Greater Philadelphia Innovation Cluster
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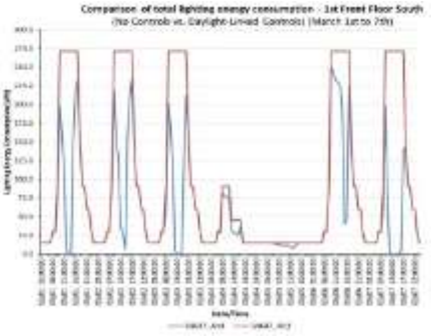
A U.S. DOE Energy Innovation Hub

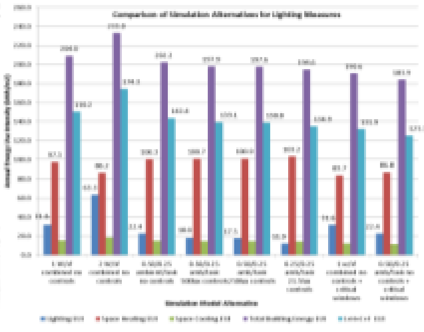
GPICHUB

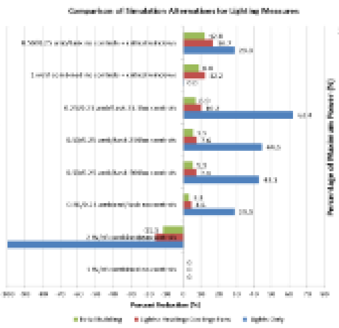
Task 2.2.11 – CMU Report 04:

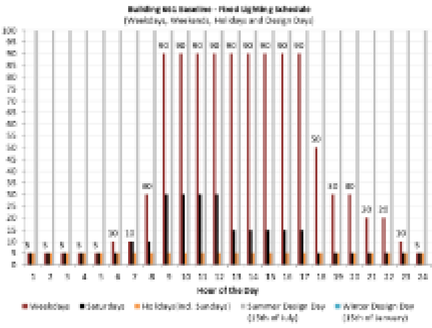
Daylighting Simulations:
Effects of Daylight Controls on Electric Lighting Energy Consumption Building 661-Case

Department of Energy Award # EE0004261









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February 2012

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Introduction/Executive Summary

This study is focused on simulation-based performance assessment of a number of electric lighting system design scenarios aiming to get energy savings with increased system efficiency coupled to daylight-linked controls while preserving visual comfort conditions for indoor spaces. Alternative simulation models analyzed in this study are developed based on the information (energy efficient lighting design scenarios) drawn from the two "Expert Workshop" reports prepared after GPIC Task 3 meeting held at March 22-23, 2011, Navy Yard, Philadelphia. These are "Expert Workshop on Enclosure" and "Expert Workshop on Lighting". Following scenarios are formed into distinct design cases and exemplified on Building 661 case through simulations:

- Typical office building of Mid-Atlantic region, combined task and ambient lighting using T-12 lambs with magnetic ballasts with lighting power density (LPD) of around 2 W/ft^2.
- Energy efficient office types with separated task (LED lamps) and ambient lights (up to date lighting systems) with reduced LPDs of 0.50 and 0.25 W/m^2 for ambient and task, respectively.
- Environmentally responsive office types, same as above but equipped with daylight-linked controls as well as glare protection measures (with 500 lux illuminance target).
- Environmentally responsive office types with *strong* separation of ambient and task light, same as above with the reduction of target illuminance to 250 lux.
- Environmentally responsive office types with *radical* separation of ambient and task light, where target illuminance for ambient lighting is reduced to 21.5 lux (to represent *moon-light light level* concept).
- Energy efficient offices with window systems having dynamic SHGCs (SHGC > 50% for winter, SHGC < 25% for summer) (realized with seasonal adjustable shading devices), with R-value greater than 4.0, and visible transmittance greater than 60%. This is the concept of *critical glazing* concept put forward during export workshops on lighting.
- Environmentally responsive office types same as above but with separated task and ambient lights and connected to daylight controls.

Two additional simulation cases that are combining high-performance enclosures cases (developed during previous parametric analysis) with daylight alternatives are investigated in this study. Detailed explanation of simulation models developed for each the above mentioned scenarios can be found in the "Simulation Model Alternatives" section of this report.

EnergyPlus v6.0 "Detailed Daylight" calculation methodology is utilized for daylight simulations conducted in this study. Geometric models were already generated during baseline modeling activities by the use of Design Builder v2.3 program. Daylight sensor locations and occupant view angles (for glare analysis) are also defined with the same program. It should be note that, parametric analysis approach followed here is OAT methodology. Therefore, simulation models do not represent combined effects of design measures explained above. Previously developed baseline simulation model (ASHRAE 90.1 2004 with Existing Envelope) is taken as a reference and necessary modifications pertaining to daylight and electric lighting systems are realized while keeping all other model input parameters constant and at their initial baseline levels.

Detailed explanations of simulation input parameters are explained in section 1, investigated simulation alternatives are summarized in section 2. Section 3 provides specification of lighting system performance indicators, a schematic representation is also given in this section. Section 4 provides a discussion on the limitations to current study for performing detailed daylight simulation exercises. Results are discussed in Section 5. Overall conclusions are finally provided in Section 6 of this report.

1. Simulation Inputs

Simulation inputs given here is only focused on electric lighting and daylighting functionalities of the simulation program. A comprehensive set of input definitions for the accepted baseline model can be found in “Whole-Building Energy Performance Modeling as Benchmarks for Retrofit Projects” report.

Building 661 Baseline Lighting System Design Parameters

Lighting system design input parameters are taken from DOE Reference Commercial Buildings – Medium Office example (Table 1). System power definition method is selected as power density (W/m^2) (the total wattage normalized by building useable floor area) instead of lighting design level (W), or power density per person (W/person). Assumed LPD for all thermal zones is 10.76 W/m^2 (1.00 W/ft^2) which is compliant to baseline requirements of energy standards (ASHRAE 90.1 2004) and represents relatively efficient luminaires (with efficient ballasts). Total installed lighting power at the building level is about 3.27 kW. In the baseline definition all lights are assumed to be general/ambient type without display and/or task lighting. EnergyPlus input of “Fraction Replaceable” is set to 1.00 which indicates that ambient lights are available to be controlled (for their 100% power input) by daylight control systems in case they are defined elsewhere in the model.

Table 1 Lighting system design parameters

Design Level Calculation Method	**Watts/Area**	
Watts per Zone Floor Area	[W/m2]	10.76
	[W/ft2]	1.00
Total Building Floor Area	[m2]	3042.89
	[ft2]	32753.40
Building Lighting Level	[W]	32753.40
Fraction Replaceable	[-]	1.00
Return Air Fraction	[-]	0.00
Fraction Radiant	[-]	0.70
Fraction Visible	[-]	0.20
Convected Fraction	[-]	0.10

It’s useful to point out that for the baseline model (with inputs defined above), design lighting levels and consequent lighting energy consumptions are directly and positively proportional to thermal zone floor surface areas (e.g., maximum lighting level, open office core zone, 11513 W, area 1070 m^2, and minimum lighting level, 1st front south zone, 603W, area 56 m^2).

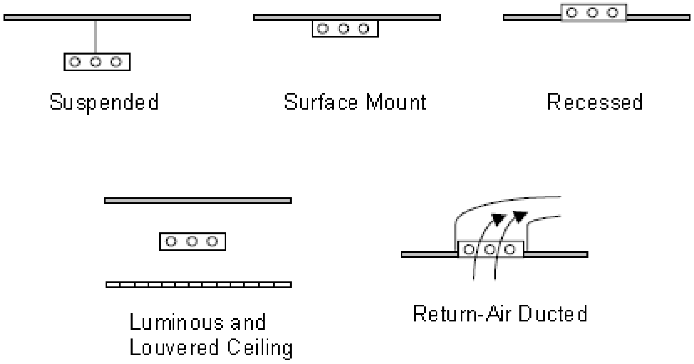

Figure 1 Different luminaire types that can be define for simulation models (EnergyPlus v6.0)

Different luminaire types can be characterized by key input parameters (Table 1) which are return air fraction, fraction radiant, fraction visible, and convected fraction. During simulation studies, “surface mount” luminaire type is assumed for all model alternatives and necessary inputs are entered to represent such fixtures (Figure 1).

Building 661 Baseline Fixed Lighting Schedule

A fixed lighting schedule assigned to all lighting fixtures in the baseline simulation model of Building 661. There’s no daylight-linked and/or occupancy-linked control in this model alternative.

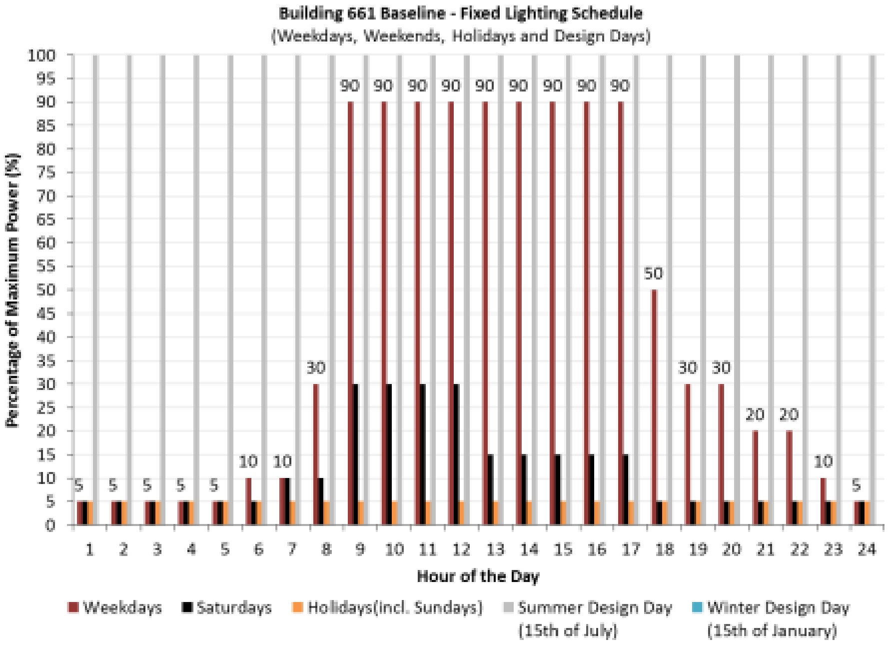

Figure 2 Fixed hourly lighting schedule for ambient lights of baseline model

Figure 2 above shows hourly profile of lighting schedule indicating percentages of maximum lighting power defined for a thermal zone (100% maximum power, 0% no power). During weekdays 9 hours of the day (from 9am to 5pm) lighting system operates at 90% of maximum power. There's 6 hours of minimum power period (5%) from 12am to 5am). There's a gradual decrease of lighting power from 50% to 10% starting from 6pm (90%), to 11pm (10%). (Evening cool-down) On the other hand, there's a gradual increase from 10% to 30% starting from 6am (10%), to 8am (30%) (morning warm-up). During Saturdays majority of the time (13 hours) lighting power is at 5%, 2 hours of warm up (10%), and 5 hours of cool-down (15%), and 4 hours of peak power (with a max. of 30%). During all holidays including Sunday lighting power is at 5%. Winter design day - 0% no lighting system Summer design day – 100% maximum possible lighting power is assumed.

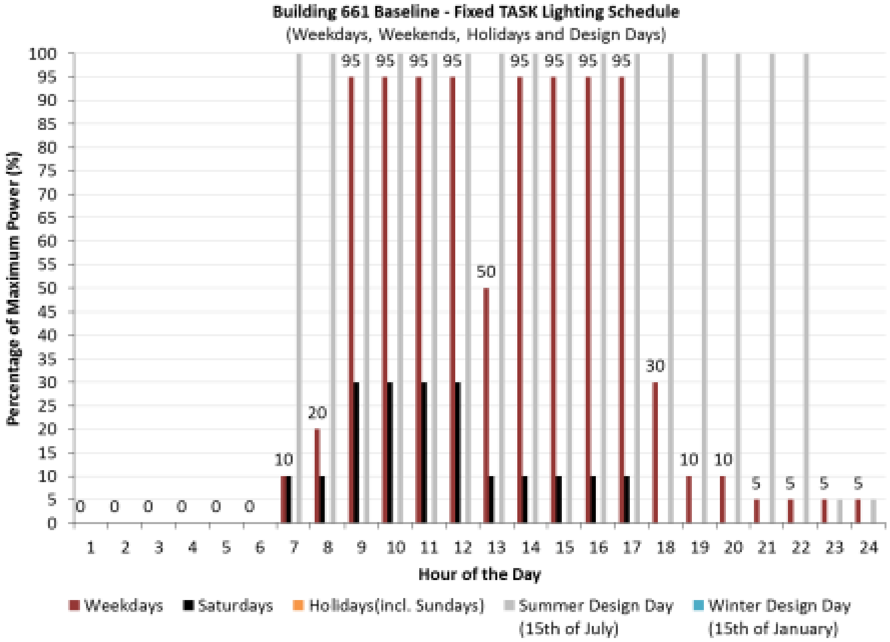

Figure 3 Fixed hourly lighting schedule for task lights of baseline model

Task lighting schedule strictly follows building occupancy schedule (BLDG_OCC_SCH). Therefore, maximum lighting power capacity of task lights are modified with respect to maximum number of people who are present in a specific thermal at a specific time. Task LPD never reaches to pre-defined maximum levels due to the fact that maximum percentage of total office population who are present in any given time is not greater than 95% (Figure 3).

Daylight Sensors, Dimming Control and Glare settings

With daylight-linked controls electric lighting system output and energy consumption is adjusted based on target illuminance levels that are read from specific sensor points in the control zone. These points can also be defined as photo-sensor/daylight sensor locations. In Building 661 case, a maximum of two daylight sensors are located 2m away from the exterior wall surface of large thermal zones (e.g., 1st floor front east). Single daylight sensor is located for smaller zones (e.g., 2nd floor front south) (Figure 4).

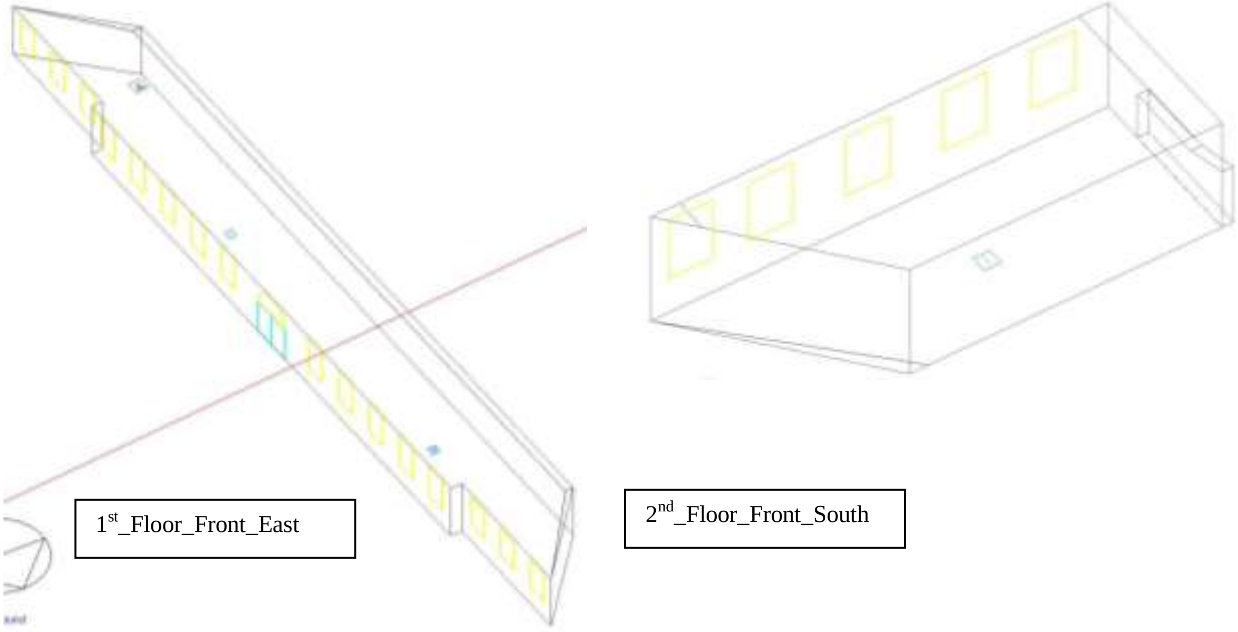

Figure 4 Thermal zones with daylight sensor locations (from Design Builder v2.3 model)

Work plane for daylight illuminance calculations (z coordinate of daylight sensors) is set to 0.8 m for all model alternatives. For thermal zones with two daylight sensors (which is the maximum number that can be defined in EnergyPlus Detailed Daylight calculation routines) each daylight sensor is assumed to be responsible for 50% of the zone (percentage covered by a sensor reflecting a fraction of the total ambient lighting that can be dimmed by a lighting sensor) with equal target daylight illuminance.

A continuous dimming control option is selected for the control of ambient lighting system. Therefore, overhead lights can be continuously and linearly dimmed from maximum electric power (corresponding to a maximum light output) to minimum electric power as the daylight illuminance increases (Figure 5).

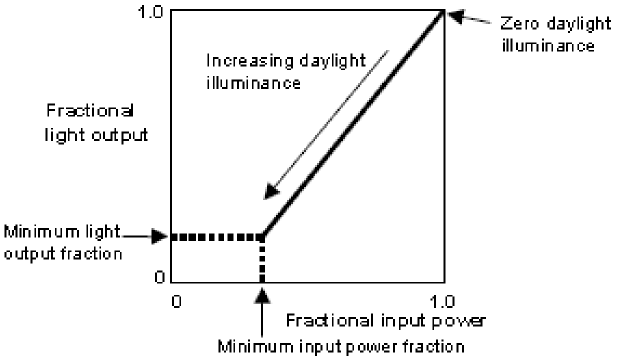

Figure 5 Fractional input power and light output as a function of daylight illuminance (EnergyPlus v6.0)

Maximum input power is already defined by LPD entries. Minimum input power fraction for all light fixtures is assumed to be 0.1 which is the lowest possible power that system can be dimmed down to. This is observed during maximum daylight illuminance times.

For simulation model alternatives incorporating adjustable shading devices, a separate control threshold is defined as maximum allowable discomfort glare index (DGI). Therefore, dynamic shading devices are deployed at conditions when DGI calculated by daylight sensors exceeds the entered control limit. This limit is selected as DGI <= 22 which is the recommended DGI for office spaces (EnergyPlus v6.0 documentation) [1]. Another model input for discomfort glare control is the view angle since daylight glare that can be sourced to a window element depends on the occupant's view direction (daylight sensor specified occupants position in the zone). Possibility of effecting by a glare source from a window is highest with view directions pointing directly window areas and decreases as the occupant looks away from the window. View angle is the positive angle from the y-axis of a thermal zone and defined separately for each thermal zone so that occupants' are facing window side (worst-case scenario) by taking into account the actual orientation of a thermal zone.

Dynamic Shading Device Type

A diffusing, medium translucent, interior roller shade is assumed for windows facing South, East, and West orientations. This device has equal solar and visible transmittance of 0.30 a thermal conductivity of 0.1 W/m K. It is assumed that the shading device is opaque to long-wave radiation with a high emissivity (0.90) (Table 2).

Table 2 Shading device input parameters

Parameter	**Units**	**Value**
Thickness (d)	m	0.0030
Conductivity (λ)	W/mK	0.100
Solar Transmittance (T_{SOL})	-	0.30
Solar Reflectance (T_{REF})	-	0.25
Visible Transmittance (V_T)	-	0.30
Visible Reflectance (V_{REF})	-	0.25
Long-wave Emissivity (Thermal Hemispherical Emissivity) (E_1)	-	0.90
Long-wave Transmittance (Thermal Transmittance) (T_{IR})	-	0.00

2. Simulation Model Alternatives

As listed in Table 3, Baseline Alt_01 is the Building 661 baseline simulation model developed over the course of GPIC energy simulation studies (ASHRAE 2004 + Existing Envelope features). Alt_02 represents typical buildings in the Mid-Atlantic region. These have connected task-ambient lighting using incandescent and/or T-12 lamps and magnetic ballasts. Alt_03 represents reduced LPDs for both ambient and task (ambient -up to date lighting systems, task -using LED lamps). Alt_04 represents Alt_02 scenario but with daylight linked controls only for ambient lights with a typical illuminance set-point of 500 lux on the desk-plane, visual comfort is maintained with another set-point for DGI which is set to 22 for office spaces. Alt_05 represents a similar scenario with Alt_04 but here illuminance set-point is decreased down to 250 lux level ("separation of ambient" and task level 1). Alt_06 represents a more "radical separation" of ambient and task lighting where lighting illuminance set-point is reduced to the level of 21.5 lux (2 fc) as a representation of "moonlight levels". Alt_07 includes a window system which satisfies the following criteria (concept of “critical glazing criteria”): R-value (IP) > 4.0, Visible Transmission > 60%, SHGC (seasonally adjustable with layers) for winter > 50%, and for summer <25%. Alt_08 is a combination of critical glazing criteria with reduced LPDs for both ambient and lighting. There are no daylight-linked controls in this alternative.

Table 3 Lighting simulation model alternatives

Model Name	**Ambient – Task Lighting Separation**	**LPD Ambient (W/SF)**	**LPD Task (W/SF)**	**Daylight -Linked Controls ***	**Control Parameter-1 Illuminance Set-point - Lux**	**Control Parameter-2 DGI** Set-point**	**Controlled Element Against Glare**	**Window Type*****
Baseline _Alt01	Connected	1.0		No	N/A	N/A	N/A	Single Clear R-value (IP) =1.0 SHGC= 0.861 Vt= 0.898 Vt/SHGC= 1.04
Alt_02	Connected	2.0		No	N/A	N/A	N/A	
Alt_03	Separated	0.50	0.25	No	N/A	N/A	N/A	
Alt_04	Separated	0.50	0.25	Yes	500	22	Interior Roller Shades	
Alt_05	Separated	0.50	0.25	Yes	250	22	Interior Roller Shades	
Alt_06	Radically Separated	0.25	0.25	Yes	21.5 (Moonlight)	22	Interior Roller Shades	
Alt_07	Connected	1.0		No	N/A	N/A	N/A	Dynamic Double Low-e Argon Winter R-value (IP) =4.9 SHGC =0.50 Vt= 0.745 Vt/SHGC = 1.49
Alt_08	Separated	0.50	0.25	No	N/A	N/A	N/A	

*- Daylight-linked controls are affecting ambient lighting only where task lighting operates on a fixed schedule.

**- DGI (Discomfort Glare Index) – Each view angle for each daylight sensor is adjusted to simulate occupants view direction is to the windows.

***-Windows of Alt_06 and Alt_07 are equipped with an external shading element (Roller Shade – Light) operated with a seasonal schedule to provide dynamic SHGC to the glazing. Sumer Time values are R-value (5.1), SHGC (0.20), Vt(0.275), Vt/SHGC (1.36)

3. Analysis of Daylighting Performance Indicators

At this point, it'll be useful to analyze a number of performance indicators (PIs) or metrics that can be used to evaluate the effectiveness of each lighting or daylighting design scenario with respect to each other. Such as analysis is depicted as a schematic diagram which is given below (Figure 6).

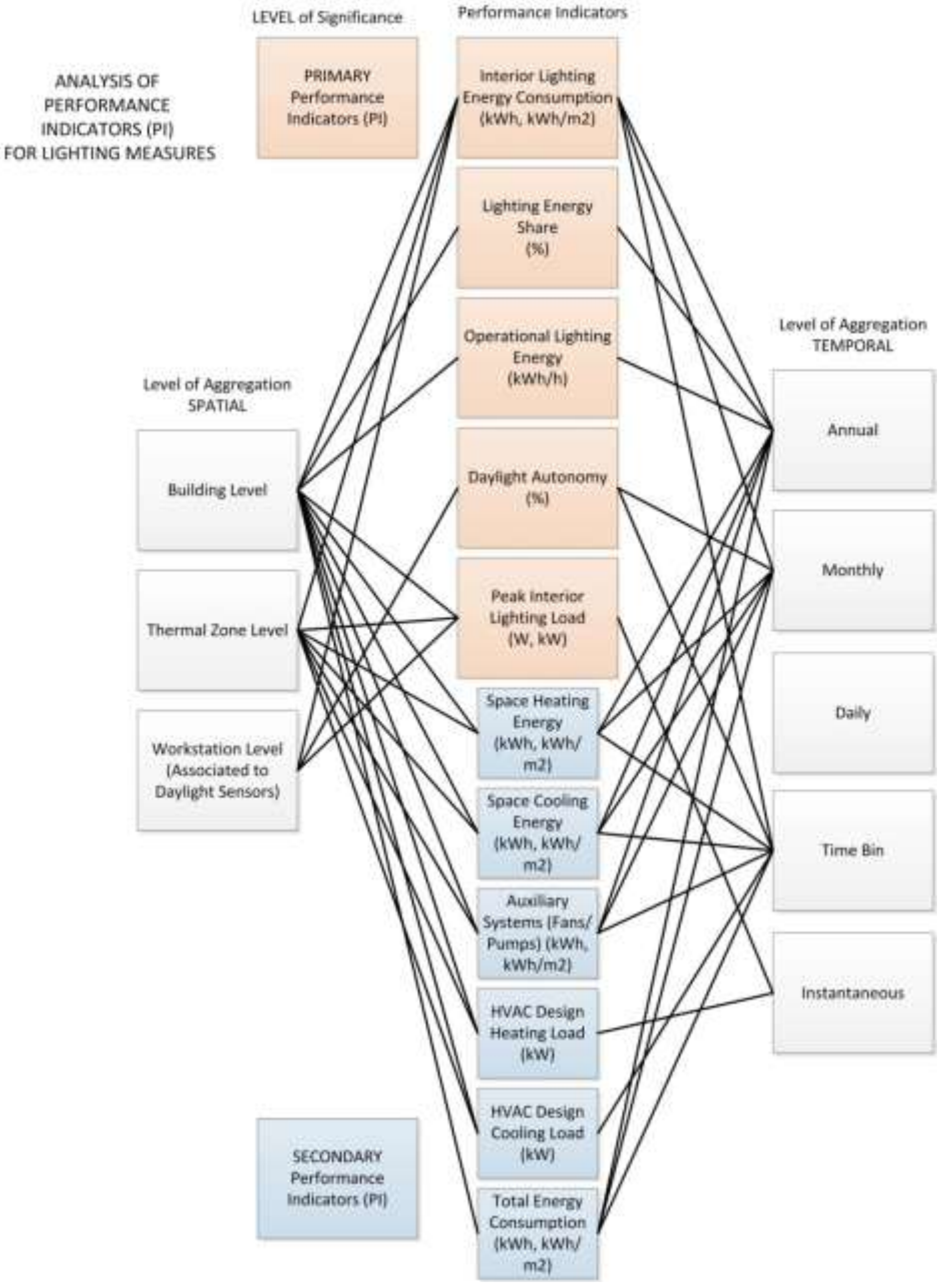

Figure 6 Schematic explanation of the analysis of performance indicator for lighting simulations

Possible PIs that can be utilized for design decision support systems focused of lighting measures are grouped into 4 categories at two different levels. One of them is the *level of significance* which differentiates PIs into two groups; primary and secondary based on a PIs relative effectiveness in describing the overall impact of a design scenario on total building performance. As can be seen from Figure 6 above, interior lighting energy (cumulative or EUI), lighting energy share (%), operational lighting energy (kWh/h), daylight autonomy (DA - %), and peak interior lighting power (W, kW) are of prime importance from lighting design point of view. On the other hand, indirect but integrated effects of lighting design measures (such as effects on space heating, cooling energy and peak loads) are categorized as secondary PIs from significance perspective. Other level of PI categorization is the *level of aggregation*. Simulation results (PIs) directly or indirectly affected by lighting design measures can be grouped by their aggregation type. For instance, we can grouped PIs that provide information about performance effects at total building level, thermal zone level, and even at individual workstation level (represented by daylight sensor points).These are forming the spatial level of PI aggregation. Another level of aggregation is time based or temporal. Simulation results (PIs) can also grouped into their characteristics for providing information at annual, monthly, daily, time bins, and instantaneous time scale levels. Schema given in Figure 6, provides the categorization of PIs with respect to grouping criteria mentioned above.

Design teams can decide on which category of PIs will be necessary based on their focus at initial phases of simulation-based lighting design studies, and consequently simulation models can be modified to generate specific outcomes pertaining to the selected PI categories and the schema given above can be helpful in categorization PIs in the first place and structuring the raw output data of simulation models as well as require post-processing procedures to be applied. Below is given brief explanations of PIs mentioned in the schema given above:

- Interior lighting energy consumption (kWh, kWh/m^2): Time-based energy consumption by the installed electric lighting system with or without coupling with daylight controls. Modified by assumed hourly, fractional lighting schedules (fixed or deterministic scheduling is applied).
- Lighting energy share (%): This is the percentage of building total site energy used for interior lighting purposes.
- Operational lighting energy (kWh/h): A mew metric mentioned in the expert workshop on lighting, it is simply the ratio of annual total lighting energy consumption to total annual occupancy hours of the office building.
- Daylight autonomy (DA - %): The average percentage of office hours in a specific month (or a time bin/period of interest) that all/a worker (at their workstation – should be associated with a daylight sensor position inside a thermal zone) in a given space get sufficient daylight to perform required eye tasks with certain ease and without the need for artificial lighting [2].
- Peak interior lighting load (W, kW): maximum power demand attributed to the electric lighting system only.
- Space Heating, Cooling, auxiliary system energy (kWh, kWh/^{2}): HVAC energy used to keep thermal comfort conditions, and IAQ levels within certain levels.
- HVAC heating and cooling design load (kW): Peak power demand required by the HVAC system to satisfy indoor equilibrium conditions, can include safety factors, can also be used as an indication of required HVAC system size.
- Total energy consumption (kWh, kWh/m^2): This PI includes (in addition to heating, cooling, fans/pumps, interior lighting) exterior lighting, interior office equipment, and service water heating energy end-use breakdowns.

4. Limitations for Conducting Detailed Simulations

Current phase of simulation-based daylight analysis studies are limited to EnergyPlus v6.0 (with Detailed: Daylight method) without resource to more sophisticated program suites such as RADIANCE-based advanced daylight analysis due to the fact that final building design features available to the researchers at this phase is missing the following[1]:

- External Enclosure System [elevation, type, size and location of windows, shading devices and related controls]
- Neighborhood System [nearby buildings, landscape elements, site topography]
- Electric Lighting System [fixture types, location, controls]
- Internal Enclosure [surface finishes, color, reflectivity]
- Organization System [workplace location and orientation, internal partitions height and finishes]

5. Simulation Results

Below (Table 4) is given a template result table for Building 661 baseline simulation (Alt-01) including some of the lighting design PIs discussed in Section 3.

Table 4 Key performance indicators for baseline model

Performance Indicator (PI)	**Value**		
	[kWh]	[kWh/m2]	[kBtu/ft2]
Interior Lighting Energy	96233.75	**31.6**	**10.0**
Space Heating	296100.58	97.3	30.9
Space Cooling	46369.68	15.2	4.8
Fans	18583.8	6.1	1.9
Total Building Energy	635922.21	**204.7**	**66.3**
	[%]		
Interior Lighting Energy Contribution	**15.4**		
	[kWh/occupant hours]		
Operational Lighting Energy	**3.20**		

Annual interior lighting EUI is about 31.6 kWh/m^2, and 15.4% of total building energy consumption (lighting energy contribution). It should be noted here that total building energy includes some other energy use categories in addition to lighting, such as interior equipment, service water heating, together with space heating, cooling and fan energy. Table 4 also reveals information about operational lighting energy (calculated as 3.20 kWh/occupant hours for the baseline model) with the assumption 29,652 hours for the whole building (occupancy hours are taken as 9 hours a day from 9am to 6pm excluding weekends and holiday) with each of 12 thermal zones having 2471 hours of office occupancy.

Table 5 below shows building level peak power loads (demands) associated with interior lighting, and heating, cooling systems. It can be seen that 96233 kwh of electric lighting energy consumption is the result of an annual operation of a 29.4 kW of a lighting system.

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[1] Augenbroe, G. "The role of simulation in performance based building". Building Performance Simulation for Design and Operation. Edt. Jan L.M. Hansen and Roberto Lamberts. Spon Press. London-New York. 2011.

Table 5 Key performance indicators for baseline model – peak loads

Performance Indicator (PI)	**Value**
	[kW]
Peak Interior Lighting Load (Building Level)	**29.4**
HVAC Design Heating Load (Building Level)	360.2
HVAC Design Cooling Load (Building Level)	199.2

Total annual lighting energy consumption of different thermal zones of the baseline model is given below (Figure 7). Since there are no daylight-linked controls in the baseline assumptions lighting energy consumption distribution by zones is proportional to zone's floor areas. Consequently, a single EUI for lighting applies to all zones, which is the same for the whole building as well (31.6 kWh/m2). Core office zone with the largest floor surface area has also the largest electric lighting energy consumption. This is one of the negative effects building shape on lighting energy, buildings with deep plan configuration can get reduced benefits from the incorporation of daylight controls. However, Building 661 has skylight systems and similar daylight benefit analysis can be conducted on such systems (only perimeter office zones are analyzed in this study).

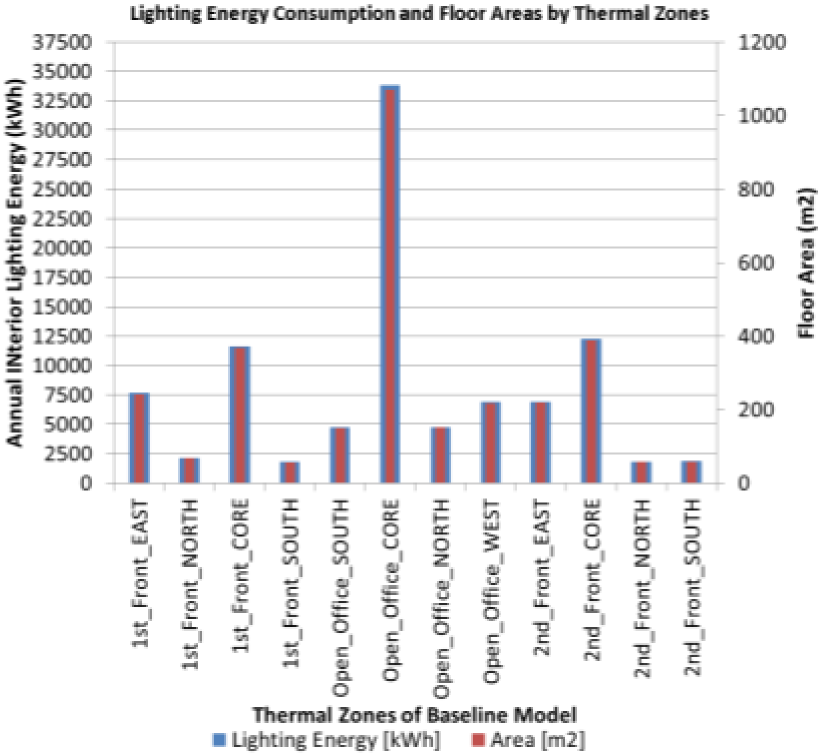


Figure 7 Comparison of annual lighting energy consumption of thermal zones (baseline model)

Analysis of Daylight Contribution to Perimeter Office Spaces

In this part, a focused analysis is conducted on two perimeter office zone so as to reveal positive contributions of daylight controls on electric lighting energy reductions.

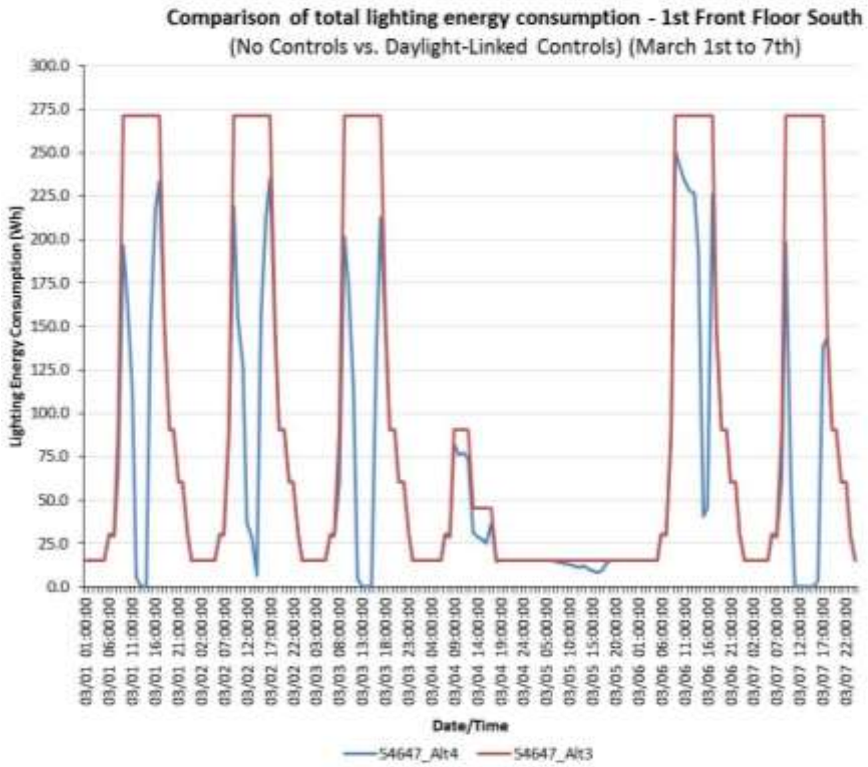


Figure 8 Weekly electric lighting energy consumption of alternative models – 1st Front South

Above is given a weekly analysis electric lighting energy consumption of two alternative models (Alt 03 with 0.5, 0.25 W/ft^2 ambient, task lighting and without daylight controls and Alt 04 same LPDs as Alt 03 but with daylight controls 500 lux target illuminance) for a south facing thermal zone (1st Front South). Time bin is the first week of March (1st to 7th). It can be clearly seen that daylight controls modifies electric lighting operation during times of sunlight availability. The net area between consumption profiles of no controls option (red line) and daylight-linked controls option (blue line) is the net energy savings for this particular week. It is predicted that Alt 03 option without controls consumes 17.0 kWh of electricity, whereas Alt 04 with daylight controls consumes around 9.7 kWh. Such usage profiles are indicating an energy savings of 49% for the first week of March.

A similar analysis with the same model alternatives is conducted for a larger perimeter zone facing east direction (1st Floor Front East) (Figure 9). Time of analysis is also the same for this thermal zone (March 1st to 7th). Simulation results showed a weekly lighting electricity consumption of 73.5 kWh for Alt 03 without daylight controls. On the other hand, alternative model with daylight controls (Alt 04) is responsible for a consumption of around 16.9 kWh. Such a situation indicates a reduction of 77% on a weekly basis. Increased energy reductions in this case can be attribute to increased glazing to wall area, and existence of two daylight sensors responsible for dimming electric lights based on illuminance contribution from windows. Figure 9 also shows the status of the installed shading device with the indication of percentage of the time in a hour when shading device is in deployed position. Shading is frequently deployed during afternoon office hours (3pm-4pm) when sun is low in the sky (an considering east direction.

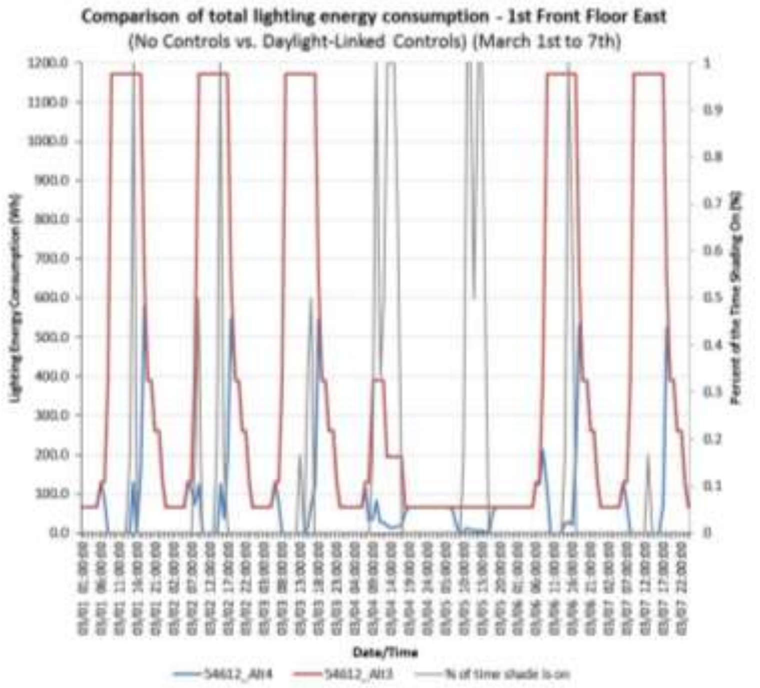


Figure 9 Weekly electric lighting energy consumption of alternative models – 1st Floor Front East

Comparative Analysis of All Model Alternatives

Below (Figure 10) is given a comparative analysis of all simulation alternatives developed throughout this study.

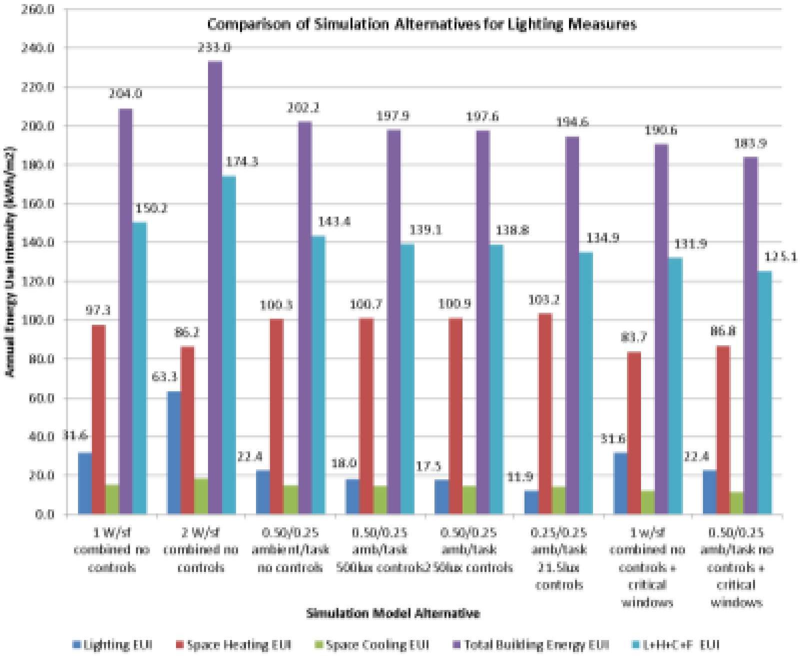


Figure 10 Performance comparison of lighting measure alternatives

Performance indicator here is the annual energy use intensity with disaggregation to lighting, space heating, space cooling, total of lighting, heating, cooling, and fans, and total building energy use. Such an analysis indicates Alt 02 representing average office in Mid-Atlantic region (LPD of 2 W/ft^2 – no controls) as the worst-case scenario. Reduction and separation of LPD to ambient and task has the most significant effect in terms of energy reduction. Incorporation of daylight controls can provide lighting energy savings in the level of 19.6% with respect to a non-controlled alternative. Total building energy consumption reductions are augmented with the assumption of critical window concept due to increased reductions of space heating and cooling. Lighting EUI can de decreased to the level of 11.9 kWh/m^2 with radical separation of ambient and task lighting with the addition of moon-light target illuminance (21.5 lux) for ambient lights only. Maximum change in space heating (in direct effect of lighting design to room heat balance) is an increase of 5.9 kWh/m^2 between baseline model and Alt-07 (radical separation with moon-light illuminance level).

As explained in Figure 11 below, highest percentage of reduction on lighting energy (with respect to baseline model) is reached (62.4%) with Alt 06 in which LPDs and target illuminance levels are dramatically reduced as explained above. A moderate level of LPD reduction with usual 500 lux target illuminance levels can save up to 43.1% of lighting energy reduction which is observed as a change of 5.5% at the building level. At this point, the significance of improving window thermal performance can be observed from the finding that even without any change in LPDs and even without the introduction of daylight controls, high performance windows can result in a total of 8.8% energy reduction at the building level without a percentage change in electric lighting energy.

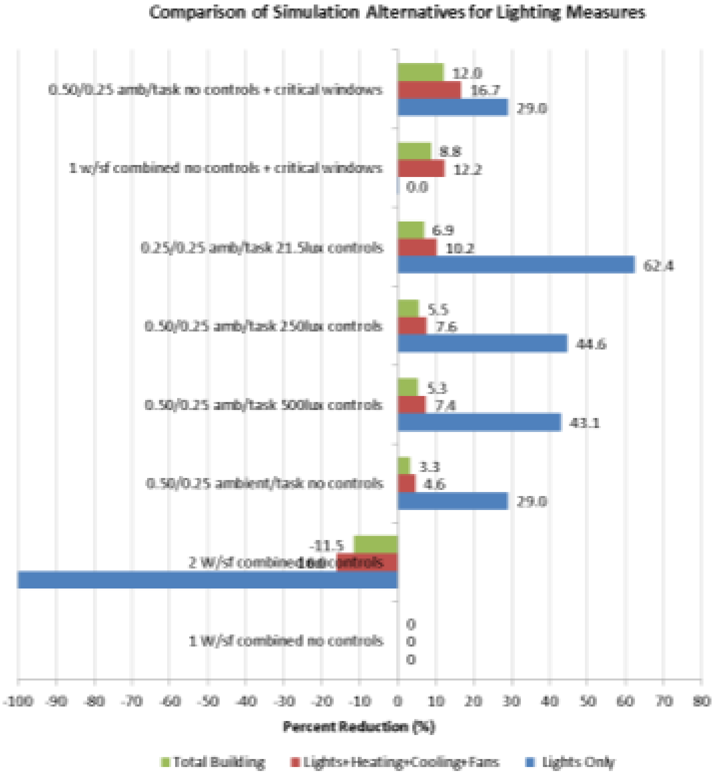
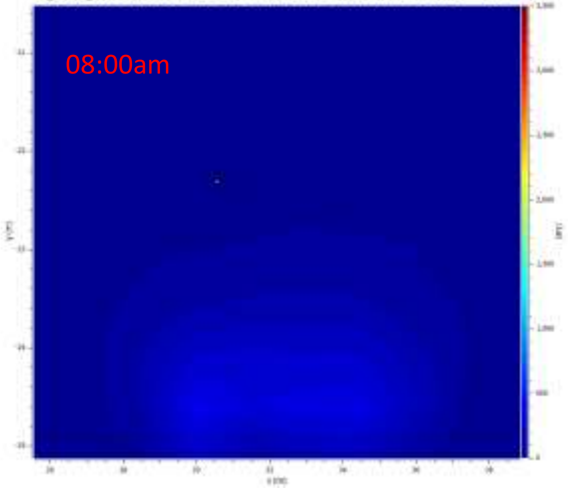


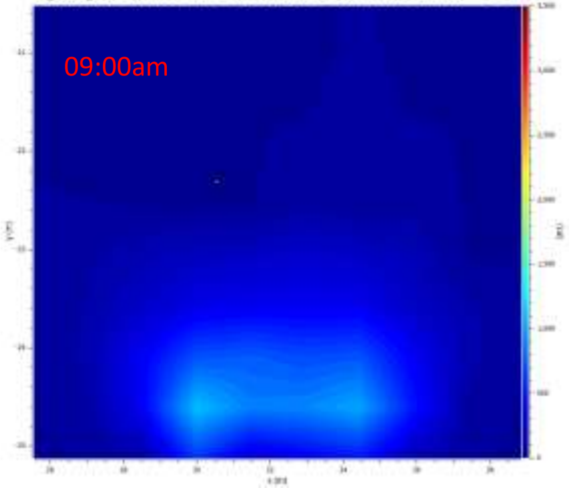
Figure 11 Relative performance comparison of lighting measure alternatives

Analysis of Daylight Illuminance Maps

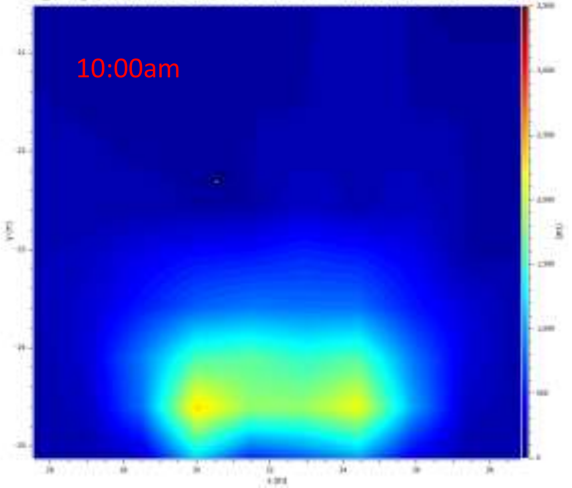
Lighting Alternative 04 - 1st Floor East - Reference Point = 18 Lux



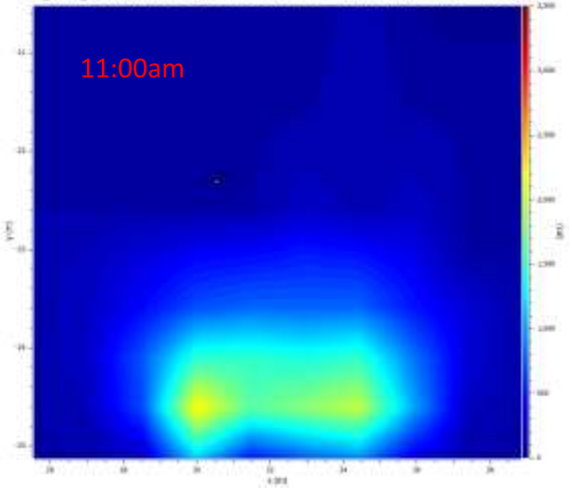
Lighting Alternative 04 - 1st Floor East - Reference Point = 51 Lux



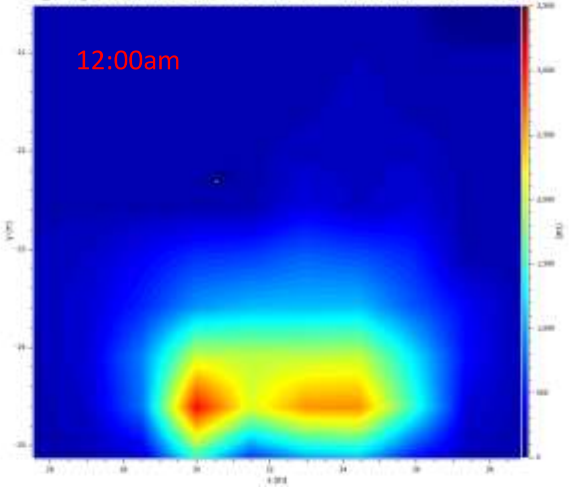
Lighting Alternative 04 - 1st Floor East - Reference Point = 109 Lux



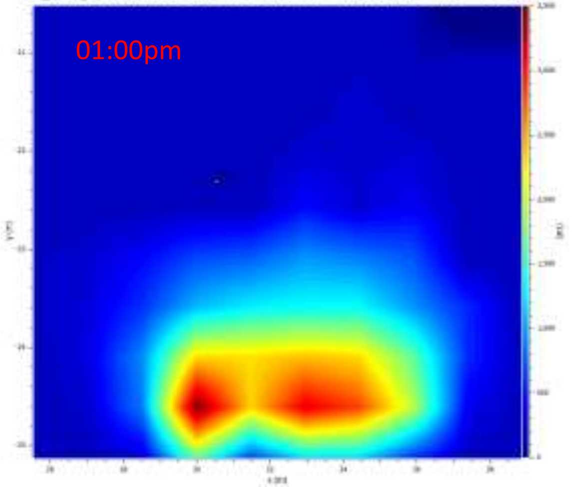
Lighting Alternative 04 - 1st Floor East - Reference Point = 103 Lux



Lighting Alternative 04 - 1st Floor East - Reference Point = 140 Lux



Lighting Alternative 04 - 1st Floor East - Reference Point = 168 Lux



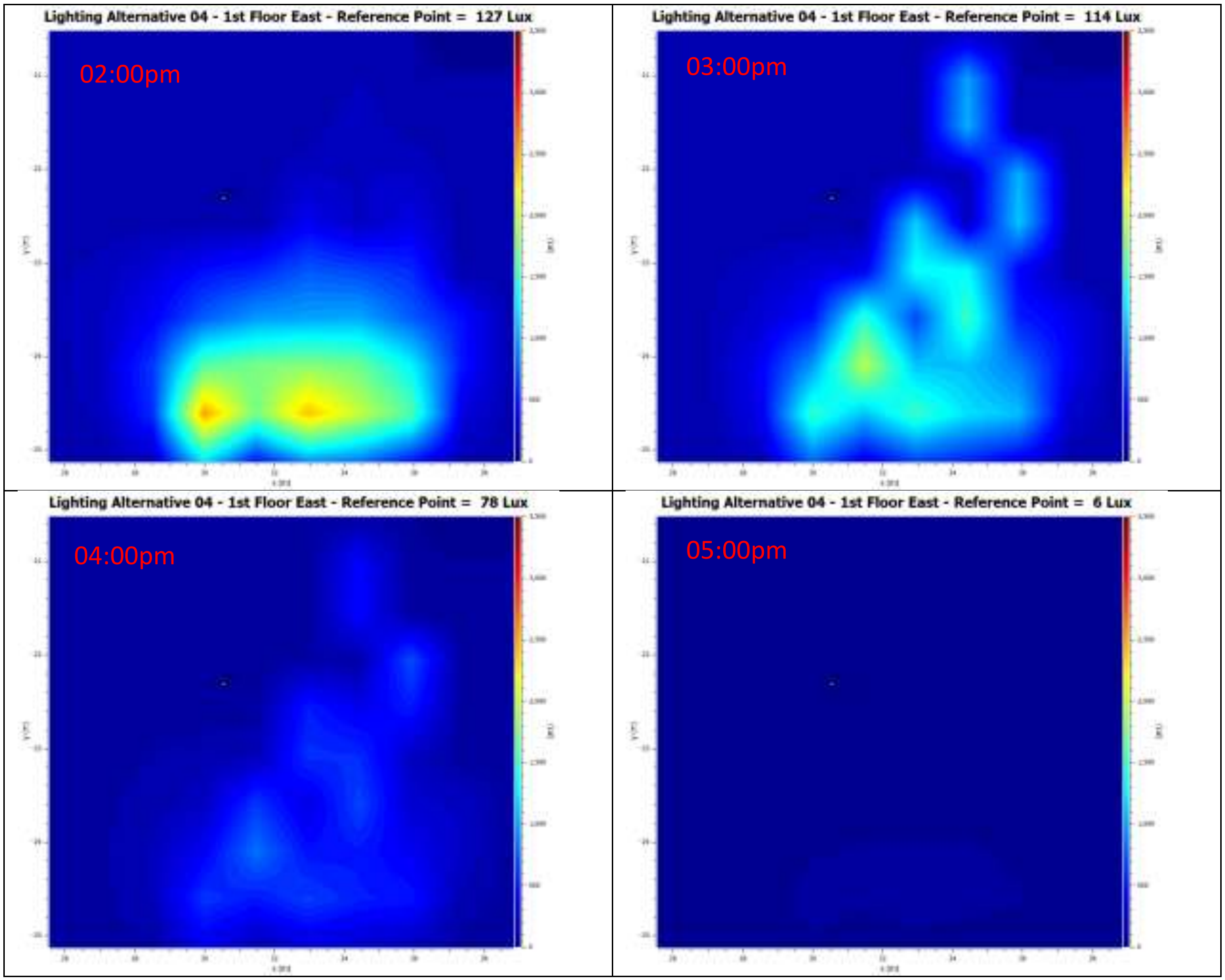


Figure 12 Series of daylight illuminance maps for 1st Floor East perimeter office zone

Figure 12 shows a series of daylight illuminance maps (for a single day for working hours of 8am to 5pm) for a perimeter office zone (1st Floor East). Daylight maps are initially defined as grid points before the start of a simulation run in EnergyPlus v6.0. The program then calculates daylight illuminance levels at each node of this grid as saves results for each hour of simulation as SQ Lite database. Visualizations are then made by the use of Open Studio Results Viewer program [3] that reads values from the database and associates reading with a color scale.

Results given above are pertaining to Alt-04, and they indicate the daylight illuminance level at reference points (coinciding with daylight sensor points). It is seen that for that particular day (December 5th) maximum illuminance is calculated as 168 lux which contributes about 33.6% of the total target illuminance of 500 lux. Daylight levels can fall down to 18 lux at 8am, and 6 lux at 5pm indicating increased use of electric lighting for that particular times of the day. Another observation is that daylight levels at grid points right next to windows can increase up to 3.5 times regular 500 lux comfort level indicating a possibility of visual discomfort which is not fully controlled by the assumed shading device. Visible transmittance of the selected shading device should be analyzed in a greater detail.

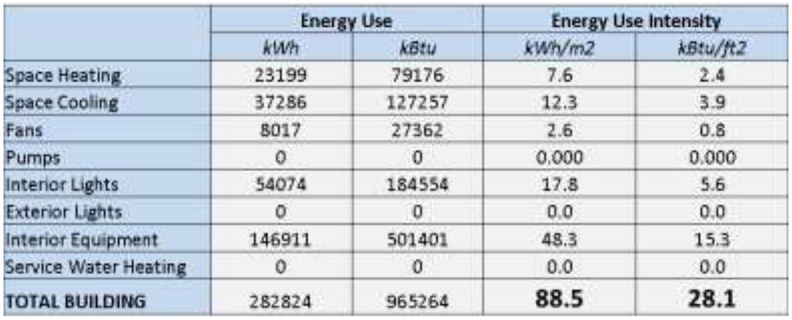
Combination Daylighting Alternatives with High-Performance Enclosures

Since all the lighting design alternative models discusses above assumes baseline inputs for all other components except lighting system and controls, it is found to be necessary to develop a couple of combination models which merge high-performance enclosures (assessed during earlier parametric analysis conducted earlier) with high-performance daylight measures (investigate in current study).

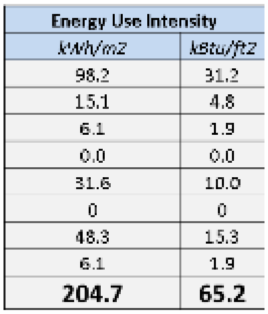
The first combination model is “building_661_comb_v1” and has the following design features:

- Walls = R-30 IP
- Roofs = R-30 IP
- Glazing = Double Low-E Argon R-4.9 IP, SHGC 0.50
- Air Infiltration = ACH 0.255
- Daylighting = Task-Ambient Separated, .25/.25 W/ft^2, interior roller shades, target illum. = 250 lux)

Table 5 Comparison of combination model 01 with the baseline



	Energy Use		Energy Use Intensity	
	kWh	*kBtu*	*kWh/m2*	*kBtu/ft2*
Space Heating	23199	79176	7.6	2.4
Space Cooling	37286	127257	12.3	3.9
Fans	8017	27362	2.6	0.8
Pumps	0	0	0.000	0.000
Interior Lights	54074	184554	17.8	5.6
Exterior Lights	0	0	0.0	0.0
Interior Equipment	146911	501401	48.3	15.3
Service Water Heating	0	0	0.0	0.0
TOTAL BUILDING	282824	965264	**88.5**	**28.1**



Energy Use Intensity	
kWh/m2	*kBtu/ft2*
98.2	31.2
15.1	4.8
6.1	1.9
0.0	0.0
31.6	10.0
0	0
48.3	15.3
6.1	1.9
204.7	**65.2**

Combination of high-performance enclosure model features with high-performance lighting model (reduced LPDs with daylight controls, and reduced target illuminance – 250 lux) can result in a total annual building energy savings of 56.7% Significantly increased envelope air-tightness (0.255 ac/h on average) combined with high-performance double low-e argon glazing and R30 walls and roof can instantly reduce space heating EUI from the level of 98.2 kWh/m^2 down to 7.6 kWh/m^2. Only marginal reduction is observed for cooling energy. Efficient and daylight-linked lighting systems can provide 43.6% energy reduction for lighting purposes.

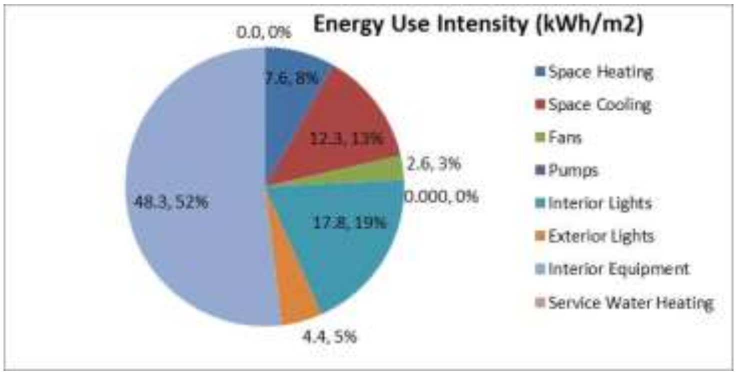


Figure 13 Annual end-use energy breakdown of combination model 01

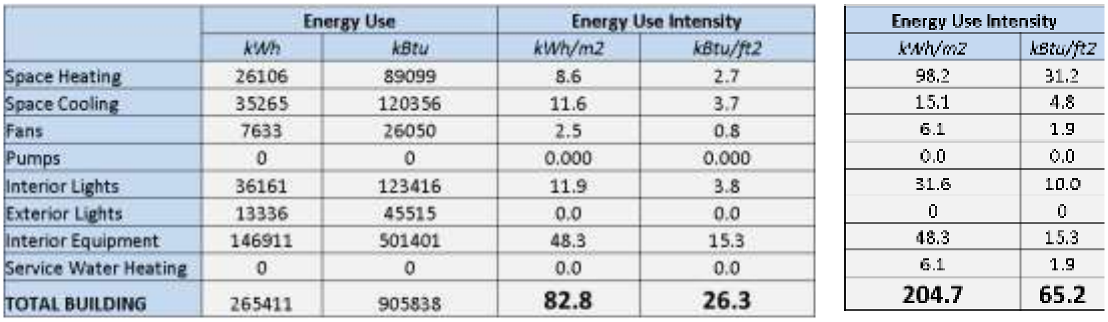
After all necessary energy reductions, annual end-use energy distribution (Figure 13) indicates the dominance of office equipment energy consumption, followed by interior lighting systems.

The second combination model is “building_661_comb_v2” and has the following design features:

- Walls = R-30 IP
- Roofs = R-30 IP
- Glazing = Double Low-E Argon R-4.9 IP, SHGC 0.50
- Air Infiltration = ACH 0.255
- Daylighting = Task-Ambient Radical Separation, .25/.25 W/ft^2, interior roller shades, target illuminance = 21.5 lux)

The main difference between the combination models is that the second model explained here has daylight target illuminance of 21.5 lux instead of 250 lux. The reduce target value represents the concept of moon-light ambient light illuminance concept generated during expert workshops of Task 3.

Table 6 Comparison of combination model 02 with the baseline



	Energy Use		Energy Use Intensity		Energy Use Intensity	
	kWh	kBtu	kWh/m2	kBtu/ft2	kWh/m2	kBtu/ft2
Space Heating	26106	89099	8.6	2.7	98.2	31.2
Space Cooling	35265	120356	11.6	3.7	15.1	4.8
Fans	7633	26050	2.5	0.8	6.1	1.9
Pumps	0	0	0.000	0.000	0.0	0.0
Interior Lights	36161	123416	11.9	3.8	31.6	10.0
Exterior Lights	13336	45515	0.0	0.0	0	0
Interior Equipment	146911	501401	48.3	15.3	48.3	15.3
Service Water Heating	0	0	0.0	0.0	6.1	1.9
TOTAL BUILDING	265411	905838	**82.8**	**26.3**	**204.7**	**65.2**

Reduction of target daylight illuminance has indirect effects of slightly increased space heating energy when space cooling energy is slightly decreasing due reduced internal heat gains from electric lighting system. For combination model 02, lighting energy gain is increased to the level of 62.3%. Total building energy analysis reveals energy saving of 59.7%.

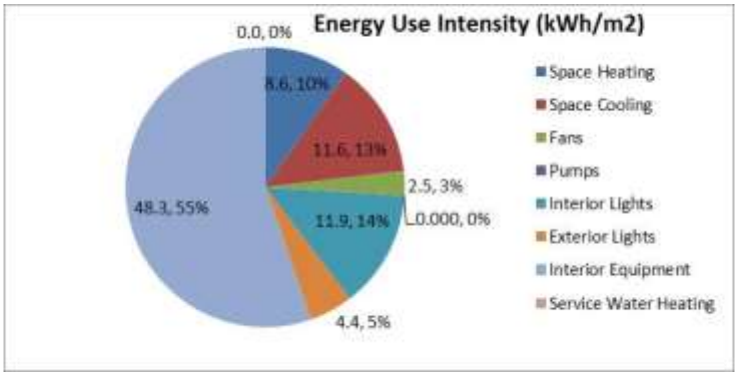


Figure 14 Annual end-use energy breakdown of combination model 02

Similar to combination model 01, this model option also shows the increased share of office equipment energy consumption which is followed by interior lights and space cooling.

6. Conclusions

Various lighting design scenarios than can be applicable to energy retrofit projects and generated during GPIC Task 3 export workshops (on lighting and enclosures) are evaluated trough detailed daylighting simulations (with EnergyPlus v6.0) of this study. Combinations of a high-performance enclosure case with two different lighting design scenarios are also simulated so as to provide decision support on best-case design models. Below are given some key findings of this study;

- Separation of ambient and task lighting together with reduced LPDs (as a consequence of high-efficient lighting fixture design) have the largest effect on the reduction of lighting energy consumption.
- Decreasing target daylight illuminance levels has minor effects on lighting energy reductions.
- It will be more effective to consider lighting design measures in combination with a high-performance envelope (especially optimize glazing systems – with reduced U-factors and a balanced SHGC levels)
- Separation of ambient and task lighting (with LPDs of 0.25 W/ft^2 assumed for both) and linking electric lighting system with daylight controls (with a target illuminance of 250 lux) and combining such as system with R30 walls and roofs and air-tight envelope (0.255 ac/h) with the inclusion of double low-e argon windows can result in 56.7% of reduction in annual total building energy consumption.

Future studies on this topic can be simulation of Building 661 case with more sophisticated daylight simulation programs (Radiance-based) so as to obtain other performance indicators (PIs) pertaining to visual comfort (Daylight Glare probability) as well as lighting system performance (such as Daylight Autonomy levels). Effect of shading device visible and solar transmittance on daylight conditions and related visual comfort levels can also be investigated in more detail.

References

[1] U.S. DOE BTP (Building Technologies Program). 2011. "EnergyPlus v6.0 Energy Simulation Software: The Encyclopedic Reference to EnergyPlus Input and Output".
[2] Augenbroe, G. 2011. "The role of simulation in performance based building". *Building Performance Simulation for Design and Operation.* Edt. Jan L.M. Hansen and Roberto Lamberts. Spon Press. London-New York.
[3] U.S. DOE BTP (Building Technologies Program). 2011. "Open Studio Application Suite". Accessed on January 02 2012. http://apps1.eere.energy.gov/buildings/energyplus/openstudio_suite.cfm