COUPLING BUILDING ENERGY AND LIGHTING SIMULATION

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ABSTRACT

In this paper, a new method of *direct run - time coupling* between building energy simulation and global illuminance simulation is outlined and discussed. Direct coupling at the time step level between *ESP-r* and *RADIANCE* provides building energy simulation with access to an internal illuminance calculation engine, thus enabling modelling of the complex interactions between artificial lighting control and the rest of the building energy domain in a fully integrated way.

INTRODUCTION

The way in which daylight is provided in the buildings will, in most cases at least, determine the quality of the indoor environment as well as the necessary auxiliary energy consumption for the building environmental control systems.

The quality of daylight is deterministic for building occupant satisfaction with their visual environment, thus directly influencing their well being and productivity. The quantitative parameters of daylight, on the other hand, are reflected in the energy costs attributed to the building environmental control systems such as artificial lighting, heating and cooling, as well as the environmental pollution caused by the power generation.

The importance of daylight quality and quantity in buildings is widely recognised. Currently there are a large number of international and national research and development activities. *DAYLIGHT EUROPE* [1] and *IMAGE - IMPLEMENTATION of ADVANCED GLAZING in EUROPE* [2] are only two examples of such activities.

In these projects, building energy simulation techniques are being employed within computer tools capable of delivering *INTEGRATED PERFORMANCE VIEW's* [3] of the complex building systems. Here, one of the number of remaining challenges to the building simulation community is artificial lighting control modelling in a fully integrated way with the rest of the problem domain.

BACKGROUND

To be successful in predicting building integrated performance all important energy interactions must be included and modelled at a sufficient level of resolution and accuracy. In this respect, artificial lighting control modelling based on the availability of daylight requires predictions of the time varying internal illuminance/luminance in the complex 3D building geometry, within which a number of different light transfer mechanisms will take place. Further to this complexity, the building 3D geometry may change in time (e.g. blinds movement) as a result of the complex *climate - building - systems - occupant* interactions.

The *CIE* overcast and clear sky *daylight factor* method is dominantly used in contemporary building energy simulation programs to model artificial lighting control. Many different methods are applied to calculate daylight factors, ranging from simple analytical calculators [4], through more sophisticated daylight factor pre-processors [5] to special lighting calculation programs such as for example *SUPERLITE* [6]. Externally acquired daylight factors either from site measurements or detailed simulation programes can be used. So while simple calculation methods cannot be used to model complex building geometry and comprehensive light transfer phenomena, it is possible to use detailed simulation programs or measurement to determine daylight factors relatively exactly.

However, the *daylight factor* method has one serious drawback. As researched in [7], [8] daylight factors, even exactly determined, are far away from constant values. As has been shown in [8], the daylight factor ratios can vary considerably, even under heavily clouded skies. There was observed a range in the order of 1:5 between the lowest and highest ratios and the values of the internal illuminance predicted from daylight factors varied as much as twice or as little as half of the real levels. Thus as concluded by this study the daylight factor would be a poor predictor of the horizontal internal illuminance.

A similar experiment [7] focused on a comparison of a predicted versus measured internal illuminance and a yearly lighting energy consumption. The study showed that while some *daylight factor* methods might give good results for integrated yearly lighting energy consumption (low mean bias error), they are not as good in predicting dynamic variations in daylight illuminance as sky conditions and sun position alter. Here, mean square root errors as much as 40% have been observed for certain sky luminance distribution models.

Another area worth considering is lighting control simulation. The hourly climatic data in the *TEST REFERENCE YEARs* restrict our ability to model illumination variations to this time step. Although the statistical sky model in *SUPERLINK* [6] allows it to account for illuminance variance within this hourly interval, it provides only integrated values. Thus it does not have the ability to model control features such as *time integration constants* and *switch - off delay times*. Artificial lighting control responds usually in the magnitude of a couple of seconds (dimming) to 5 - 30 minutes (on - off). Thus using hourly averages will significantly alter dynamics of the system response. The significance of this aspect has not been fully quantified up till now and an attempt is made in this study.

On the other hand, the importance of lighting control algorithms, photo-cell vision solid angle and photosensor position in a room have been reported [9]. It was shown that these features of the lighting system will significantly influence their ability to provide the reference light levels, explicitly assumed to be met by all the current thermal simulation programs.

However elegant and relatively simple to implement *daylight factor* methods are, in many cases they will fail to simulate dynamic performance of the real lighting control systems. A more robust method, allowing for short time step daylight distribution variability, capable of coping with complex building geometry and comprehensive light transfer phenomena, as well as able to account for important lighting control settings, photosensor design and location is needed.

METHOD

As has been discussed in the previous section, the current status of artificial lighting control modelling suffers in predicting the dynamic behaviour of these control systems. Relatively high inaccuracies in predicting the internal daylight illuminance will result in inadequate switching or dimming. These inaccuracies will be carried through to the predicted dynamic history of a casual heat gain as well as the electric power demand of the artificial lighting.

The improvements required over the existing methods should allow for:

- Short time step dynamic variance in daylight source - sky luminance distribution as the function of available solar irradiation data;
- Generic building geometry - fully three dimensional as - built realistic shapes;
- Variable building geometry (e.g. shading or light redirecting devices movement);
- Comprehensive light transfer phenomena by multiple reflections and transmissions;
- Important artificial lighting control features as switch - off light level, switch - off delay time constant, photo-cell sensor construction and location;
- Integration of the artificial lighting into the global building energy and environmental system.

Building energy simulation is capable of coping with the integration of artificial lighting control into the global building energy and environmental system. On the other hand, recent developments in global illumination simulation [10] brought detailed lighting simulation programs capable of modelling complex geometry and generic light transfer mechanisms. Thus the method of directly *coupling energy and lighting simulation* seems to be promising one.

Two existing simulation environments have been selected, based on their abilities to fulfil a number of the particular objectives set up for this study. These are *RADIANCE* [10] as a global illumination simulation environment and *ESP-r* [4] as a building energy and environmental simulation environment. Both simulation tools are considered the *state-of-the-art* in their domains. They both run under *UNIX*™ operating systems which provides a powerful *multi - tasking* platform to allow the computationally intensive *run - time coupling* approach to be implemented. Further to this, both programs are freely available, well documented, and versatile research tools.

COUPLING SIMULATIONS

It is out of the scope of this paper to give a detailed discussion of the theory behind the building energy simulation represented here by *ESP-r* [4] and the global illuminance simulation represented by *RADIANCE* [10]. Both of these simulation environments are well established and reported in great detail elsewhere.

In the implemented approach of *direct run - time coupling* of *ESP-r* and *RADIANCE*, it is *ESP-r* which acts as the simulation controller and integrator. (Figure 1).

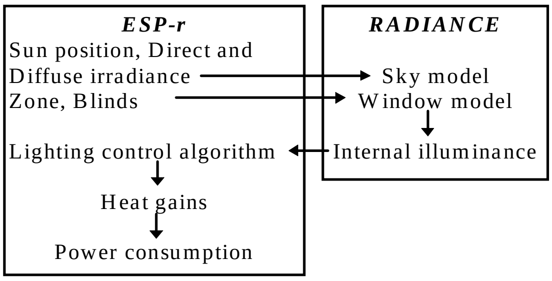

Figure 1. Information flows between thermal and lighting simulations at the time step level.

At each simulation time step (when lighting control is active and daylight available) the casual gain control algorithm initiates lighting simulation by transferring information about solar position, direct normal and diffuse irradiance, zone and blind characteristics.

The link between *ESP-r* and *RADIANCE* works as follows: Running a thermal simulation *ESP-r parent* process initiates a *child* lighting simulation *RADIANCE* process in the *foreground*. This causes the *parent* process to stop and wait until the *child* process finishes. The *child* lighting simulation process is initiated by running *RADIANCE* control script with a number of command line parameters:

timeillum *SALT* *SAZI* *DIR* *DIF* *ZONE* *BLIND*

where:

timeillum	script name;
SALT	solar altitude (^{o});
SAZ	solar azimuth (^{o});
DIR	direct normal solar irradiance (W/m^2);
DIF	diffuse horizontal irradiance (W/m^2);
ZONE	thermal zone identification (-);
BLIND	shading device position identification (-).

This information is sufficient for the lighting simulation control script to generate a sky luminous distribution model and carry out illuminance simulation at the specified sensor locations for the particular thermal zone and the shading device positions (Figure 1). The script principal processes are carried out in the following order:

1. read command line parameters;
2. generate sky model (for given insolation conditions);
3. re-build scene model (update sky and blind models);
4. calculate internal illuminances (at sensor locations for given thermal zone);
5. write temporary data exchange file.

When the daylight sensors' internal illuminance have been calculated for the given sky conditions, thermal zone and blind positions, the values are written into a temporary data exchange file. The *parent* process will automatically restart when the *child* process is completed. Restarted *parent* process will read calculated internal illuminance values from the temporary data exchange file and return them into the lighting control algorithm. Then, based on the selected control strategy, the fraction of the artificial light *on* is determined and the corresponding casual gain and electric power demand are derived.

Sky angular luminous distribution model

Currently two approaches are possible. Sky scan measurements of the real skies are available and could be used, as demonstrated in [12], to produce relatively accurate time varying internal illuminance predictions. However, there are only few locations where this special data is available and probably none where also corresponding climate data (air temperature, relative humidity, wind speed and direction) are at hand. For practical purposes the mathematical models have to be used. The *Perez* sky luminance distribution model [11] was used in this study. The author is fully aware of the complex issues underlying the sky angular luminous distribution models. As a separate paper would be needed to discuss models' performance in different luminous climates, no more space is attributed to this problem here. In principle, any of the existing models could be applied to suit the local luminous climate [15].

The direct normal and diffuse horizontal irradiance are the principal *Perez* model [11] input parameters. As one of the objectives of this study is to develop simulation capable of tracing short-term variances in the daylight availability it needs use of *DESIGN REFERENCE YEARs* [13] which, in addition to 60 minutes averages, hold 5 minutes averages of the short - term direct normal irradiance. Here, the probability density and autocorrelation of short-term global and beam irradiance algorithm [14] was employed. If necessary also the short-term diffuse horizontal irradiance could be modelled. In this study linear interpolation between 60 minutes average values was used to derive short-term 5 minutes averages of the diffuse irradiance. It remains open to investigate the influence of the more realistic sub - hour variance of the diffuse irradiance on the prediction of lighting control performance.

Blind control

Currently *ESP-r* acts as the blinds controller based on the internal zone air temperature, external air temperature or the level of the incident solar irradiance on the particular window plane. Simple on - off control is implemented. Information about blind position is transferred to *RADIANCE* (*BLIND* parameter), which in turn modifies the geometry of the lighting model (i.e. window with or without blinds, see Figure 2).

Artificial lighting control

Currently within *ESP-r's* casual gain control module a number of control algorithms are implemented (on - off, stepped, linear proportional dimming), which explicitly assume ideal control behaviour. Two component internal illuminance sensors are implemented. Firstly, the daylight component is determined by daylighting simulation in *RADIANCE* and secondly, the artificial lighting component is added within the *ESP-r* control algorithm. The control settings such as lux set point, switch - off reference lux level, switch - off delay time, minimum dimming light output, minimum electric power of lights and the sensor positions can be specified.

LIGHTING CONTROL CASE STUDY

To demonstrate the application of the developed method of *direct run - time coupling*, a limited lighting control case study is presented here.

The case study comprises a single office unit (4.5 x 8 x 3.2 m) with a upper light shelf window and a lower vision window with movable blinds. Figure 2 shows the problem geometry as well as the lighting and blind control interactions.

The office is lit by four luminaires each with two 50W high frequency fluorescent lamps. The total circuit power per luminaire is 111W of which 11W is fixed high frequency (regulation ballast) control gear loss. The lamp luminous output can be regulated between 10% and 100% of the full light output.

Daylight linking control is implemented via two daylight sensors, the first located at 4m and the second at 7m from the windows, measuring hemispherical horizontal illuminance at the work plane level.

The blind control sensor is located at the vision window plane measuring vertical global irradiance. The setpoint for the blinds rotation to the shading position (45^{o}) was set to 300 W/m^2.

Within this illustrative case study, two objectives were identified. The first was to investigate the influence of the short-term (5 minutes) variance of the direct normal irradiance as compared to 60 minutes average values. The second was to quantify the importance of the switch - off light reference level and switch - off delay time lighting control settings. Here the switch - off light reference level control setting is defined as the percentage of the lux set point at which the lights are being switch off. The switch - off delay time lighting control setting is defined as time delay in number of the simulation time steps, before lights are switched off.

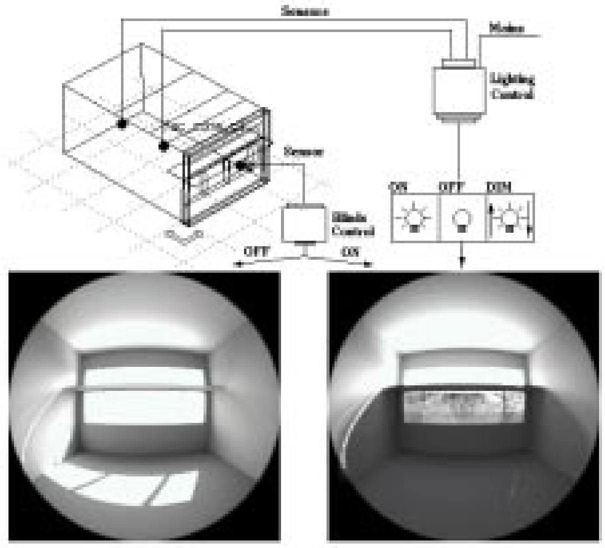

Figure 2. Thermal and lighting model configuration used in the lighting control case study.

A sample of the *DESIGN REFERENCE YEAR* for Bergen, Norway [16] was used in this study, as obtained from The Norwegian Meteorological Institute. All simulations were carried out over the month of April, which was selected because of relatively higher variance of the short-term direct normal irradiance.

Simulation time step comparison

The following lighting control settings were applied: daylight sensor lux set point of 400 lx, switch - off light reference level of 150% (dimming) and 250% (on-off) of the lux set point; for the dimming control minimum light dimming 10% of full light output and minimum power dimming 10% of full circuit power; switch - off delay time 0 minutes for 60 minutes time step (as there is not enough resolution to model this parameter) and switch - off delay time 15 minutes (i.e. 3 time steps) for 5 minutes time step simulations.

Table 1 shows predicted power and heat energy consumption while Figure 3 and Figure 4 show examples of the predicted dynamics of the average instantaneous power demand.

Table 1. 60 minutes versus 5 minutes time step comparison of the predicted lighting and heating energy consumption.

	Lighting power consumption		Heating consumption	
	(kWh/ April)		(kWh/ April)	
	60 min	5 min	60 min	5 min
On-off	67.48	69.38	71.53	65.91
Dimming	33.36	32.52	95.84	91.48

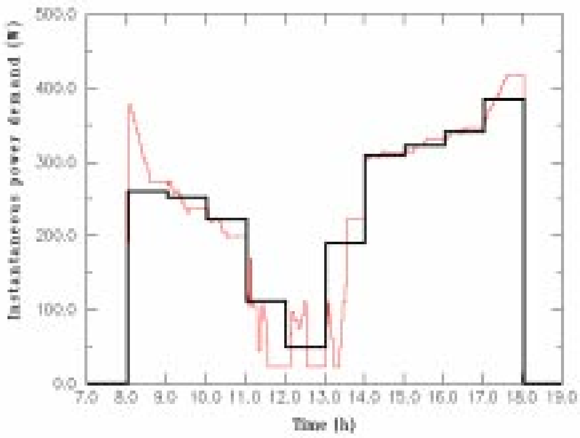

Figure 3. Comparison of 60 minutes (thick line) versus 5 minute (thin line) predictions of average instantaneous lighting power demand for dimming control.

As can be seen from Table 1, relatively low differences can be observed between 5 minutes and 60 minutes predictions of the lighting energy consumption. Relative differences of -2.8% (on - off) or +2.6% (dimming) for 60 minutes time step could be considered as insignificant taking into the consideration the overall problem uncertainty level.

On the other hand, if short time step dynamics of the lighting control is of concern, as illustrated in Figure 3 and Figure 4, more than 100% relative errors can be observed between 5 minutes and 60 minutes time step predictions.

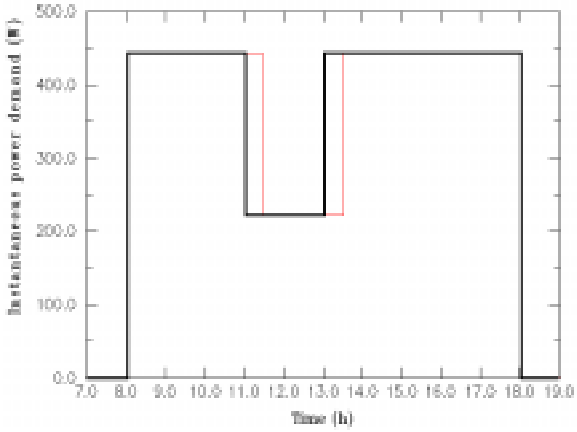

Figure 4. Comparison of 60 minutes (thick line) versus 5 minute (thin line) predictions of the average instantaneous lighting power demand for on - off control.

Thus if one is only concerned with long term lighting energy consumption, it seems to be satisfactory to use 60 minutes time step (solar irradiance data) resolution. On the other hand, if more realistic short-term dynamic behaviour of the lighting control is the issue then 5 minutes time step (solar irradiance data) will give much better result resolution. An example of the later could be detailed explicit plant modelling where accurate short time step load information is necessary.

Lighting control optimisation (5 min time step)

Switch - off light reference level - here the study was limited only to the on - off control with daylight sensor lux set point of 400 lx. Switch - off light reference levels were varied from 200% to 300% of the lux set point and switch - off delay time was kept at 15 minutes (i.e. 3 time steps).

Table 2 shows predicted power and heat energy consumption. As can be seen this lighting control setting has a strong influence on the resulting predictions. Differences as large as 14.4% (for 250% setting) and 25.5% (for 300% setting) are observed relative to the 200% setting. In real on - off lighting control systems the switch - off light reference levels are usually set to values over 200%. Thus lights are not being switched off immediately after daylight meets the lux set point.

Switch off delay time for on - off control - here the following lighting control settings were applied: daylight sensor lux set point of 400 lx, switch - off light reference level of 250% of the lux set point, and switch - off delay time varying from 0 to 30 minutes.

Table 2. Comparison of influence of switch - off light reference level setting on the predicted lighting and heating energy consumption.

Switch - off light reference level	Lighting power consumption	Heating consumption
(%)	(kWh/ April)	(kWh/ April)
200	60.64	71.19
250	69.38	65.91
300	76.09	62.08

Table 3 shows predicted power and heat energy consumption. As can be seen a maximum difference of 5% is predicted between 0 and 30 minutes switch - off delay time settings. Clearly, the difference will be strongly dependent on the number of switch - off cycles which is determined by lux set point and switch - off light reference level settings. Thus much higher differences could be expected for lower lux settings in this case.

Table 3. Comparison of influence of switch - off delay time setting on the predicted lighting and heating energy consumption.

Switch - off delay time	Lighting power consumption	Heating consumption
(minutes)	(kWh/ April)	(kWh/ April)
0	67.32	67.26
15	69.38	65.91
30	70.69	65.05

Switch - off delay time for dimming control - here the following lighting control settings were applied: daylight sensor lux set point of 400 lx, switch - off light reference level of 150% of the lux set point, minimum light dimming 10% of full light output, minimum power dimming 10% of full circuit power and switch - off delay time varying from 0 to 30 minutes.

Table 4 shows predicted power and heat energy consumption. As can be seen, a maximum difference of 1% is predicted between 0 and 30 minutes switch - off delay time settings. Here the influence of this setting is rather insignificant for the energy consumption predictions. This can be attributed to the low minimum dimming light power demand (10%) when the lights go off. Similarly, as already said for on - off control, higher differences could be expected for the lower lux switch - off settings.

CONCLUSIONS

It has been shown in this paper that the method of *direct run - time coupling* between building thermal and lighting simulation is a promising approach. It allows explicit modelling of the many important interactions between artificial lighting control and the rest of the building energy domain. If a short time step and sub - hourly solar irradiance or illuminance climate data are used, relatively realistic dynamic behaviour of the lighting control can be predicted.

Table 4. Comparison of influence of switch - off delay time setting on the predicted lighting and heating energy consumption.

Switch - off delay time	Lighting power consumption	Heating consumption
(minutes)	(kWh/ April)	(kWh/ April)
0	32.31	91.65
15	32.52	91.48
30	32.63	91.37

There are still a number of outstanding problems, which require further research:

- The effect of using solar irradiance data and sky angular luminance distribution models as opposed to the measured real skies needs more detailed investigation to quantify its effect on predictions.

- For long term (e.g. annual) simulations it is probably worthwhile to consider further lighting simulation run time optimisation. Two approaches are being suggested here. One approach of using daylight coefficients [17], [19] or another approach with *Perez* model [11] parameters grouped into classes [18] could reduce significantly running time.

- More explicit lighting control modelling could be easily implemented to account for light photosensor design, orientation and location at the lighting simulation side. More detailed (e.g. opened or closed loop controls [9]) models of the lighting control algorithms could be implemented together with power flow artificial lighting component models [20] at the thermal simulation side.

- Shading or light redirecting devices movement simulation needs a more detailed approach to model complex *occupant - automatic control* interaction.

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