Dynamic lighting and cooling demand simulation in an urban context

Patana Rattananavathong[1]**, Phil Jones**[1,*] **and Simon Lannon**[1]

[1] Welsh School of Architecture, Cardiff University, UK, [*] jonesp@cardiff.ac.uk

Abstract: The conventional building simulation method places the sensor at centre of the room to control the lighting output of the whole room without considering urban context. In the practical situation, sensors will be placed in a position that control a zone of light fixtures. This research aims to propose a new method for optimising the daylight sensor position in different urban contexts and creating a lighting output schedule from those sensors for use in dynamic building energy simulation. The model shows the most optimal position to place daylight sensor for each orientation and urban context and at which point more overshadowing increases energy consumption. This research also shows that building simulations without and with context can produce different results for energy consumption of up to 30%.

Keywords: parametric, daylight sensor position, building energy simulation

Introduction

Lighting in office buildings is one of the design components that has effect on both lighting and cooling in term of energy consumption. Thailand is located in a warm and humid climate zone, which needs cooling to produce an environment to meet occupant satisfaction. Artificial lighting is needed to provide the necessary illuminance levels to meet the user needs, which contributes to the space cooling load due to the heat releases from light fixtures. So, reducing lighting loads also reduces the cooling load. The use of daylight can offset the level of artificial lighting, but this can incur solar gains that again may increase the space cooling load. Office design and the level of glazing therefore needs to be considered in the context of the balance between daylight, artificial lighting and solar gains, to provide a satisfactory energy efficient visual environment.

Previous research (Li and Lam 2001; Franzetti, et al. 2004; Ghisi and Tinker 2005; Krarti, et al. 2005; Li, et al. 2006; Roisin, et al. 2008) have shown that daylighting can help to reduce the needs for artificial lighting. However, only Freanzetti, et al. (2004) takes into account of the cooling loads whereas others focus only on lighting loads. There are mainly three methods to estimate the potential for reducing lighting loads

Field measurement

The first is the field measurement for lighting levels in actual buildings. Li and Lam have investigated the potential of a dimming control system by based on a case study office building in Hong Kong (Li and Lam, 2001). The research provided accurate result from empirical data collection. However, the research also illustrated limitations such as time frame, orientation and design variations. The measurements were carried out for four months from November to February with only North and South orientations. Li, et al. also used actual building in Hong Kong for measuring dimming control system (Li, et al., 2006). The measurements were carried out over seven months from February to August, with a single lighting sensor position in the measured office. These examples indicate that field measurement of light dimming control systems can provide accurate data but with limited constraints such as time frame of the measurement and the building configuration.

The field measurement method can also perform some real-world scenarios that is relatively complex to implement in simulation such as integrating user behaviour into the variables (Aghemo, et al., 2014 and Chraibi, et al., 2016). Nevertheless, the results from the research are context-specific as Li, et al. (2006) has stated that the results are applicable only to the building with similar layouts and systems.

Combined field measurement and building simulation

The second method is a combination of field measurement and building simulation. Research (Franzetti, et al. 2004; Ghisi and Tinker 2005) have shown the use of field measurement to validate the results from simulation to increase the the reliability with empirical data measurement. Ghisi and Tinker (2005) have extensively shown the potential of using the simulation program, VisualDOE, for thermal simulation and daylight, using the daylight factor calculation method proposed by Hopkinson, et al. (1996). Daylight factor calculation can be carried out for a range of reference points in a space, and compared to measurements at a light sensor position, by taking into account of the sky component, the external reflected component and the internal reflected component. The simulation was performed with 1,100 cases consist of 5 room ratios, 10 room dimensions, 11 window sizes and in two locations, Leeds (UK) and Florianopolis (Brazil). The research shows relatively reliable results using VisualDOE, with an average of 0.4% difference from field measurements. Daylight measurements were performed over four days during February on the roof of the Civil Engineering Building, University of Leeds, UK. Frenzetti, et al. (2004) used a slightly different approach for validating daylighting result. Daylighting calculations were carried out using the LIGHT calculation module. The validation was achieved by comparing lighting levels from LIGHT with measured lighting levels from the laboratory located in Research Centre of EDF, Les Renardieres, France. The results showed a good correlation rate of 0.9 for lighting levels below 1,000lux, which is in the range that has impact on dimming control system. This comparison was carried out to validate the LIGHT calculation module, which Frenzetti, et al. (2004) used later in the research to simulate daylighting levels in various scenarios.

Pre-validated building simulation

The third method for investigating a dimming control system is to use a pre-validated building simulation program. Roisin, et al. (2008) has shown the use of a simulation program to the extent that simulates lighting levels for Brussels, Stockholm and Athens with six variations of control system for all four directions of North, South, East and West. The lighting simulation was carried out using Daysim, which as Rosin et al. (2008) has been validated in a number of previous research studies (Reinhart and Herkel 2000; Reinhart and Walkenhorst 2001). Bodart and Herde (2002), Krarti, et al. (2005) and Roisin, et al. (2008) have also shown the capabilities of using a simulation program to analyse various variables such as shapes, window sizes, orientations and locations.

Roisin, et al. (2008) has shown a relatively high lighting energy saving that ranges from 45 to 61%. Each light fixture in the research has its daylight sensor. This practice can produce the highest energy reduction possible. However, this may be unpractical for an open plan office to have a daylight sensor for every light fixture.

Bodart and Herde (2002) also shows a high lighting energy reduction from 50 to 80%. Bodart and Herde stated that it was because “the light sensor is located in the center of the room.”. Placing daylight sensor at the centre of the room to control the whole room causes the deeper area away from the window to have the light intensity lower than the setpoint. Hence, the larger the room the higher the reduction. Mistrick, et al. (2000) has also shown an extensive use of Daysim with two lightsensor positions coupling with twenty-tree conditions to test eight different daylight sensor behaviours

Table 1: Shows more details of how different methods were performed

Research	**Method**	**Model**	**Lighting System**	**Context**
Li and Lam, (2001)	Field measurement	Width 2.8m x Length 4.5m x Height 2.4m Facing North and South	- Two light sensors per room. A sensor controls two or three light fixtures. - From November 1999 to February, March and April 2000	Fixed context
Li, et al., (2006)	Field measurement	Width 10.29m x Length 5.88m x Height 2.39m Facing North West	- One light sensor controls a zone - From February to August 2004	Fixed context
Franzetti, et al., (2004)	Mixed	Width 3m x Length 6m x Height 2.35m Facing North, East and South	- LIGHT - Laboratory measurement was performed to compare with result from LIGHT - Nine light sensors across the room	Clear
Ghisi and Tinker, (2005)	Mixed	2:1, 1.5:1, 1:1, 1:1.5 and 1:2 room ratios Facing North, South, East and West	- BRS Simplified Daylight Table - Light sensor at the centre of each 50cm x 50cm grid across the room	Clear
Krarti, et al., (2005)	Simulation	Width 3.8m x Length 3.7m x Height 2.7m Facing North, South, East and West	- DOE-2.1E - Light sensor at centre of the room controls the whole room.	Clear
Roisin, et al., (2008)	Simulation	Width 3.05m x Length 6.55m x Height 3.05m WWR 33% Facing North, South, East and West	- Daysim - One light sensor controls one light fixture	Clear

The development report and case studies from Architectural Energy Corporation (AEC, 2006) introduces the Sensor Placement Optimization Tool (SPOT) which has the option to generate the optimal photosensor positions. In the SPOT program, there is a button stated 'Auto-Generate Photocell Position'. However, what it does is performing correlations between the illuminance of selected point in the zone and the illuminance of 315 ceiling grid points. According to the SPOT Version 5.0 User's Manual (Daylighting Innovations), the position generated from the auto-generate sensor position would be the default location. This method is useful to the ceiling type photosensor with the selected point represents the specific working position.

Problem statement and aim

Across the three methods previously explained, there are three main practices to control lighting output from daylight sensor. See Table 1.

1. A single sensor located at the centre of the room which controls the lighting for the whole room. Simulation methods often use this practice to estimate the energy reduction from utilising daylighting. However, positioning the sensor at centre of the room, to control the lighting output for the whole room, will generally result in the deeper area of the plan having a light intensity lower than the required set-point. Moreover, the inefficiency of a sensor increases as the sensor has less sky-view angle (Bodart and Herde, 2002), which implies that the sensor should be closer to the window to increase its efficiency.
2. A single sensor controls one light fixture above it. This practice is also sometimes used in simulation-based research (Rosin, et al. 2008). This pratice often results in a high energy reduction rate, although, it is not often used in an open plan office where the location of office desks are not known or often move around.
3. A single sensor controls a zone of light fixtures. This practice is widely used in real world situation and field measurement-based research. Nevertheless, results are often case-specific and less generalise comparing to practice a and b, as seen in Table 1 that the room sizes are small and the time frame spans only a few months.

For simulation-based research, positioning the lighting sensor other than at the centre of the room or at the centre of every grid points across the room is hard to determine because there is no guideline for it yet. Furthermore, context, which should play a major role, is often excluded from the simulation. These two notions have led to the research described in this paper, which aims to propose a new method for optimising the daylight sensor position in different urban contexts and creating a lighting output schedule from those sensors for use in dynamic building energy simulation.

Methodology

There are two steps in this research. The first is to find an optimum position of daylight sensor and establish the parameter of the circuit. The second is to use the selected sensor position and the zone each sensor controls in energy simulation. The research has considered 115 configurations, using two sets of variables. The first set is a range of window areas, namely, 20%, 40%, 60%, 80% and 100%. The second set of variables is the urban context configurations of surrounding buildings, with some 23 configurations of heights of surrounding buildings.

To achieve the aim, this research has used a parametric modelling tool called Rhinoceros and Grasshopper (McNeel, 2007) to investigate energy consumption (lighting and cooling) from different lighting senor positions and building configurations. The Ladybug and Honeybee plug-in is used to connect the model with Daysim for daylighting simulation (Roudsari, et al., 2013). The results from Daysim are then transferred to grasshopper to optimise daylight sensor position. These positions are used to create lighting output schedules parametrically using a meta-file to create text-based input for dynamic building energy simulation, using the HTB2 building energy model (Lewis and Alexander, 1990). The details are explained in following sections.

Model

A high-rise office with a typical floor plan of 40 x 40 m with a 3.5 m floor to floor height has been studied (Chirarattananon and Taveekun, 2004; Kofoworola and Gheewala, 2008; Yanwaidsakul and Sreshthaputra, 2013). Wall to window ratios (WWR) range from 20% to 100% in 20% steps. The space has five zones; facing North, South, East, West and a 20 x 20 m core.

Context conditions

The urban context condition used in this research is Bangkok, Thailand. According to the building regulation (Ministerial Regulation No.55 (B.E. 2543) (A.D. 2000)), high-rise building has to have at least 6 metres set-back from the site boundary. The condition can be simplified into the context factor (1). The increment of the factor starts at 0.5 and increases in 0.5 steps, which represents the height of surrounding building at 6 meters and distance at 12 meters to the *CF* at 11.5 which represents the height of surrounding building at 138 meters (40 storey) and distance at 12 metres.

$$\text{Context Factor } (CF) = \Delta H/D \qquad (1)$$

where: ΔH = difference in height between the zone and surrounding building; D = distance between the buildings.

Finding daylight sensor positions

Light intensity near the window or light source is always higher than the further from the window or the light source. This behaviour means that if the light intensity at the given point is above the set point, the area closer to the window would always have the light intensity over the set point. This notion means it is reasonable to have a sensor control the area closer to the window but not deeper since the deeper area would have lower light intensity than the set point. Li D.H.W., et al. (2006) has also used daylight sensor to control parameter with this logic but the sensor position was not placed at the most optimal position.

$$DPV = 1; \text{ if light intensity is above the setpoint} \qquad (2)$$
$$DPV = \text{light intensity/setpoint; if light intensity is below the setpoint}$$

For the first step in this research, test points are placed every 0.5m starting from 0.25m distance from the window at 0.75m above the floor. Annual daylight simulation was performed by using Daysim through Honeybee. Then, the light intensity of each test point is converted to daylighting potential value (*DPV)* by dividing by 500, if the intensity is below 500lux. If the intensity is above 500lux, the daylight potential value is 1.0, where 500lux is the lighting set-point (2). This conversion gives out the daylight potential value for positioning daylight sensor which would be at the point with the highest value. All daylight potential values for the whole year are added together for each point. Each point then multiplies with the area that it would control the lighting output (3). The result then shows that although the test point that is closer to the window has higher daylight potential value but with smaller area it covers, its true potential after multiplication is lower than other positions with lower daylight potential value but higher coverage area (Figure 1).

$$True\ Potential = A*DPV \qquad (3)$$

where: A = the area that the daylight sensor controls the light circuit; DPV = Daylight potential value

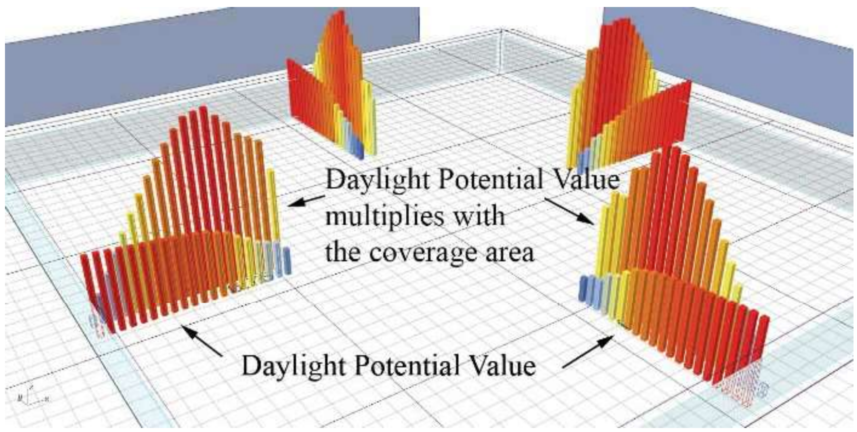

Figure 1: Shows the visual of daylight potential value on each testing *point*

The daylight sensor positions and the zone that each one covers are selected from the position with the highest value for each orientation and each *CF*.

This study uses Grasshopper and Honeybee to perform the lighting simulation for various reasons. The first and foremost is the coupling between Grasshopper that can perform brute force to number sliders which will initiate all simulations at one go and Daysim that export the result of each simulation into *.ill files, which are text files, in each separated folder. The authors then ran a Python script to read the results from *.ill files later without interrupting the continuing daylight simulation. Running each task separately reduces the amount of time to fix the error if occurs.

Grasshopper is also capable for reading the result back to create visualisation such as shown in Figure 1 or, in this study, to create schedules for performing energy simulation later in HTB2s.

Schedule and power output

This research uses schedule profiles for from ASHRAE 90.1 (2013). The lighting schedule for dimming control zone was created from combining the factor from lighting output ranges from 0.1 when the light intensity is at 500lux or higher and at 1.0 when the intensity is at 0lux. The output factor from daylight intensity is only used for 8-12 and 13-18 hour of weekday. The rest of the hours use ASHRAE 90.1 (2013) which lighting schedule was added with 5% emergency lighting. ASHRAE 90.1 (2013) also provides lighting schedule with occupancy sensor but occupancy sensor is not within the scope of this study.

Power outputs in this study are 8W/m^2, 10W/m^2 and 70W/person for lighting, equipment and occupancy with 10m^2/person (CIBSE, Guide A, 2006). Total energy consumption consists of the on-site consumptions (end-uses) of lighting, cooling and equipment.

Energy simulation

The second step of this study is to perform the dynamic energy simulation to see the result of this daylight positioning method in context. The modelling consists of five zones per floor with two lighting circuits, dimmable and non-dimmable, for North, South, East and West. The areas of each dimming control zone for each window size and *CF* are different as well. HTB2 was used for performing building energy simulation for various reasons such as, the model is in a text format which is relatively easy to make changes and create cases parametrically. HTB2 is also able to handle the dynamic change of lighting schedule because the way HTB2 controls the of power outputs.

In HTB2, the power output of each lighting circuit is specified by the total amount of power output not by the area and one zone can also have multiple circuits. This feature allows model of the zone to be the same but only change the amount of power output for dimming control circuit and non-dimming control circuit. The schedule of each circuit is specified within the lighting file using the factor where 1.0 is 100% and 0 is 0% power output. Furthermore, the schedule can be override for more detailed control in DIARY files, where each DIARY file contains the schedule of each day with in the year.

Since HTB2 uses text-based files for modelling, they can be produced by using meta-file method (Fragaki, et al., 2008). The authors used python, a programming language, to create scripts that produce HTB2 files from meta files. All simulations were run by using one batch file that was created later according to the directory of HTB2 files.

Fragaki, et al. (2008) and Glazer (2016) show that EnergyPlus, a building energy simulation program, can also perform a similar technique. However, in this study, HTB2 has some advantages over EnergyPlus. EnergyPlus file is a single IDF file, whereas HTB2 files are separated into smaller files. One HTB2 file contains only a few lines of information. This characteristic allows HTB2 files to be created from meta files more efficiently because the script does not have to go through many lines to modify the target variables. Some HTB2 files that has no change can be copied and pasted in to the destination folders right away. DIARY files in HTB2 create schedule for each day. EnergyPlus can also have each schedule for each day but with more complexity and a larger IDF file.

In summary, HTB2 and meta-file method allow authors to create models and run simulations with minimal effort.

Limitation

The major limitation in this work is that the study did not include the blinding in one of the variables. The authors are aware of the blinding feature that is already existed in DAYSIM. However, the use of blinding depends on either glare or energy intensity, 50 W/m^2, on a given point is generally tested in closed plan space. This research used open plan space as a case study which is different in characteristic. Moreover, the main aim of this research is to propose a new method for optimising the daylight sensor position in different urban contexts. Blinding and any type of shadings are outside the scope of this research.

Results and discussion

While the aim of this research is to propose a new method for optimising the daylight sensor position and creating schedule for building simulation, the energy consumption is a byproduct of the methodology. Hence, there are three aspects of results the authors would like to present; position of the sensor under different configurations, relationship of lighting load and cooling load and the last is the performance of total energy consumption.

Daylight sensor position

Table 2 shows nearest and furthest daylight sensor positions for the lowest and the highest *CF* of each orientation and WWR. The daylight sensor position ranges from 6.75m for the South side with a 100% WWR with 0.5 *CF* to 0.75m for West, South and East with 20% WWR with a 11.5 *CF*. The result also shows that 80% and 100% WWR have the same sensor positions. This is because the larger window area from 80% to 100% WWR does not increase sufficient daylight potential value and also perform worse for overall energy consumption due to more solar heat gains through the window. Another reason 100% WWR has the same sensor positions as 80% WWR is because the limit of the height of the window. This means that if the shape is taller, it is possible that the sensor could be deeper.

The daylight sensor positions are closer to the window when overshadowing increases at a different rate for different orientations. However, at around *CF* 3.0 to 5.5, all orientations have the same depth of the sensors (Figure 2). This behaviour happens because the sensor starts to receive only diffuse daylight which is the same in all directions. All WWRs have similar characteristic with the example of 60% WWR in Figure 2 because the size of the window only determines the amount of daylight coming through, which similar to having higher *CF*.

Table 2: Shows closest and furthest daylight sensor position depth from window in metre (m)

WWR	CF	North	South	East	West
20	**0.5**	1.75	1.75	1.75	1.75
	11.5	1.25	0.75	0.75	0.75
40	**0.5**	3.25	3.25	3.25	3.75
	11.5	1.75	1.75	1.75	1.75
60	**0.5**	5.25	5.25	5.25	5.25
	11.5	2.75	2.75	2.75	2.75
80	**0.5**	6.25	6.75	6.25	6.75
	11.5	3.25	3.25	3.75	3.25
100	**0.5**	6.25	6.75	6.25	6.75
	11.5	3.25	3.25	3.75	3.25

Relationship of lighting load and cooling load

More overshadowing from urban context, higher *CF*, increases lighting load from lesser daylighting availability and at the same time decreases cooling load from lesser solar gain. However, lighting load starts to overtake cooling load around *CF* 2.0 to 3.0 as shown in Figure 3 where Cooling + Lighting starts to incline.

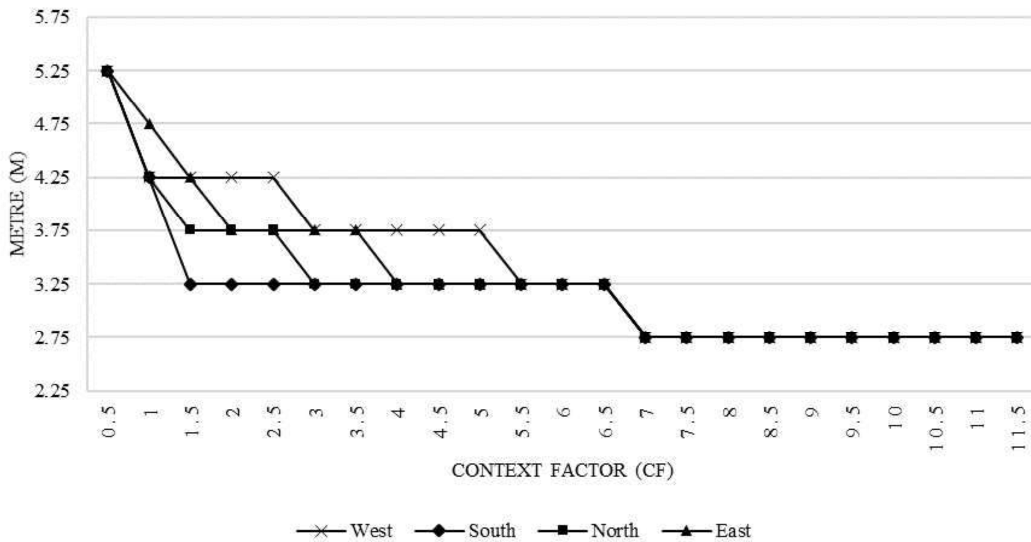

Figure 2: Shows sensor positions for WWR 60% with different CF

Figure 3 also shows another crucial notion which was stated in previous section that doing building simulation without context can lead to a difference. The result shows that the case with higher WWR has higher different in energy load between *CF* 0.5 and 11.5. The different from lighting load can be up to around 30%, 30%, 25%, 15% and 10% for WWR at 100%, 80%, 60%, 40% and 20%, respectively. Cooling loads also show similar differences from 10% to 25%. The result correlates with Samuelson, et al., (2016) which says that the different in energy consumption from building simulation between with and without-context ranges from 8 to 31%.

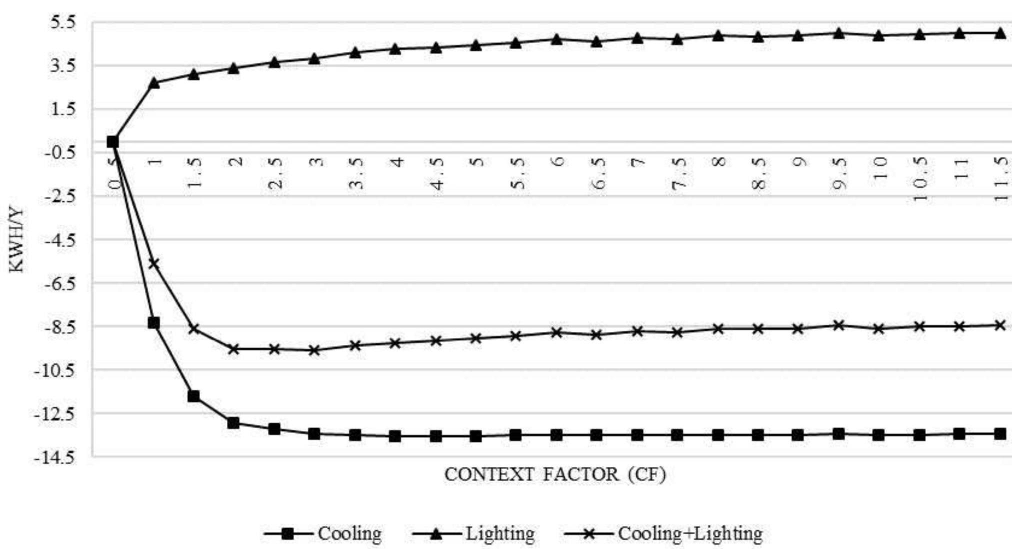

Figure 3: Shows energy consumption of cooling, lighting and both cooling + lighting

Total energy consumption

Total energy consumptions from all orientations with daylight sensor show similar characteristic which the consumptions drop to a certain point and then start to incline (Figure 4). The result shows that the lowest energy consumption is reached when the *CF* is around 2.0 to 3.5 then, the consumption increases as overshadowing increases. This is caused by the increased level of lighting loads preceded by a reduction in cooling load from overshadowing as shown in Figure 3.

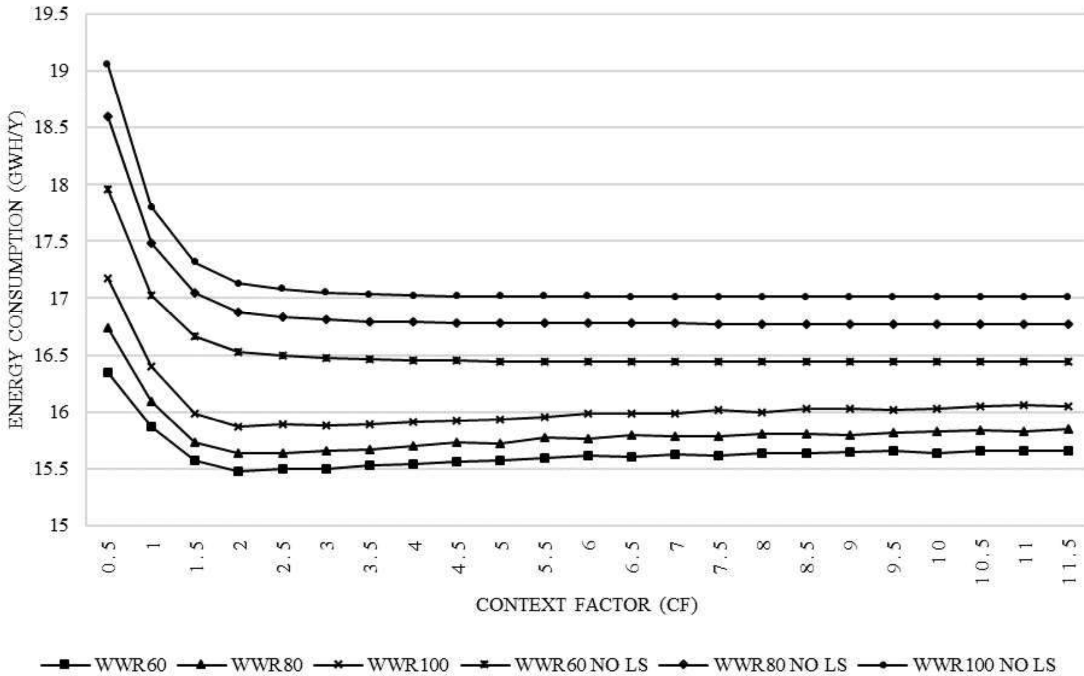

Figure 4: Shows total energy consumption of cases with and without light sensor

The energy consumption from 100% WWR is higher than 80% WWR with the same daylight sensor positions means that the exceeded energy consumption comes from the heat gain through fabric with a little to no benefit from daylighting.

Figure 4 also shows the different between cases with daylight sensor and without daylight sensor. The result shows that implementing daylight sensor reduces more energy than decreasing window size even at the high *CF*. The reductions for cases without daylight sensor are purely from overshadowing which continue to decrease but with a slower rate as *CF* increases.

Conclusion

The aim of this research is to propose a new method for optimising the daylight sensor position within the different urban contexts and creating a lighting output schedule from those sensors for use in dynamic building energy simulation. This has reflected the aim by first, reviewed some literatures which show that there are some problems and limitations with implementing daylight sensor in both simulation-based and field measurement-based research.

Then, the methodology was formed into two steps. Frist is to find the most optimal position for placing the daylight sensor and then perform building energy simulation to see the result in different contexts.

The first step shows that daylight sensor position is closer to the window when there is less daylight availability either from overshadowing or smaller window area. The position depths from the window ranges from 0.75m to 6.75m depends on the orientation, window size and context.

The results show that the area of the building with a *CF* less than 2 should improve its overshadowing until it reaches the same as *CF* of 2. On the other hand, the area with a *CF* more than 2 should consider improving daylight utilisation to reduce lighting loads and cooling loads.

This research also shows that building simulations without and with context can produce different results for energy consumption of up to 30%.

Recommendations for further work

This daylight sensor positioning method should be tested against other methods such as one sensor per one light fixture in various dimensions especially the cost efficiency of the system.

The method should be investigated with wider range of variables such as external shadings and contexts or couple with behavioural models (Bourgeois, et al., 2006). There might be the point where daylight sensor is not sufficient to implement anymore. There might also be the situation with some fabric materials or different lighting power levels that the daylight sensor is not cost effective anymore.

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