHGC) are equal for baseline glazing, based on the experimentally assessed linear relation between the two coefficients [9]. The switchable glazing state is automatically selected by the EnergyPlus function to maintain 500 lux horizontal illuminance at the reference point at 0.8 m height from the floor.

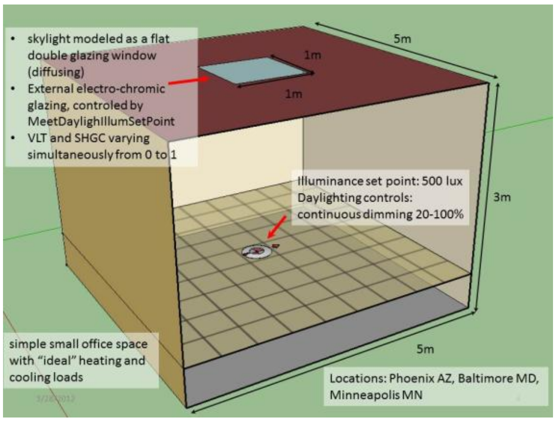

Fig. 4 – The simple office space with skylight

Five simulation runs are performed for each of the three weather files:

1) Without skylight
2) Skylight with ASHRAE 90.1 compliant properties
3) Same as #2 with addition of lighting controls
4) Same as #3 with electrochromic glazing instead of the baseline skylight
5) Same as #4 with electrochromic glazing disabled during the heating season

The results of the 15 simulations are reported in Table 3 with a breakdown of lighting and HVAC consumption. Percentage values for energy savings in cases #3, #4 and #5 are relative to case #2, because case #1 does not present any fenestration.

Due to the simplifications introduced in the modeling phase the results should be considered in relative terms, i.e. to determine how lighting and fenestration controls affect electric lighting and HVAC energy requirements in different locations relative to the ASHRAE 90.1 compliant non-dynamic case. Occupant comfort is not taken into consideration at this stage beyond maintenance of 500 lux minimum illuminance at the work plane. The most critical observations are as follows:

- **Lighting**: Lighting controls produce relative energy savings on lighting energy of 58-60%, with consequent positive effect on cooling loads and negative effect on heating loads, due to reduction of heat contribution from the electric lighting system.
- **Cooling**: Positive impact of switchable glazing on cooling consumption providing additional energy savings over those from the lighting controls. Savings are higher than values found in literature.
- **Heating**: Negative impact of switchable glazing on heating energy requirements, in addition to the negative effect of lighting controls.
- Positive overall effect of using switchable glazing only during summer, i.e. disabling them during the heating season, resulting in reduction of cooling savings but, on average, giving a larger positive contribution to heating loads.

As previously stated, comparison between absolute values and, therefore, total savings might be highly influenced by the modeling simplifications. Particular attention should be given, though, to the increased loads in heating-dominated climates, like Minneapolis, MN, where the negative effects of switchable glazing on heating loads balanced the positive effects on lighting and cooling reduction bringing the overall performance back to the baseline of the ASHRAE-compliant fenestration case.

2.2 DOE validated models with custom control algorithms using the BCVTB

After the small office space simulations, the same approach is adopted with DOE standardized building models with realistic control algorithms and taking into account occupant visual comfort, seeking validation in comparison to real buildings.

The US Department of Energy (DOE), within the framework of the so-called "Commercial Building Initiative" [10], published a set of "standard or "reference energy models for the most common commercial buildings to serve as a starting point for energy efficiency research. The models represent reasonably realistic building characteristics and construction practices" [11] and are optimized for different US climates.

From the various available standard models in EnergyPlus v5.0, a small office prototype building is chosen, with the following characteristics (Fig. 5):

- One core zone and four daylit perimeter zones
- WWR = 0.212
- Windows and constructions optimized for the three US climates of Phoenix (AZ), Baltimore (MD) and Minneapolis (MN) according to ASHRAE 90.1-2004 standard
- Detailed design for HVAC system: natural gas for heating loads, electricity for cooling loads

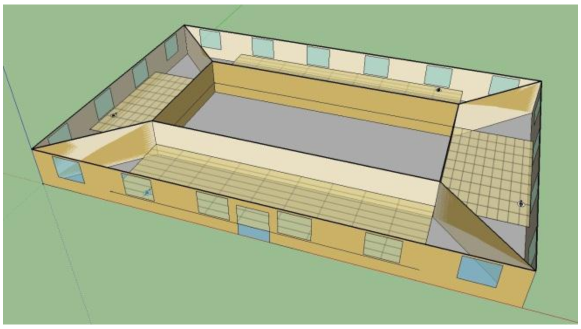

Fig. 5 – DOE standard small office building model

Workplane illuminance maps and daylighting control points are placed in each of the four daylit perimeter zones.

Five simulations runs are performed for each of the three US locations:

1) Baseline: no controls, ASHRAE 90.1 glazing
2) Same as #1 with addition of lighting controls
3) Same as #2 but with switchable glazing, using the "MeetDaylightIlluminanceSetPoint" control function of EnergyPlus
4) Same as #3 with switchable glazing disabled during the heating season
5) Switchable glazing is managed using a custom control algorithm implemented in the BCVTB

The BCVTB supports implementation of custom control algorithms in EnergyPlus through its external interface. Newly released actuators support glazing switching at every timestep at one of four discrete states (VLT = SHGC = {65%, 10%, 2.5%, 0%}). The control algorithm takes into account daylight workplane illuminance and glare index values at each reference point, the zones' occupancy level, mean air temperature and thermostat setpoint. In case #5 the control algorithm selects at every simulation timestep the switchable glazing state that minimizes energy consumption without negative effects on occupant visual comfort.

The main difference with the small office space with the single skylight is that the performance results of the base case for the 5-zone small office are validated, thus allowing comparison of absolute values. Table 4 summarizes the simulations output. For cases #1 through #4:

- **Lighting**: savings are similar in the three locations, ranging between 35% and 41%, with positive contributions of electrochromics. Savings are lower than in the previous simulation runs because only perimeter zones benefit from daylight harvesting. HVAC loads are consequently influenced by the reduction of heat gain from reduced lighting.
- **Cooling**: Switchable glazing have a positive effect on cooling loads, quite regular in absolute values, from 10% savings in Phoenix to 21% in Minneapolis in addition to the savings from the lighting controls.
- **Heating**: Switchable glazing have a negative effect on heating loads, fairly constant in percentage values, between 11% and 14%. This highlights once more the negative effects in heating-dominated climates. Deploying switchable glazing only during the cooling season helps reduce heating season penalties.

The control strategy does not take into account occupant luminous comfort, i.e. disabling glass switching in winter can produce discomfort glare, while fully tinted windows can be highly unpleasant for vision.

In case #5 where occupant luminous comfort is also considered for the control of the switchable glazing, the positive effects on both cooling and heating loads are reduced in comparison to the values achieved in case #4, resulting in a slight increase of the total building energy consumption compared to the cases where luminous comfort is not considered. However the energy reduction is still very significant: compared to the baseline case #1, total annual savings for case #5 are 28.9 GJ (23%) in Phoenix, AZ, 17.2 GJ (10%) in Minneapolis, MN, and 17.9 GJ (15%) in Baltimore, MD.

In general, the estimated savings from lighting and fenestration controls are again equal or higher than those of previous studies found in the literature.

3. Linear model development

As shown in the previous section, electric lighting and fenestration controls for daylight harvesting have significant energy efficiency potential. However, performing such simulations for actual building projects requires significant effort. Moreover, it requires detailed input, which is not usually available during the early, schematic phases of building design. As a result, consideration of potential benefits from advanced lighting and fenestration controls becomes prohibitively expensive. To resolve this issue, a simplified energy savings predictive model is developed, utilizing a small number of key variables that are most critical in the consideration of energy savings from advanced lighting and fenestration controls for daylight harvesting. Parametric simulations are then performed bracketing the value range of each parameter with low, medium and high values. The results of the simulations are then used to determine regression coefficients in logical expressions that link the identified key variables to lighting, cooling and heating energy requirements.

3.1 Simplified Energy Savings Predictive Model Identification

The first step towards the development of a simplified predictive model is the identification of key variables that have the most effect on the energy savings potential of electric lighting and fenestration controls for daylight harvesting. The following variables are identified as the most appropriate:

- LES [lm/W]: luminous efficacy of electric light sources
- E [lm/m^2]: average illuminance levels, taking into account over and under-illuminated areas
- Occupant behaviour, in terms of lighting system management (dimming, on/off switching,…)
- h_{OP} [h]: occupancy, annual hours of operation
- WWR [-]: Window-to-Wall ratio
- LSG [-]: light to solar gain ratio (VLT/SHGC) for the glazing. This variable reflects the heating contribution given by daylight, i.e. the luminous efficacy of the daylight radiation (LER). The higher the LSG value the higher the performance of the glazing, i.e. less solar heat gain for the same amount of transmitted visible light
- Location, in terms of Cooling Degree Days (CDD) and Heating Degree Days (HDD).

The floor surface area of the building isn't included in the list since specific energy consumption [J/m^2] is ultimately relevant: extrapolation of results for buildings much larger than the simulated models shall be carefully evaluated.

The following assumptions can be made:

- "E" (illuminance value) is constant for a specific commercial building type, as it is generally set by regulations worldwide
- Lights are switched on and off according to occupancy schedules, which in turn are constant for specific commercial building types
- All spaces are day-lit, i.e. the model is valid to the extent that all areas taken into account have daylight availability
- The model is linear to the above listed variables or their reciprocals

According to these assumptions, three of the above listed variables (E, h_{OP}, occupants' behaviour), can be considered constant for a specific building type, i.e. not impacting its energy balance. As these factors are left out, only four variables (WWR, LES, LSG and Location) remain as initial conditions strongly affecting the impact of electric lighting and fenestration controls on building energy use.

The total energy consumption of a building is simplified in this study as the sum of lighting, heating and cooling loads. Therefore, three different functions are needed to predict each component:

- L: impact on lighting energy savings
- H: impact on heating energy increase
- C: impact on cooling energy savings

A negative effect of daylight harvesting on heating loads is assumed, as a consequence of the previous simulations' output.

A thorough theoretical analysis follows, with the aim of assessing whether the four identified independent variables impact each of the three aforementioned functions, the strength of this relationship and if the dependence is direct or inverse. The following pattern is obtained for the three functions:

$$L = \alpha_L * \frac{1}{LES} + \beta_L * WWR \qquad [1]$$

$$H = \alpha_H * \frac{1}{LES} + \beta_H * \frac{1}{WWR} + \gamma_H * \frac{1}{LSG} + \delta_H * HDD \qquad [2]$$

$$C = \alpha_C * \frac{1}{LES} + \beta_C * WWR + \gamma_C * \frac{1}{LSG} + \delta_C * CDD \qquad [3]$$

Where α_i, β_i, γ_i, δ_i (i = {L, H, C}) are real constants to be determined by simulations and multivariate linear regression techniques, and "ad hoc" normalization is introduced to constrain each function in the interval [0,1]. Since all the components are positive, H represents heating losses in absolute value.

L, H, C will predict respectively lighting savings, heating losses and cooling savings by the means of the linear functions f_L (L), f_H (H), f_C (C). In the same way, f_{LC} (L, C) can be used to predict aggregated savings in lighting and cooling, while f (L, H, C) can predict total savings, considering heating as well:

$$f_i(i) = a_i * i + b_i \quad [4]$$

With i = {L, H, C}

$$f_{LC}(L,C) = a_{LC} * (L + C) + b_{LC} \quad [5]$$

$$f(L,H,C) = a * (L - H + C) + b \quad [6]$$

3.2 Parametric simulations in JEPlus

Since the patterns in Equations [1] to [6] are theoretically determined, batches of parametric simulations are needed as litmus paper of the developed model validity. JEplus, a JAVA shell allowing users to define parameter trees and run customized simulation batches on a single building model, is adopted for the purpose.

The goal of these parametric runs being to evaluate the impact of the four previously identified variables on a building model energy consumption, 81 simulations are performed by permutation of the following values of the key parameters:

- LSG = {1, 1.5, 2} for the windows. LSG=1 baseline case has ASHRAE 90.1-2004 compliant properties for each location
- LES = {15 lm/W, 80 lm/W, 150 lm/W}, corresponding respectively to incandescent, fluorescent and LED light sources
- WWR = {0.15, 0.30, 0.60} with windows evenly distributed and centered on the four lateral facades of the building
- Location: HDD = {1131, 3782, 6315} and CDD = {5150, 1655, 1163} values calculated for the three locations of Phoenix (AZ), Baltimore (MD), Minneapolis (MN)

Building constructions are optimized for each location according to ASHRAE 90.1-2004.

Simulations are performed combining all possible 3^4 = 81 permutations of the above listed values. Each simulation is performed twice in order to compare the initial "baseline" case with a "best practice" daylight harvesting system installed in the space, the latter being simulated by the addition of lighting and fenestration controls in EnergyPlus.

Fig. 6 depicts the 100 m² office model used for the simulations, in its configuration with WWR = 0.15 and with the predisposition for daylighting controls to monitor daylight illuminance values in the space.

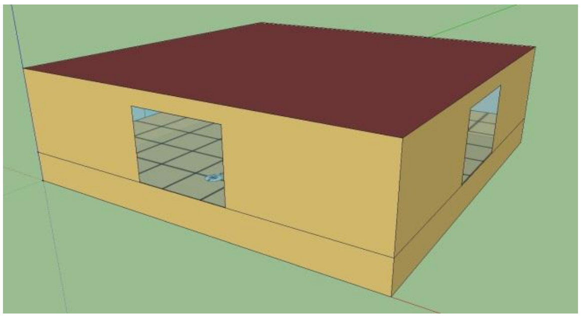

Fig. 6 – The small office model used for the parametric runs (WWR = 0.15)

The output variables for the 162 resulting simulations are:

- Lighting load
- District cooling load
- District heating load

For the HVAC system, simplified "ideal loads" are considered instead of a customized HVAC apparatus which adds unnecessary simulation time and complexity for the high-level perspective of the study. In order to reflect the impact of cooling loads on electricity consumption, a COP value of 4 is again assumed for the cooling system. Relative and absolute values of lighting and HVAC loads are checked for consistency by comparison with the DOE commercial buildings reference models.

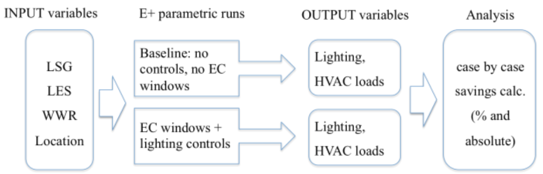

Fig. 7 – The parametric simulations approach

Since the model aims at predicting savings generated by daylighting solutions in different conditions, an analysis is performed in Microsoft Excel in order to assess savings generated by the addition of lighting and fenestration controls compared to the baseline cases for each set of LES, LER, WWR and location as input variables. The analysis approach is illustrated by the diagram in Fig. 7: for every set of input variables combination, two runs are performed - with and without fenestration and lighting controls - and savings are calculated in absolute and percentage values.

With the energy saving data obtained from the parametric runs, an extensive analysis is performed in Microsoft Excel in order to examine the impact of each single variable, with a sensitivity analysis evaluating the model at its "partial derivatives".

3.3 Multivariate linear regression coefficients

The output of the parametric simulations gives fundamental indications to correct the previously identified equations. After the adjustments, least squares multivariate linear regression is used to determine the coefficients in Equations [1], [2], [3]. The modifications and final results are here shown for the three components L, H and C:

- Lighting savings: WWR impact is negligible ($\alpha_L = 1$, $\beta_L = 0$). Lighting savings in GJ are predicted with $R^2 = 0.993$. New equations are:

$$L = \frac{1}{LES} \qquad [7]$$

$$f_L(L) = 38.46 * L - 0.1788 \qquad [8]$$

- Heating increase: not impacted by LES and proportional to WWR, not to its reciprocal. Heating losses in GJ are predicted with $R^2 = 0.807$. New equations are:

$$H = \beta_H * WWR + \gamma_H * \frac{1}{LSG} + \delta_H * HDD \qquad [9]$$

$$\{\beta_H, \gamma_H, \delta_H\} = \{6.326, 1.127, 7.395\}$$

$$f_H(H) = -15.97 * H + 5.518 \qquad [10]$$

- Cooling savings: fairly constant in absolute values, not impacted by location ($\delta_C = 0$). Cooling savings in GJ are predicted with $R^2 = 0.962$. New equations are:

$$C = \alpha_C * \frac{1}{LES} + \beta_C * WWR + \gamma_C * \frac{1}{LSG} \qquad [11]$$

$$\{\alpha_C, \beta_C, \gamma_C\} = \{0.979, 3.749, 2.012\}$$

$$f_C(C) = 17.576 * C - 3.792 \qquad [12]$$

4. Discussion and result analysis

The least squares regression analysis shows good effectiveness of the model at predicting the three components of energy consumption. Lighting and cooling savings can be estimated with a high degree of confidence, while heating increase is the most difficult to forecast. This suggests comparing the validity of the model for the aggregated functions f_{LC} (L, C) and f (L, H, C), accounting respectively for electricity savings (lighting and cooling) and total savings.

Results in Fig. 8 and Fig. 9 show very good prediction capabilities for aggregated savings: heating losses can therefore be also accurately estimated as the difference between total savings and savings on lighting and cooling loads.

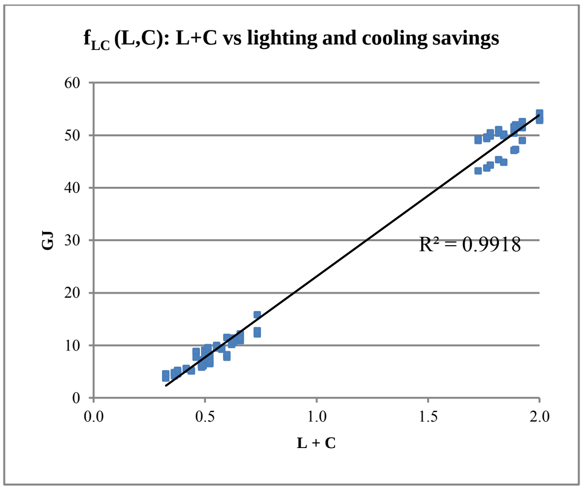

Fig. 8 – f_{LC}: (L+C) vs lighting and cooling savings

5. Conclusions

The developed multivariate regression linear model can predict with a satisfactory degree of confidence savings in lighting, cooling and heating which can be obtained by electric lighting and fenestration controls for daylight harvesting. The prediction can be made starting from a handful of simple and easy-to-determine variables, thus eliminating the need for extensive simulations and detailed building descriptions. Results shown in the paper are obtained for a 100 m^2 office building, thus extrapolation to other types and size of buildings should be carefully evaluated.

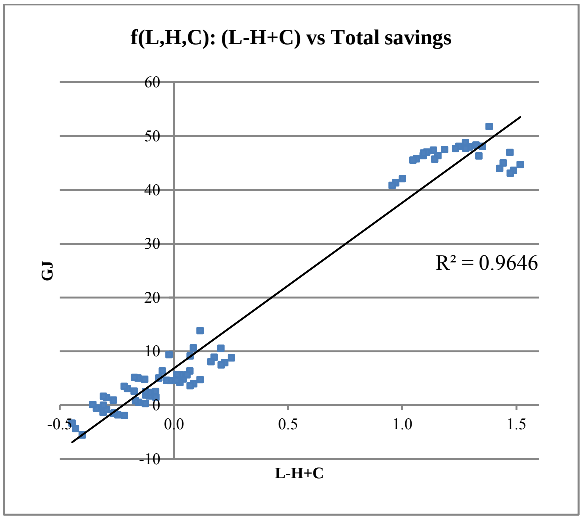

Fig. 9 – f: (L-H+C) vs total savings

Further developments are foreseen to be the inclusion of economic factors in order to assess the value of lighting and fenestration control systems in building design, and compare them to the investment costs of energy efficiency measures.

Future developments could also include the realization of a quick energy analysis tool to provide order-of-magnitude energy savings indications to be implemented in early, schematic phases of building design, policy making and investment analyses.

Building simulation shall have two paths in the future: on one hand, extremely powerful and dynamic tools (e.g. EnergyPlus) are needed to increase precision in detailed single buildings simulations, while quick and easy-to-use high-level tools should be adopted for decision-making support in consideration of energy strategies, where order-of-magnitude indications are sought. It is the authors' belief that the parametric simulations approach used for model development as presented in this paper is very promising for further formalization and adoption in energy efficiency practice.

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Phoenix, AZ

#	Skylight?	Lighting Controls?	Fenestration Controls?	Lighting [GJ]		Cooling [GJ]		Heating [GJ]		Total [GJ]	
1	no	no	no	2.86		4.97		1.18		9.01	
2	yes	no	no	2.86		5.15		1.16		9.17	
3	yes	yes	no	1.16	-59%	4.82	-6%	1.37	18%	7.35	-20%
4	yes	yes	yes	1.14	-60%	4.54	-12%	1.56	34%	7.24	-21%
5	yes	yes	yes, only summer	1.14	-60%	4.64	-10%	1.37	18%	7.15	-22%

Baltimore, MD

#	Skylight?	Lighting Controls?	Fenestration Controls?	Lighting [GJ]		Cooling [GJ]		Heating [GJ]		Total [GJ]	
1	no	no	no	2.86		0.76		5.76		9.38	
2	yes	no	no	2.86		0.90		5.77		9.53	
3	yes	yes	no	1.17	-59%	0.69	-23%	6.40	11%	8.26	-13%
4	yes	yes	yes	1.17	-59%	0.54	-40%	7.32	27%	9.03	-5%
5	yes	yes	yes, only summer	1.17	-59%	0.55	-39%	6.52	13%	8.24	-14%

Minneapolis, MN

#	Skylight?	Lighting Controls?	Fenestration Controls?	Lighting [GJ]		Cooling [GJ]		Heating [GJ]		Total [GJ]	
1	no	no	no	2.86		0.48		9.35		12.69	
2	yes	no	no	2.86		0.61		9.52		12.99	
3	yes	yes	no	1.18	-59%	0.43	-30%	10.24	8%	11.85	-9%
4	yes	yes	yes	1.17	-59%	0.28	-54%	11.53	21%	12.98	0%
5	yes	yes	yes, only summer	1.17	-59%	0.29	-52%	10.66	12%	12.12	-7%

Table 3 – Simulations for the simple office with skylight case (end uses loads)

Phoenix, AZ

#	Lighting Controls?	Fenestration Controls?	Lighting [GJ]		Cooling [GJ]		Heating [GJ]		Total [GJ]	
1	no	no	56.69		59.82		9.04		125.55	
2	yes	no	36.84	-35%	55.79	-7%	10.39	15%	103.02	-18%
3	yes	yes	33.34	-41%	49.98	-16%	11.88	31%	95.20	-24%
4	yes	yes, only summer	33.34	-41%	51.08	-15%	9.27	3%	93.69	-25%
5	yes	yes, 4 states (BCVTB)	33.34	-41%	52.89	-12%	10.72	19%	96.95	-23%

Baltimore, MD

#	Lighting Controls?	Fenestration Controls?	Lighting [GJ]		Cooling [GJ]		Heating [GJ]		Total [GJ]	
1	no	no	56.69		19.79		44.40		120.88	
2	yes	no	35.29	-38%	17.40	-12%	50.90	15%	103.59	-14%
3	yes	yes	33.85	-40%	14.74	-26%	58.16	31%	106.75	-12%
4	yes	yes, only summer	33.85	-40%	15.25	-23%	46.59	5%	95.69	-21%
5	yes	yes, 4 states (BCVTB)	34.32	-39%	15.45	-22%	53.23	20%	103.00	-15%

Minneapolis, MN

#	Lighting Controls?	Fenestration Controls?	Lighting [GJ]		Cooling [GJ]		Heating [GJ]		Total [GJ]	
1	no	no	56.69		12.28		97.07		166.04	
2	yes	no	35.59	-37%	11.03	-10%	106.59	10%	153.21	-8%
3	yes	yes	34.04	-40%	8.71	-29%	117.82	21%	160.57	-3%
4	yes	yes, only summer	34.04	-40%	9.65	-21%	100.14	3%	143.83	-13%
5	yes	yes, 4 states (BCVTB)	37.32	-34%	9.54	-22%	102.02	5%	148.88	-10%

Table 4 – Simulations for the DOE standard, validated small office model (end uses loads)