An Illuminance Ratio Prediction Method for Daylighting Control of Buildings

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ABSTRACT

An Illuminance Ratio Prediction Method for Daylighting Control of Buildings

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Heating, cooling and lighting are the dominant sectors of energy consumption in commercial buildings. Controlling solar radiation through windows will improve the illuminance distribution as well as energy efficiency of buildings. Advanced window systems with motorized shading controlled in conjunction with light dimming constitute a promising approach for improving energy efficiency of buildings. However, the performance of current controlled daylighting systems is neither sufficiently reliable nor accurate, thereby reducing their widespread adoption.

The uncertainty of light dimming control system performance is largely due to prediction of workplane illuminance. This makes the system unreliable and sometimes more complex. To improve the performance of light dimming control systems, the prediction of the workplane illuminance must be considered first. Without thorough understanding of systems, their control may not be achieved efficiently.

A new daylight prediction method, Illuminance Ratio Prediction (IRP) method, is proposed in this thesis for an integrated daylighting control system. The proposed method, which is theoretically developed based on radiosity

theory, shows that the illuminance ratio of two arbitrary surfaces in a space in the presence of one initial light source with varying quantity at a fixed location is always constant. The proposed method was experimentally proved. With the IRP method, reliable and accurate predictions of daylighting parameters such as the workplane illuminance, the exterior vertical illuminance and the solar heat gains through the window systems, were obtained as the basis for development of an integrated daylighting control methodology.

The methodology was validated in an outdoor test-room with dimmable electric lighting and a window with built-in motorized blinds. The algorithm was calibrated with a workplane sensor control. Then, an integrated daylighting control system using an interior front wall sensor for prediction was successfully tested. It was found that this system could maintain both the workplane illuminance level and the solar heat gains at the desirable level by simultaneous controls of light dimming and blind tilt angle. With active daylighting control, significant energy savings may be achieved in energy consumption for lighting and cooling. One important asset of the methodology developed is that motorized blinds are optimally tilted so as to admit just enough daylight to satisfy workplane illuminance requirements predicted with IRP method, thus reducing cooling loads due to potential excessive solar gains.

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NOMENCLATURE

C : Correlation coefficient

d : Profile angle (degree)

DL : Electric light dimming level (%)

E : Illuminance (lx)

F : View factor

G : Solar irradiance (Watt)

IRP : Illuminance Ratio Prediction

K_m : Light loss factor

M : Correlation ratio

Me : Final luminous exitance (lm/m^2)

Mo : Initial luminous exitance (lm/m^2)

T : Luminous exitance transfer factor

T' : Illuminance transfer factor

α : Solar altitude angle (degree)

α^* : Absorptivity

β : Blind tilt angle (degree)

γ : Surface solar azimuth angle (degree)

ε : Emissivity

ρ : Reflectivity

ϕ : Luminous flux transmittance

ω : Daylight angle (degree)

Subscript

DBW : Daylight contribution on a back wall sensor

DCL : Daylight contribution on a ceiling sensor

DFW : Daylight contribution on a front wall sensor

DWP : Daylight contribution on a workplane sensor

EBW : Electric light contribution on a back wall sensor

ECL : Electric light contribution on a ceiling sensor

EFW : Electric light contribution on a front wall sensor

EWP : Electric light contribution on a workplane sensor

EX : Daylight contribution on an exterior vertical sensor

G : Irradiance through the window

gc : Ground component

gw : From ground to window

h_out : Exterior horizontal

in : Interior

sc : Sky-sun component

SP : Set point

sw : From sun to window

TFW : Total light contribution on a front wall sensor ($DFW + EFW$)

TWP : Total light contribution on a workplane sensor ($DWP + EWP$)

v_out : Exterior vertical

CHAPTER 1

INTRODUCTION

1.1 Background

The proper utilization of daylight in buildings to complement or replace electric light reduces energy consumption while enhancing occupant comfort. In a typical building, where over 70 percent of its energy use is for electric lighting, heating and cooling, significant energy savings may be achieved by reducing electric lighting in its perimeter zone, thereby also reducing cooling load and peak electric demand. In addition, lowering electricity consumption through utilization of daylight may contribute in reducing the need to build more fossil fuel power generating plants and the resulting greenhouse gas emissions.

Increasing interest in the use of daylighting arises from growing evidence of its very real, positive effects on human performance. Pleasant, comfortable daylighted spaces increase occupant and owner satisfaction, decrease absenteeism, may lease at better-than-average rates, and typically have lower tenant turnover rates [Salares and Russell (1996), LBNL (1997), Edwards & Torcellini (2002) and Heschong et al. (2002)]. Research has shown that building occupants tend to favor daylighting over electrical lighting, especially in Canada where very cold winters make them spend most of their active time indoors [Galasiu et al. (2001)].

Advanced window systems, composed of glazings and shading devices, have been developed to maximize the energy saving potential of daylighting, while improving comfort and visual performance. These systems work effectively in response to outdoor conditions by varying their visual transmittances, solar heat gains, and thermal conductance. However, the performance of these systems is highly dependent on their control strategies, because the solar properties and weather conditions continuously change with time.

It is necessary to control daylight through window systems to avoid glare and redistribute it deep into the room by means of control shading devices. Shading devices can be multi-purpose [Athienitis and Tzempelikos (2001 and 2002)]: block direct sunlight and solar heat gains during the cooling season, allow the maximum amount of daylight and solar heat gains during the heating season, while, at the same time, control the sunlight by diffusing it into the space without causing glare on clear days, and allow all the available daylight under overcast days. In modern offices, the need for efficient automation systems is greater than ever and the motorized shading devices are promising for achieving optimum energy-efficient building control.

Lighting systems linked to available daylight have been promoted qualitatively by means of new energy efficient lighting equipment, improved lighting design practice and automatic management. An automatic lighting control system can reduce the electric lighting energy consumption in buildings by as much as half [Leslie (2003)]. This system aims to maintain a total illuminance level at the workplane at least equal to the target design level with minimum use of electric lighting. It may be difficult to precisely achieve the target design level in practice due to the difference in the spatial distributions of daylight and electric light in the space and practical necessity of mounting the photosensor on the ceiling rather than at the workplane surface. In addition, the performance of this system is affected by the control algorithm used to relate the photosensor signal to desired electric light level and by the geometry and location of the photosensor [Rubinstein (1989a and 1989b)].

1.2 Research Motivation

Daylighting in buildings contributes to significant energy savings as well as enhanced human performance. Despite years of high interest and field-test results, daylight control systems have been applied in a very low percentage of real buildings, and often, did not operate properly nor successfully [Galasiu et al. (2001)]. This may be attributed to inaccurate information on actual interior spatial illuminance distributions by admitted daylight and controlled electric light. Inherently, the light dimming control system frequently could not achieve its performance goal, target design illuminance level, so that the occupant would complain or disable the system.

Research issues for light dimming control systems have included determining optimum photosensor locations, determining optimum photosensor shielding configurations from electric lighting and daylighting sources, and devising more sophisticated control algorithms to disaggregate the predictable electric lighting illuminance contribution from the complex daylight illuminance contribution [Lee et al. (1999), Ranasinghe and Mistrick (2003) and Ehrlich et al. (2003)]. Although the solutions from many research groups have been improved, they are still unreliable and dependent on solar position, sky conditions, and shading devices (venetian blind tilt angles).

Accurate light dimming control has many advantages, such as saving electric light energy, reducing peak demand, and providing a comfortable and pleasant work environment. Reliable control may be achieved through accurate workplane illuminance prediction. As fenestration systems become more dynamic, e.g., use of electrochromic glazings or venetian blinds integrated between the glazings, light dimming controls must accommodate this added performance complexity. Increasingly, daylighting controls will be linked to whole building energy management systems as owners attempt to improve their control over energy management of the entire building [Selkowitz and Lee (1998)].

1.3 Scope and Objectives

The major objectives of this research are as follows:

- Develop an integrated daylighting system for control of a motorized shading/daylight device and electric light dimming so as to enhance building energy efficiency.
- Demonstrate application of integrated control system strategies implemented with the developed methodology to control the amount of daylight so as to reduce cooling loads due to excessive solar heat gains.

When developing the above, continuous dimming will be considered, as this is theoretically optimal from a comfort and also an energy point of view. This work will contribute towards improving the energy efficiency of buildings by reducing overall energy consumption. It will also contribute towards an improved indoor environment and better productivity.

This research is focused on control of commercial/institutional buildings where direct sun penetration is not desirable because of glare. It is also focused on control of daylight through window systems and considers continuous dimming rather than switching or multi-level switching. It is applied to one control zone with one group of lighting fixtures running parallel to the window. Motorized venetian blinds integrated between the glazings are employed as a shading device. The window system will be considered as a diffuse light source mainly by sidelight. Although the thesis experimental work considers motorized venetian blinds, it may also be extended to other systems such as electrochromic coatings or roller blinds controlled in a similar manner.

Physiological and psychological aspects of daylight must be the main consideration in developing daylighting control systems. This research, however, is focused on developing an integrated daylighting control system with which daylight distributions in the room and several parameters affecting the system are well identified. Then control strategies considering human preference can be simply and flexibly implemented with low risk of losing system reliability.

1.4 Overview of the Thesis

Chapter 2 presents a literature review on daylighting control systems in detail to identify how the systems work and what are the weaknesses of the current systems. Dynamic building envelopes with shading devices integrated in the window systems and innovative passive daylighting systems are reviewed. Three basic light dimming control system components, photosensor configurations and workplane illuminance prediction methods are reviewed in detail. Integrated control of dynamic building envelopes with light dimming control and *HVAC* systems are reviewed and research needs are identified.

A new workplane illuminance prediction method is introduced in Chapter 3. Based on radiosity theory, internal spatial light distribution is analyzed and the illuminance ratio of two surfaces with one initial light source in an enclosure is derived.

Some applications with the proposed prediction method for daylighting control systems are addressed.

In Chapter 4, the test facility employed in experimental verification is first described. Electric light prediction results are analyzed to verify the proposed illuminance ratio prediction method. Daylight prediction with controlled daylight transmission is analyzed and correlations are obtained. Light source instability effect on correlations is also discussed. Finally, correlation equations for predictions of the workplane illuminance, the exterior vertical illuminance and the irradiance with a front wall sensor illuminance are obtained.

Chapter 5 presents an integrated daylighting control system, which controls workplane illuminance level while preventing excessive solar heat gains.

Finally, conclusions and recommendations for future work are given in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Daylighting applications in buildings have received increased attention since the energy crisis of the mid-1970s. Recently, environmental concerns and frequent electricity blackouts have contributed in further attracting interest in daylighting. There are pros and cons for daylighting in buildings because daylight comes along with radiant heat that is desirable in the heating season but not in the cooling season. Therefore, daylighting must be controlled qualitatively and quantitatively taking into account occupants' preferences.

The use of daylight to replace or supplement electric lighting in commercial buildings can result in significant energy and demand savings [Selkowitz & Lee (1998), Leslie (2003) and Li & Lam (2003)]. Most of the savings can be achieved by high performance fenestration systems with appropriate shading device control supplemented by electric light dimming systems and integrated control strategy. Consequently, the active controls of advanced fenestration systems with electric light dimming can reduce heating and cooling system equipment sizes significantly, especially in commercial buildings.

With more than three decades of research efforts, the accuracy and reliability of the light dimming control systems have been improved. However, the procedures of installing and commissioning systems are complicated and the performance of the system is still not satisfactory for real applications. That might be the main reason why few light dimming control systems are utilized in real buildings even though the benefits are apparent. This has been attributed [Galasiu and Atif (2000)] to a lack of understanding of actual interior spatial illuminance distributions by admitted daylight and controlled electric light.

Advanced fenestration systems with controllable shading devices are reviewed. The performance of motorized venetian blinds is analyzed with their control strategies in detail. Passive daylighting systems, which are continuously developed and employed in real buildings, are examined. To understand the system, three basic components of the light dimming system and how they are connected with each other in real applications are described. Research efforts to increase system performance are reviewed in different categories such as photocell configurations and prediction methods. In addition, integrated control strategies of light dimming systems with window systems and their impact on *HVAC* systems are reviewed. Finally, research needs are discussed.

2.2 Dynamic Building Envelopes

The dynamic building envelope system considered here is a fenestration system that is integrated with shading devices so that it can respond dynamically and effectively to solar radiation incident on its façade. The words *dynamic building envelopes*, *high performance glazings*, *advanced fenestration systems* and *smart windows* appear to be used interchangeably in the literature. New technology and better integration with daylighting may allow advanced fenestration systems to improve the comfort and performance of building occupants, add value and reduce energy operating costs for building owners, and assist in national and global efforts to reduce greenhouse gas emissions that contribute to global warming [Selkowitz (1999)]. Dynamic building envelope technologies include actively controlled venetian blinds, motorized shades and screens, dispersed liquid crystal glazing, fluidized glazings and frames, electrochromic glazings, controlled natural ventilation windows, and photovoltaic building façades which may be semi-transparent [Lampert & Ma (1993)].

To effectively design and control dynamic building envelopes, the basic factors that affect their performance and occupant comfort must be identified. They are well documented in several references [Athienitis & Santamouris (2001) and Selkowitz & Lee (1998)]. Some factors related to daylighting control are reviewed below.

- Net heat transfer across the fenestration system by conduction, convection, and longwave radiation. This is usually assessed as proportional to the window effective thermal conductance (*U-value*), measured with techniques such as the guarded hotbox method [ASTM (1989)].
- Net transmitted solar radiation, which enters the living space either directly (as beam solar radiation) or indirectly (as diffuse or reflected). ASHRAE [1997] uses the concept of solar heat gain coefficient (*SHGC*) to assess this. *SHGC* is a dimensionless number between 0 and 1 that indicates the total heat transfer due to solar radiation.
- Visible transmittance or daylight transmittance that is the fraction of visible light striking the fenestration system that will pass through. Visible transmittance values account for the eyes' relative sensitivity to different wavelengths of light. Fenestrations with a high visible transmittance can create glare problems when the beam solar radiation comes from one direction.

Selkowitz and Lee [1998] reviewed advanced fenestration systems and the key performance issues that successful systems must address. They discussed the research directions in advanced fenestration systems and how these efforts might lead to hardware and system solutions that fulfill the multiple roles that these systems must play in terms of energy efficiency, comfort, visual performance, health, and amenity in future buildings. Several themes that emerged from the analysis in terms of required performance attributes for fenestration systems are 1) control spectrum of transmitted luminous flux to reduce cooling loads, 2) dynamic control of intensity and direction of transmitted luminous flux to reduce cooling loads, control glare, and improve light distribution, 3) support for changing occupant needs and to enhance satisfaction and performance in addition to energy savings.

Smart windows, which can dynamically change their solar-optical properties in response to changing performance requirements, are one of the newly emerging systems. There are two basic types of smart windows [Carmody et al. (1996)]: passive and active devices. Passive devices respond directly to environmental conditions such as light level or temperature, while active devices can be directly controlled in response to occupant preferences or heating/cooling system requirements. The main passive devices are photochromics and thermochromics; active devices include liquid crystal, dispersed particle and electrochromics.

Electrochromic Glazing can change transparency over a wide continuous range, from about 10 to 70 percent light transmittance in less than one minute (depending on window size), with a corresponding wide range of control over solar heat gain. The coating darkens as it switches and provides a view out under all switching conditions.

Switching occurs at very low voltage (1-2 volts) and removing the voltage stops the electrochromic process without affecting the window's present state of transmittance. Reversing the voltage returns the window to its original state. It could reduce peak electric loads, provide added daylighting benefits, and enhance productivity. To ensure visual and thermal comfort, however, it requires occasional use of interior or exterior shading systems when direct sun is present [Lee et al. (2000)].

Venetian blinds are the most commonly used shading devices although their thermal properties are not well defined, because of the complexity of the interreflectance of the slats. Benefits due to the automatic control of venetian blinds (plus with motorization) are: 1) they can increase daylight levels towards the rear of deep rooms, 2) they can block the direct sunlight preventing glare problems and provide comfort for occupants, 3) they can reduce cooling load in the summer time while providing enough daylight to permit the design workplane illuminance level, and 4) they can minimize conduction heat losses through the fenestration at nights during the winter time if blinds are integrated between the panes.

The overall transmittances, which are necessary information in daylighting control systems, vary depending on slat angle, slat color, incident solar angles, and sky conditions [Tzempelikos (2001), Molina et al. (2000), Guillemin & Morel (1999), and Aleo et al. (1994)]. Aleo et al. [1994] measured the average solar transmittances of several non-homogeneous shading devices (including venetian blinds) under real outdoor conditions using two pyranometers to determine the ratio of the transmitted to the incident solar irradiance. The incident solar irradiation was measured using a fixed pyranometer located outside on the same plane of the shading, while the transmitted solar irradiation was measured by a moving pyranometer located behind the shading. A two axis-tracking bench enabled them to quickly perform different tests by varying the angular position of the slats with respect to the sun. They found that the direct solar transmittance was not affected by the variation of the solar azimuth and changed only because of a variation of the solar altitude in the horizontal venetian blinds.

Another experimental study was conducted by Tzempelikos [2001]. A window system with venetian blinds integrated between the two panes (*Vision Control*) was used for producing general and accurate transmittance equations. Using analytical regression techniques, he developed the transmittance equations of visible and solar radiation for both clear and overcast sky conditions. The transmittance equations were dependent on solar incident angle and blind tilt angle, and used for simulation study of energy savings from simultaneous control of the blinds and electric light dimming. He used two fixed pyranometer-photosensor sets, one set mounted inside and one outside.

Molina et al. [2000] proposed a Monte Carlo method to calculate the properties of shading devices (venetian blinds) integrated in windows. The optical properties of the slat surface for direct and diffuse radiation were considered separately and the distribution of solar radiation through the slats was calculated by using a Monte Carlo method. They found that the model developed had good accuracy compared with experimental results.

An automatic controller offers the ability to continuously adjust the devices' geometry to achieve an optimum balance between shading and daylighting [Scheatzle (1990)]. The optimum blind tilt angle, which accounts for thermal, optical, and occupant preferences, according to solar position can be derived for adjusting blind tilt angle at any control time step. Guillemin and Morel [1999] calculated the critical slat angle that just completely cut the direct radiation. The parameters used are slat width, distance between two slats, slat angle, and solar altitude angle. Tzempelikos [2001] derived the optimum blind tilt angle which blocks direct sunlight while allowing maximum outside view. However, the case of blocking excessive daylight, which increases cooling load in the summer, was not included.

Two control strategies for operation of venetian blinds in conjunction with electric lighting control were compared by Papamichael et al. [1988]. While both strategies aimed at blockage of direct sunlight penetration, the first provided maximum possible slat openness and the second maximum possible workplane illuminance. The results showed that the two different control strategies might result in significantly different daylight levels in the space, especially when the ground reflectance was high. They pointed out that other control strategies, such as minimizing glare, maximizing visibility, minimizing cooling or heating loads, or combinations of the above are also possible and may be more desirable in some cases. Moreover, different control strategies may be considered during different seasons to further improve the annual performance of operable fenestration systems.

Control of daylight distribution has both a quantitative element (the provision of adequate illuminance to meet the needs of typical visual tasks) and an equally important qualitative element (providing a pleasant and comfortable luminous environment, as perceived by the occupant) [Selkowitz and Lee (1998)]. With a fenestration system integrated with venetian blinds, the quality of distributed daylight may vary with shape, color, material, type, and reflectance of blind slats; the redirected daylight can be diffuse or direct beam.

Two different types of glazing with integrated Venetian blinds were studied for characterizing thermal and optical performance [Breitenbach et al. (2001)]. The spectral and spatial distributions of the transmittance were measured with the Cardiff goniospectrometer, which is capable of collecting angle and wavelength dependent optical properties of fenestration systems in a single measurement. They found that the spatial distribution of the light is strongly influenced by the shape of the slats: curved horizontal slats produce an upwardly directed fan shaped distribution, whereas for flat slats the light is essentially transmitted in the forward direction.

2.3 Passive Daylighting Systems

Several kinds of daylighting systems have been developed and constructed in real buildings to improve the distribution and visual comfort, to utilize direct sunlight, and to provide daylight for interior, windowless rooms [Iwata et al. (2001), Littlefair (2000), and Majoros (1998)]. Innovative daylighting systems work by redirecting incoming sunlight or skylight to areas where it is required. These systems, unlike dynamic building envelopes described in the previous section, are fixed or passive devices. Typical systems are reviewed briefly.

Anidolic zenithal opening (Fig. 2-1 (b)) is based on nonimaging optics and an attracting daylighting solution. Two major components are 1) Compound Parabolic Concentrator (*CPC*), which is used for its angular admission, and 2) Compound Parabolic Deconcentrator, which spreads the rays, emerged from *CPC* toward the room. The anidolic daylighting efficiency is dependent on the photometric quality of its surfaces. This lighting concept guarantees total protection against direct sunlight and lets diffuse skylight penetrate the building. In addition, it improves visual comfort significantly and provides higher daylighting level compared to the shed (a conventional solar protective top-opening) does [Courret et al. (1994)].

Light shelves (Fig. 2-1 (c)) reduce the light near the window and increase it at the back of the room, thus ensuring a better uniformity; they use direct sunlight and reduce glare. One major problem with light shelves is maintenance and cleaning, especially when they are external in the Canadian climate, they also collect snow and ice. Various clever profiles have been developed to respond to the changing solar altitude angle. The *Valra* system (Fig. 2-2) employs a reflective flexible film, which is in an enclosed space so that it can be kept clean and adjusted as required.

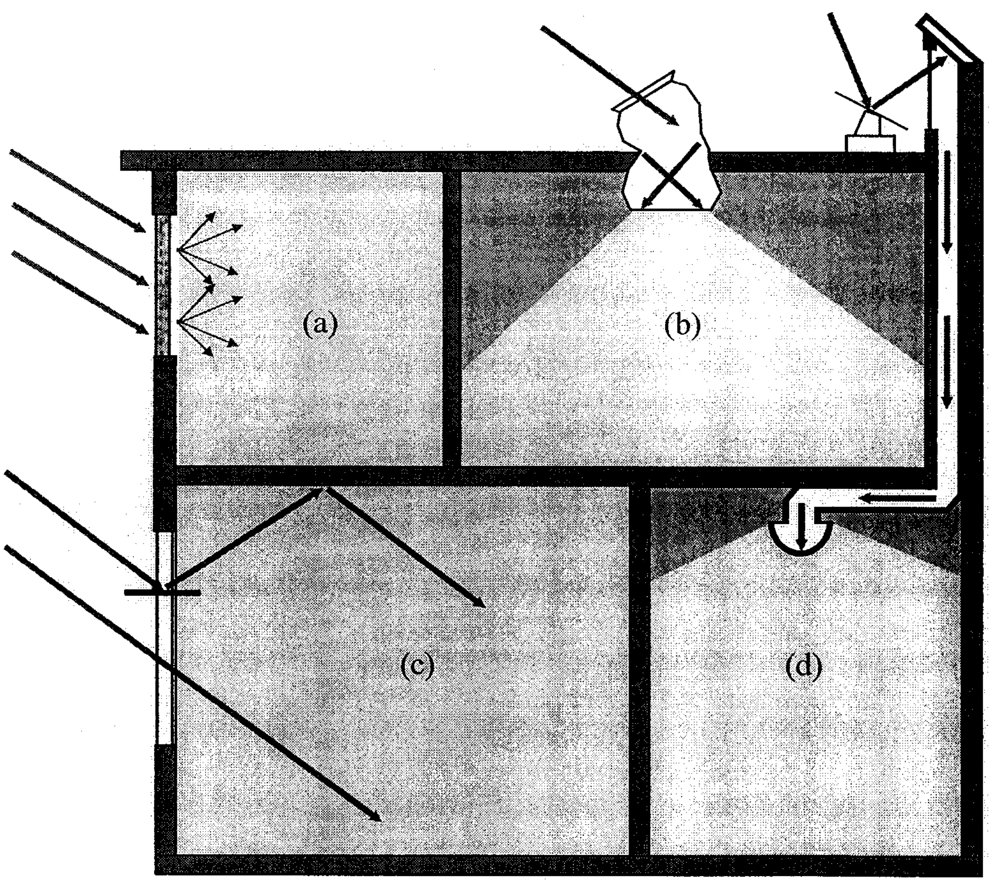


Figure 2-1 Schematic of passive daylighting systems (a) Translucent glazing (b) Anidolic zenithal opening (c) Light shelf (d) Light pipe system

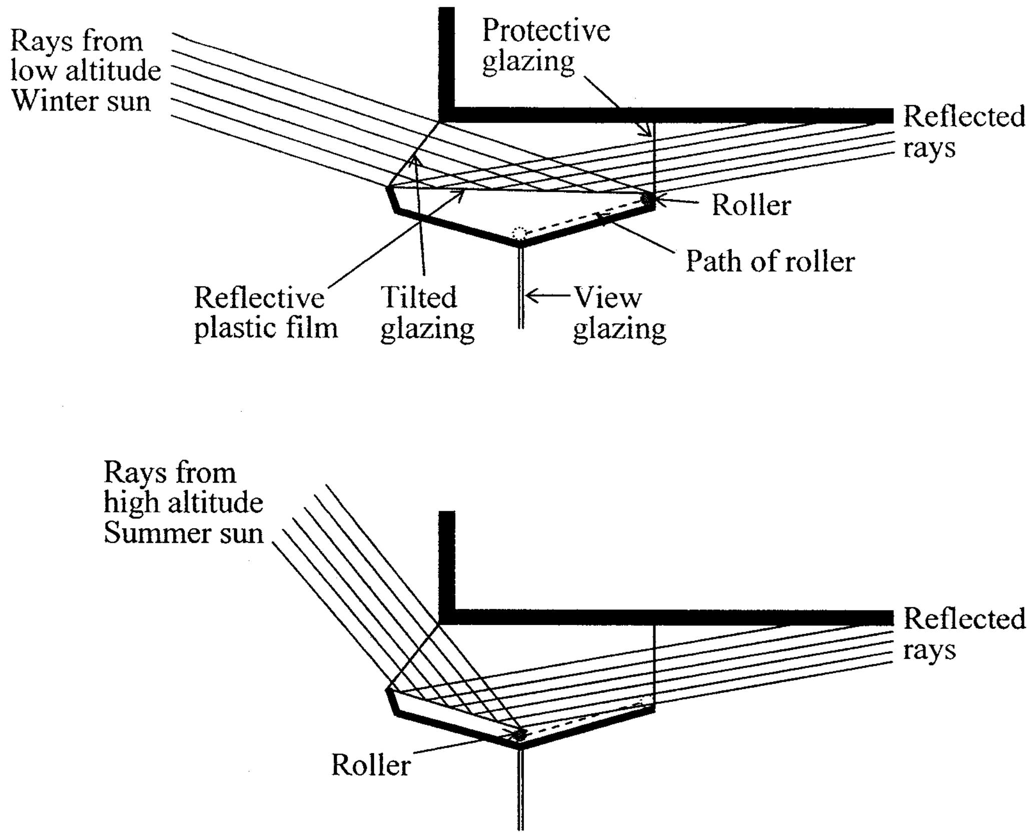


Figure 2-2 The *Valra* system of light shelves with seasonal adjustment (From Majoros [1998])

Light pipe systems (Fig. 2-1 (d)) consist of three main parts: the heliostat, a light conduit, and an emitter in the room. It collects and concentrates sunlight, conduits it to the desired point in the building and emits it through a diffuser. The simplest system may serve one emitter, but larger, multi-point systems have also been constructed. The efficiency of the system is primarily dependent on the light conduit, its quality and its length. The efficiency of a good system can exceed 25% (measured from the sunlight incident on the primary collector to the light emitted into the room).

Jenkins and Muneer [2003] proposed a light pipe model that predicts light levels resulting from a pipe of given dimensions, to investigate the effectiveness of light pipes.

The proposed model can be used for appropriate pipe sizing so as to maximize energy saving for a given project. The heat gains and glare problems associated with light pipes are less than in the case of windows. Similarly, heat loss at night and in winter months is significantly less.

A prismatic glazing is a grooved sheet with narrow strips of a prismatic cross-section. Normally one side is smooth and the other side has a pattern of saw-tooth section. A prismatic sheet can be included between the two panes of a double glazed window, usually in the upper part (about 1/3 of the height) of the window or indeed the prismatic sheet can be formed by one of the double glazing panes (with the smooth side outwards). Its effect will be very similar to that of the light shelf. Lorenz [2001] studied a new glazing unit consisting of two panes with interlocking, horizontal prismatic ribs with a triangular cross-section and a prism angle of 90 degrees. In comparison to other glazings, he found that it did not reduce the outside view appreciably and achieved relatively uniform illumination of a room with daylight. During the summer and the transitional seasons it provided protection against solar irradiation and distinctly reduced irradiated heat fluxes. The reflecting surfaces of the prismatic ribs did not create glare.

Translucent materials (Fig. 2-1 (a)) are effective transmitters of light, but change the direction of light as it is transmitted. A glass-based translucent insulating glazing has emerged recently [Milburn (2000)]. It diffuses light effectively, converting direct beam sunlight into soft diffuse natural light, and features dual-in custom configuration of light transmittance, allowing designers to optimize illumination levels and glazed area. It also offers superior thermal and sound insulation value. The impact on daylighting patterns of replacing vision glass with translucent glazings is bright, soft, and functional natural illumination [Milburn and MacMillan (2003)].

Hybrid solar lighting systems are the newly emerged lighting systems. These consist of five major elements [Muhs (2000) and Earl & Muhs (2001)]: 1) light sources (both sunlight and electric light), 2) sunlight collection and tracking systems, 3) light distribution systems, 4) hybrid lighting control systems, and 5) hybrid luminaires. In these systems, the spatial illumination variability inherent to conventional topside daylighting is eliminated because the light will always emerge in the room at the same place traveling the same direction. Fluctuations in the intensity of collected solar light require rapid compensation by electric lamps to maintain a constant room illumination that is the main consideration to develop a hybrid luminaire. Researches indicated that passive distribution and use of the visible portion of solar energy is the preferred use of solar energy when nonrenewable energy displacement, cost effectiveness, and lighting quality are the primary deployment drivers.

2.4 Light Dimming Control Systems

2.4.1 System components

The goal of light dimming control systems is to supplement the minimum electric light to maintain the target area (workplane) illuminance level at the desirable level given available daylight through window systems. Achieving this objective is complicated, because the workplane illuminance must be predicted indirectly instead of using the real workplane illuminance for light dimming control. Direct prediction of the workplane illuminance is ideal; however, a sensor on the workplane will be shaded occasionally by occupants or objects nearby and it is difficult to maintain the performance of the sensor. Therefore, the prediction of daylight and electric light contributions on the workplane should be the main consideration in lighting control systems. The prediction is usually accomplished by using photocells mounted inside and/or outside. With predicted workplane illuminance and appropriate control algorithms, the target design illuminance level will be accomplished with electric light dimming.

The photoelectric controlled lighting systems consist of three basic components [Rubinstein et al. (1989)]:

- A photocell that detects the illuminance level in a space and generates an electrical signal proportional to it.
- A controller that gets the signal from the photocell and converts it to a control signal for a dimming unit.
- A dimming unit that varies the electric light output by altering the amount of power flowing to the lamps.

Figure 2-3 illustrates how these components are interconnected in a typical building application. The controller gets the ambient light levels in the space (both electric and daylight) and adjusts the electric light output according to its built-in algorithm.

There are three simple control algorithms that can be employed in daylight responsive lighting control systems. These are closed-loop integral reset, open-loop proportional, and closed-loop proportional control algorithms [Rubinstein et al. (1989)].

Closed-loop integral reset control: This is the simplest control algorithm. An integral reset controller compares the instantaneous photocell signal to a pre-set reference level and continually adjusts the fractional dimming level so that the measured photocell

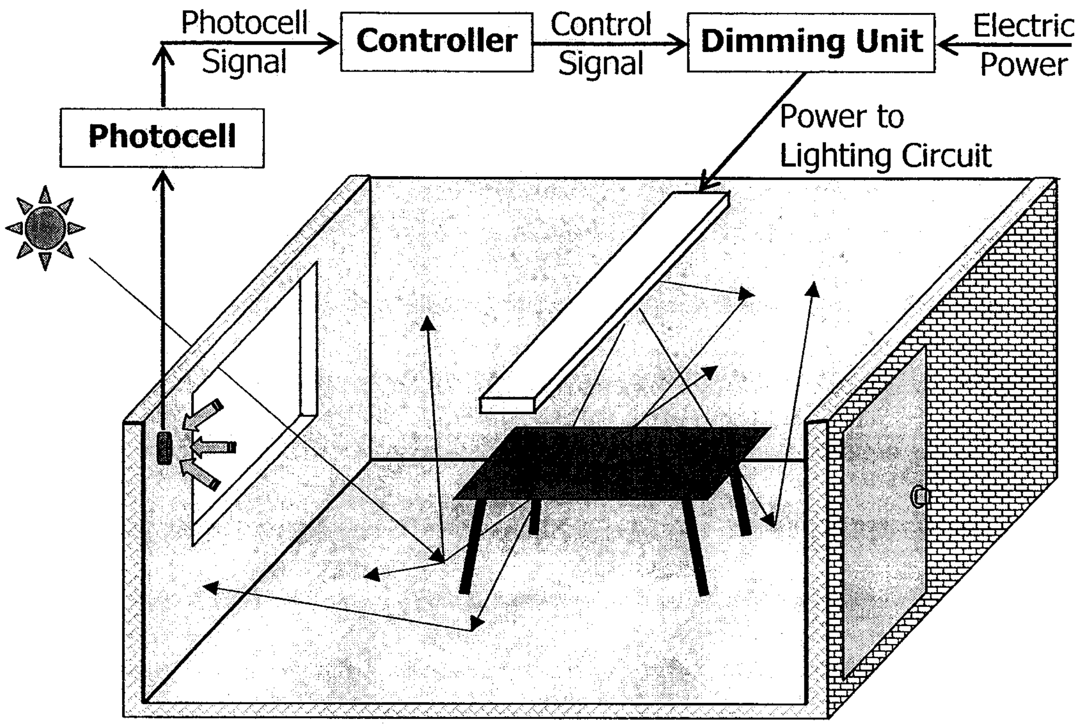


Figure 2-3 Illustration of lighting control system components
(Modified from Lawrence Berkeley National Laboratory [1997])

signal is maintained at a constant reference level. In practice, this reference level is empirically determined by setting the electric light to target illuminance at night (nighttime calibration). The voltage generated is measured and a reference circuit in the logic circuit is adjusted so as to establish that voltage as the set-point voltage. The photocell's output value under this condition then becomes the reference level to be maintained under all conditions.

Open-loop proportional control: With this type of control, the photocell is mounted so that it does not detect the controlled quantity (electric light). Instead, the photocell is used to detect only the independent stimulus, daylight. The open-loop proportional control algorithm simply establishes a linear relationship between the measured photocell signal and the dimming level. This linear relationship can be expressed as the slope in a graph relating the fractional dimming level and photocell signal. If the photocell signal is zero, the full electric lights occur. As the daylight stimulus exceeds zero, the electric lights are dimmed according to this relationship. By adjusting the value of slope at an appropriate daylight condition (daytime calibration), the installer sets the system sensitivity to accommodate the particular room and lighting conditions at that time.

Closed-loop proportional control: For this control, the photocell should be located so that it detects both electric light and daylight. But unlike integral reset, the photocell signal is not kept constant. Rather, the controller adjusts the electric light output so that the dimming level is a linear function of the difference between the photocell signal and its signal at the nighttime calibration level. The nighttime calibration is identical to that performed for an integral reset control. This system can measure not only the daylight striking the photocell but also the system's response to this stimulus. As with an open-loop proportional control, a daytime calibration must be performed to adjust the system sensitivity so that the slope of the response is appropriate to the specific room and daylight conditions. The illuminance is measured at the task surface and the slope of the photocell response is adjusted until the total illuminance (daylight plus dimmed electric light) equals the desired level. The desired level generally equals the light level of full electric lighting at night.

It is recommended that if the photocell location makes it susceptible to the electric light, then closed-loop integral reset or proportional algorithms should be used. On the other hand, if the photocell is located outside the controlled space so that it detects only daylight, the system should use the open-loop proportional control algorithm.

2.4.2 Photocell Configurations

The photocell is usually mounted in the ceiling or on the exterior of the building façade rather than at the task surface. A task-located sensor would be very susceptible to interference from the occupants and nearby objects, and would be difficult to connect electrically to the rest of the control circuitry. The minimum number of photocells should be used per building to reduce equipment cost and simplify installation.

The main benefit of placing the photocell on the exterior is that it can greatly reduce hardware costs. For example, only one or a few photocells per façade instead of one sensor per space (office) can be utilized for all control zones in the same façade where many spaces exist (especially in commercial buildings). Then, the interior illuminance of each control zone is calculated by transfer factors (Daylight Transmittance [Tzempelikos (2001) and Athienitis & Tzempelikos (2001)] and Ratio of Illuminance Model [Molteni and Morel (1999)]). It gives less accuracy than using an interior photocell per zone since it uses empirically derived transfer factors and in some case part of the façade can be shaded (this can, however, be precalculated). The accuracy in predicting workplane illuminance is an important issue in lighting control environment. The more accurate, the better control. This will save more lighting electricity, reduce additional cooling load, and thus reduce peak demand as well as serve occupants by creating a comfortable working environment.

Little research on photocell configurations (location and view) has been performed. A research by Rubinstein et al. [1989] showed that a closed-loop proportional dimming algorithm with a partially shielded photocell provided the best overall performance when the photocell was located 3.1 m from the window in a room with a direct lighting system. Their study utilized a scale model of an architectural space and considered different types of photocells (unshielded, partially shielded, and fully shielded) and different control algorithms (open-loop proportional, closed-loop proportional and closed-loop integral reset control).

Mistrick and Thongtipaya [1997] analyzed a variety of different photocell conditions to determine their impact on system performance. The parameters studied were room orientation, sky conditions, electric lighting systems, and photocell shielding types. Based on their study, they found that a partially shielded photocell provided reasonably good performance under most conditions and the best control of electric lighting in response to daylight was achieved with a direct lighting system.

Lawrence Berkeley National Laboratory [1997] published guidelines for daylighting with windows based on research spanning two decades. With respect to photocell configurations, they pointed out that photocell placement must be determined considering the daylight control algorithm, type of lighting system, and task location and that photocell field of view must be restricted according to the control algorithm.

Photocell configuration and performance in large open spaces were studied by Ranasinghe and Mistrick [2003]. Three types of sensors having different spatial response functions with different control algorithms were analyzed. Their conclusions from this study were that 1) the sensor with the narrowest field-of-view provides the best overall correlation between sensor signal and the daylight illuminance level, 2) the system performance can be improved by applying appropriate control algorithms, 3) a sensor should be configured and positioned to minimize its direct view of the windows. These are quite typical results, but provide valuable calibration guidelines for current lighting control systems.

2.4.3 Prediction Methods for the Workplane Illuminance

The average workplane illuminance and the illuminances at several key points on the workplane in a space are important for control and design of daylighting . Calculation procedures for daylighting design have four major steps [Kaufman (1981)]:

- Information on the luminances and illuminances to be expected from the sun and sky is assembled. Usually, two sky conditions are considered, namely overcast and clear sky.
- With the sun and sky data in hand, the external illuminance (vertical, horizontal, or sloped) on the fenestration can be predicted. This may be not only direct radiation from the sun and sky but also reflected radiation from the ground and adjacent structures.
- The usual transmission characteristics of the fenestration material must be known. Generally there are two types of transmittances to consider, namely direct transmittance with sunlight and diffuse transmittance with clear or overcast skylight. The transmittances of the fenestration for these two types of input may be different and the former may depend on solar altitude.
- The final step is to process the luminous flux, which enters the interior space.

Even though these calculation procedures are for daylighting design, these can be adopted to the control daylighting by replacing the first and second steps with real-time measurement of daylight quantities. There are many procedures for the interior illuminance prediction method (the final step): lumen method of sidelighting, daylight factor method, RI (Ratio of Illuminances) model, radiosity method, and the method by using internal photocell with the appropriate control algorithm. Each of methods will be described and reviewed.

Lumen method of sidelighting: With the direct and reflected vertical illuminances in hand, the light loss factor (K_m), which consists of dirt depreciation and window dirt depreciation, *C* and *K* factors, which are coefficients of utilization, and the luminous flux transmittance (ϕ) are calculated or obtained. The transmitted luminous flux for the horizontal workplane illuminances by sky-sun component (E_{sc}) and ground component (E_{gc}) are

$$E_{sc} = \phi_{sw} \cdot C_s \cdot K_s \cdot K_m \tag{2-1}$$

$$E_{gc} = \phi_{gw} \cdot C_g \cdot K_g \cdot K_m \tag{2-2}$$

The method is limited to certain types of window controls and geometries and depends on obtaining several coefficients of utilization. This is largely empirical, so it is not an appropriate basis for control.

Daylight factor method: The lumen method is popular in the United States, while the daylight factor method has been widely used in Europe where cloudy skies predominate. Daylight factor (*DF*) is defined as the ratio of the illuminance at a point on a plane produced by the luminous flux received directly or indirectly at that point from a sky of a given luminance distribution to the illuminance on a horizontal plane produced by an unobstructed hemisphere of this same sky.

$$DF = E_{in} / E_{h\_out} \tag{2-3}$$

where E_{in} and E_{h_out} are the interior illuminance and the external horizontal illuminance, respectively.

Daylight may reach a point on a horizontal plane within a room in three ways as shown in Fig. 2-4. The sky component (*SC*) is that portion of the daylight factor due to daylight received directly at the point from the sky. The externally reflected component (*ERC*) is that portion of the daylight factor due to daylight received directly at the point from externally reflected surfaces. The internally reflected component (*IRC*) is that portion of the daylight factor due to daylight that reaches the point from internal reflecting surfaces. The daylight factor is the sum of its three components, given by

$$DF = SC + ERC + IRC \tag{2-4}$$

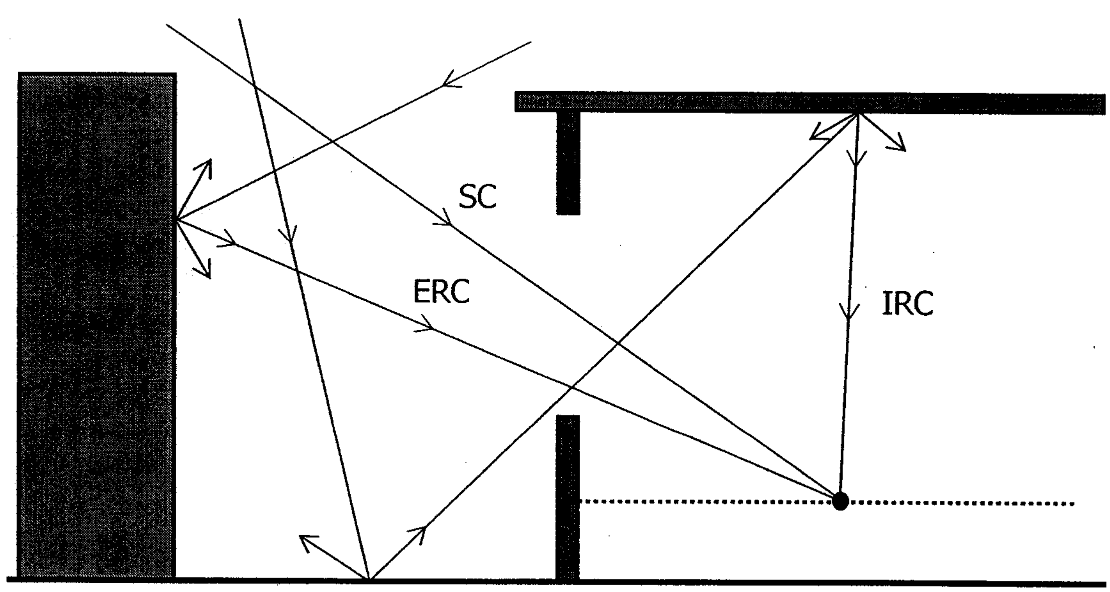


Figure 2-4 Three components in the daylight factor method
(From Murdoch [1985])

The basic daylight factor method has been limited to the overcast sky case, in particular to the uniform overcast sky and to the *CIE* (International Commission on Illumination) overcast sky.

RI (Ratio of Illuminances) model: Molteni and Morel [1999] proposed a modified daylight factor model, RI model. They pointed out that the problem behind daylight factor method is using the external horizontal illuminance that gives no information relative to the room orientation. The idea for a more reliable daylight model is to use another variable characterizing the external solar illuminance. The best one giving information on the actual weather conditions is the vertical outside illuminance on the façade where the window is located.

The experimental study by comparison between the RI model (E_{in} / E_{v_out}) measurement and the usual daylight factor model (E_{in} / E_{h_out}) measurement with no direct sunlight showed that RI model led to much higher accuracy. Finally, the simple model (developed with an exponential curve), which approximates both overcast and clear sky conditions, had good agreement with measurements by 10 to 30% lighting level differences between estimated and measured illuminance.

Radiosity method: Illuminance on a plane surface is comprised of a component due to the luminaires and/or fenestration illuminating the point directly (Direct Component, *DC*) and a component due to the luminous room surfaces illuminating the point (Interreflected Component, *IC*). This distinction is computationally important since the relative size of the two components comprising the total horizontal illuminance can be quite different. Usually, the effects on a plane surface illuminance are predominated by *DC* rather than *IC*. Where *IC* is large, however, the accuracy of the *IC* calculation is the accuracy of the overall calculation [DiLaura (1979)].

Goral et al. [1984] presented a calculation model of the interaction of light between diffusely reflecting surfaces for computer graphics. The major assumption was that all surfaces are ideal diffuse (*Lambertian*) reflectors. The procedure was applicable to arbitrary environments composed of such surfaces, and it could account for direct illumination from a variety of light sources and all multiple reflections within the environment. This is based on energy conservation and analysis used in thermal engineering for the calculation of radiation heat exchange in enclosures.

Tsangrassoulis et al. [1996] conducted theoretical analysis of various shading systems to calculate illuminance in the interior of a room under various sky luminance distributions. The daylight coefficient method was used and this method was compared with existing radiosity and ray-tracing methods. The daylight coefficient is defined as the ratio between luminance of a patch of sky and the illuminance in the building due to light from that patch. The advantages of this method are 1) it can model complicated geometry, 2) it is suitable for innovative daylighting systems with complex properties, and 3) once a set of daylight coefficients has been computed, it is possible to find illuminance at different points in the interior of a building under a large number of sky luminance distributions with minimal extra effort. However, this is numerically complex and very time-consuming so that it is not an appropriate method for control.

Athienitis and Tzempelikos [2001] adopted a simplified version of this method for the numerical simulation of an office space light dimming control with automated venetian blinds. Their main assumption was that the window interior surface was considered as a diffuse luminous source emitting daylight in all directions in the room. The initial luminous exitance of the window was calculated by using daylight transmittance, which was a function of blind tilt angle, solar incidence angle, and sky condition. They estimated energy savings from the simulation control of the blind and electric light dimming.

The method based on a use of internal photocell with an appropriate control algorithm: This is the most general method in the area of daylighting controls [Lee et al. (1999), Mistrick & Thongtipaya (1997), and Rubinstein et al. (1989)]. They used an inside photocell (down-facing and partially shielded) and found correlation between a sensor input signal and the desired variable (e.g., workplane illuminance). Using a fully instrumented, full-scale testbed facility, Lee et al. [1999] monitored daylighting performance with a venetian blind. The photocell's field-of-view had a cut-off angle of 46° in the direction of the rear wall and window and 56° in the direction of the two sidewalls so that the photocell cannot see directly the light source through the window. The correlation coefficient, M_{fit}, and monitored data, M (the ratio of measured workplane illuminance to photocell signal for any given instant in time) were compared to control electric lighting (with modified closed-loop proportional algorithm); if M is greater than M_{fit}, then the actual workplane illuminance is greater than the predicted workplane illuminance, and vice versa. They found that the ratio of workplane illuminance from daylight to photocell signal is characterized in terms of solar condition and venetian blind angle.

2.5 Integrated Control Strategy

The potential energy saving by integrating control strategies for dynamic building envelops with control of lighting and *HVAC* systems is a lot more than that from individual control strategies [Guillemin and Morel (2001)]. Moreover, an improvement of thermal and visual comfort under continuously varying conditions contributes to improved working environments, well-being and raises productivity. Even with their highly promising features, only a few building control systems have adopted these control strategies in the building energy management systems.

Guillemin and Morel [2001] developed an innovative self-adaptive integrated control system for heating, shading and artificial lighting. The system increased the overall performance of the building energy management system and the indoor comfort. The integrated system was built on the principle of three nested control loop levels. Genetic algorithm for an adaptation task was undertaken in order to improve the efficiency of the overall system. They used textile blinds as shading device. The blind controller performed differently in two distinct situations, namely user present and absent. When the user is present, it primarily provides optimal visual conditions in the room, otherwise, only thermal considerations are taken into account in order to minimize the heating energy consumption. The blind position is determined through an RI model, which depends on the blind position. The RI model with the vertical outside illuminance provides the natural horizontal inside illuminance so that the artificial lighting system controls the electric light power in order to complete the illuminance up to the user level setpoint. The heating controller uses the power profile of the previous day to modify heating power depending on the current conditions and applies it to the current day. Two rooms were used for their experimental study. One room was equipped with the integrated system and one room with a conventional controller (no automatic blind control, no automatic artificial lighting control, proportional heating controller with saturation). The most significant quantitative result was the total energy consumption: the integrated system saved 25% of energy in comparison with the conventional controller. However, they pointed out in their final remarks that the saving might be due to the energy efficient control of blinds and the smart heating controller with the energy-saving setpoint applied during nights and weekends. The comparison must be carried out with individually controlled systems (automatic blind control, automatic artificial lighting control, proportional heating controller with saturation) to quantify real benefits by the integrated control system.

The perimeter zone energy balance between daylight admission and solar heat gain/loss rejection can be optimized by controlling dynamic building envelope and lighting systems. Lee et al. [1998] conducted field measurement studies with a full-scale testbed facility consisting of two side-by-side, southeast-facing private offices. An automated venetian blind was operated in synchronization with a dimmable electric lighting system to block direct sun, provide the design workplane illuminance, and maximize view. Daily lighting load (*kWh*), daily cooling load (*kWh*) and peak cooling load (*W*) were measured for energy saving comparison between dynamic and static venetian blinds with and without dimmable daylighting control. The cooling system was not integrated in this system; however, it kept the interior air temperature at a constant level ($\pm 1\,°C$). Significant energy savings and peak demand reductions were attained with the automated venetian blind with lighting system (integrated system) compared to a static venetian blind with the same dimmable electric lighting system.

The energy performance of simple control strategies based on instantaneous, measured data was compared to the performance of optimum hypothetical dynamic envelopes (an electrochromic glazing system and an automated venetian blind) and lighting system in order to determine the incremental benefit of using more complex predictive control algorithms [Lee and Selkowitz (1995)]. The predictive energy control algorithm involves pre-calculating the lighting and cooling energy balance for all positions or states of the dynamic envelope and lighting system at each time step, then selecting the system position that yields the least energy use. They found that energy and peak demand savings are highly dependent on the control strategy of the dynamic envelope and lighting system; a predictive control algorithm is useful for the automated venetian blind, while a simpler, non-predictive control algorithm is better for more advanced envelope systems incorporating spectrally selective, narrow-band electrochromic coatings.

2.6 Research Needs

The performance of light dimming systems is influenced not only by climate and site differences but also by photocell configurations and control algorithms used. A major drawback in current light dimming control systems is that most of the research efforts to develop control dimming solutions focus on applying different combinations of photosensor configurations and control algorithms without a systematic approach. In addition, research is limited to typical cases: horizontal workplane target for task tuning, venetian blinds for shading devices and a space with one window system.

Moreover, it appears that there is not much detailed research on workplane illuminance prediction. Without understanding the systems, their control cannot be achieved efficiently. The workplane illuminance is usually predicted with photocell mounted somewhere in the room. The uncertainty of control dimming comes from the prediction of the workplane illuminance [Park and Athienitis (2003)]. This causes system unreliability and complexity especially with intricate shading device performance. To improve the performance of the system, prediction of the workplane illuminance must be considered primary in light dimming control systems.

Light distributions by the daylight source transmitted through window systems in an enclosed space are discussed and a new workplane illuminance prediction method is introduced in chapter 3.

CHAPTER 3

ILLUMINANCE RATIO PREDICTION METHOD

3.1 Introduction

It is necessary to understand light distributions in an enclosed space to predict workplane illuminance. The light distribution in an enclosure will vary with the location of the light source. Light distributions with a fixed light source location of perfectly diffuse light, are well identified theoretically and have been applied in several lighting simulation programs [Siegel and Howell (1981)].

The light distributions produced by the daylight source through windows are continuously changing according to solar and shading device positions, because of the moving location of the light source. In the case of direct daylight penetration by which new light source on the room surface will be generated, the light distribution will be completely different. A model for light distributions with varying light source location must be developed for a reliable and accurate workplane illuminance prediction method.

A new workplane illuminance prediction method for daylighting control systems based on the radiosity theory is introduced in this chapter. Applications to light dimming control systems and HVAC systems with controlled window systems are discussed. Some of the benefits compared with other methods are addressed.

3.2 The Illuminance Ratio Prediction (IRP) Method

The luminous exitance is analogous to the radiosity in the enclosure theory of radiation exchange so that all restrictions and assumptions to be applied are the same as those applied in that theory. Consider a closed space whose boundary is divided into areas (N surfaces) so that the following conditions are met over each of these areas [Siegel & Howell (1981) and Murdoch (1985)].

- The temperature is uniform.
- The emissivity (ε), absorptivity (α^*) and reflectivity (ρ) are independent of wavelength and direction so that $\varepsilon = \alpha^* = 1 - \rho$.
- All energy is emitted and reflected diffusely.
- The incident and hence reflected energy flux is uniform over each individual area.

Establish the following definitions:

Mo_i = initial luminous exitance of surface i

Me_i = final luminous exitance of surface i

ρ_i = reflectance of surface i

E_i = illuminance on surface i due to the other room surfaces

F_{ij} = view factor from surface i to surface j

and indices i and j stand for surface $1, 2, \ldots, N$.

"Initial" means flux leaving the surface prior to reflections (i.e., sources or apparent sources such as daylight transmitted through window with blinds blocking beam solar radiation) and "final" means the total flux ultimately leaving the surface including reflected flux. Thus the final luminous exitance of surface i after repeated reflections can be expressed as

$$Me_i = Mo_i + \rho_i \cdot E_i \tag{3-1}$$

also

$$E_{ij} = \frac{Me_j \cdot A_j \cdot F_{ji}}{A_i} = \frac{Me_j \cdot A_i \cdot F_{ij}}{A_i} = Me_j \cdot F_{ij} \tag{3-2}$$

or in matrix form

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} & \cdots & F_{1N} \\ F_{21} & F_{22} & \cdots & F_{2N} \\ \vdots & \vdots & & \vdots \\ F_{N1} & F_{N2} & \cdots & F_{NN} \end{bmatrix} \begin{bmatrix} Me_1 \\ Me_2 \\ \vdots \\ Me_N \end{bmatrix} \tag{3-2'}$$

where E_{ij} is the contribution of surface j to the illuminance E_i.

Using Eqs. (3-1) and (3-2), rewrite Mo_i as

$$Mo_i = Me_i - \rho_i \cdot \sum_{j=1}^{N} Me_j \cdot F_{ij} \tag{3-3}$$

This Eq. (3-3) can be written in matrix form as

$$\boldsymbol{Mo} = (\boldsymbol{I} - \boldsymbol{D}) \cdot \boldsymbol{Me} \tag{3-4}$$

where $\boldsymbol{Mo}$ = initial luminous exitance matrix ($N \times 1$), $\boldsymbol{Me}$ = final luminous exitance matrix ($N \times 1$), $\boldsymbol{I}$ = $N \times N$ identity matrix, and $\boldsymbol{D}$ = $N \times N$ matrix whose elements is $D_{ij} = \rho_i \cdot F_{ij}$.

If the luminous exitance transfer factor, $\boldsymbol{T}$ is defined as

$$\boldsymbol{T} = (\boldsymbol{I} - \boldsymbol{D})^{-1} \tag{3-5}$$

or

$$[T]_{N \times N} = \begin{bmatrix} 1-\rho_1 F_{11} & -\rho_1 F_{12} & \cdots & -\rho_1 F_{1N} \\ -\rho_2 F_{21} & 1-\rho_2 F_{22} & \cdots & -\rho_2 F_{2N} \\ \vdots & \vdots & & \vdots \\ -\rho_N F_{N1} & -\rho_N F_{N2} & \cdots & 1-\rho_N F_{NN} \end{bmatrix}^{-1} \tag{3-5'}$$

the final luminous exitance is expressed as

$$\boldsymbol{Me} = \boldsymbol{T} \cdot \boldsymbol{Mo} \tag{3-6}$$

or

$$\begin{bmatrix} Me_1 \\ Me_2 \\ \vdots \\ Me_N \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1N} \\ T_{21} & T_{22} & \cdots & T_{2N} \\ \vdots & \vdots & & \vdots \\ T_{N1} & T_{N2} & \cdots & T_{NN} \end{bmatrix} \begin{bmatrix} Mo_1 \\ Mo_2 \\ \vdots \\ Mo_N \end{bmatrix} \tag{3-6'}$$

Combining Eqs. (3-2′) and (3-6′) yields

$$\boldsymbol{E} = \boldsymbol{T}' \cdot \boldsymbol{Mo} \tag{3-7}$$

or

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} T'_{11} & T'_{12} & \cdots & T'_{1N} \\ T'_{21} & T'_{22} & \cdots & T'_{2N} \\ \vdots & \vdots & & \vdots \\ T'_{N1} & T'_{N2} & \cdots & T'_{NN} \end{bmatrix} \begin{bmatrix} Mo_1 \\ Mo_2 \\ \vdots \\ Mo_N \end{bmatrix} \tag{3-7'}$$

where $\boldsymbol{T'}$, illuminance transfer factor is defined as

$$\boldsymbol{T}' = \boldsymbol{F} \cdot \boldsymbol{T} \tag{3-8}$$

or

$$[T']_{N\times N} = \begin{bmatrix} F_{11} & F_{12} & \cdots & F_{1N} \\ F_{21} & F_{22} & \cdots & F_{2N} \\ \vdots & \vdots & & \vdots \\ F_{N1} & F_{N2} & \cdots & F_{NN} \end{bmatrix} \begin{bmatrix} T_{11} & T_{12} & \cdots & T_{1N} \\ T_{21} & T_{22} & \cdots & T_{2N} \\ \vdots & \vdots & & \vdots \\ T_{N1} & T_{N2} & \cdots & T_{NN} \end{bmatrix} \tag{3-8'}$$

where F is the view factor and T is the luminous exitance transfer factor. T' depends on the geometric orientation to light source (luminous exitance) surfaces and reflectance of the surfaces. A space with different geometry or having different surface reflectance will have completely different illuminance distributions under the same initial luminous exitance. The accuracy of the illuminance estimate will be increased with smaller element surface areas. However, this will increase computational time.

With a careful observation of Eq. (3-7), the prediction of the workplane illuminance can be simplified without loss of accuracy. It is not required to calculate the illuminance transfer factor; that is, it is not necessary to calculate view factors and measure the reflectance of all subdivided surfaces. However, the exact workplane illuminance can be predicted easily, especially in a light dimming control system where an indirect prediction method is employed to complement electric light for the target design illuminance level. Consider an enclosure where there is only one light source (initial luminous exitance, Mo) on surface 1 so that $Mo_1 \neq 0$ and $Mo_k = 0$ for k = 2, 3, ..., N. Then the illuminance of surface i from Eq. (3-7') is

$$E_i = T'_{i1} \cdot Mo_1 \qquad (3\text{-}9)$$

The illuminance ratio of two surfaces m and n due to a light source on surface 1 is then

$$\frac{E_m}{E_n} = \frac{T'_{m1} \cdot Mo_1}{T'_{n1} \cdot Mo_1} = \frac{T'_{m1}}{T'_{n1}} \qquad (3\text{-}10)$$

where T'_{m1} and T'_{n1} are illuminance transfer factors for surfaces m and n to the initial light source surface 1. The ratio of two surfaces' illuminance is then the ratio of two surfaces' illuminance transfer factors, which is constant for the given space geometry and surface properties. Therefore, it can be concluded that the illuminance ratio of two arbitrary surfaces in an enclosure is always kept constant even with varying quantity of the initial light source (Mo_1).

Equation (3-7) is derived for a space composed of diffuse-gray surfaces. This is an idealized case considered to simplify the computations. However, it is expected that this equation will be applicable without much error for a real space where diffusely emitting and partly specularly reflecting surfaces coexist, because both illuminance transfer factors (T'_{m1} and T'_{n1}) will be modified simultaneously and thus their ratio is not expected to change. This can also be applied for a light source that is either perfectly diffusing or with some specular component. It can be concluded that the illuminance ratio of two arbitrary surfaces in a real space is always constant with varying quantity of the one initial light source that distributes luminous flux in a consistent way.

3.3 Applications to Daylighting Control Systems

In the daylighting control environment, at least two light sources must be considered; one for the daylight through the window systems and one for the electric light, which will complement design workplane illuminance level by dimming. The daylight and electric light contributions to the photocell and the workplane are different (because of the different locations of the light sources) so that a separate prediction must be employed for the two light sources.

Electric light from a lighting fixture (luminaire) is designed to distribute luminous flux in a predictable manner. The workplane illuminance then can be predicted indirectly with a photocell located somewhere in the space rather than on the workplane. The dimming of the luminaire will not affect the illuminance ratio of two surfaces (workplane surface and surface with photocell) according to Eq. (3-10).

The daylight admitted through window systems can be direct or diffuse. With direct daylight admission into the room, the initial light source would be beam daylight projection on the room surfaces so that its location and surface area will be changing continuously according to the position of the sun; numerous ratios would be required to predict workplane illuminance with the illuminance ratio prediction method. If the light source location and surface area were fixed, then only one ratio would be needed to predict daylight in the space.

A window system with shading devices as a light source can be treated as a luminaire such as a dimmable spotlight, which aims at one fixed point and distributes variable amounts of light consistently. It is possible to achieve consistent daylight distribution in the space by means of shading device control. The illuminance ratio, for the venetian blinds for example, could be a function of angle of incidence on the blade of the blinds because the way daylight is distributed into the space will change with the solar altitude, surface solar azimuth and blind tilt angles.

There are two general cases for two light sources that can be considered in daylighting systems: two different window systems on the same façade and two window systems on different façades. The reason for cases without luminaire is that only one illuminance ratio is needed for the electric light predictions with one fixed photocell location and this is easily predictable with or without presence of window systems. It is difficult to obtain illuminance ratios for two window systems without employing exterior sensors and transmittance of window systems.

Consider the illuminance ratio of two surfaces *m* and *n* due to two light sources on surfaces 1 and 2 so that $Mo_1 \neq 0$, $Mo_2 \neq 0$ and $Mo_K = 0$ for k = 3, 4, ..., N. The ratio is then

$$\frac{E_m}{E_n} = \frac{T'_{m1} \cdot Mo_1 + T'_{m2} \cdot Mo_2}{T'_{n1} \cdot Mo_1 + T'_{n2} \cdot Mo_2} \qquad (3\text{-}11)$$

where T'_{m1}, T'_{m2}, T'_{n1} and T'_{n2} are illuminance transfer factors for surfaces *m* and *n* to the initial light source surfaces 1 and 2. They are all constant for the given space geometry and surface properties. Unlike the ratio with one light source (Eq. (3-7)), however, it is difficult to generalize prediction method since the ratio is highly dependent on initial light sources (Mo_1 and Mo_2).

Assuming the ratio for one light source, Mo_1 is a constant a, then the illuminance transfer factor for surface m to light source on surface 1 is as follows:

$$\frac{E_m}{E_n} = \frac{T'_{m1}}{T'_{n1}} = a \tag{3-12}$$

$$T'_{m1} = a \cdot T'_{n1} \tag{3-12$'$}$$

The illuminance transfer factor for surface m to light source on surface 2 is

$$\frac{E_m}{E_n} = \frac{T'_{m2}}{T'_{n2}} = b \tag{3-13}$$

$$T'_{m2} = b \cdot T'_{n2} \tag{3-13$'$}$$

assuming that the ratio due to a light source, Mo_2 is a constant b. Now Eq. (3-11), with substitution of Eqs. (3-12′) and (3-13′), becomes

$$\frac{E_m}{E_n} = \frac{a \cdot T'_{n1} \cdot Mo_1 + b \cdot T'_{n2} \cdot Mo_2}{T'_{n1} \cdot Mo_1 + T'_{n2} \cdot Mo_2} \tag{3-14}$$

If the two ratios a and b are equal ($a = b = c$), then the ratio for two window systems will be c as follows:

$$\frac{E_m}{E_n} = \frac{c \cdot T'_{n1} \cdot Mo_1 + c \cdot T'_{n2} \cdot Mo_2}{T'_{n1} \cdot Mo_1 + T'_{n2} \cdot Mo_2} = c \tag{3-15}$$

This relationship would be useful for controlling real daylit buildings. It might be difficult to find the same ratio for two light sources. More than two window systems will be similar to this case, but it will be more difficult to make them the same ratio. Note, however, that the majority of cases consist of one or two window systems.

Another important application to daylighting control in buildings is that the solar heat gains through window systems can be predicted by utilizing the spectral luminous efficacy of radiant flux* [Muneer (1995)]. Similar to predicting the workplane illuminance, the correlation between the sensor reading and the solar heat gain on interior surface of window would always be constant under the same radiosity theory assuming that solar and light properties of surfaces are approximately equal. The amount of heat gains through window systems is an important factor for heating and cooling load calculations.

It is expected that the external vertical illuminance can also be predicted with IRP method under the same daylight transmission. As the shaded area on the window surface increases, total daylight transmission of the window system will decrease accordingly. Unless the window surface is shaded, a linear correlation between an inside surface illuminance and an exterior vertical illuminance can be obtained.

The advantages of the IRP method are its simplicity, accuracy and reliability. The simplified prediction procedure makes light dimming control with high prediction accuracy more readily applicable to real buildings. The location of the photocell can be anywhere in the room and change of photocell views cannot affect the illuminance ratio since the ratio of two surfaces is a function of their location relative to the initial light source (window system). Accurate workplane illuminance prediction will improve the performance of daylighting control systems, hence enhancing energy efficiency.

The outside weather condition whether cloudy, sunny or variable, will not affect the illuminance ratio. However, the reliability of the method will be highly dependent on

* The quotient of the luminous flux at a given wavelength by the radiant flux at that wavelength. It is expressed in lm/W.

the window systems. If the window systems can be controlled similar to luminaires, one can achieve the highest accuracy of the workplane illuminance predictions. Anidolic zenithal opening, light pipe system in windowless room, motorized roller blinds, electrochromic coatings and translucent glazings would be good applications.

3.4 Conclusion

It was found theoretically that the illuminance ratio of two arbitrary surfaces in an enclosed space in the presence of one light source with varying quantity at a fixed location is always constant. This finding can be applied to workplane illuminance prediction in daylighting control systems if the daylight through window systems is distributed similar by the light from luminaires. This can also be applied to predict the exterior vertical illuminance and the solar heat gains through window systems so that integrated control of light dimming, shading, heating and cooling can be further improved.

Flexible location of the photocell will facilitate calibration and commissioning of real applications. Accuracy and reliability of the IRP method will improve the system performance significantly and make the systems applicable to real buildings. Ideal cases for perfect workplane illuminance prediction, that is, for reliable light dimming controls, would be daylit rooms with window systems working perfectly like luminaires that is with repeatable consistent light emission distributions.

Experimental verification for electric light, daylight and combined light prediction is described in chapter 4.

CHAPTER 4

EXPERIMENTS ON DAYLIGHT CHARACTERIZATION AND VALIDATION OF IRP METHOD

4.1 Introduction

The workplane illuminance, the exterior vertical illuminance and the irradiance through the window system are important daylighting parameters for daylighting control systems. It was found that these parameters could be predicted theoretically with one interior light sensor when beam solar radiation is excluded. In this chapter, the experimental results for daylight predictions with the proposed Illuminance Ratio Prediction (IRP) method are described. An outdoor test-room with computer controlled lighting system (with continuous dimming), window system (with motorized venetian blinds) and heating/cooling system was used. The objectives of this experimental study were to validate the proposed IRP method for the workplane illuminance predictions and to obtain correlation equations for daylighting control with one interior light sensor. The details of the test facility and data acquisition and control system are described.

Results of the electric light prediction with random light dimming simulation are analyzed to verify the proposed illuminance ratio prediction method. Daylight prediction with controlled daylight admission is analyzed and correlations for different daylight angles are obtained. Light source instability effect on correlations is discussed. Finally, correlation equations as a function of the daylight angle for the prediction of the workplane illuminance, the exterior vertical illuminance and the solar irradiance with a front wall sensor illuminance are obtained.

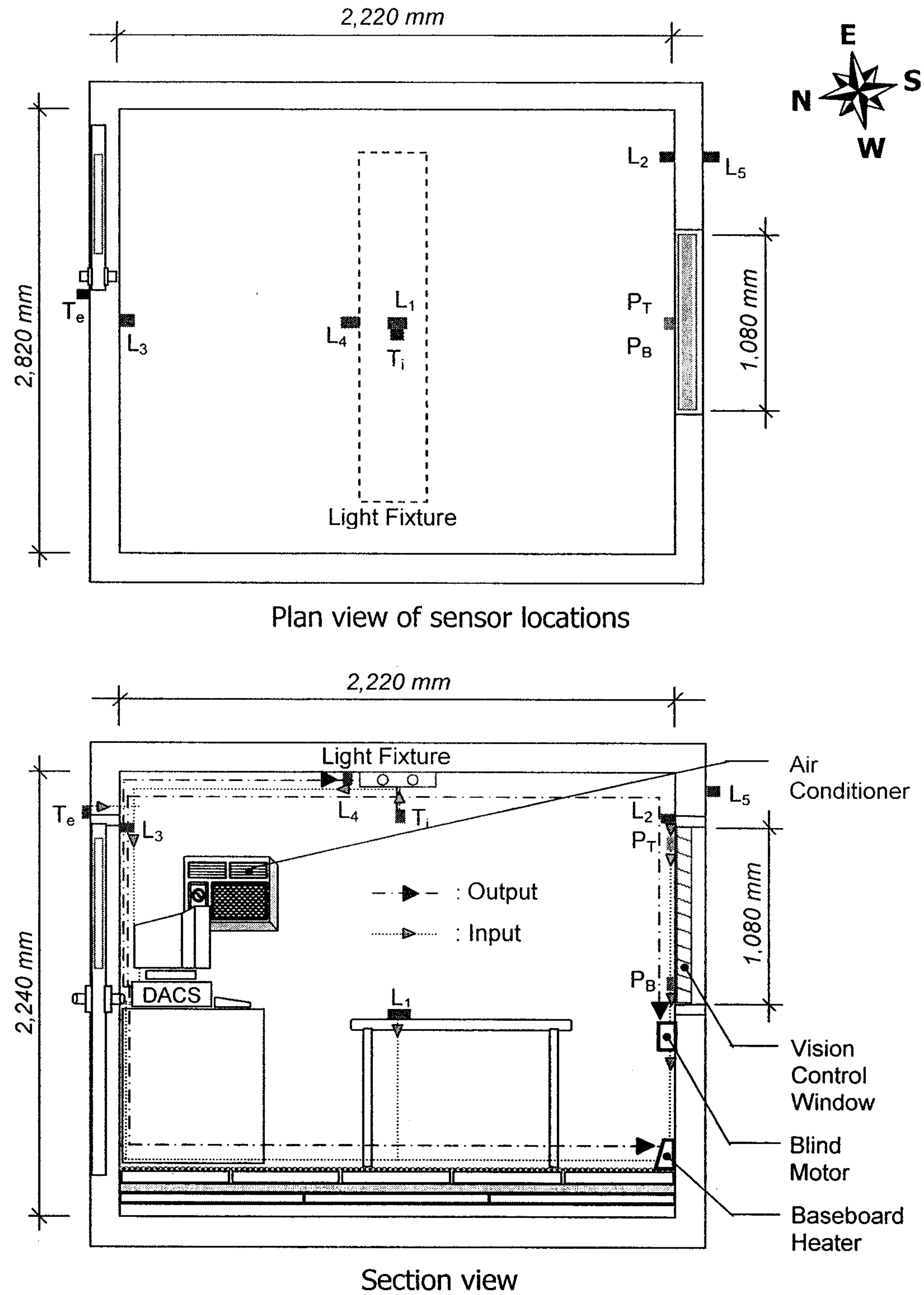
4.2 Test Facility

4.2.1 Test room

An insulated outdoor test-room on the roof of the BE building of Concordia University in Montreal (Latitude: 45 °N, Longitude: 74 °W) was operated for daylighting control studies under real weather conditions. The interior dimensions of the test-room are $2.82m \times 2.22m \times 2.24m$. The test-room has cream-white painted walls, acoustic ceiling and carpeted floor. The measured reflectance of test-room surfaces are: floor 17%, ceiling 66%, wall 68%, window 8% with blinds closed and 6-10% with blinds opened, and desk 52%.

Two lighting fixtures each with two *T8 32W* lamps and dimmable fluorescent ballasts were installed. These are mounted on the ceiling parallel to the window along the centerline of the test-room. The installed window system was *VISION CONTROL*, which is a double glazed window with venetian blinds integrated between two glazings with one low-emissivity coating. The existing heating (baseboard heater) and cooling (air conditioning) systems were employed to maintain the temperature approximately constant (23 °C). The window and lighting systems are described in more detail below.

A number of T-type thermocouples, pyranometers and light sensors were placed in different locations for measuring indoor and outdoor temperature, the solar irradiance and the illuminance, respectively. All were connected to the data acquisition system. A schematic of the test-room appears in Fig. 4-1 and its outside view is shown in Fig. 4-2.



Legend	Subscript				
T: Thermocouple	1:Workplane	2:Front wall	3:Back wall	4:Ceiling	5:Exterior vertical
L: Light meter	e:Exterior	i:Interior			
P: Pyranometer	T:Top	B:Bottom			

Figure 4-1 Schematic of the test-room and sensor locations

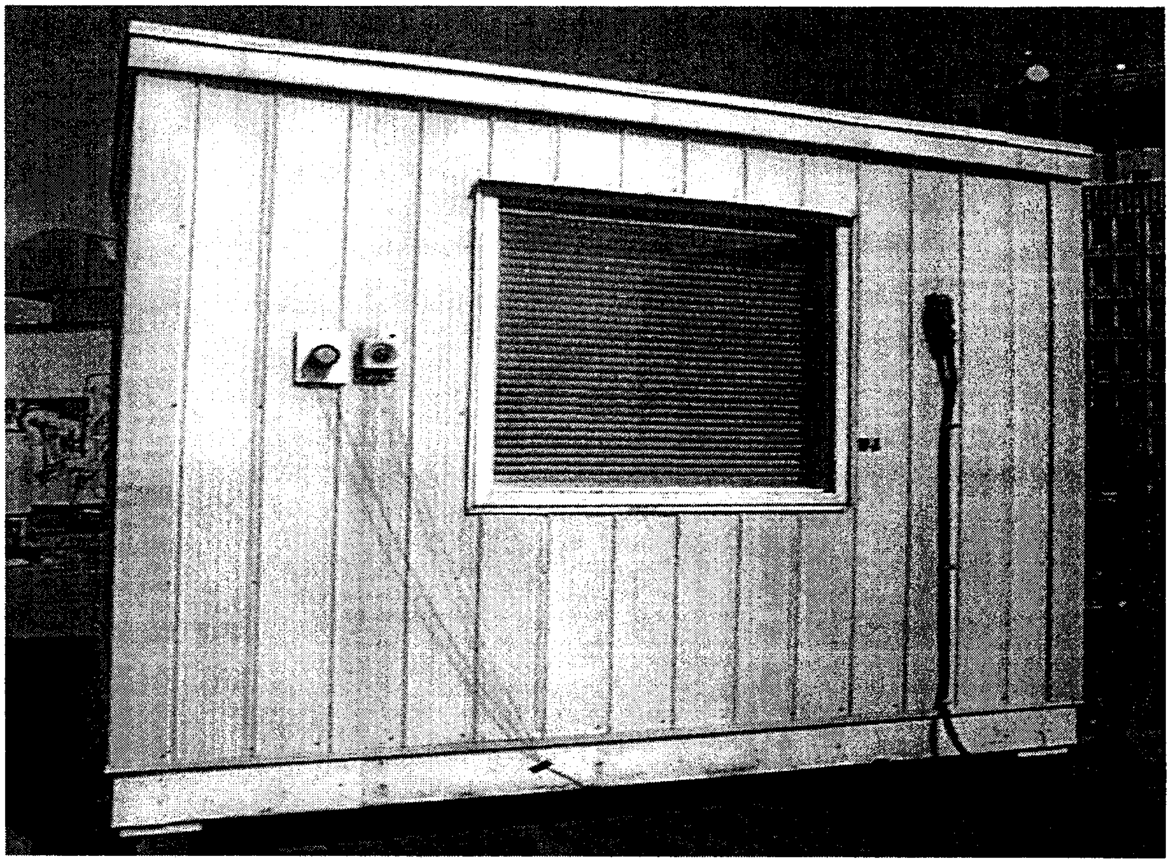


Figure 4-2 Photo of the test-room

4.2.2 Window system

One window system (window with blinds and motor) was installed in the center of the test-room façade facing 10 degrees East of South. The window system (trade name *VISION CONTROL*) is a double-glazed window with a low emissivity coating and highly reflective horizontal louvers integrated between the two panes (Fig. 4-3 (a)). The dimensions of the window are $1.08m \times 1.08m$. The louvers are made of extruded aluminum and hollow-chambered profile with overlap. The blades are convex with interlocking type ends, 35*mm* wide and 6*mm* thick (Fig. 4-3 (b)). The finish of the louvers is baked-enameled Duracron Color Glossy White K-1285. The rotation of the blades can be 180 degrees in a continuous cycle by manual or motor operation.

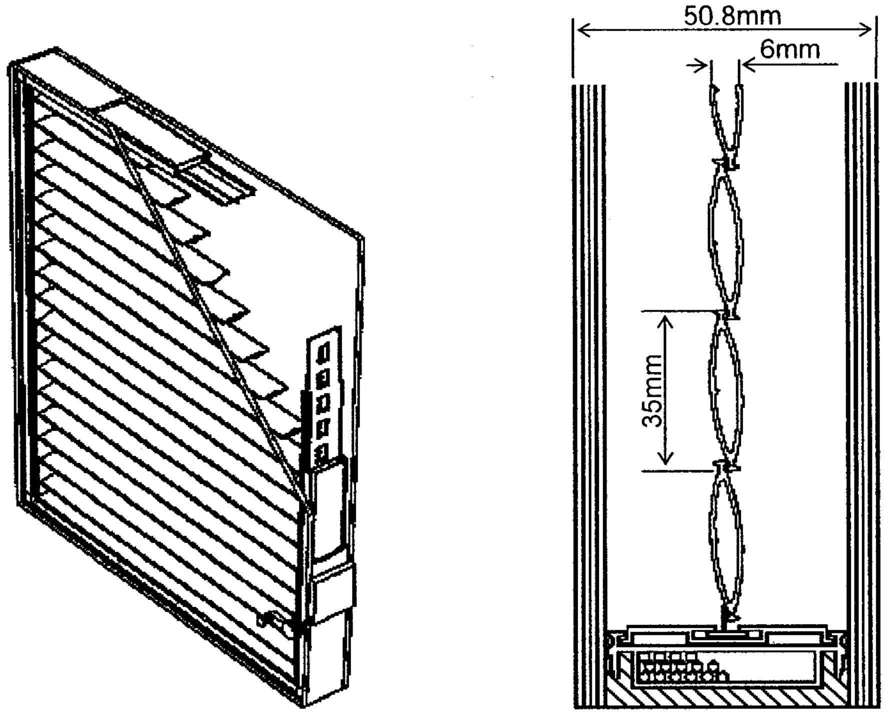
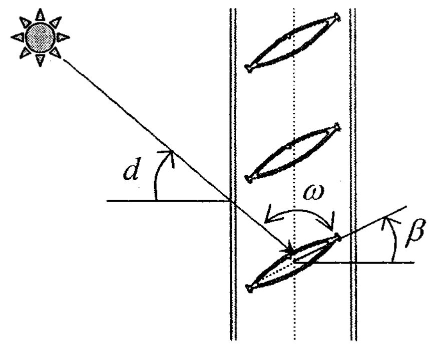


Figure 4-3 (a) Illustration of *VISION CONTROL* window and (b) Interlocking blades (From Unicel Inc.: www. visioncontrol.qc.ca)

A blind tilt angle (β) of 0 °corresponds to horizontal, a positive β corresponds to a downward angle with a view of the ground from the inside room, and a negative β corresponds to an upward angle with a view of the sky from the interior. This angle was controlled to block direct daylight penetration for the daylight prediction. The rotation range of the tilt angle was from 0 degrees (fully open) to 70 degrees (not closed completely but no direct beam can penetrate) since the blades of the blind are overlapping as shown in Fig. 4-3(b). The control angle was obtained from the profile angle, which is the projection of the solar altitude angle on a vertical plane perpendicular to a window (Fig. 4-4). Figure 4-5 shows the control angles corresponding to profile angle variations to block direct daylight.



$$d = \tan^{-1}\left(\frac{\tan\alpha}{\cos\gamma}\right)$$

α: solar altitude

γ: surface solar azimuth

$\omega = 180^{\circ} - d - \beta$

Figure 4-4 The profile angle (d), the blind tilt angle (β) and the daylight angle (ω)

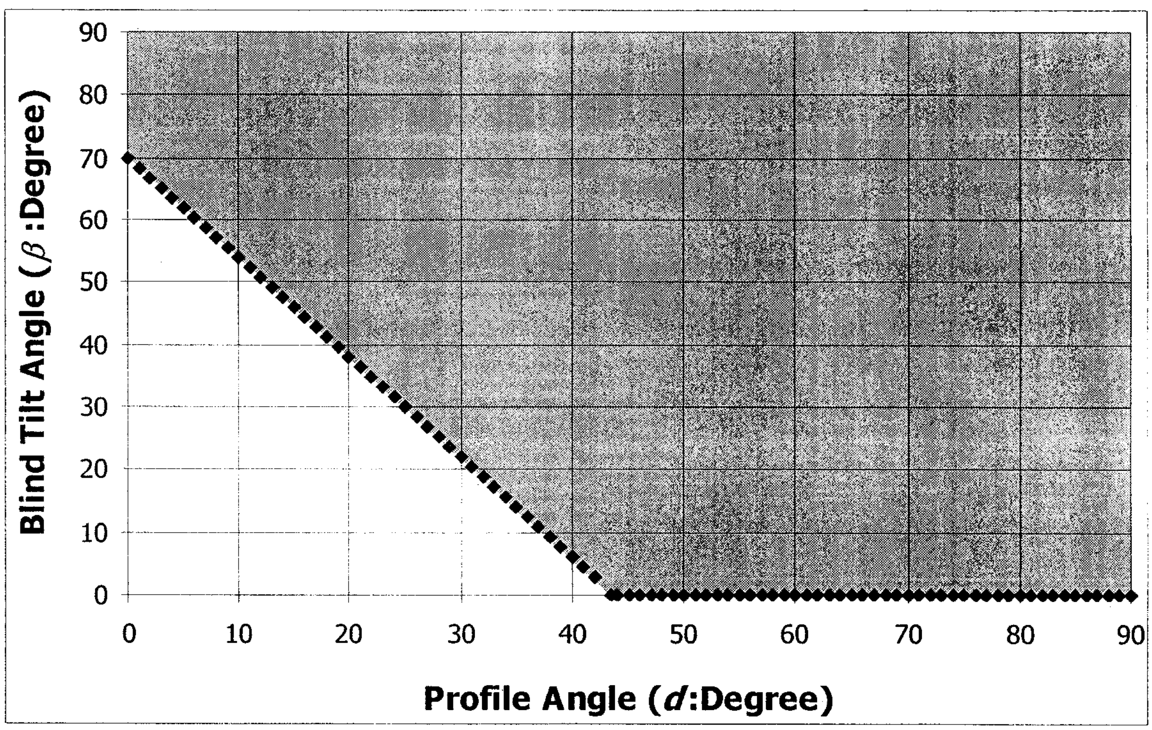


Figure 4-5 The direct daylight block angles corresponding to the profile angles

4.2.3 Lighting system

Two lighting fixtures employed in experimental studies are equipped with electronic fluorescent dimming ballasts (Mark VII 0-10*V* from Advance Transformer Co.), each of which dims two *T8 32W* lamps from 5% to 100% continuously and with a 0 to 10*VDC* signal. They start the lamps at any selected light output. These are direct fixtures without reflectors and diffusers and mounted on the ceiling parallel to the window along the centerline of the test-room. The lighting was operated at full output for 100 hours when it was installed to obtain effective dimming level control. The lighting was dimmed as a single zone system.

Electric lighting energy consumption can be reduced with appropriate light dimming control. The employed ballast offers energy savings approximately proportional to the reduction in lighting output. Figure 4-6 shows the correlation between electric lighting energy consumption and lighting output for the two *T8 32W* lamps. The actual input power consumption is of course double for two lighting fixtures (two lighting fixtures each with two *T8 32W* lamps). This data is necessary to estimate energy savings by light dimming controls.

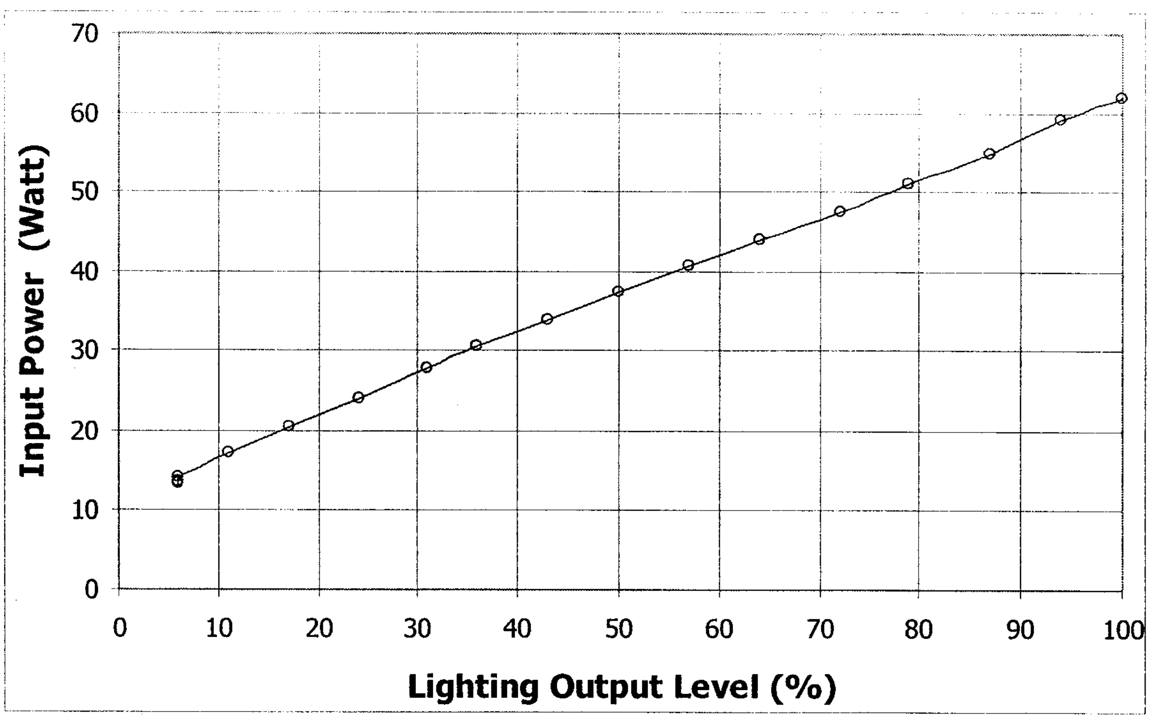


Figure 4-6 Electric lighting power consumption for two T8 32W Lamps
(Source from Advance Transformer Co.)

4.2.4 Data acquisition and control system

Two data acquisition systems were employed to conduct experimental studies: *IOTech* [IOtech (2000)] and *Agilent* [Agilent (1999)]. The former is a PC-based 12-bit *IOtech DaqBook 120* with Analog Input/Outputs, Digital Input/Outputs, and Frequency Input/Outputs. 16 channels were used for analog inputs of the illuminance and the solar irradiance. One of these channels can be expanded by connecting a *DBK19 Thermocouple* so that another 16 channels for temperature are measured. *DaqBook 120* has only two analog output channels whose signals go through 12-bit D/A converter that generates voltages of 0 to ±5 Volts. These two output channels were used for the lighting and window blind control. Heating and cooling systems are controlled on/off through digital output.

A new software featuring data acquisition with integrated control system (Total Control System, *TCS*) was developed for this research project (Fig. 4-7). The *TCS* is programmed in Visual C++ with the enhanced Application Programming Interface language, which is supported by *IOtech Inc.* [IOtech (1999)]. The advantage of this system is the fast scan rate (up to 10 μs per scan). However, the accuracy of the data decreased with the fast scan rate. Some data were collected with this system.

The other data acquisition system is a *34970A Data Acquisition/Switch Unit* (Agilent) [Agilent (1999)], which offers powerful measurement performance, flexibility and ease of use. It features 6½ digits (22 bits) of resolution, 0.004% basic *VDC* accuracy and ultra-low reading noise. With the fast scan rate, however, the accuracy dropped. Two different modules of *34901A 20 Ch Multiplexer* for data outputs and *34907 Mutifunction Module* for control inputs were added in this system.

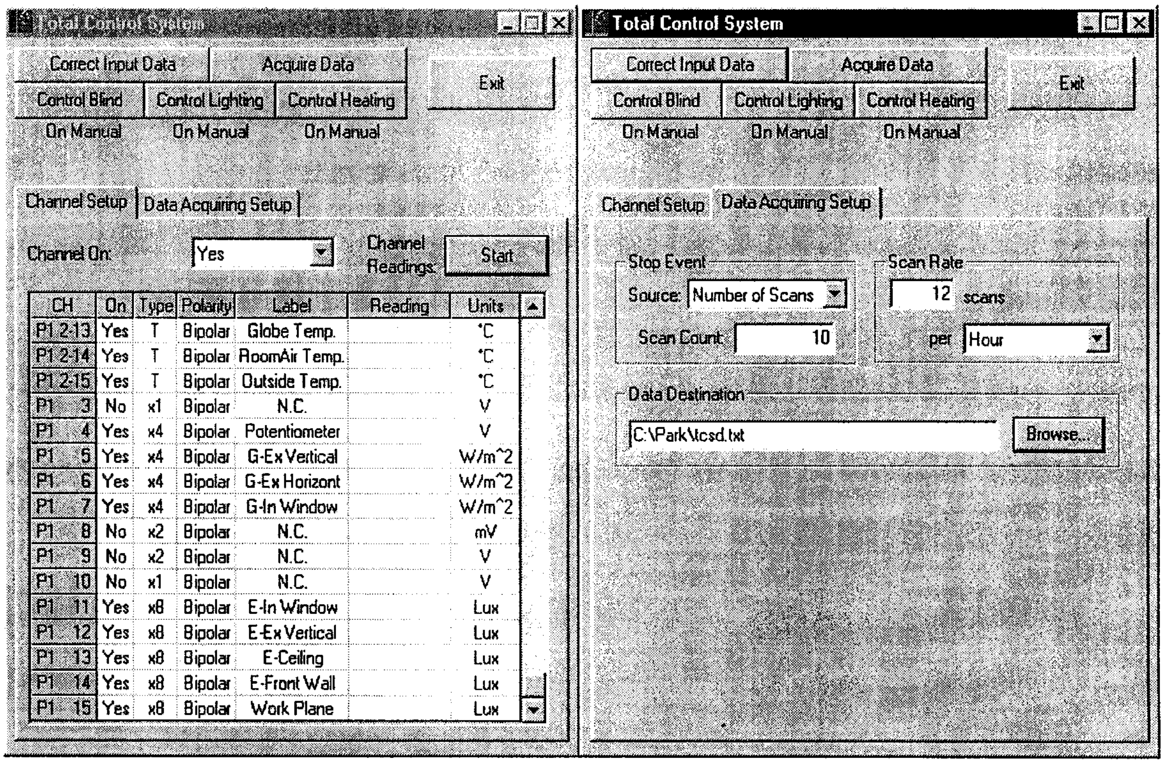


Figure 4-7 Total control system programmed in C++ for data acquisition and control with IOTech instrument (*Daqbook 120*)

A computer program (Total Control System) was developed in *Agilent VEE Pro 6.1* [Agilent (2000)], which is a powerful graphical programming environment for fast measurement analysis and control (Fig. 4-8). This program consists of three main options for manual, automatic and energy saving controls. The majority of the data for correlations were collected with the automatic control option where all data were sampled and logged automatically at a specified time, and the blind tilt angle and the inside temperature were controlled with the given control options. With the energy saving control option, real daylighting control was implemented with necessary data logging (workplane illuminance, blind tilt angle, dimming level, etc.) for analysis.

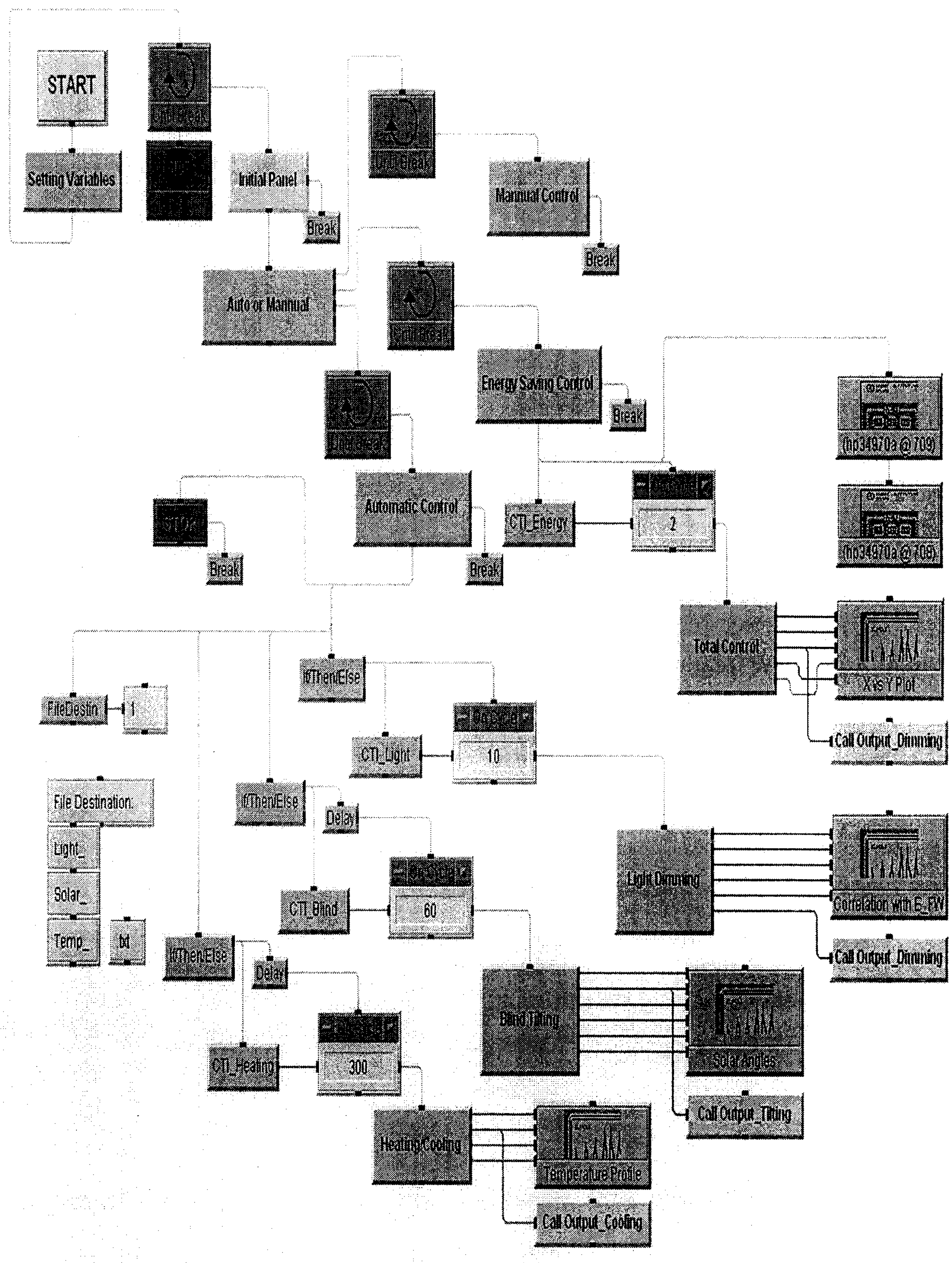


Figure 4-8 Total control system programmed in VEE Pro 6.1 for data acquisition and control with Agilent instrument (*34970A Data Acquisition/Switch Unit*)

4.3 Electric Light Prediction

During this part of the test the focus was on electric light illuminance prediction. The window was completely covered so that the electric light was the only light source so as to develop correlations between the workplane illuminance and the illuminances of surfaces where control sensors are placed. Three different control sensor locations were tested; front wall, back wall and ceiling (see Fig. 4-1). The electric light was dimmed randomly from 0 to 100% of lighting output (0 to 8*VDC* controls)* to simulate actual control conditions. Dimming and data collection were conducted every 10 seconds for one hour. To obtain stable illuminance data, data were sampled and logged 5 seconds after every dimming action. The profile of random electric light dimming level is depicted in Fig. 4-9.

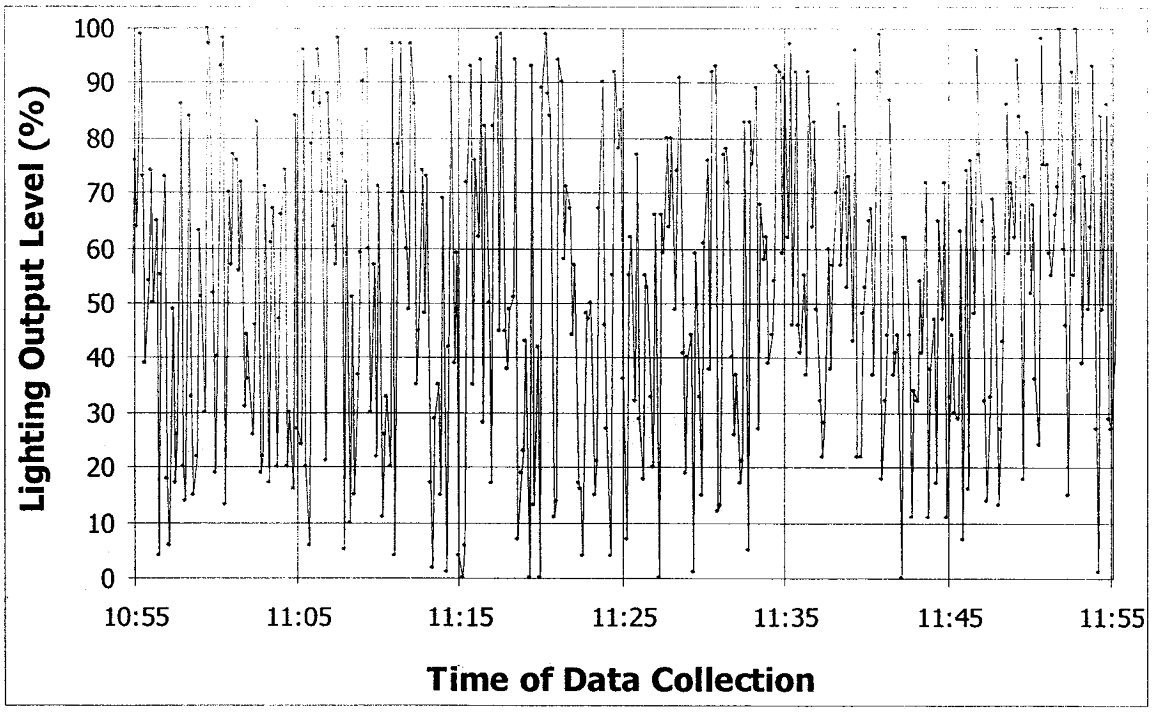


Figure 4-9 Electric light level profile with 10-second-random dimming

* Unlike product specifications, the actual control input range was found to be from 0 to 8 *VDC* instead of 0 to 10*VDC*.

Light distributions with random electric light dimming were obtained by means of the surface illuminances measured for four different sensor locations (Fig. 4-10). The ceiling sensor had the highest level of illuminance since it was located near the light source (direct light) and facing the desk, which has a higher reflectance compared to other surfaces (first reflected light). It was found that the correlation between electric lighting output level and any surface illuminance is linear and the effective light dimming ranges are from 15% to 100%* of lighting output. Some of the deviations from higher dimming levels are caused by the AC input power fluctuation. Generally, AC power is supplied with a variation of ±5% of the maximum voltage (114 to 126 *VAC* for 120 *VAC*). In addition to this, the increased power consumption within the building increases the range of fluctuations. With the input voltage fluctuations, it was found that the workplane illuminance was fluctuated around 30 *lx* at the maximum dimming level.

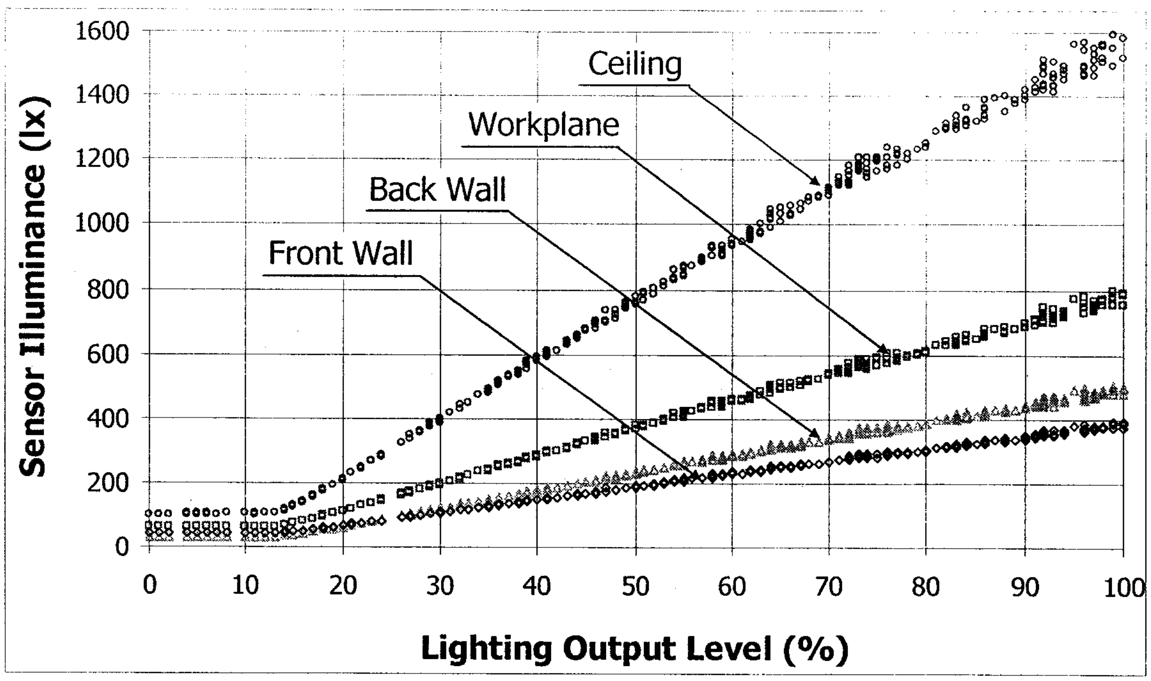


Figure 4-10 Electric light distributions on four surfaces of different sensor locations

* This dimming range was found to be different from the product specifications (5% to 100%).

The correlations between the workplane illuminance and the sensor illuminances for three different locations were found to be linear even with unstable lighting outputs at higher dimming levels as shown in Fig. 4-10. There are some deviations at higher light levels in Fig. 4-11 for a correlation between ceiling sensor illuminance and workplane illuminance. This might be caused by electrical noise from lighting fixtures since the ceiling sensor was placed near them. It can be observed from the results that the ratio is only dependent on the geometric relationship between two surfaces. Therefore, the workplane illuminance can be predicted with a flexible sensor configuration (location and field-of-view) for any given space conditions.

To predict the workplane illuminance with the sensor, the illuminance ratio for each sensor must be obtained. The illuminance ratios as derived with Eq. (3-11) are depicted in Fig. 4-12. This was done by zero offset data; at the minimum dimming level

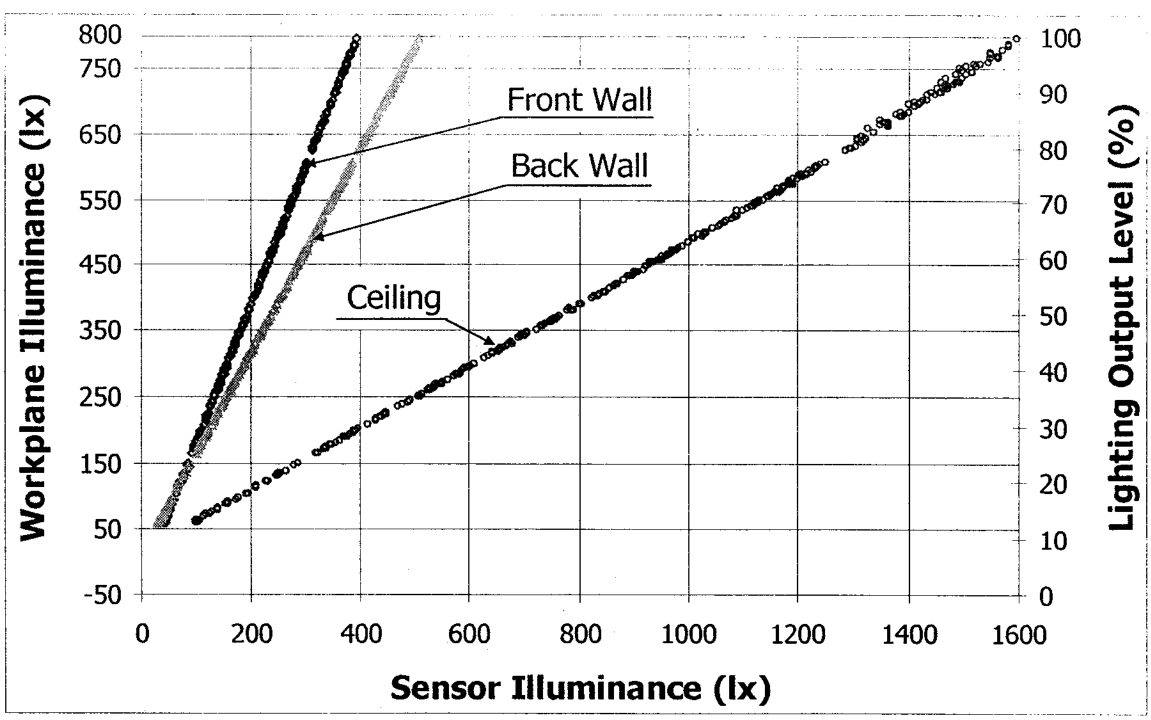


Figure 4-11 Correlations between the workplane illuminance and the illuminances for three different sensor locations

(0 to 15%), workplane, front wall, back wall and ceiling illuminance were 60 *lx*, 42 *lx*, 30 *lx* and 99 *lx*, respectively. With the front wall sensor illuminance 200 *lx*, for example, the workplane illuminance can be predicted as 391 *lx* ((200 - 42) × 2.096 + 60). The three sensors were found to predict the workplane illuminance well (R^{2*} for front wall sensor, back wall sensor and ceiling sensor are 0.99998, 0.99996 and 0.99915, respectively).

From electric light prediction results, it was found that the lighting source does not need to be diffuse, nor do the surfaces in the test-room. That is, any kind of lighting system such as direct, indirect, semi-direct, etc., can be considered with this prediction method. Any room shape with different kinds of surfaces, polished, rough or matte surface can be considered. However, the light source must be one and from the fixed location.

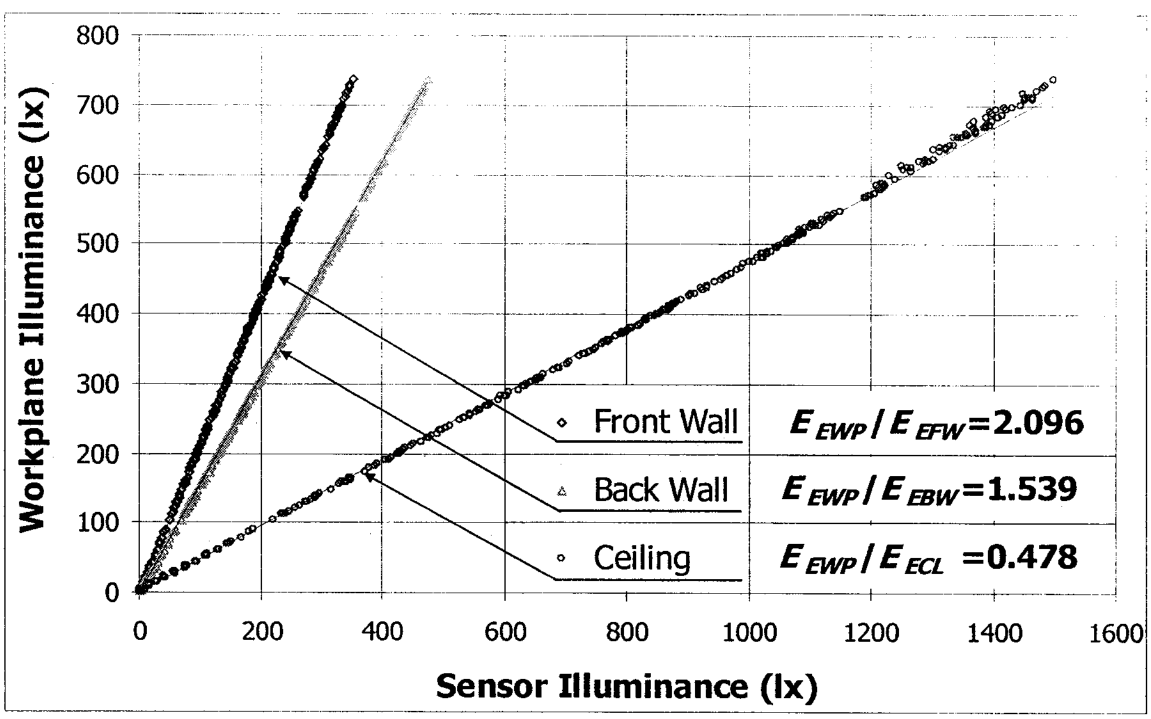


Figure 4-12 Illuminance ratios of the workplane surface to the three different surfaces

* The square of the Pearson product moment correlation coefficient through data points in y's and x's. It shows how well the data match with the regression line.

4.4 Daylight Prediction

It was found that the illuminance ratio of two surfaces in a room is constant if the light source has a fixed location. This finding can be extended to a window that behaves like a luminaire. The daylight through a window can be treated as an electric light source when direct sunlight is blocked. If direct sunlight is admitted then it is as if additional light sources are present at the points where the transmitted beam daylight is incident. Once the window system acts like a luminaire, then the workplane illuminance can be predicted similar to an electric light prediction. A *VISION CONTROL* system, which is a double-glazed window with controllable venetian blinds between the glazings, was employed to predict the workplane illuminance level with three different locations of sensors; front wall, back wall and ceiling as electric light predictions (see Fig. 4-1 for sensor locations). Electric light was kept at the minimum dimming level (15%) during data collection to obtain correlations for light dimming control.

The blind tilt angle was controlled to create a consistent light source. The way daylight is distributed after striking on the blinds can be controlled by continuously adjusting the blind tilt angle so that the daylight angle (Fig. 4-4) can remain constant. The daylight angle (ω) is defined as follows:

$$\omega = 180^\circ - d - \beta \qquad (20^\circ \le \omega \le 136.5^\circ) \tag{4-1}$$

where d is the profile angle and β stands for the blind tilt angle. All angles are expressed in degrees. It is expected that reliable correlations with the daylight angle can be obtained since it is a universal angle. From previous research [Park and Athienitis (2003)], the correlation for daylight prediction was found to be dependent on the blind tilt angle, the solar altitude angle and the surface solar azimuth angle.

Six different daylight angles were examined to obtain correlations between the workplane illuminance and three different sensor illuminances for daylight predictions and performance of sensor configuration: 80, 90, 100, 110, 120 and 130 degrees. The maximum possible daylight angle is 136.5 degrees when the profile angle is 43.5 degrees and blind tilt angle is 0 degrees while blocking direct daylight. The minimum possible angle is 20 degrees when the profile and blind tilt angles are 90 and 70 degrees, respectively. With this minimum angle, however, most of the daylight will be blocked. In addition, when the blind tilt angle is increased, the daylight transmission is significantly decreased. Therefore, the range of daylight angle to obtain correlation was chosen to be between 80 degrees (70 degrees of profile angle and 30 degrees of blind tilt angle for instance) and 130 degrees.

Data were collected for six different daylight angles in 2002 and 2003. The daylight angle is a universal angle for any time of a year and for any location of the window because the angle was calculated in accordance with the solar angles (i.e., the solar altitude angle, the blind tilt angle and the surface solar azimuth angle) and the window location. The data sampling and logging (every minute) for one or two days (in case of rainy day) from 6:00 to 19:00 were performed for each case of the daylight angle.

Correlations between the workplane illuminance and the illuminances for three different sensor locations are depicted in Fig. 4-13 for different daylight angles. It can be observed that linear correlations between the workplane illuminance and the sensor illuminances can be obtained except for the back wall sensor. From the data analysis, however, it is found that the scattered data for the back wall sensor were caused by reflected beam daylight from adjacent buildings. The back wall sensor was facing the

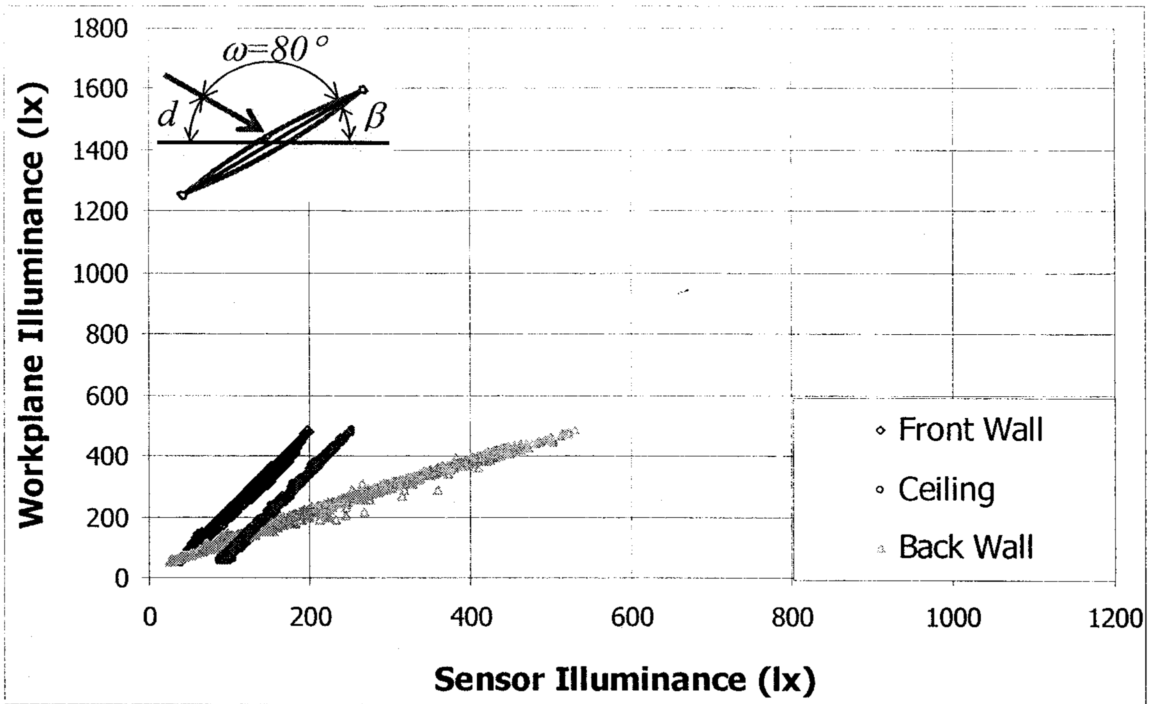


Figure 4-13(a) Correlations between the workplane illuminance and the illuminances for three different sensor locations for the daylight angle $\omega = 80^{o}$

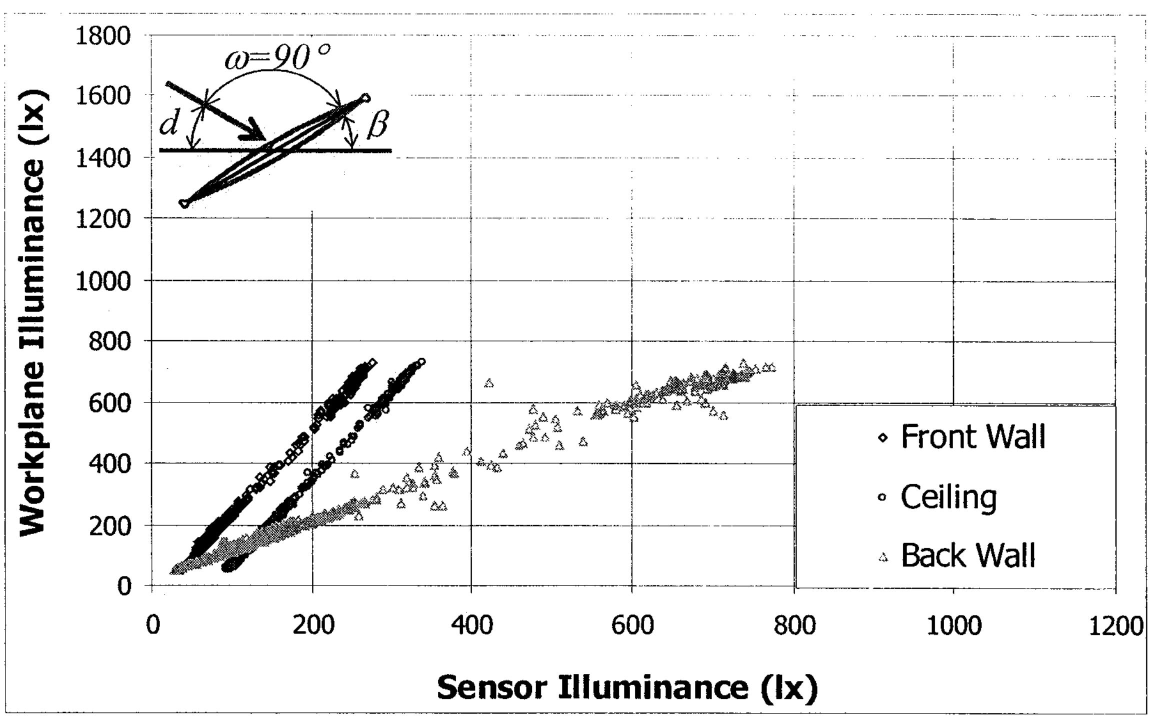


Figure 4-13(b) Correlations between the workplane illuminance and the illuminances for three different sensor locations for the daylight angle $\omega = 90^{o}$

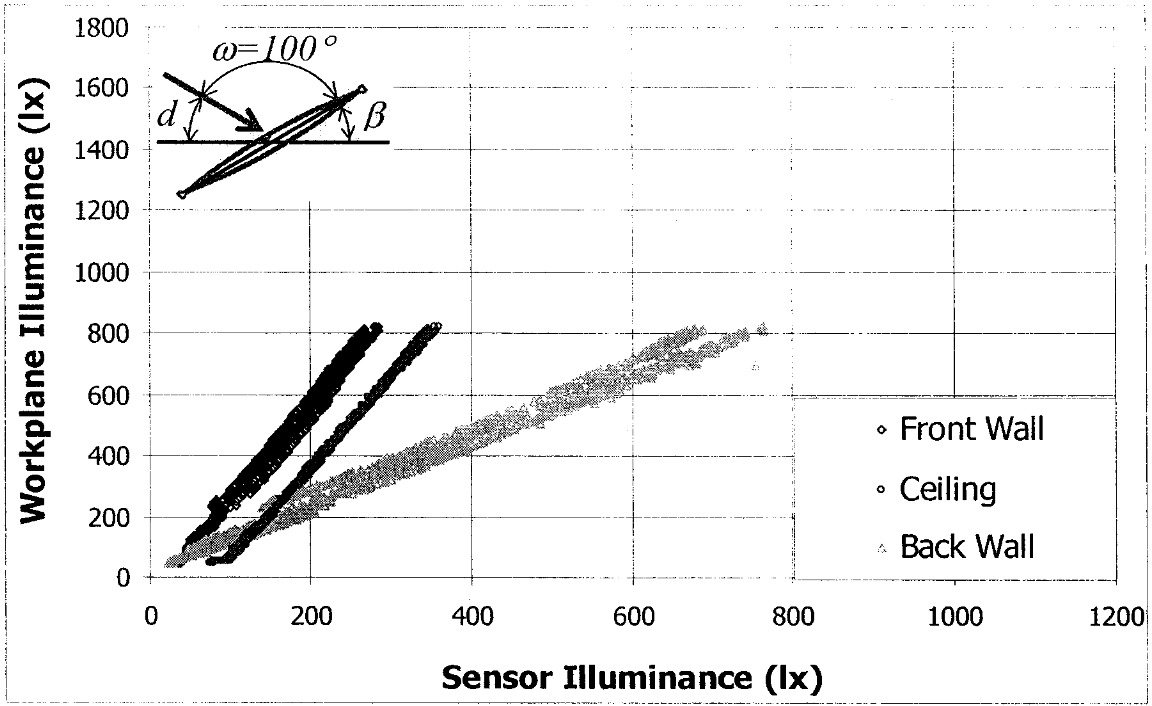


Figure 4-13(c) Correlations between the workplane illuminance and the illuminances for three different sensor locations for the daylight angle ω = 100 ^{o}

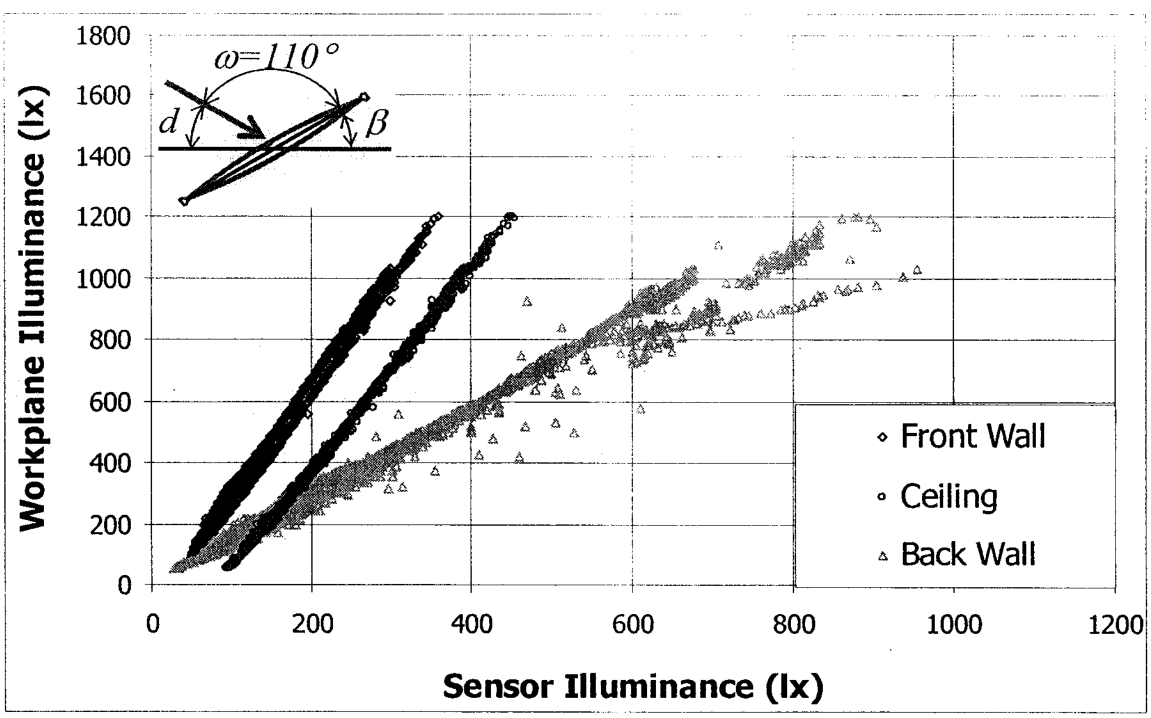


Figure 4-13(d) Correlations between the workplane illuminance and the illuminances for three different sensor locations for the daylight angle ω = 110 ^{o}

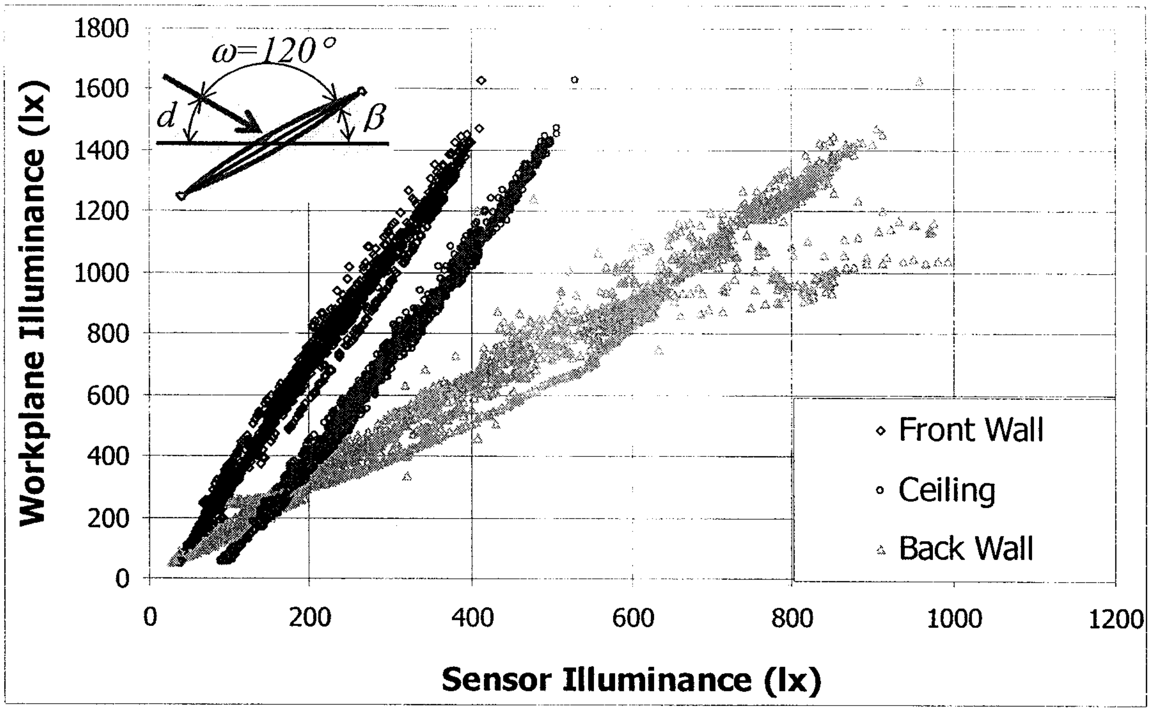


Figure 4-13(e) Correlations between the workplane illuminance and the illuminances for three different sensor locations for the daylight angle $\omega = 120^{o}$

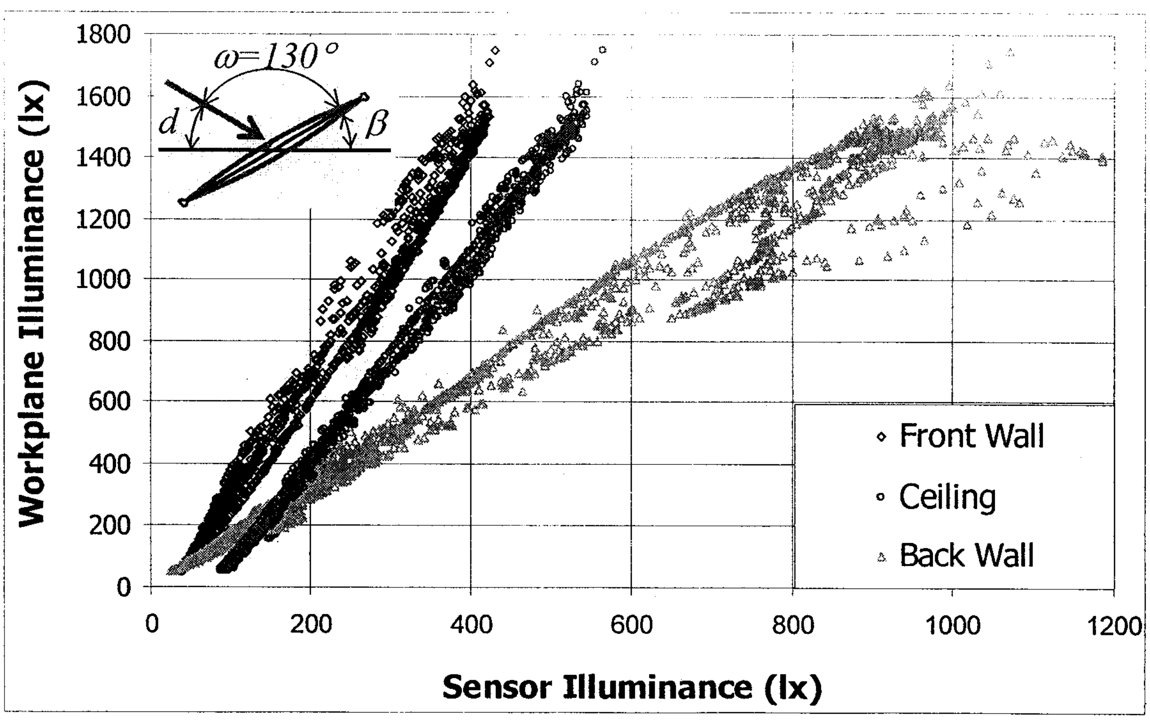


Figure 4-13(f) Correlations between the workplane illuminance and the illuminances for three different sensor locations for the daylight angle $\omega = 130^{o}$

window and thus it directly detected reflected beams around 12:30 to 13:30 except for the daylight angle of 100 degrees (Fig. 4-13 (C)). These reflected beams, however, had little effect on the other correlations (especially for the daylight angle of 110 degrees). This can be explained from the fact that the admitted reflected beams (first hit the back wall and reflect to the other surfaces with reduced luminance) are distributed evenly to the workplane and the other sensors. Therefore, the light distribution in the space is mostly due to the initial light source.

As the daylight angles increased, the deviations from linear correlation increased. These might be caused by the performance of window system since it was modeled similar to a luminaire; by experimental measurement uncertainties in the angles; and by daylight instability in measurement point of view, which is discussed in the following section. With the front wall sensor and the ceiling sensor, the workplane illuminance can be obtained with minimal deviation from the real workplane illuminance. The ceiling sensor, however, was affected by electrical noise as the dimming level increases as observed in the electric light prediction section. So the front wall sensor was employed to predict the workplane illuminance for light dimming and shading device controls.

Figure 4-14 presents the measured data for six different daylight angles that show the workplane illuminance and the front wall sensor illuminance with their linear correlations, which are obtained in the following section. It can be observed that the illuminance ratio increases with increasing daylight angle; that is, the wider the opening of the blind, the less final daylight amount reaches the front wall sensor. It can also be observed that deviations from the linear correlations increase with increasing daylight angle.

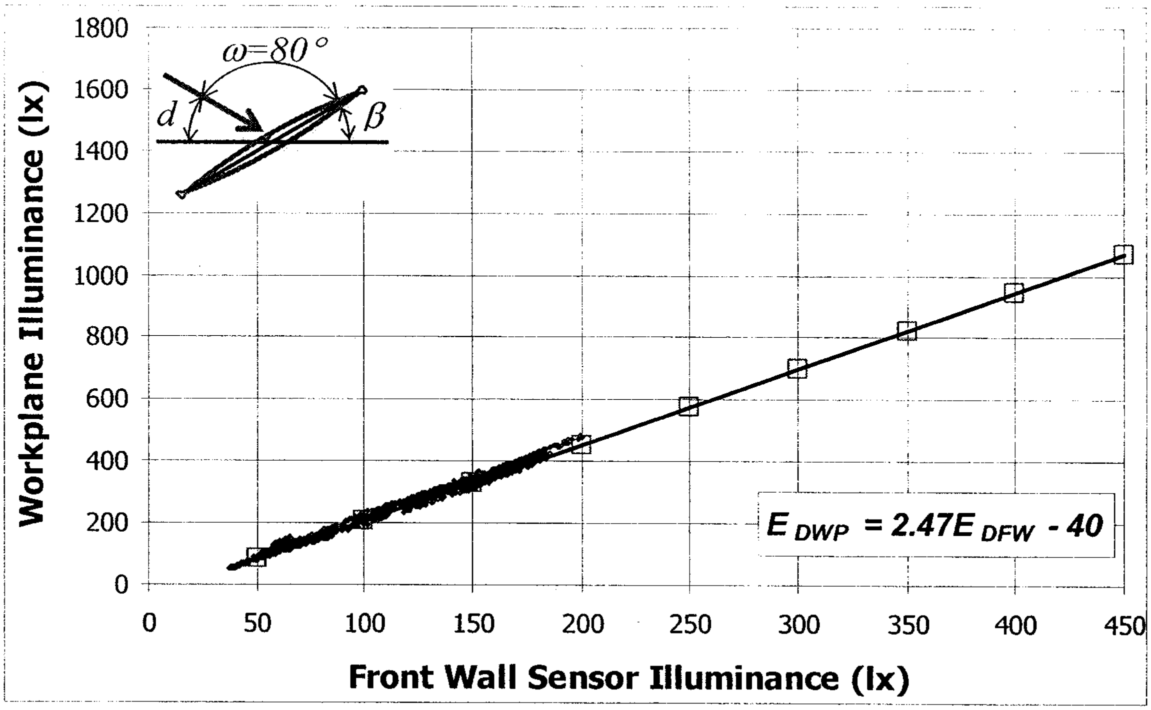


Figure 4-14(a) Correlation between the workplane illuminance (E_{DWP}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 80^{o}$

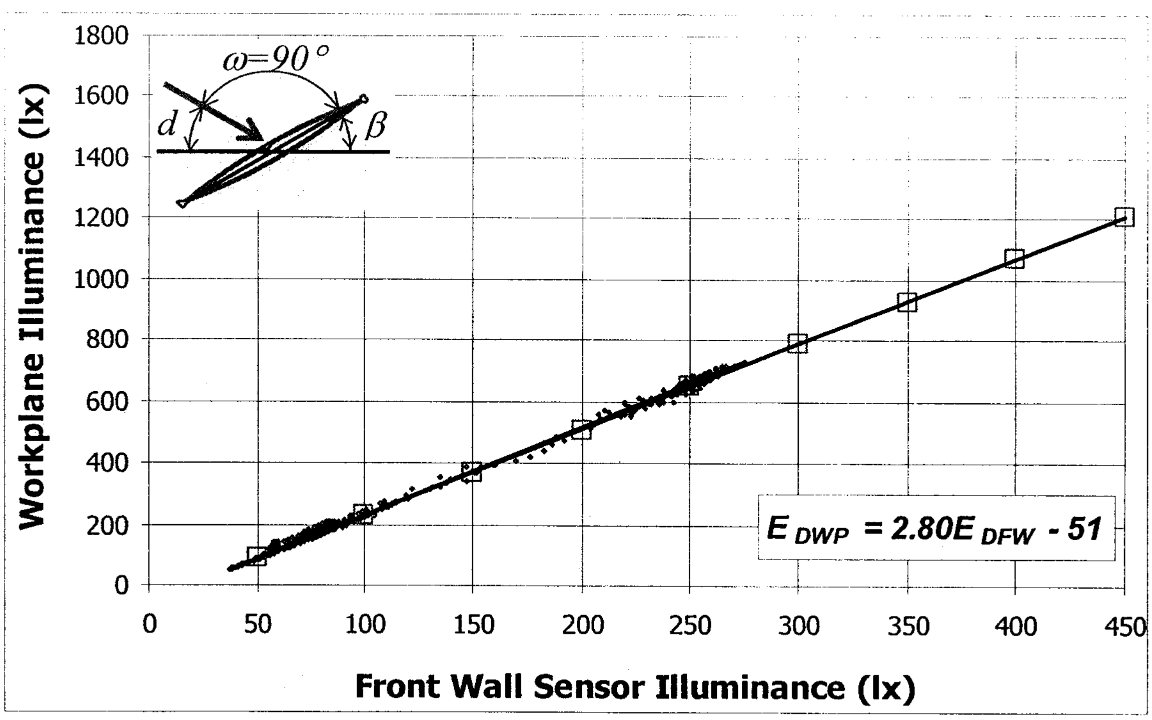


Figure 4-14(b) Correlation between the workplane illuminance (E_{DWP}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 90^{o}$

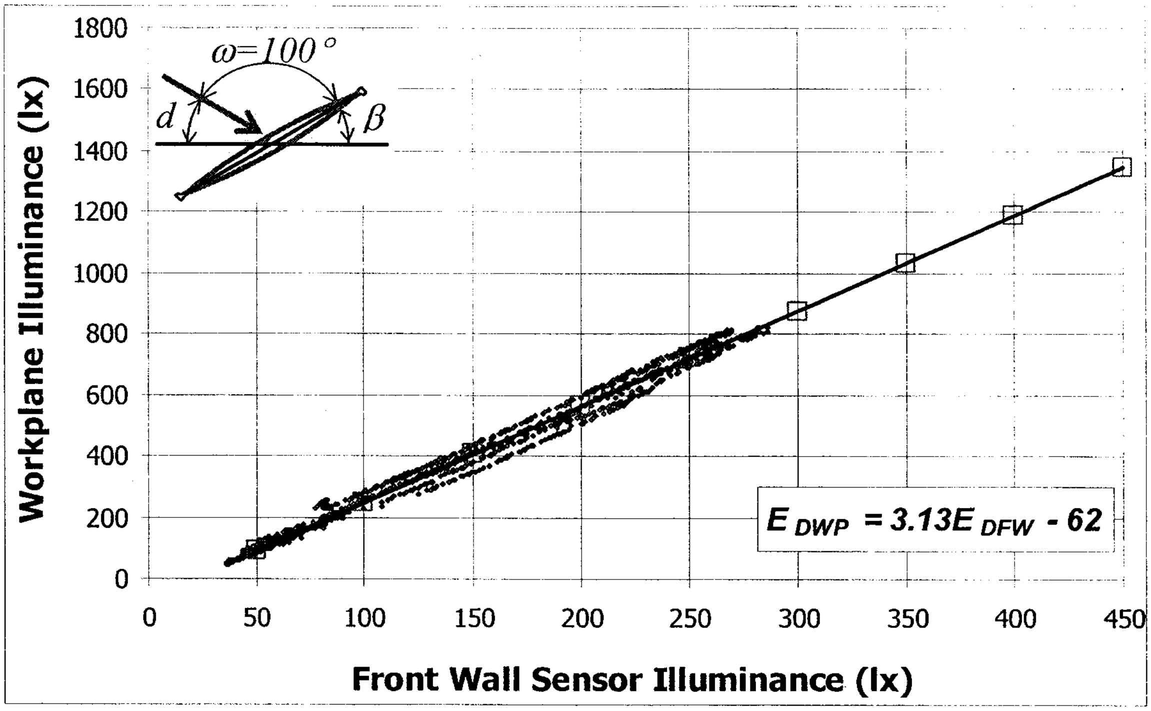


Figure 4-14(c) Correlation between the workplane illuminance (E_{DWP}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 100^{o}$

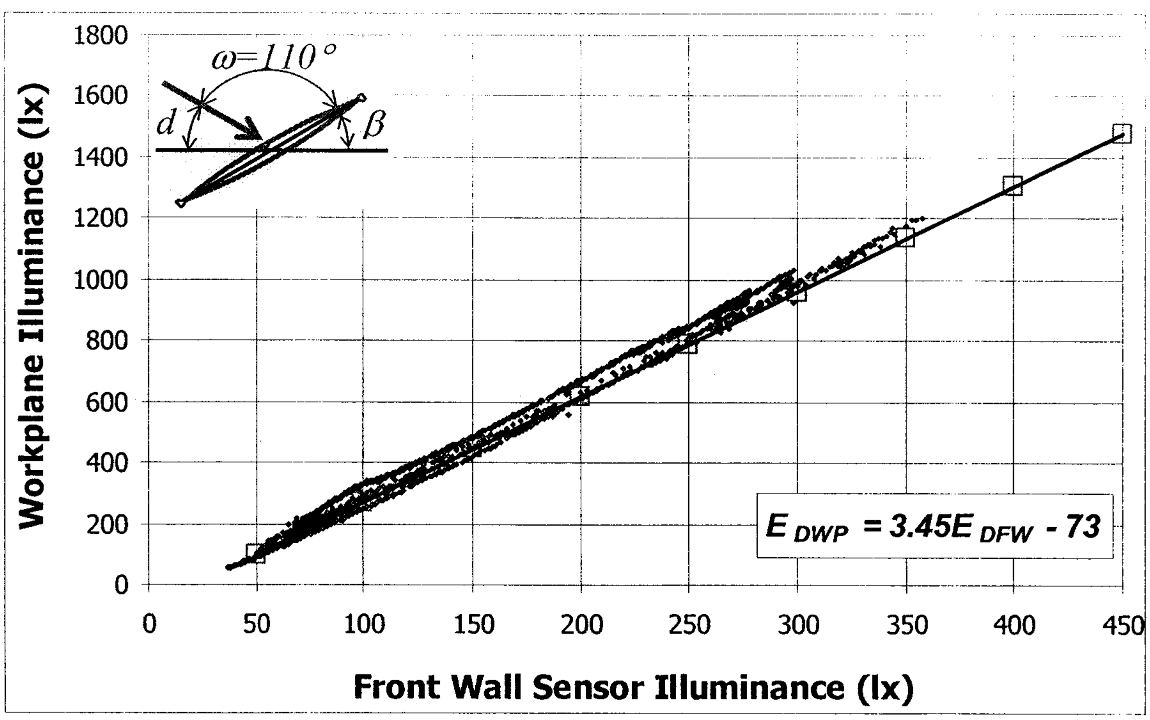


Figure 4-14(d) Correlation between the workplane illuminance (E_{DWP}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 110^{o}$

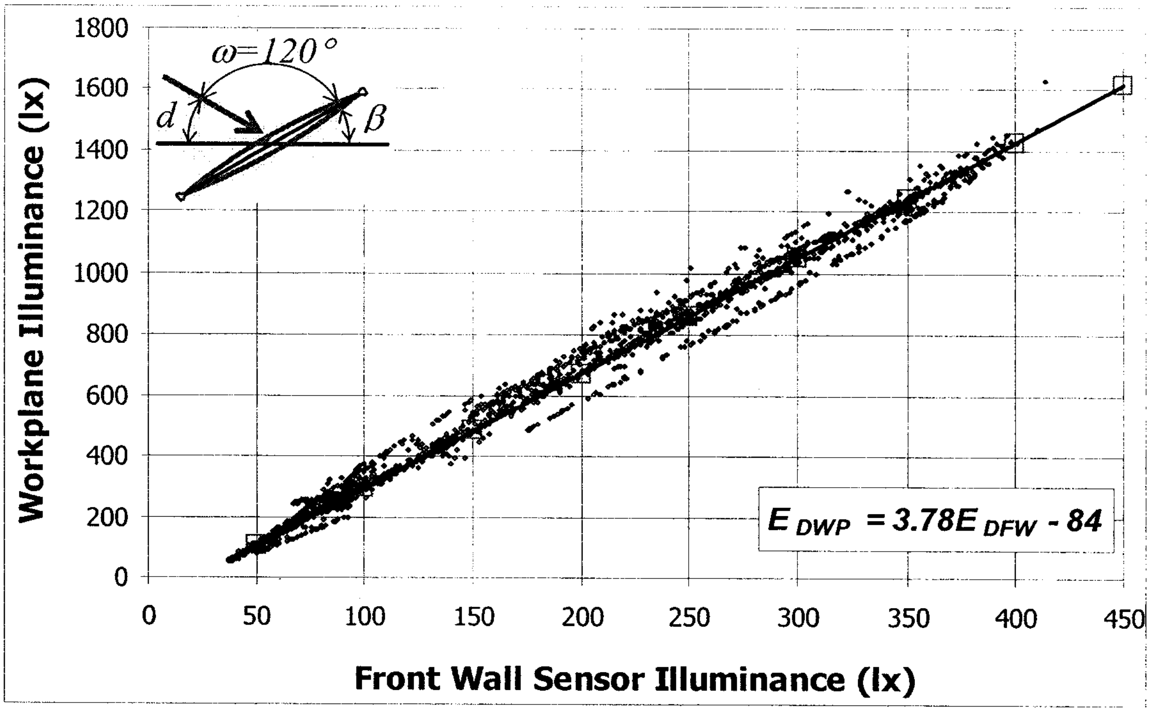


Figure 4-14(e) Correlation between the workplane illuminance (E_{DWP}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 120 ^{o}

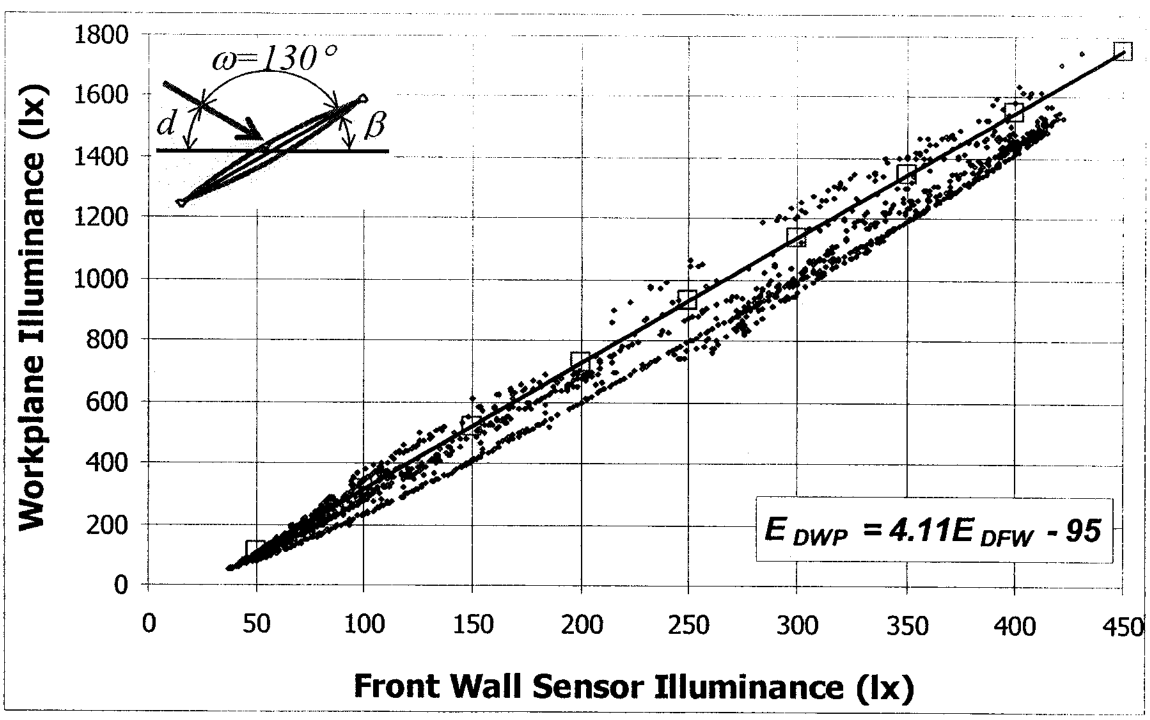


Figure 4-14(f) Correlation between the workplane illuminance (E_{DWP}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 130 ^{o}

The correlation between the exterior vertical illuminance and the front wall sensor illuminance with measured data is presented in Fig. 4-15. Compared to the workplane illuminance, the exterior vertical illuminance is hard to present with a linear correlation especially with daylight angle 80 degrees (Fig. 4-15(a)). As the shaded area of the window surface increased, the daylight transmission of the window system decreases accordingly. When this happens, the correlation between the front wall sensor illuminance and the exterior vertical illuminance will not be constant. It can be observed that there are some data spread around lower front wall illuminance levels.

It was difficult to measure the solar heat gains through the window system because of the integrated blinds within the glazings and continuous changes of window shaded area. To obtain irradiance through the window system approximately, two pyranometers were set at the top and bottom of the inside window surface; the top detects for shaded area and the bottom is for daylit area. The shaded and daylit areas were calculated at each data logging time and then the irradiance was obtained. Figure 4-16 shows the calculated irradiance through the window and the front wall sensor illuminance with their correlation for different daylight angles.

The general correlation equation as a function of the daylight angle for predictions of the workplane illuminance, the exterior vertical illuminance and the irradiance through the window system with the front wall sensor illuminance is derived in a later section. Because of daylight instability characteristics from a measurement point of view, the correlations for predicting several daylighting parameters were significantly affected. Therefore, in the next section, the effect of light source instability on the correlations is discussed first.

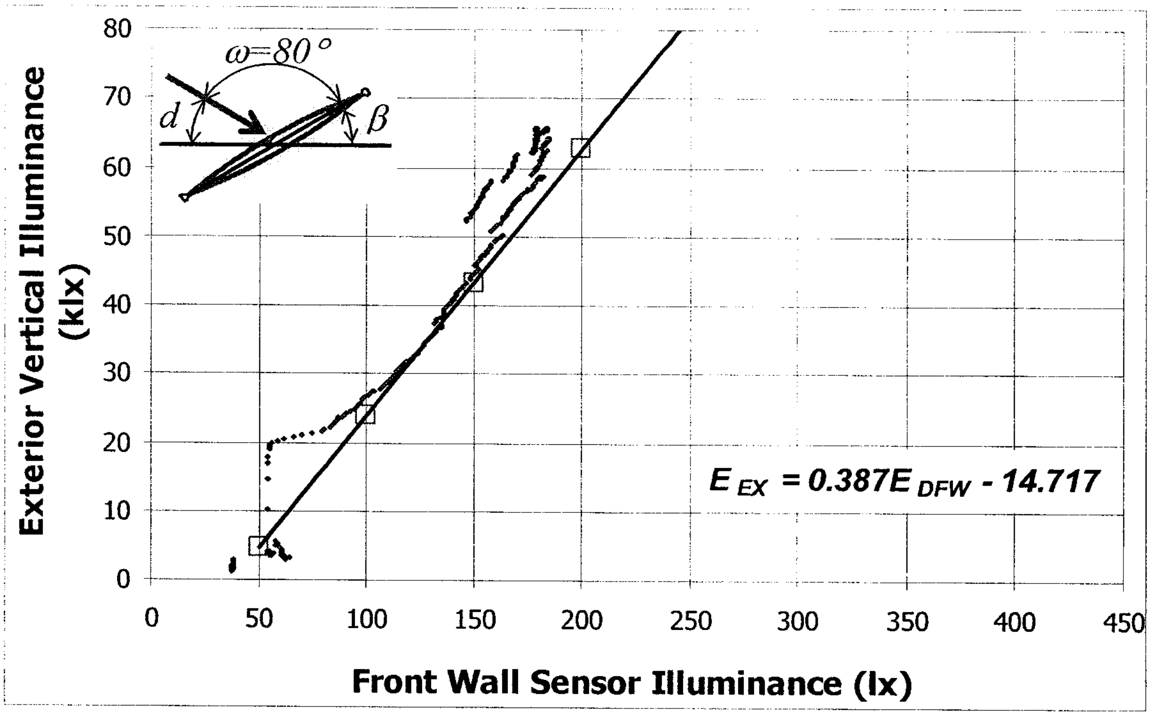


Figure 4-15(a) Correlation between the exterior vertical illuminance (E_{EX}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 80°$

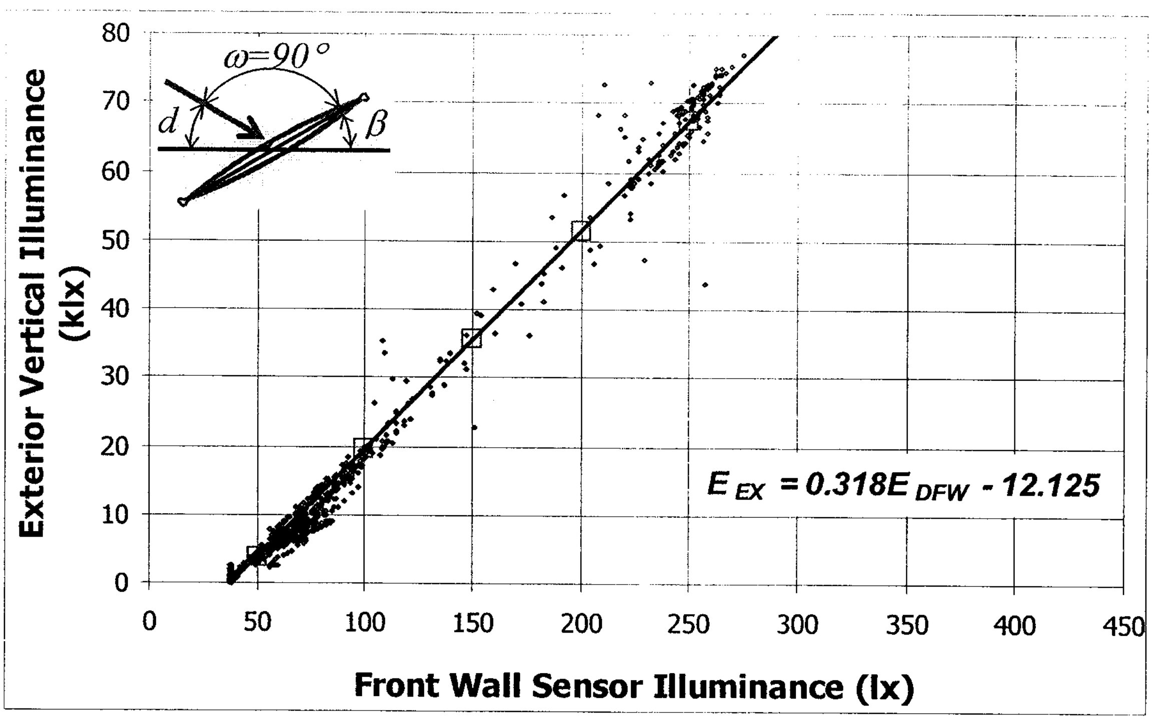


Figure 4-15(b) Correlation between the exterior vertical illuminance (E_{EX}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 90°$

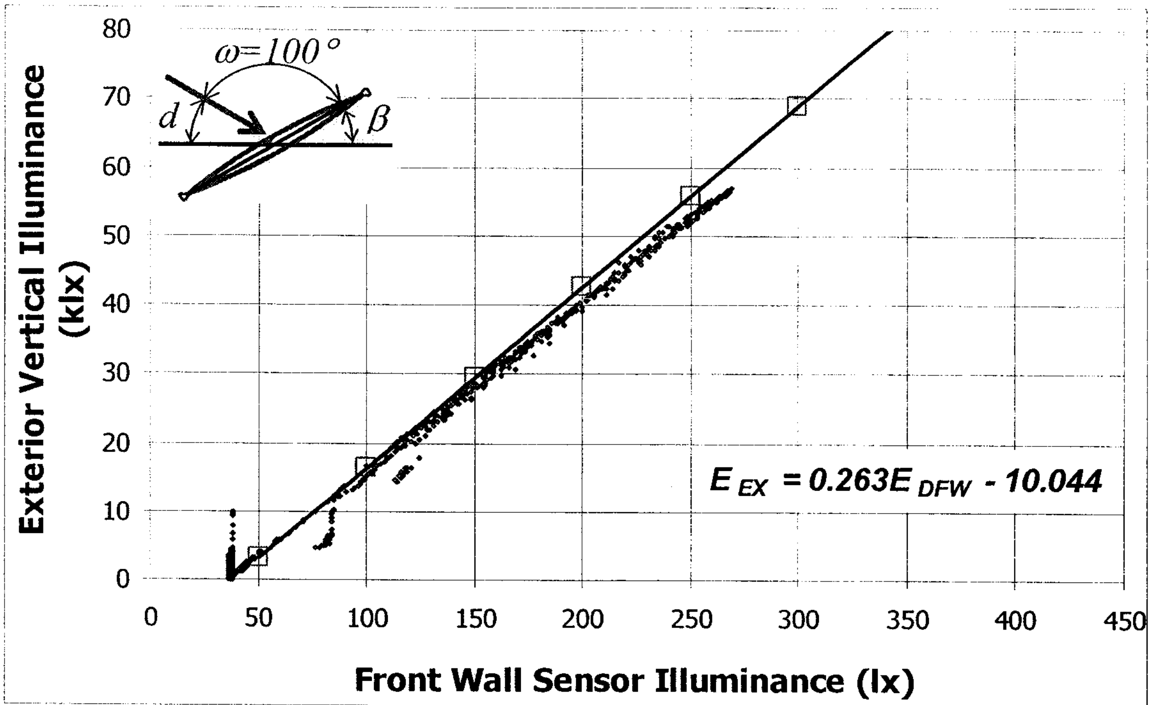


Figure 4-15(c) Correlation between the exterior vertical illuminance (E_{EX}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 100 °

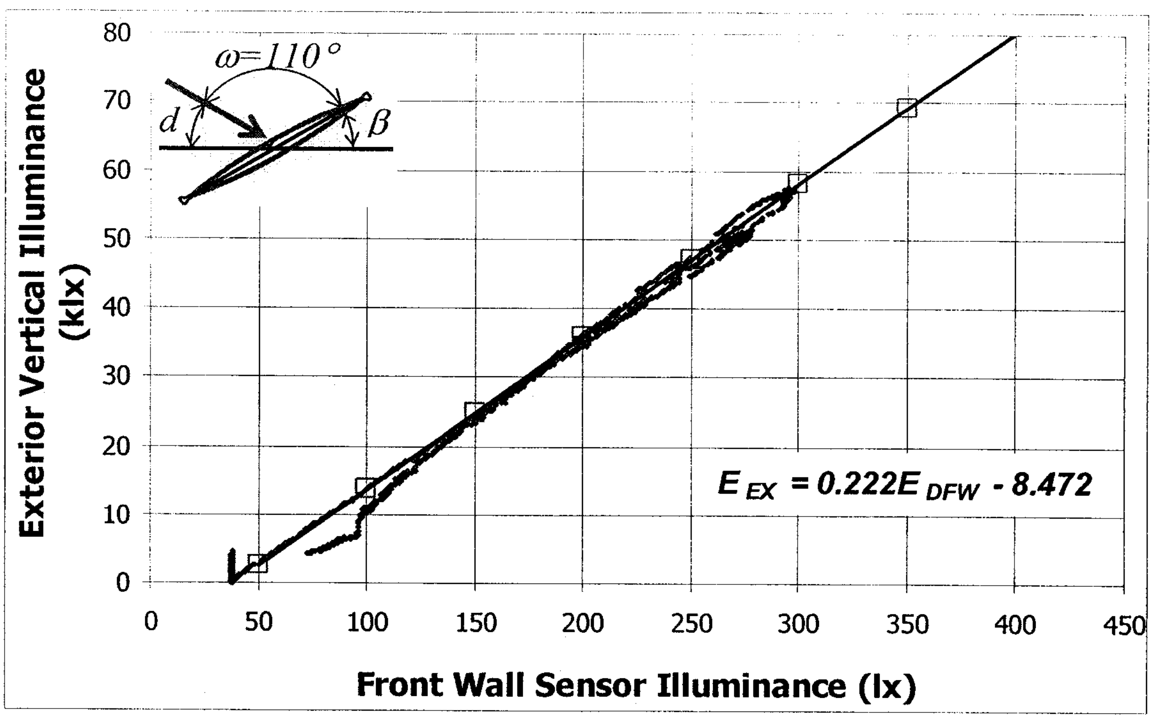


Figure 4-15(d) Correlation between the exterior vertical illuminance (E_{EX}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 110 °

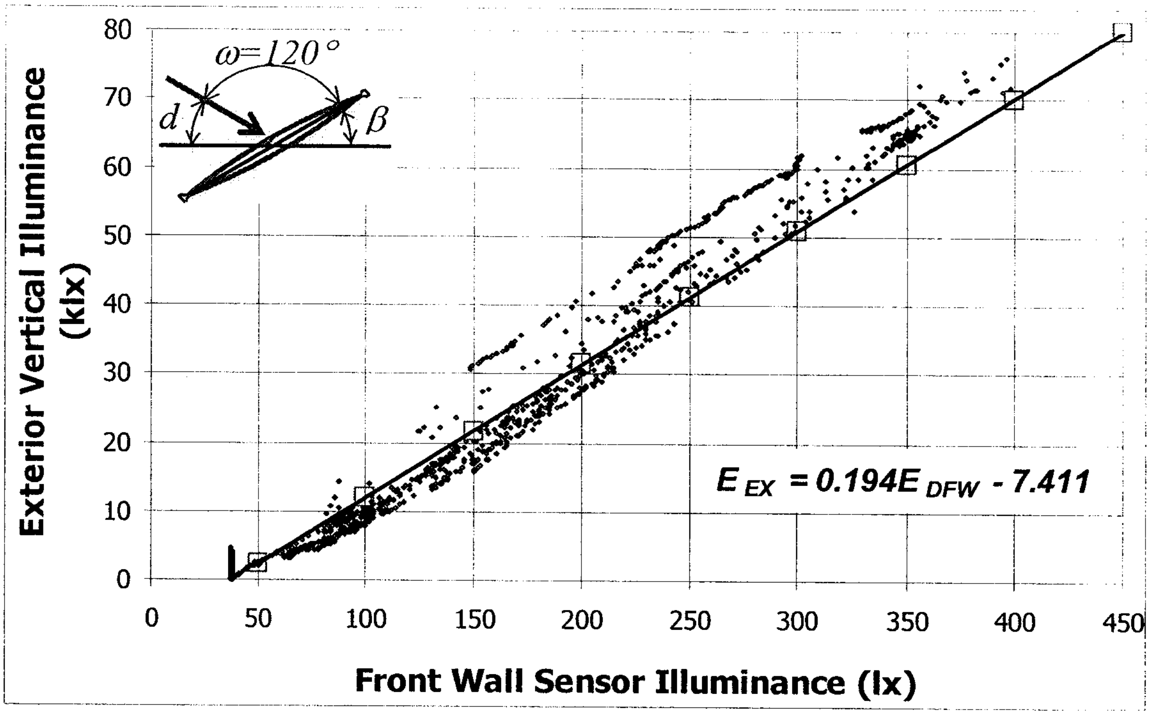


Figure 4-15(e) Correlation between the exterior vertical illuminance (E_{EX}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 120°

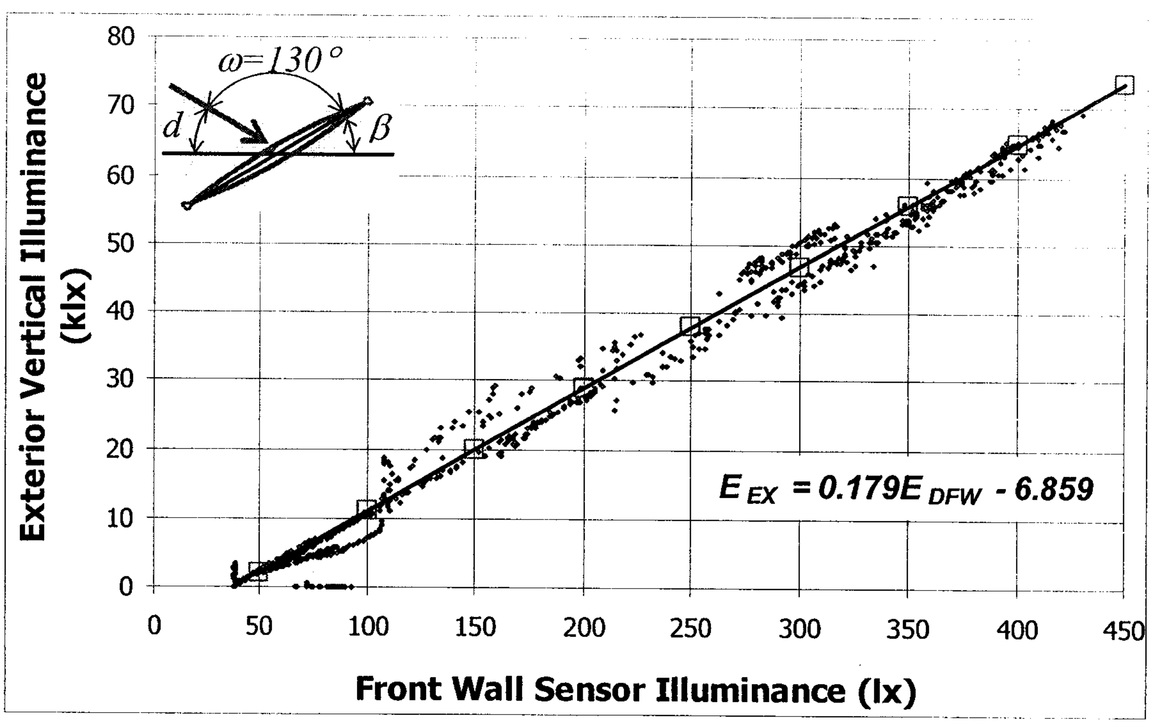


Figure 4-15(f) Correlation between the exterior vertical illuminance (E_{EX}) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 130°

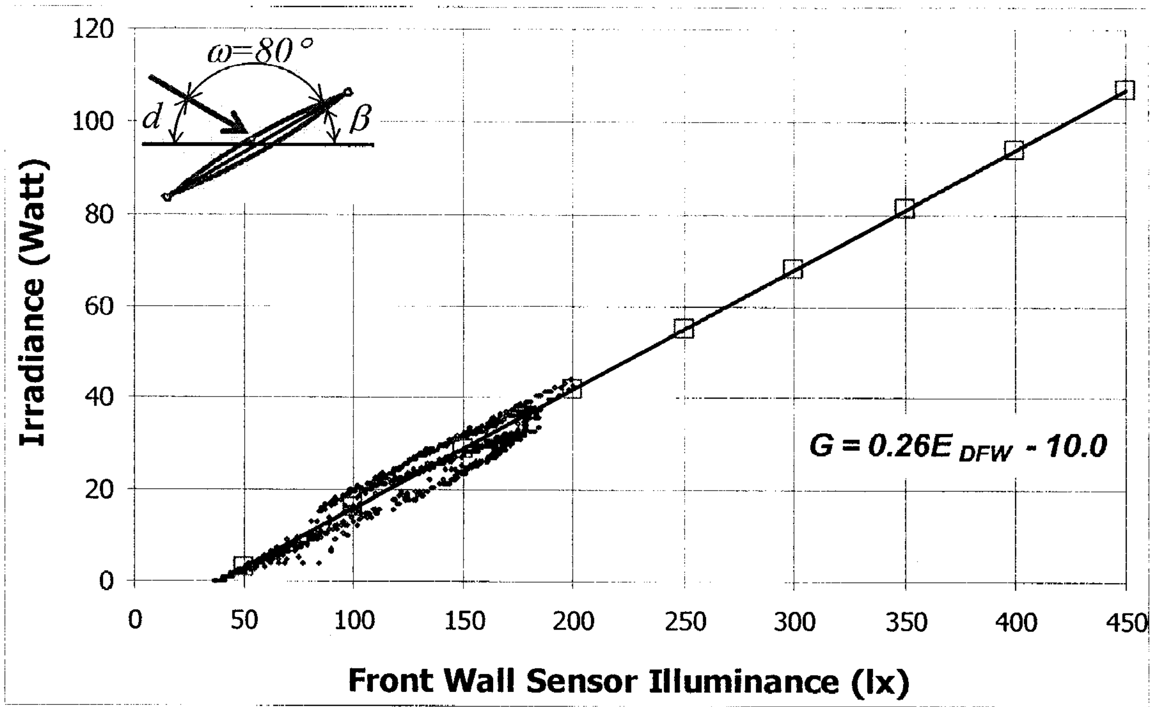


Figure 4-16(a) Correlation between the irradiance (*G*) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 80^{o}$

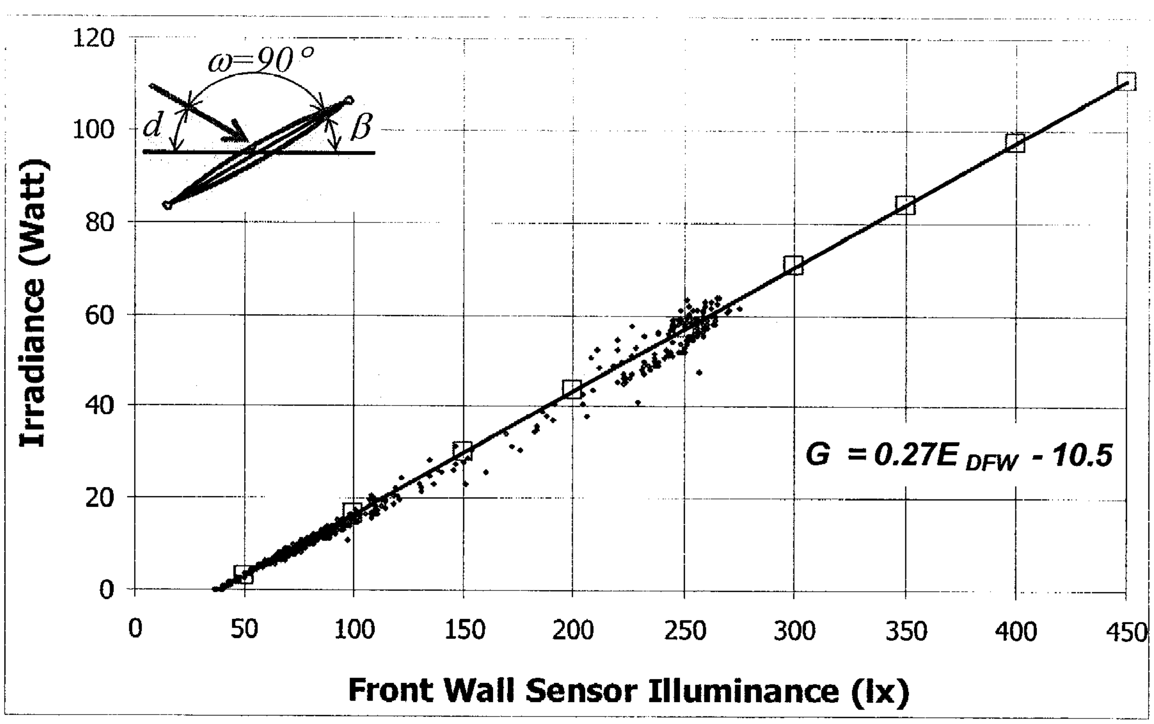


Figure 4-16(b) Correlation between the irradiance (*G*) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 90^{o}$

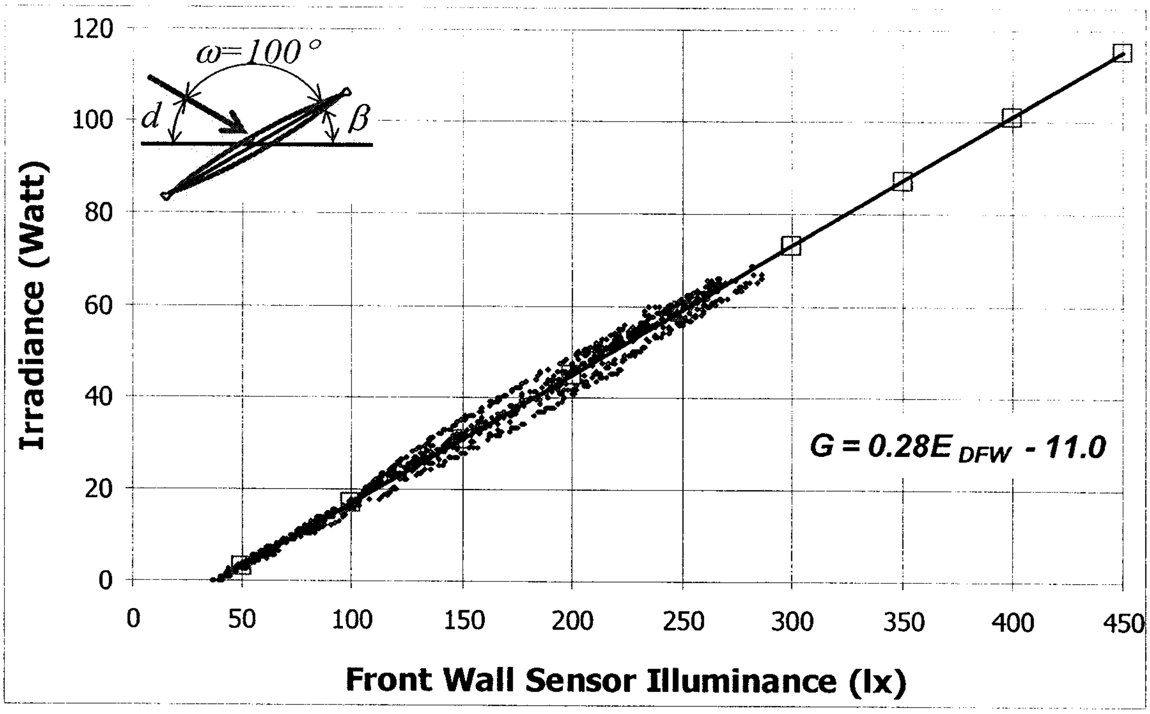


Figure 4-16(c) Correlation between the irradiance (*G*) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 100^o$

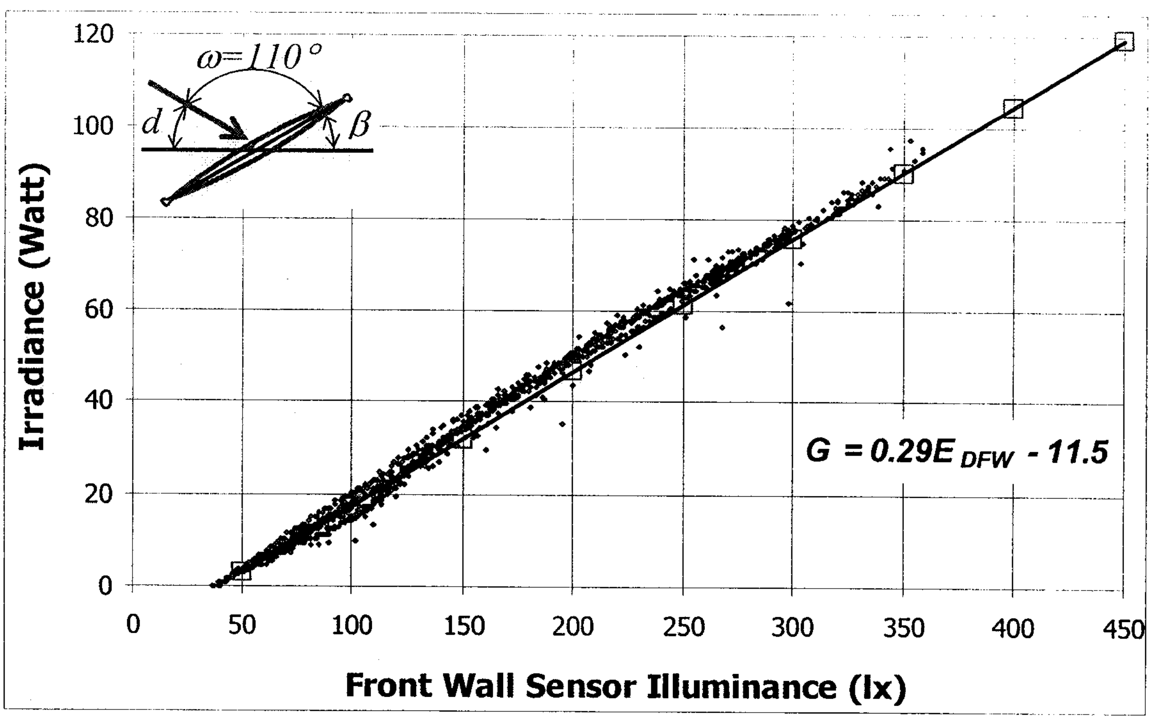


Figure 4-16(d) Correlation between the irradiance (*G*) and the front wall sensor illuminance (E_{DFW}) for the daylight angle $\omega = 110^o$

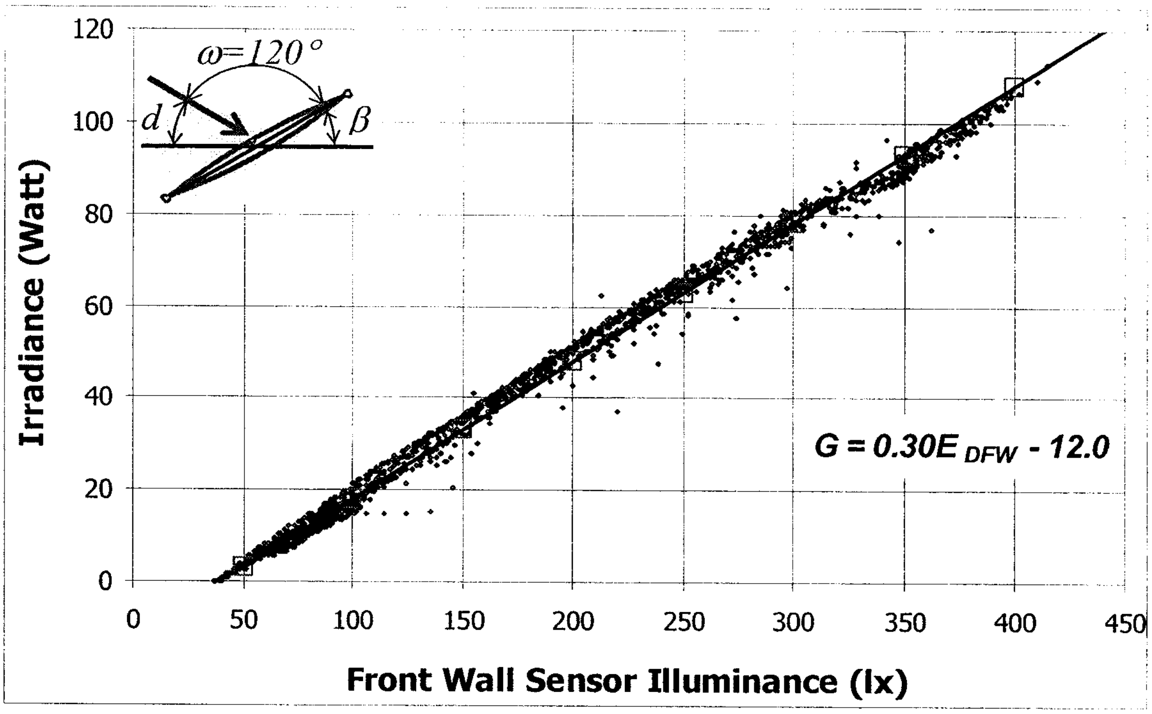


Figure 4-16(e) Correlation between the irradiance (***G***) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 120 °

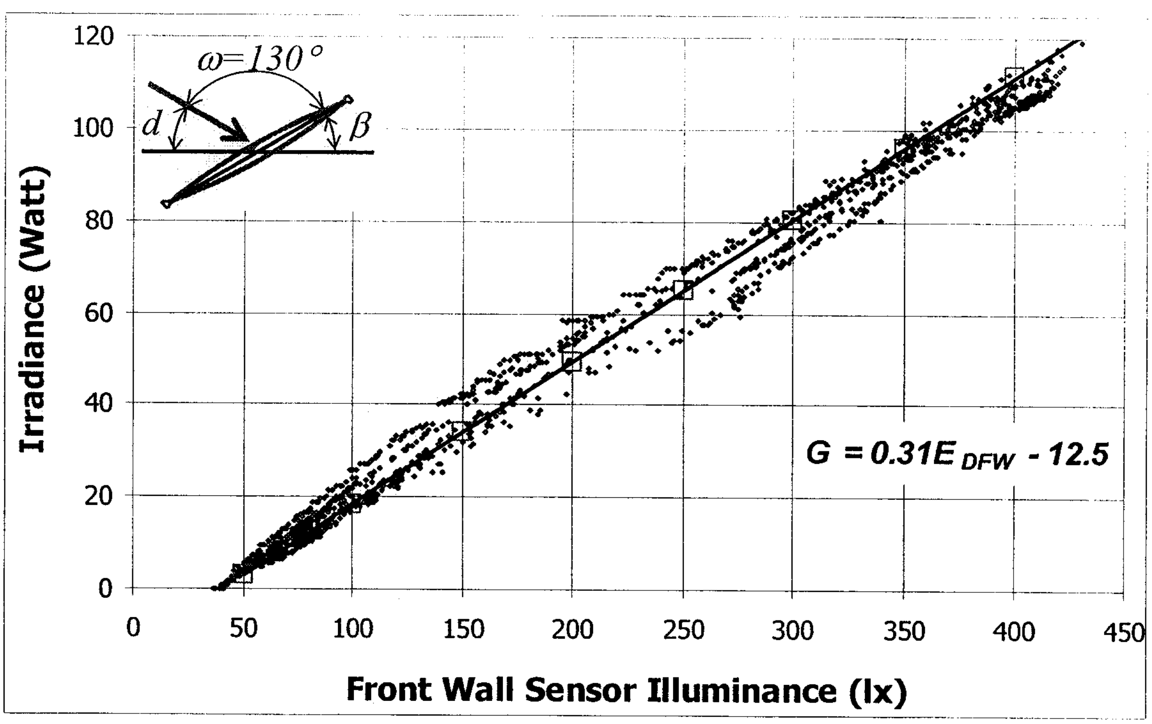


Figure 4-16(f) Correlation between the irradiance (***G***) and the front wall sensor illuminance (E_{DFW}) for the daylight angle ω = 130 °

4.5 Light Source Instability Effect on Correlations

The correlation between the two sensors must be obtained to predict the daylighting parameters in daylighting control systems. It is generally expected that two identical sensors will respond to the same output identically under the same conditions. When the light source status is unstable, the outputs of both sensors are not proportional because of sensor accuracy or scan rate of the data acquisition system. The accuracy of the sensor is generally decided under the stable source condition.

Figure 4-17 presents the illuminance relationships for the workplane and the front wall sensor as shown in the electric light prediction section. However, the data were sampled (and logged) at different times after dimming action (the data shown in Figs. 4-9 to 4-12 are sampled 5 seconds after dimming). They were sampled 0.1, 0.3, 0.5 and 1 seconds after random light dimming as shown in (a), (b), (c) and (d) of Fig. 4-17, respectively. It can be readily observed that, when the light source is unstable, the correlation cannot be obtained correctly even though the relationship is proportional. This is due to the fact that the fluorescent lamp needs a certain period of time to have a stable output.

The effect on correlation for daylight source, which is hardly stable from the measurement point of view, was examined with two identical light sensors placed next to each other. One of the sensors was filtered to imitate the workplane and front wall sensors. The result showed that the illuminances of the two sensors were not proportional (Fig. 4-18). Figure 4-19 shows the illuminance profile of one of the sensors. The deviations are caused by unstable daylight conditions from 13:00 to 15:00. The effects are found to be more significant as daylight source changes rapidly.

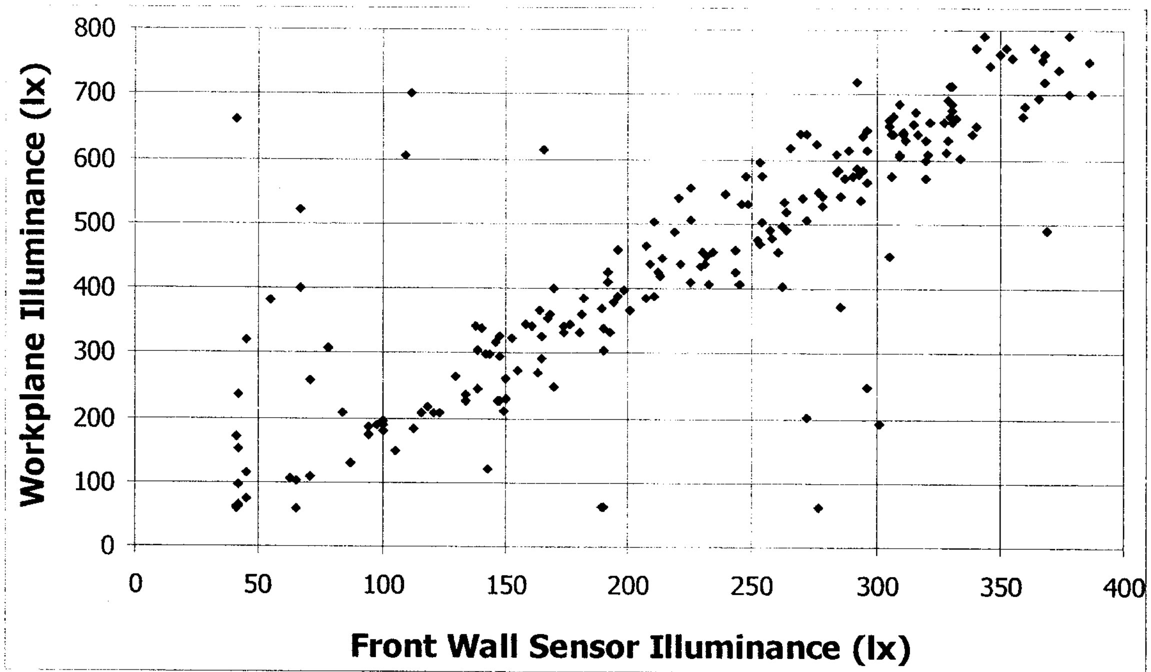


Figure 4-17(a) Correlation between the workplane illuminance and the front wall sensor illuminance (logged 0.1 second after random dimming)

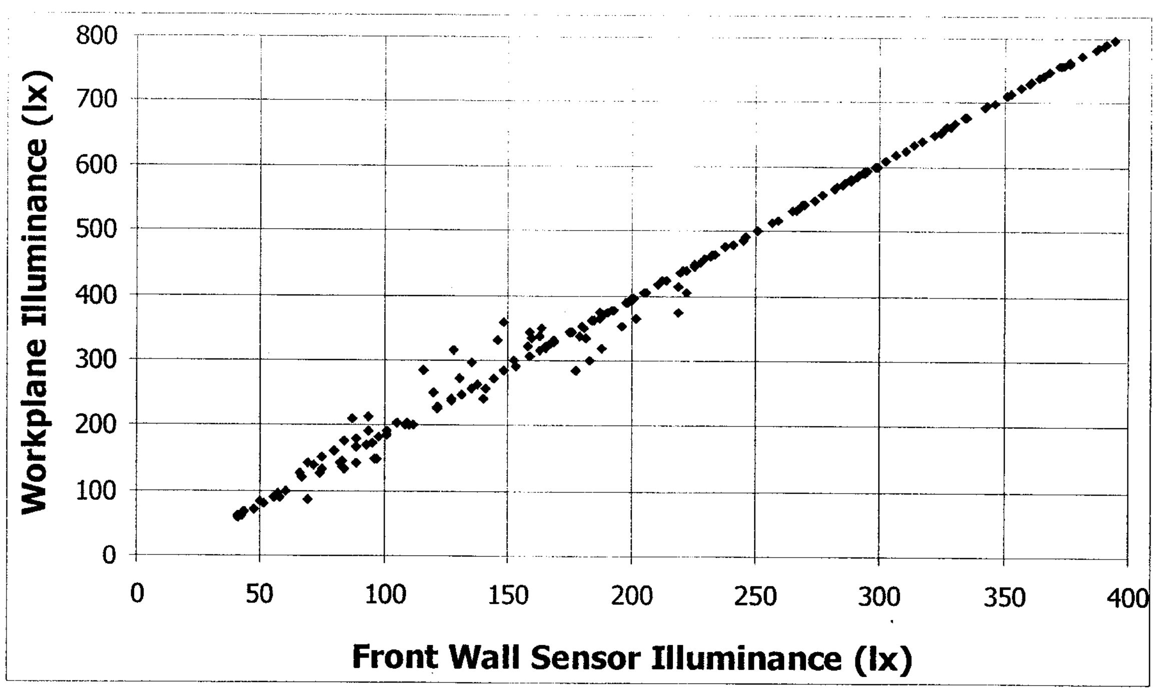


Figure 4-17(b) Correlation between the workplane illuminance and the front wall sensor illuminance (logged 0.3 second after random dimming)

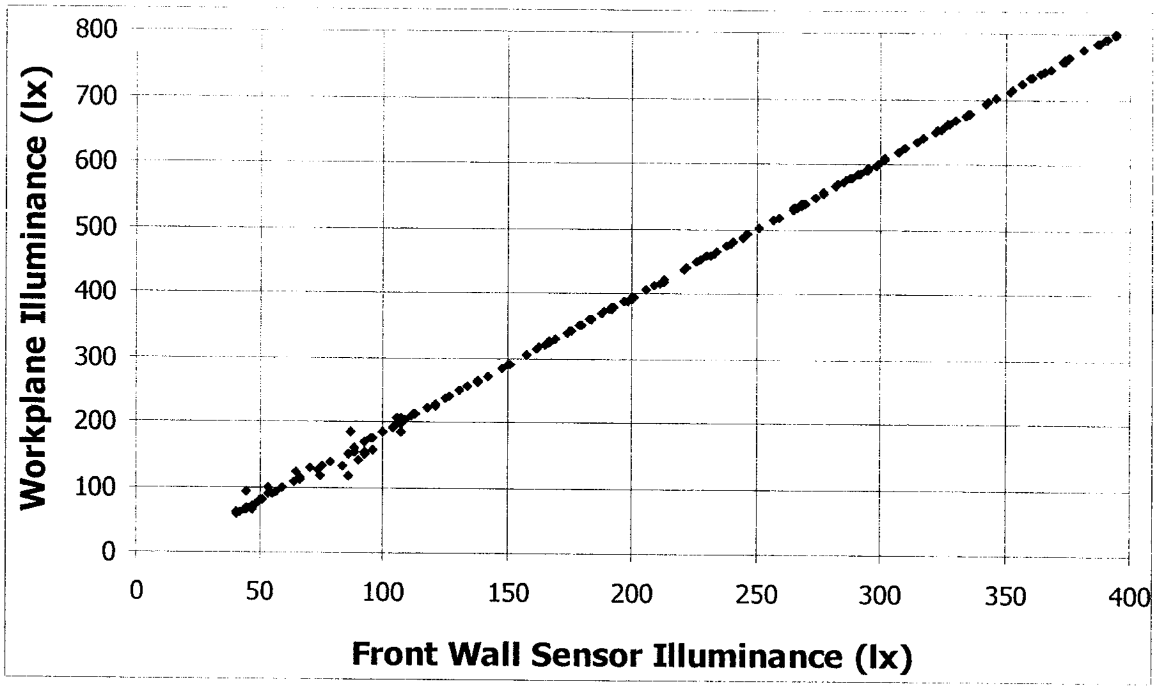


Figure 4-17(c) Correlation between the workplane illuminance and the front wall sensor illuminance (logged 0.5 second after random dimming)

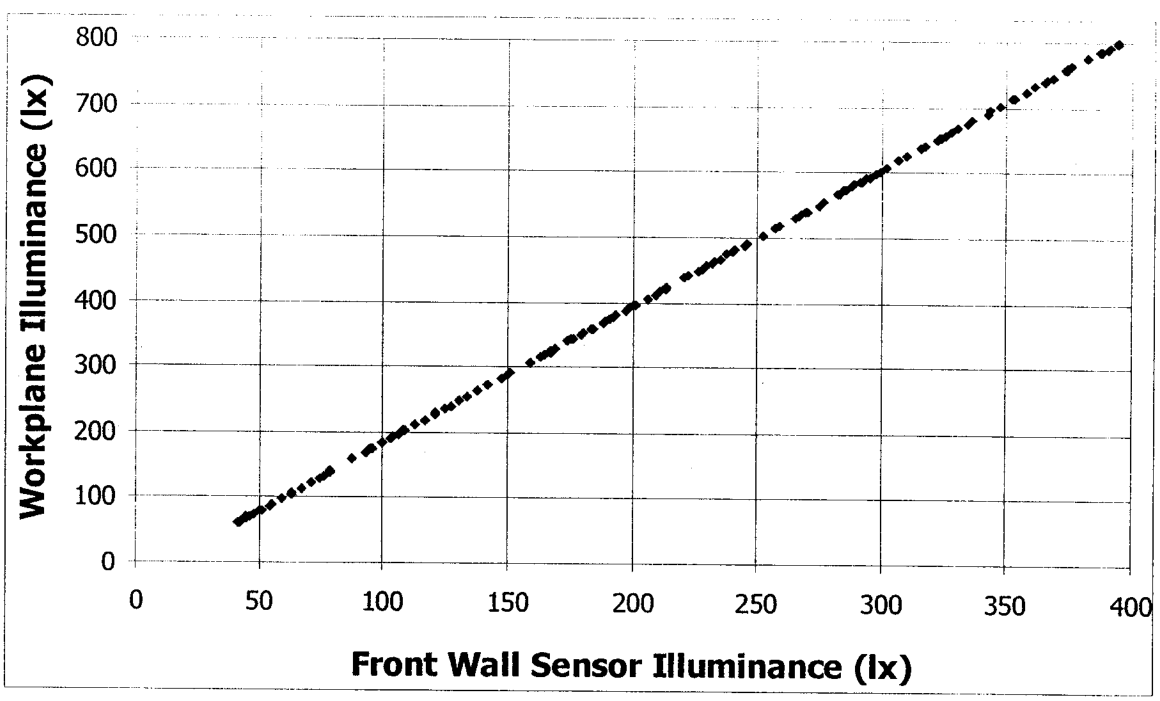


Figure 4-17(d) Correlation between the workplane illuminance and the front wall sensor illuminance (logged 1 second after random dimming)

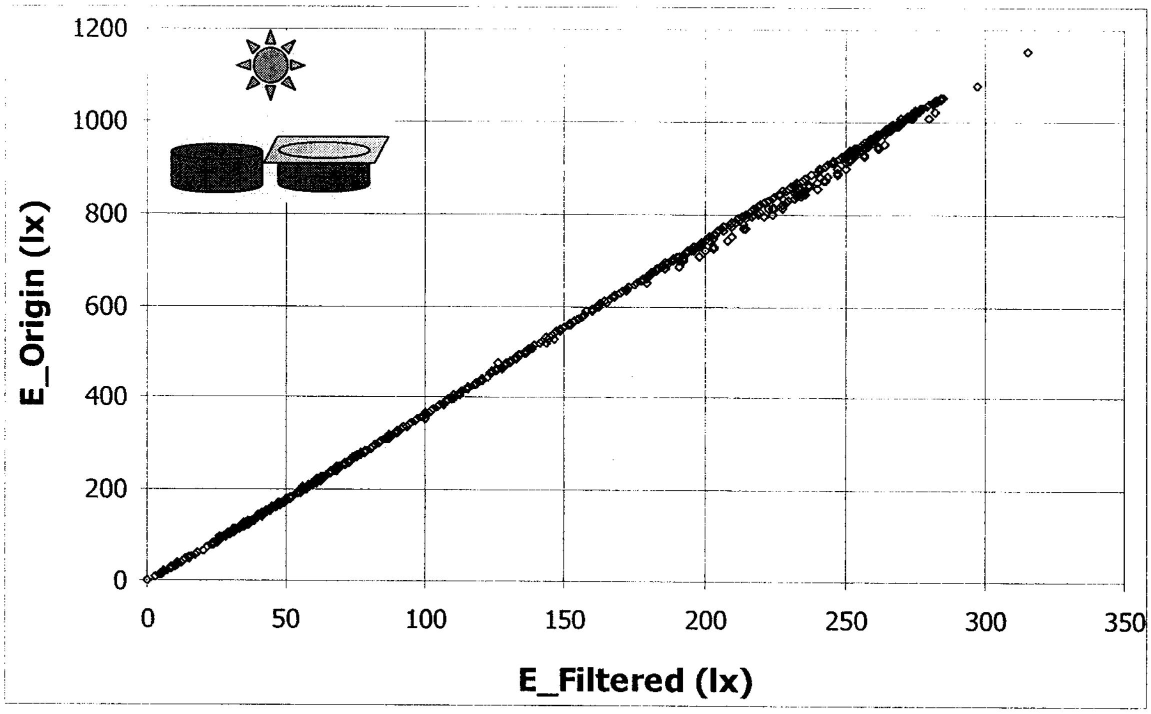


Figure 4-18 The illuminance relationship between the two sensors placed next to each other (one is covered with filter)

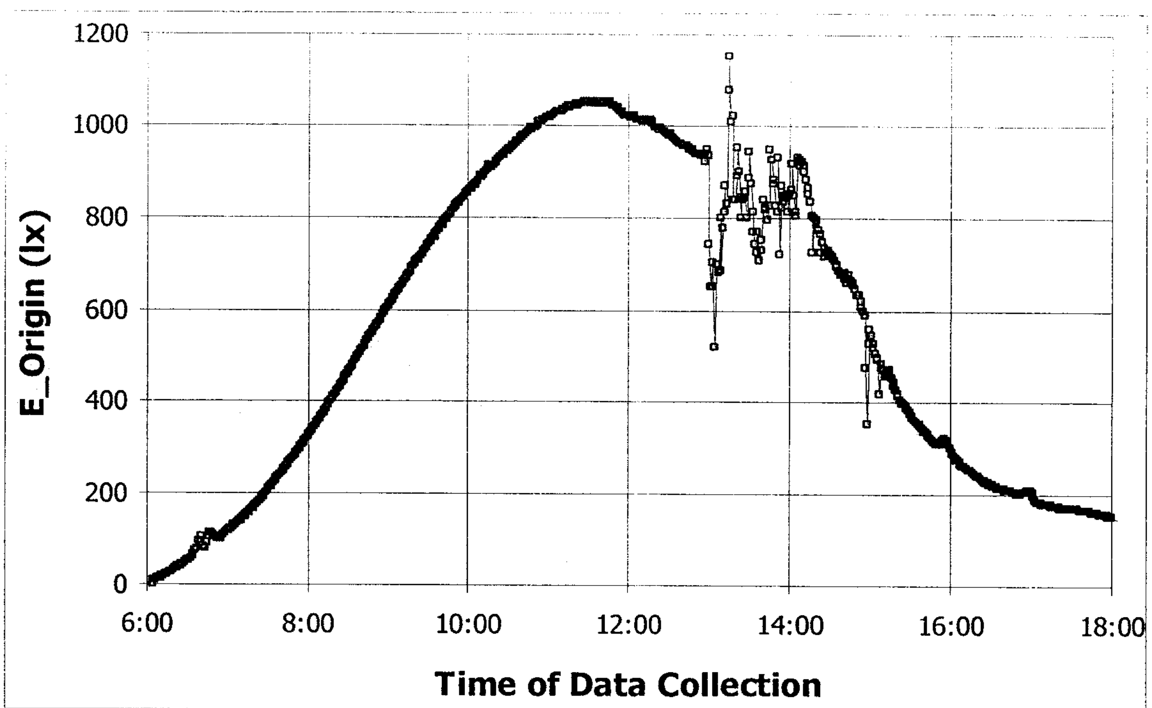


Figure 4-19 The illuminance profile (stability of daylight source vs. time)

Figure 4-20 shows another data sample (data collected with *Daqbook 120*) of daylight instability effect on the correlation between the workplane illuminance and the front wall sensor illuminance. There are three distinct lines, which occurred at different times of data collection as shown in Fig. 4-21. From this result, it can be observed that two different correlations were made under mostly stable daylight source conditions. Under the assumption of a linear relationship, the correlation based on this data will be underestimated when the source is steadily increased (time before solar noon) and overestimated when it is steadily decreased (time after solar noon). It can also be observed that even under unstable daylight conditions, a linear correlation can be made but this is an extreme case.

There is a sampling interval between channels in data acquisition systems so that it is impossible to measure two channels data simultaneously. There is also a data integration period, which is the period of time that the instrument's analog-to-digital converter samples the input signal for a measurement. This integration time affects the measurement resolution and measurement speed; the longer the integration time, the better resolution and vice versa. This might be one of the reasons for higher error in correlations under sudden daylight changes.

4.6 Correlations for Daylighting Control

Three different daylighting parameters in daylighting control systems can be predicted with one interior light sensor under the condition of no direct daylight admission. With the front wall sensor, which was chosen to be the best sensor location, correlation functions are derived as a function of the daylight angle for the workplane illuminance,

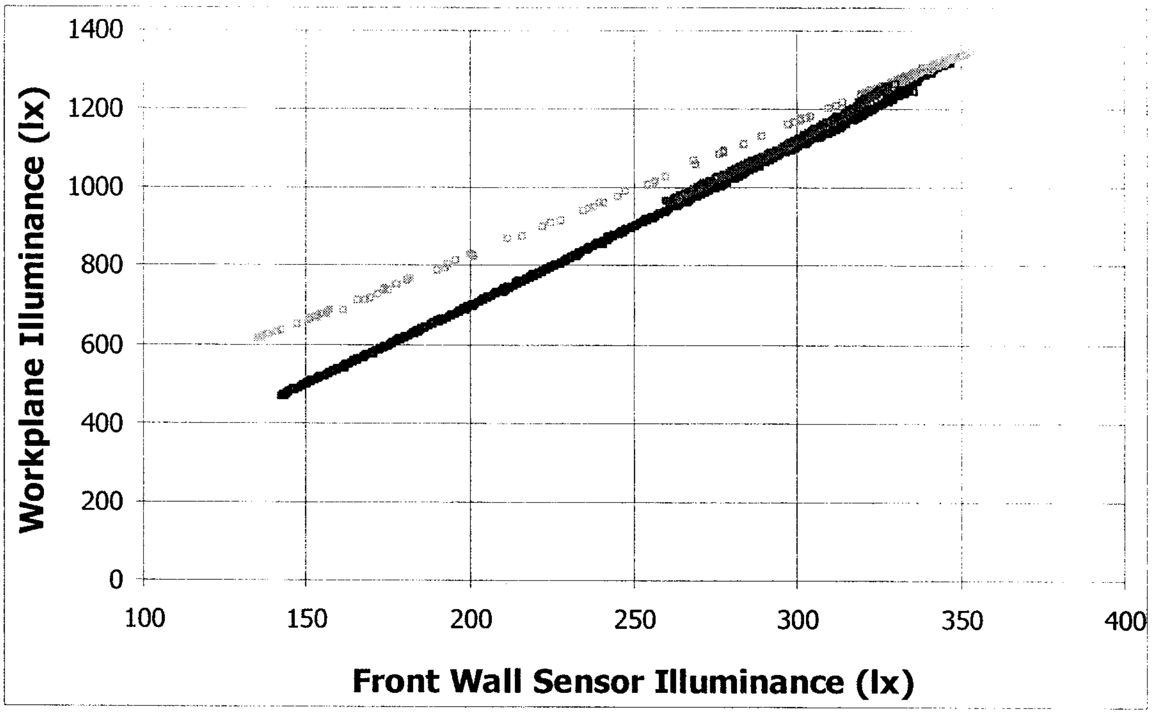


Figure 4-20 The illuminance relationship between the workplane and the front wall

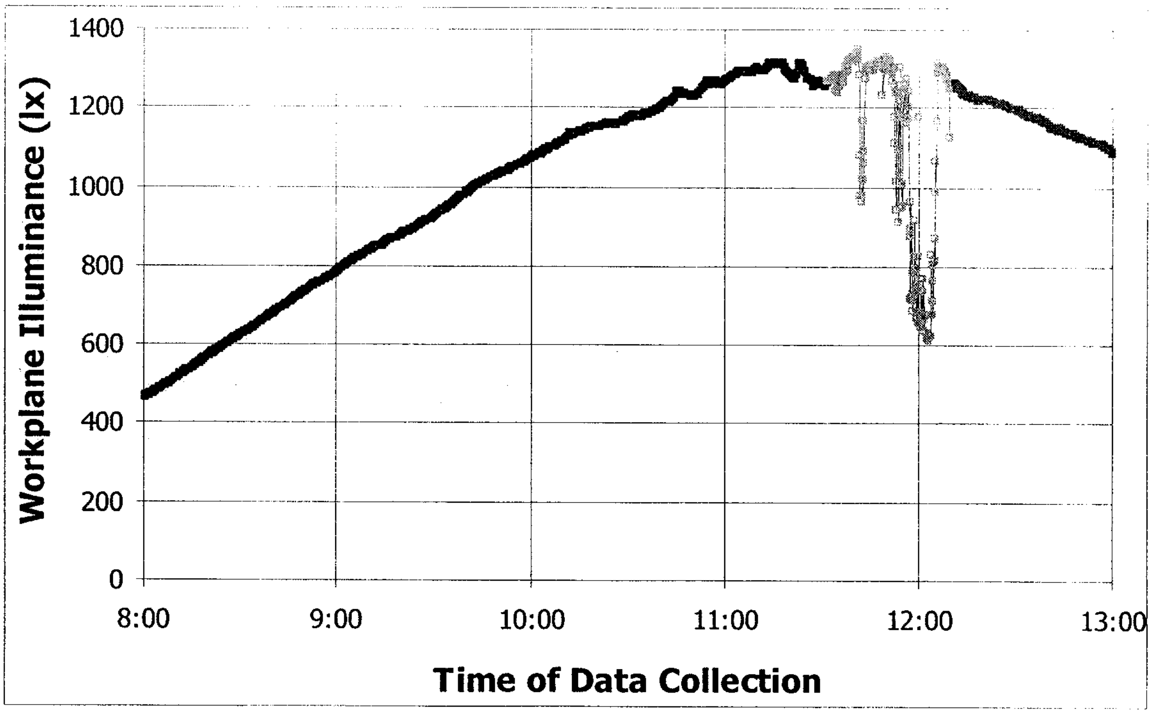


Figure 4-21 The workplane illuminance profile (stability of daylight source vs. time)

the exterior vertical illuminance and the irradiance through the window system. From the correlations of each daylight angle, two fitted slopes for the illuminance ratio (*M*) and the illuminance coefficient (*C*) were obtained. The daylighting parameters (illuminance, *E* or irradiance, *G*) are obtained with the front wall sensor illuminance (E_{DFW}) as follows:

$$E = M \cdot E_{DFW} - C$$

or

$$G = M \cdot E_{DFW} - C \tag{4-2}$$

For the workplane illuminance prediction, both the illuminance ratio and the illuminance coefficient were found to be proportional to daylight angle as follows (Fig. 4-22):

$$M_{DWP\_DFW} = 0.0328 \cdot \omega - 0.154 \tag{4-3}$$

$$C_{DWP\_DFW} = 1.091 \cdot \omega - 46.9 \tag{4-4}$$

Then the correlation equation for the workplane illuminance (E_{DWP}) prediction with the front wall sensor illuminance is as follows from Eq. (4-2):

$$E_{DWP} = (0.0328 \cdot \omega - 0.154) \cdot E_{DFW} - 1.091 \cdot \omega + 46.9 \tag{4-5}$$

The illuminance ratio and the illuminance coefficient for the exterior vertical illuminance prediction were found to be both described by the following quadratic equations (Fig. 4-24).

$$M_{EX\_DFW} = 0.000067 \cdot \omega^2 - 0.018224 \cdot \omega + 1.415232 \tag{4-6}$$

$$C_{EX\_DFW} = 0.00255 \cdot \omega^2 - 0.69265 \cdot \omega + 53.8089 \tag{4-7}$$

The correlation equation for the exterior vertical illuminance (E_{EX}) prediction with the front wall sensor illuminance from Eq. (4-2) is as follows:

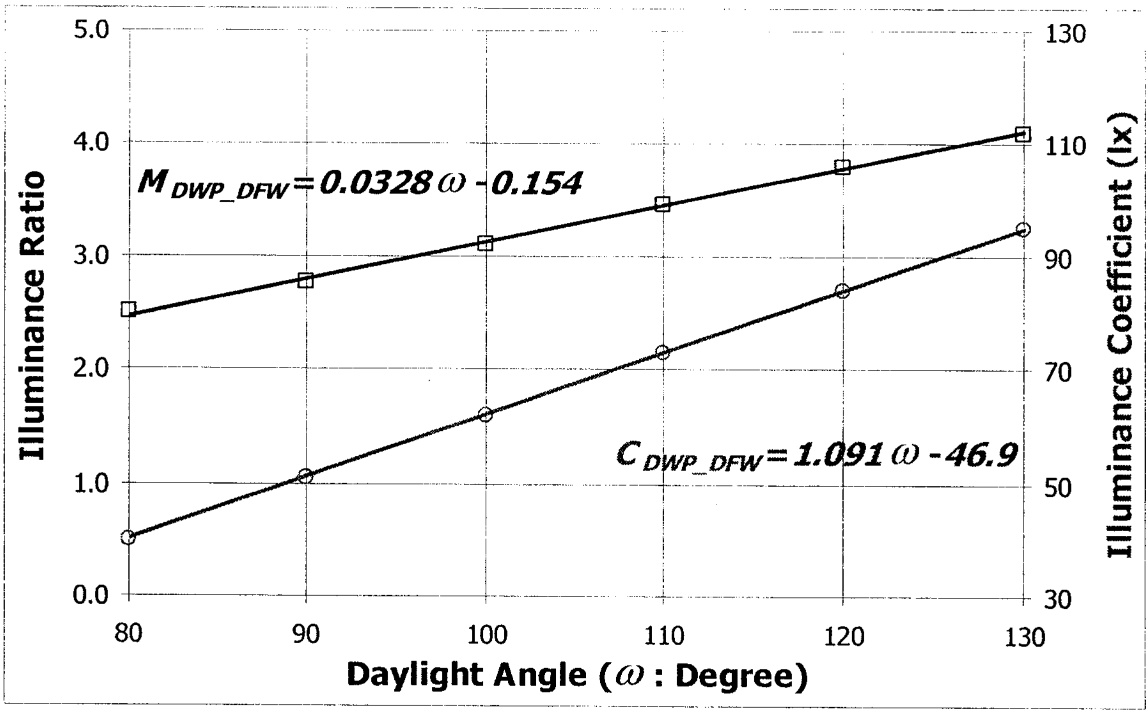


Figure 4-22 Illuminance ratios and coefficients for different daylight angles in the workplane illuminance prediction with the front wall sensor illuminance

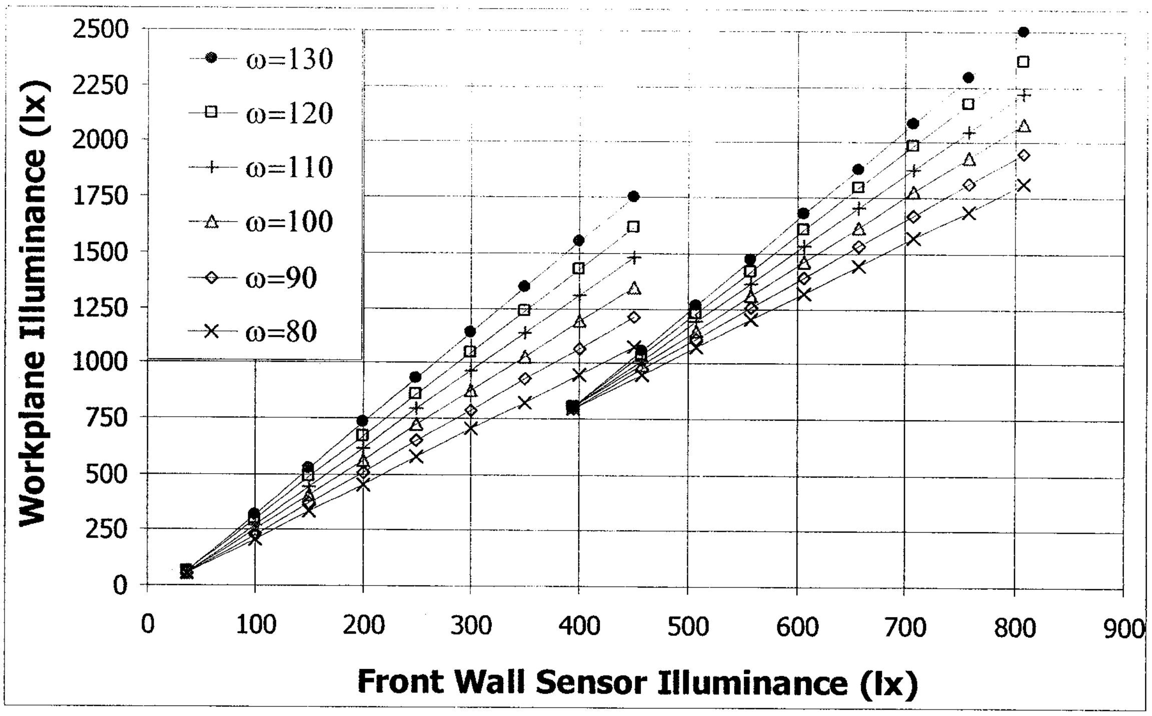


Figure 4-23 Workplane illuminance prediction with the front wall sensor illuminance at 15% and 100% of electric lighting output level

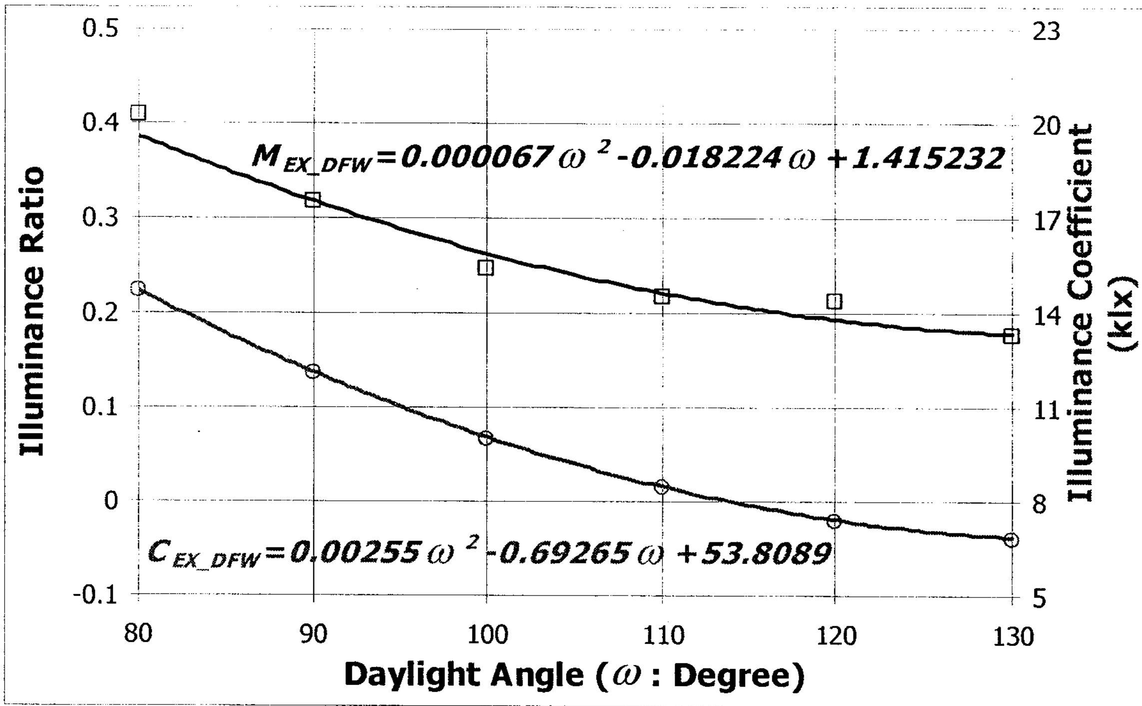


Figure 4-24 Illuminance ratios and coefficients for different daylight angles in the exterior vertical illuminance prediction with the front wall sensor illuminance

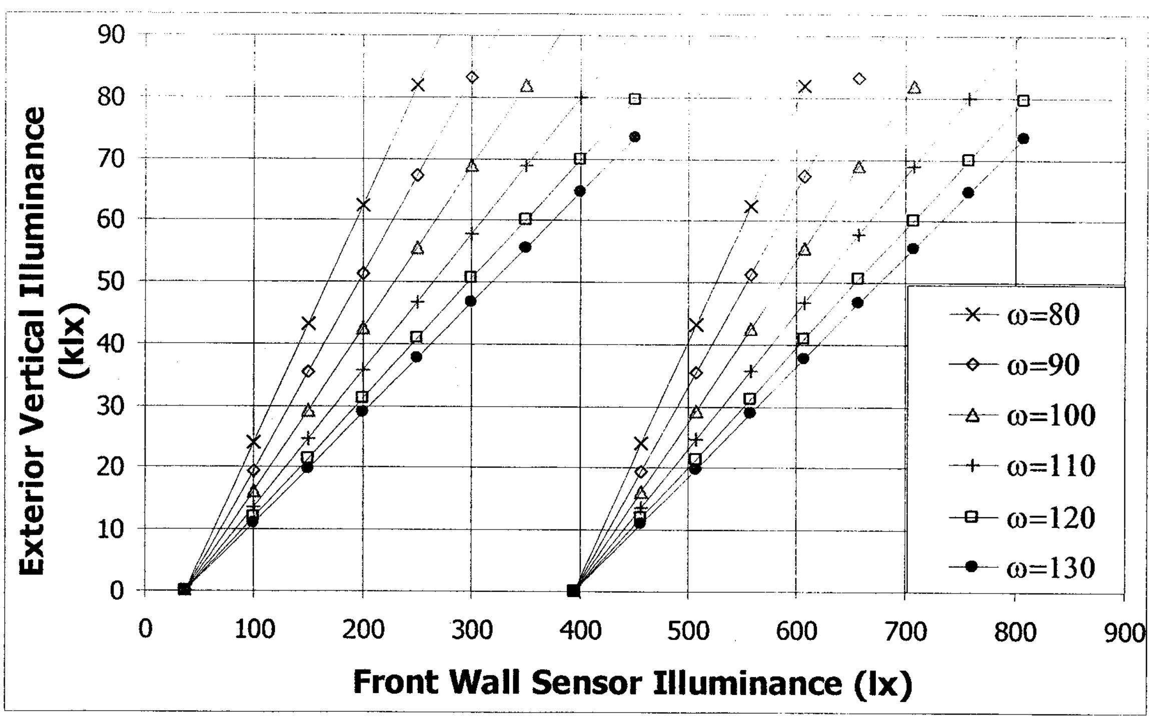


Figure 4-25 Exterior vertical illuminance prediction with the front wall sensor illuminance at 15% and 100% of electric lighting output level

$$E_{EX} = (0.000067 \cdot \omega^2 - 0.018224 \cdot \omega + 1.415232) \cdot E_{DFW}$$

$$- 0.00255 \cdot \omega^2 + 0.69265 \cdot \omega - 53.8089 \quad (4\text{-}8)$$

The solar irradiance ratio and the irradiance coefficient for the window solar irradiance prediction were found to be described by the following linear relationships (Fig. 4-26).

$$M_{G\_DFW} = 0.001 \cdot \omega + 0.18 \quad (4\text{-}9)$$

$$C_{G\_DFW} = 0.05 \cdot \omega + 6 \quad (4\text{-}10)$$

The window solar irradiance (G) prediction with the front wall sensor illuminance is as follows:

$$G = (0.001 \cdot \omega + 0.18) \cdot E_{DFW} - 0.05 \cdot \omega - 6 \quad (4\text{-}11)$$

The workplane illuminance, the exterior vertical illuminance and the window irradiance predictions with the front wall sensor illuminance, are depicted in Figs. 4-23, 4-25 and 4-27, respectively (The daylight angle, ω, in all equations is expressed in degrees).

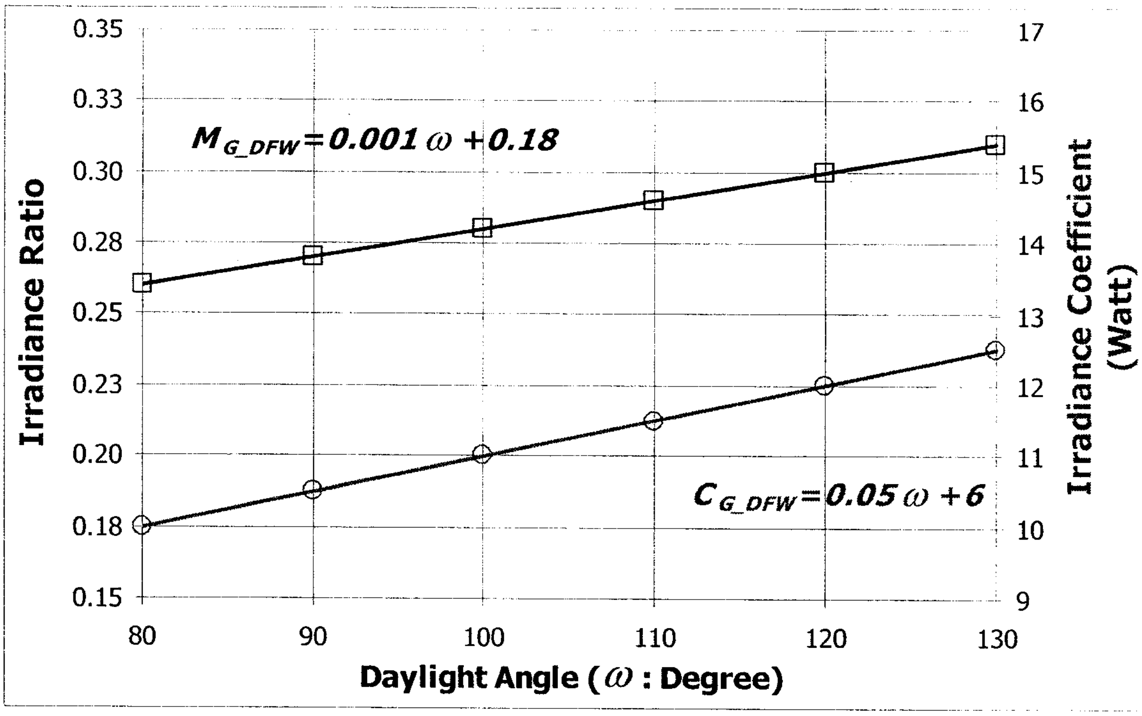


Figure 4-26 Irradiance ratios and coefficients for different daylight angles in the irradiance prediction with the front wall sensor illuminance

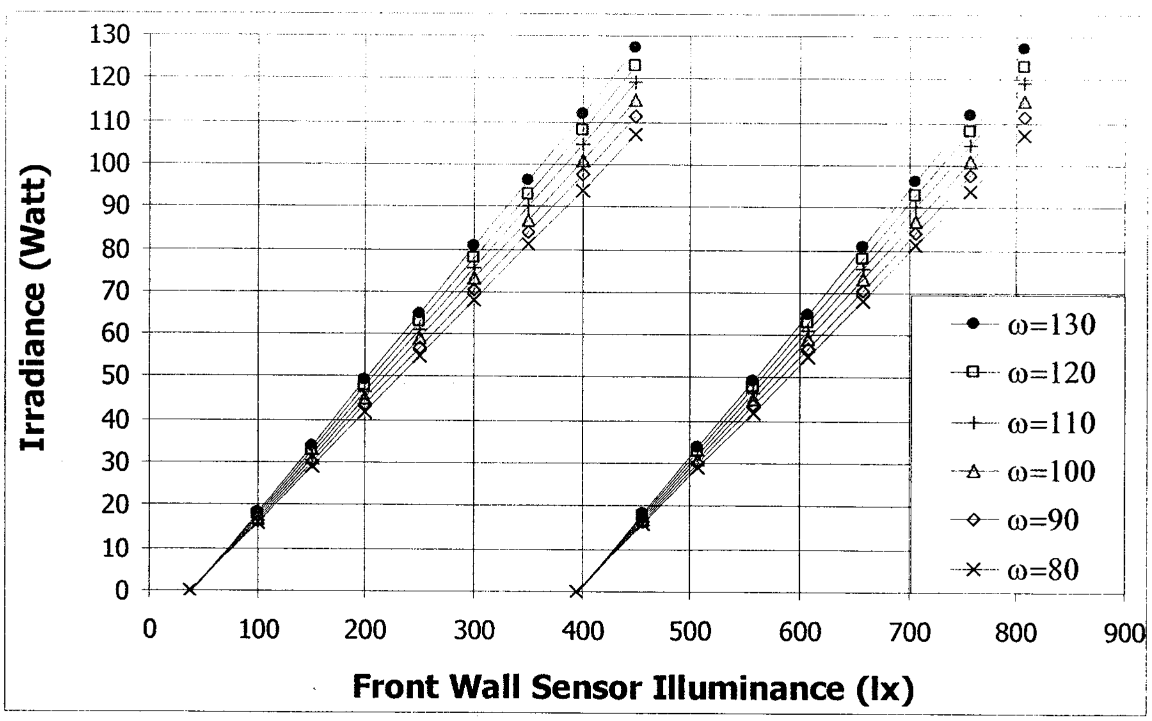


Figure 4-27 Solar irradiance prediction with the front wall sensor illuminance at 15% and 100% of electric lighting output level

4.7 Conclusion

From the electric light prediction experiment, it was found that the illuminance ratio of two arbitrary surfaces in a room is always constant if only one light source is present. In addition to the flexible sensor configuration (location and field-of-view), any lighting system and any room shape with different kinds of interior surfaces can be considered with the illuminance ratio prediction method.

With shading device control to exclude beam radiation, the window system can act as one consistent light source so that constant illuminance ratios for different daylight angles can be obtained. It was found that one interior light sensor could predict several useful daylighting parameters in daylighting control systems such as the workplane illuminance, the exterior vertical illuminance and the solar irradiance on the window system.

Light source instability effect was found to affect significantly the correlation, which is an important factor to be considered in developing accurate light dimming control systems and to understand the daylight distribution in the room. With obtained correlations, an integrated daylighting control system is developed and its performance is analyzed in the next chapter.

CHAPTER 5

INTEGRATED DAYLIGHTING CONTROL SYSTEM

5.1 Introduction

In conventional daylighting control systems, the workplane illuminance is usually obtained indirectly with photocell(s) mounted on the ceiling, wall, exterior façade or their combinations. The workplane illuminance prediction causes system unreliability especially with complex window shading devices such as motorized venetian blinds. Without knowing system behavior, they cannot be efficiently controlled. With the illuminance ratio prediction method, it is found that several useful daylighting parameters for daylighting control in buildings can be efficiently predicted with only one interior light sensor.

Electric light dimming and shading device (motorized venetian blind) controls with the correlation equations derived in Chapter 4 are performed in this chapter. The exact daylighting parameters (i.e., the workplane illuminance and the exterior vertical illuminance) cannot be obtained with predictions; neither can perfect control. Basic control technique and parameters such as control time intervals of electric light dimming and changing blind tilt angle are examined with a workplane sensor control. Based on this, an integrated daylighting control system, which controls the workplane illuminance level while preventing excessive solar heat gains, is developed with the predicted daylighting parameters by using a front wall sensor. The procedure for general applications with the Illuminance Ratio Prediction (IRP) method is explained.

5.2 Control with the Actual Workplane Illuminance

5.2.1 Electric light dimming control

The purpose of the light dimming control is to complement the target design illuminance level with electric light, hence to maximize daylight use and save energy. It is necessary to know the target (workplane) illuminance level at a given light dimming level. Figure 5-1 is the same as Fig. 4-6 without back wall and ceiling illuminances. Two linear correlations for the workplane illuminance (E_{EWP}) and the front wall sensor illuminance (E_{EFW}) were obtained as follows:

$$E_{EWP} = 8.32 \cdot DL - 48.6 \quad (5\text{-}1)$$

$$E_{EFW} = 3.97 \cdot DL - 9.7 \quad (5\text{-}2)$$

where DL stands for electric light dimming level expressed in percent (between 15 and

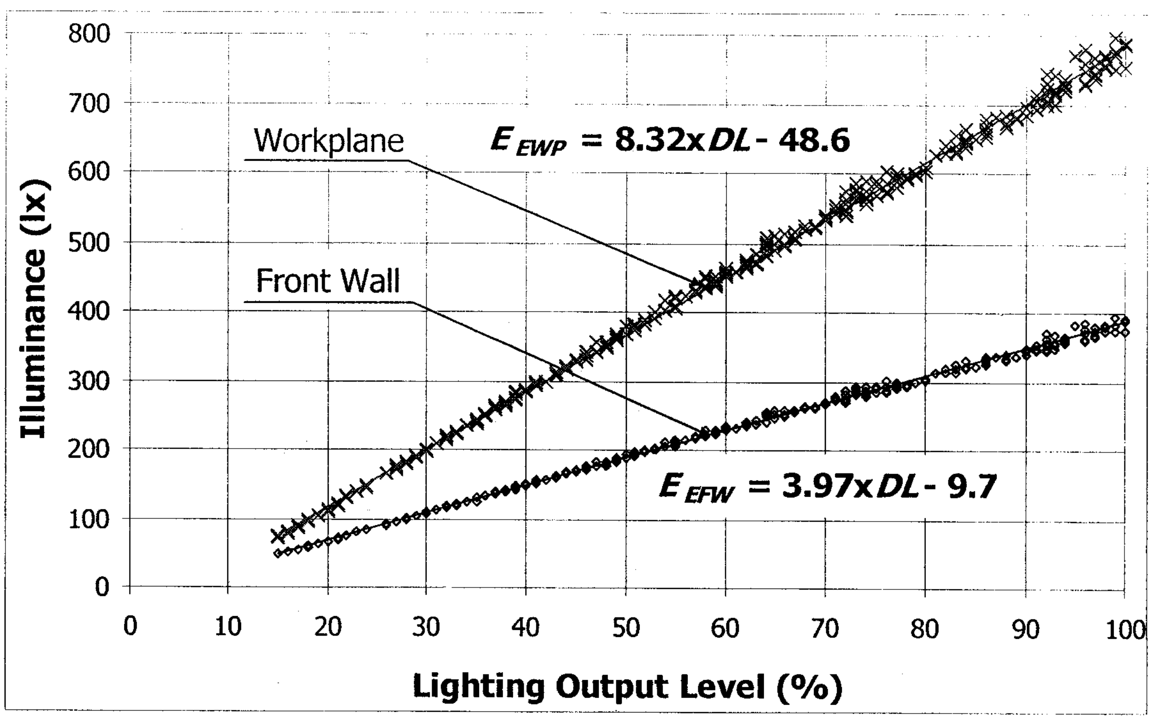


Figure 5-1 Correlations between the light dimming level (***DL***) and the workplane illuminance (***E_{EWP}***) and the front wall sensor illuminance (***E_{EFW}***)

100). There are some deviations from both correlations because of unregulated power supply. The workplane illuminance and the front wall sensor illuminance at 68% light dimming level, for example, will be 517 *lx* and 260 *lx*, respectively. The actual illuminance levels, however, are expected to vary within ±20 *lx* of calculated illuminance levels.

From Eq. (5-1), the light dimming level, *DL* can be calculated for a new dimming level calculation as follows:

$$DL = 0.12 \cdot E_{EWP} + 6 \qquad (5\text{-}3)$$

where the minimum and maximum dimming levels are set to be 15 and 100, respectively. In other words, even though the calculated new dimming level is lower than 15 or higher than 100, the new dimming level is set to 15 or 100, respectively.

The workplane illuminance in the daylit room (E_{TWP}) consists of a daylight contribution (E_{DWP}) and an electric light contribution (E_{EWP}). To complement the design workplane illuminance level (E_{SP}), daylight contribution to the workplane can be obtained as follows:

$$E_{DWP} = E_{TWP} - E_{EWP} \qquad (5\text{-}4)$$

where electric light contribution, E_{EWP} can be obtained with the current light dimming level, *DL* by using Eq. (5-1) and the total workplane illuminance, E_{TWP} is a real workplane illuminance measured by a workplane sensor. Now the difference between the design workplane illuminance and daylight contribution to the workplane illuminance is the amount to be provided with the new dimming level. This amount is used in Eq. (5-3) instead of E_{EWP} to calculate a new light dimming level as follows:

$$DL = 0.12 \cdot \left(E_{SP} - E_{DWP}\right) + 6 \qquad (5\text{-}5)$$

The workplane illuminance is kept over the design illuminance level by applying the newly calculated light dimming level unless the daylight changes abruptly. This is highly dependent on the lighting system characteristics, that is, how quickly the system reaches a desired dimming level. The transient response of lighting fixtures is not considered in this research. However, the abruptness of the workplane illuminance level change can be minimized. When the daylight contribution to the workplane decreases rapidly, a higher dimming level than the calculated one (fast ramp rate) can be applied to ensure that the design illuminance level is always maintained. Conversely, when it increases (this is not a problem to maintain over the design level but it may have a significant impact on cooling loads), a lower dimming level than the calculated one (slow fade rate) can be applied. Note that the human visual system proves to be more sensitive to a decrease than to an increase of the stimulus [Kryszczuk and Boyce (2002)].

Figure 5-2 shows the effect on the workplane illuminance levels by applying the fast ramp and slow fade rate of new dimming levels. With the measured workplane illuminances and dimming levels, simulations for different rates of fade and ramp were performed. The best rate combination found from the simulation is 1.5 and 0.5 times of calculated dimming level for fast ramp rate and slow fade rate, respectively. The top graph in Fig. 5-2 is a simulated workplane illuminance profile with slow fade and fast ramp rate of the dimming level. The bottom graph shows a measured workplane illuminance profile with light dimming control based on calculated dimming levels. The significance of lower design illuminance data around 12:40 to 13:00 was minimized, but that of higher data was increased inversely.

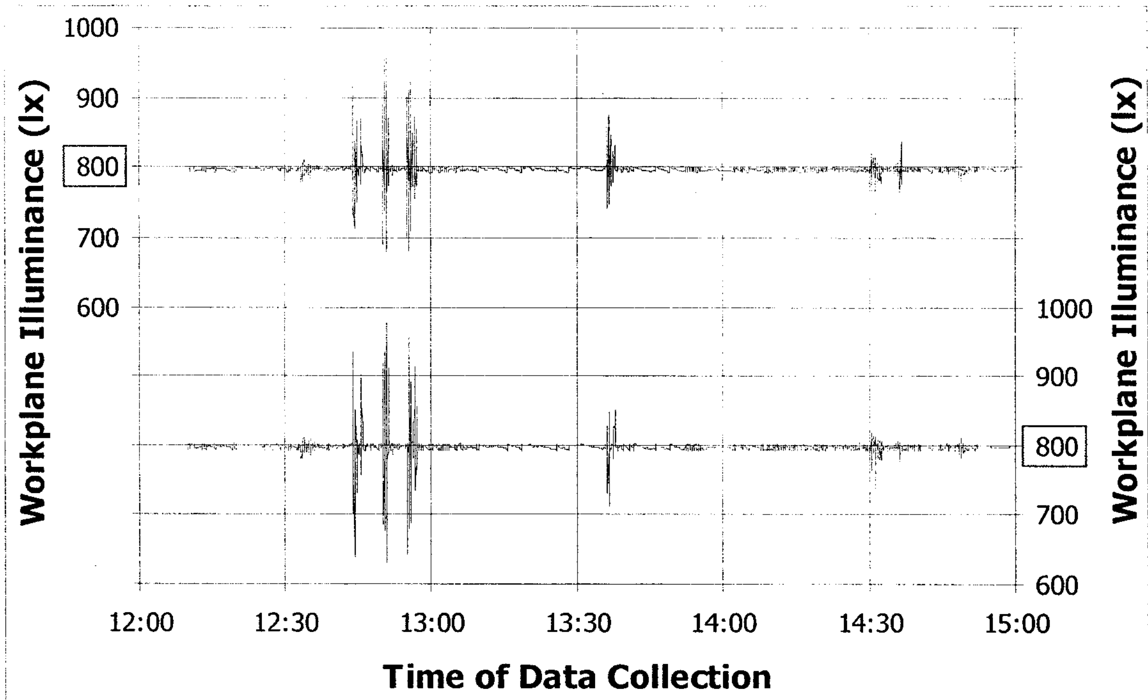


Figure 5-2 With and without slow fade and fast lamp rate effects on the workplane illuminance level control

Minimizing control time interval can be another solution in order to ensure that the workplane illuminance is always above the design level even with a fast-varying daylight source. The instant light level adjustment is an ideal solution so that the occupant does not notice any change of dimming levels while the design level is always maintained. With less than 1 second of control time interval, however, the workplane illuminance level oscillated because of frequent change of dimming levels especially when the difference between the current and the new dimming level is large. It can also be explained by the response of the electric light source, which needs at least 1 second to stabilize as found in the previous chapter. More than 1 second of control time interval showed similar results, but the design workplane illuminance could not be maintained for the periods of the interval.

Light dimming control with real workplane illuminance measurement was performed to maintain 800 *lx* (to utilize full electric lighting output) of design workplane illuminance level with a control time interval of 2 seconds. The blind tilt angle was continuously adjusted to block direct daylight every 3 minutes. Data were collected every 2 seconds for one full day from 8:00 to 17:00 of local time. Typical results are presented in Fig. 5-3. The workplane illuminance was almost perfectly maintained at 800*lx* by continuous electric light dimming level control. The stable control is due to the fact that the data were collected under a cloudy day, that is, daylight conditions were stable or slowly varying throughout the day.

Figure 5-4 shows another result of light dimming control with a workplane sensor but under variable sky condition and blind tilt angle fixed at 40 degrees. From the data analysis, it can be observed that illuminance levels lower than the design illuminance level occurred due to sudden daylight source changes between the periods of control action. Illuminance levels higher than the design level are acceptable most of time except for the time of room overheating by excessive solar gains in the cooling season.

5.2.2 Integrated system control

A motorized shading device can be used to not only block direct daylight but also to adjust daylight amount to a desirable level. To do so, the external vertical illuminance level and the daylight transmittance of the window system must be obtained. It was found that the workplane and the external vertical illuminances could be obtained with the front wall sensor illuminance prediction developed in the previous chapter. Therefore, the external vertical illuminance can be predicted with the workplane illuminance.

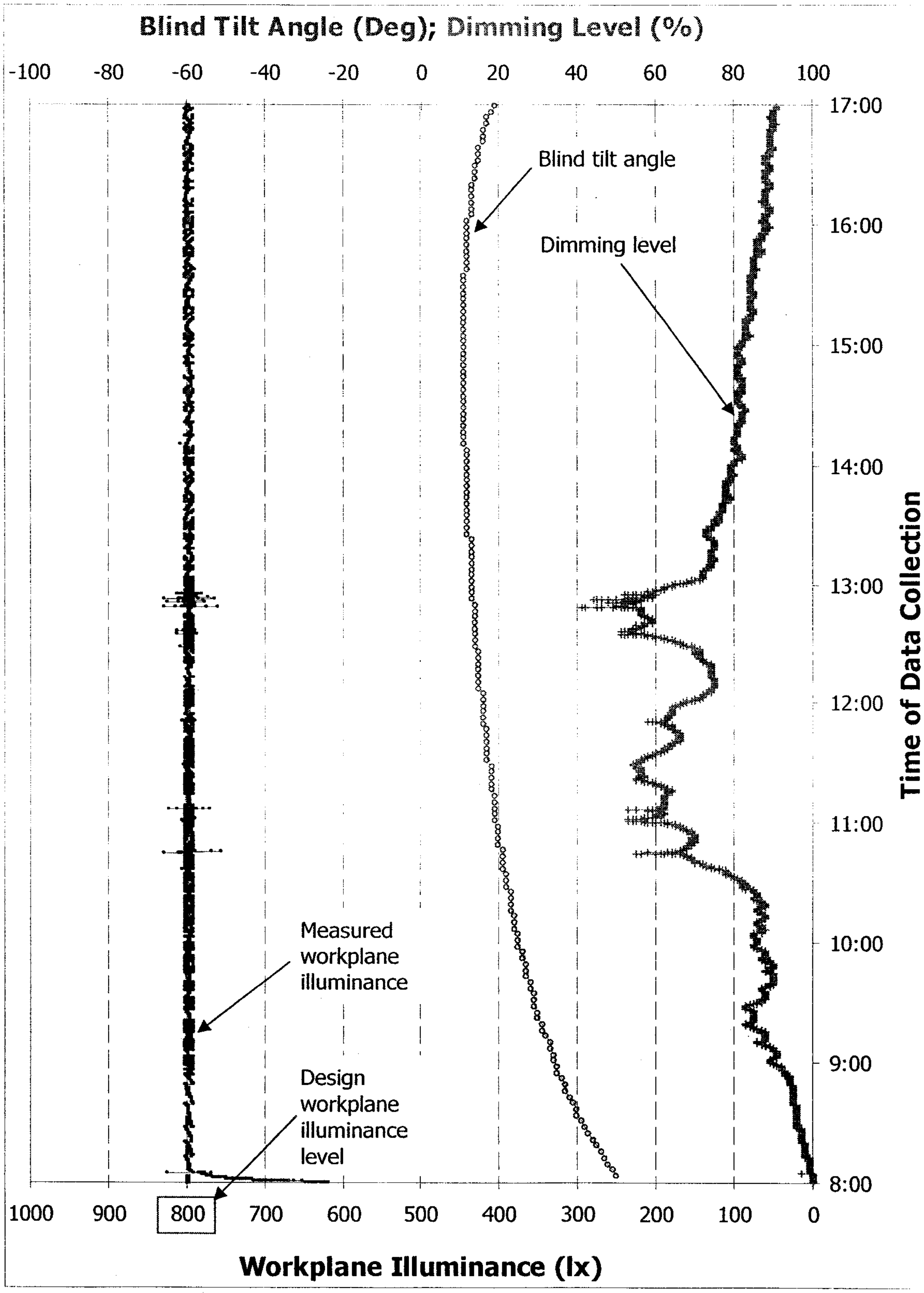


Figure 5-3 Daylighting control system performance with no direct daylight admission under a cloudy day (workplane sensor control)

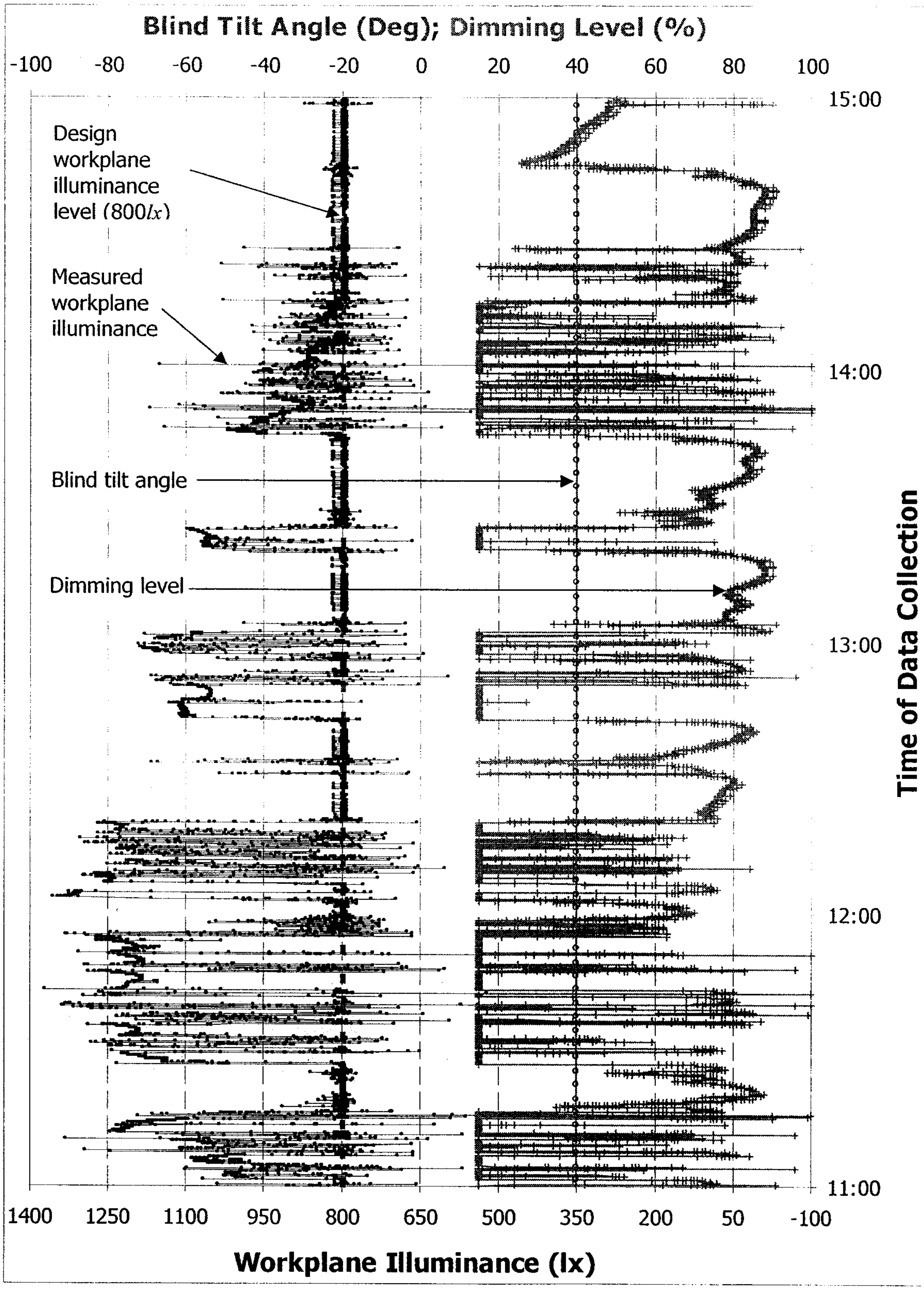


Figure 5-4 Daylighting control system performance with a fixed blind tilt angle under a variable sky day (workplane sensor control)

The external vertical illuminance can be obtained by combining Eqs. (4-5) and (4-8) as follows:

$$E_{EX} = (0.000067 \cdot \omega^2 - 0.018224 \cdot \omega + 1.415232) \cdot \frac{E_{DWP} + 1.091 \cdot \omega - 46.9}{0.0328 \cdot \omega - 0.154} - 0.00255 \cdot \omega^2 + 0.69265 \cdot \omega - 53.8089 \quad (5\text{-}6)$$

With this equation, correlations for different daylight angles were obtained. The illuminance ratio and the illuminance coefficient for the exterior vertical illuminance prediction were found to be well described by the following quadratic equations (Fig. 5-5).

$$M_{EX\_DWP} = 0.000034 \cdot \omega^2 - 0.009248 \cdot \omega + 0.670864 \quad (5\text{-}7)$$

$$C_{EX\_DWP} = 0.00211 \cdot \omega^2 - 0.55479 \cdot \omega + 39.16446 \quad (5\text{-}8)$$

The correlation equation for the exterior vertical illuminance (E_{EX}) prediction with the workplane illuminance (E_{DWP}) from Eq. (4-2) will therefore be as follows:

$$E_{EX} = (0.000034 \cdot \omega^2 - 0.009248 \cdot \omega + 0.670864) \cdot E_{DWP} - 0.00211 \cdot \omega^2 + 0.55479 \cdot \omega - 39.16446 \quad (5\text{-}9)$$

Figure 5-6 shows the prediction of the exterior vertical illuminance with the workplane illuminance. The correlations from the calculation were compared with those based on measured workplane illuminance and external vertical illuminance for six different daylight angles as shown in Fig. 5-7.

Now the external vertical illuminance can be predicted approximately with the measured workplane illuminance (daylight contribution only) and the daylight angle. This external vertical illuminance is used to control the blind tilt angle so as to admit daylight amount near the design workplane illuminance level. The new daylight angle can be calculated from Eq. (5-9) with the design workplane illuminance (E_{SP}) as follows:

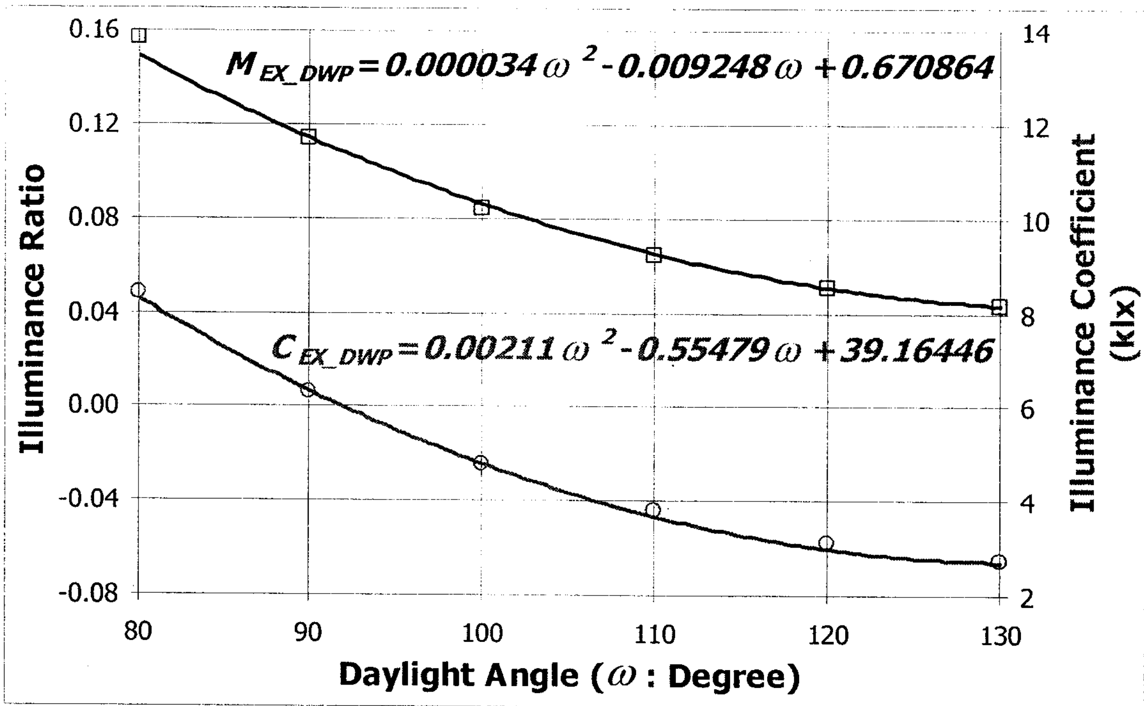


Figure 5-5 Illuminance ratios and coefficients for different daylight angles in the exterior vertical illuminance prediction with the workplane illuminance

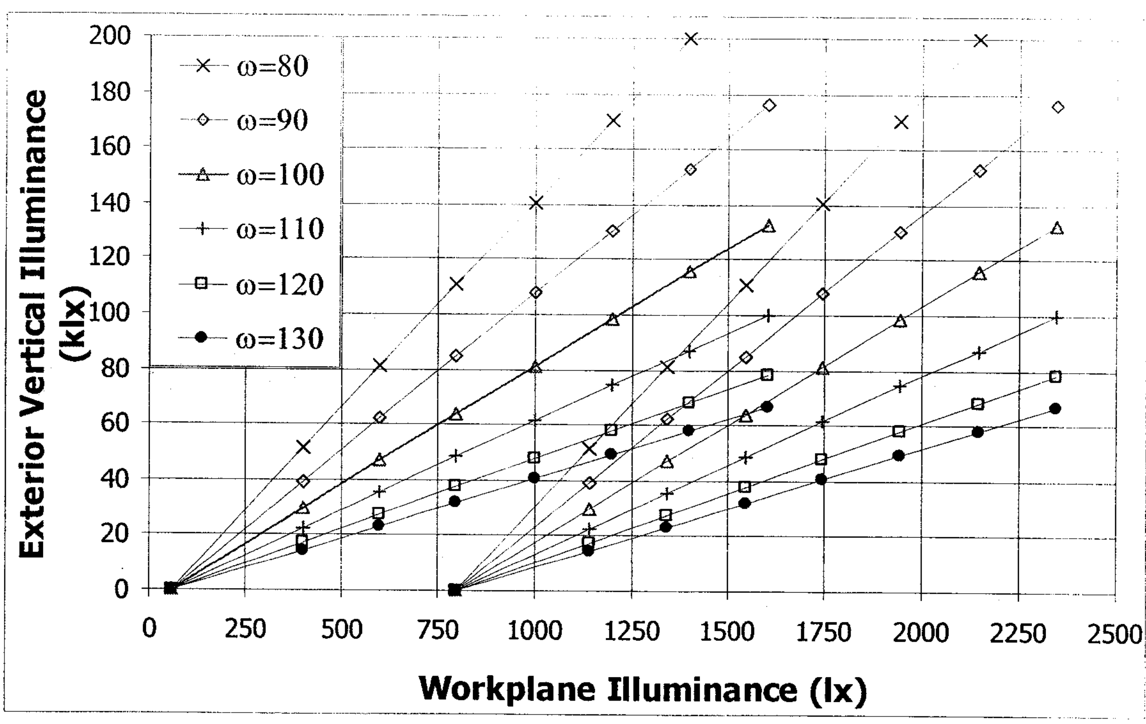


Figure 5-6 Exterior vertical illuminance prediction with the workplane illuminance at 15% and 100% of electric lighting output level

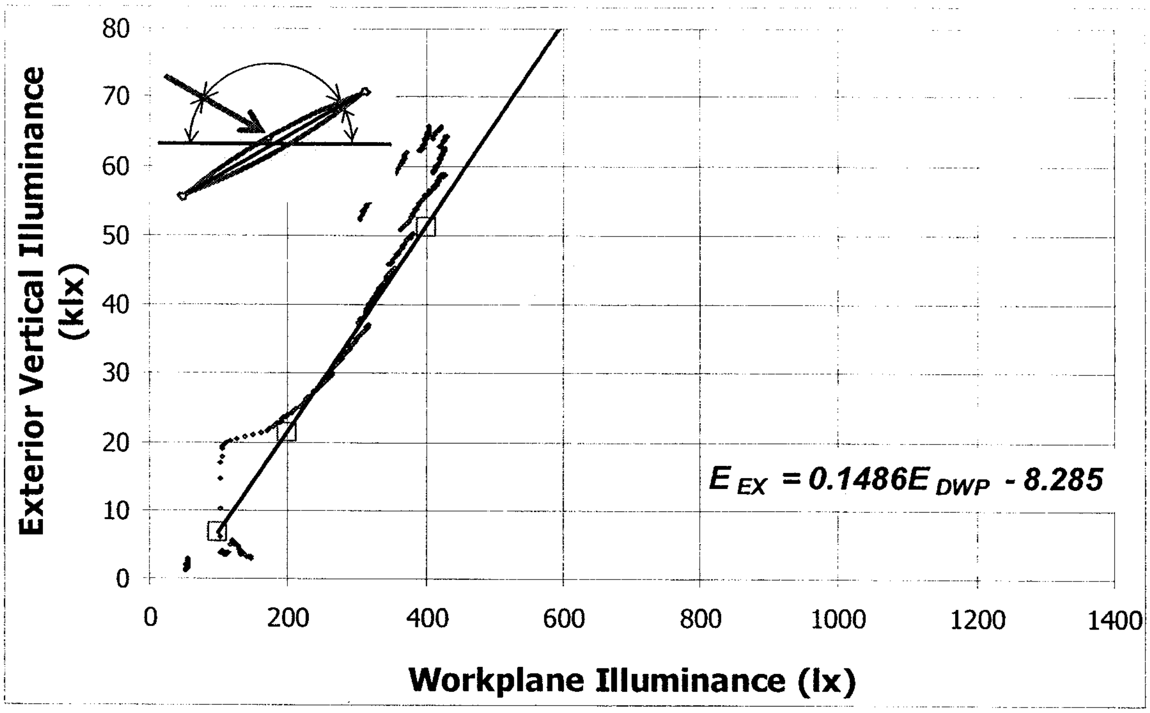


Figure 5-7(a) Correlation between the exterior vertical illuminance (E_{EX}) and the workplane illuminance (E_{DWP}) for the daylight angle $\omega = 80^{o}$

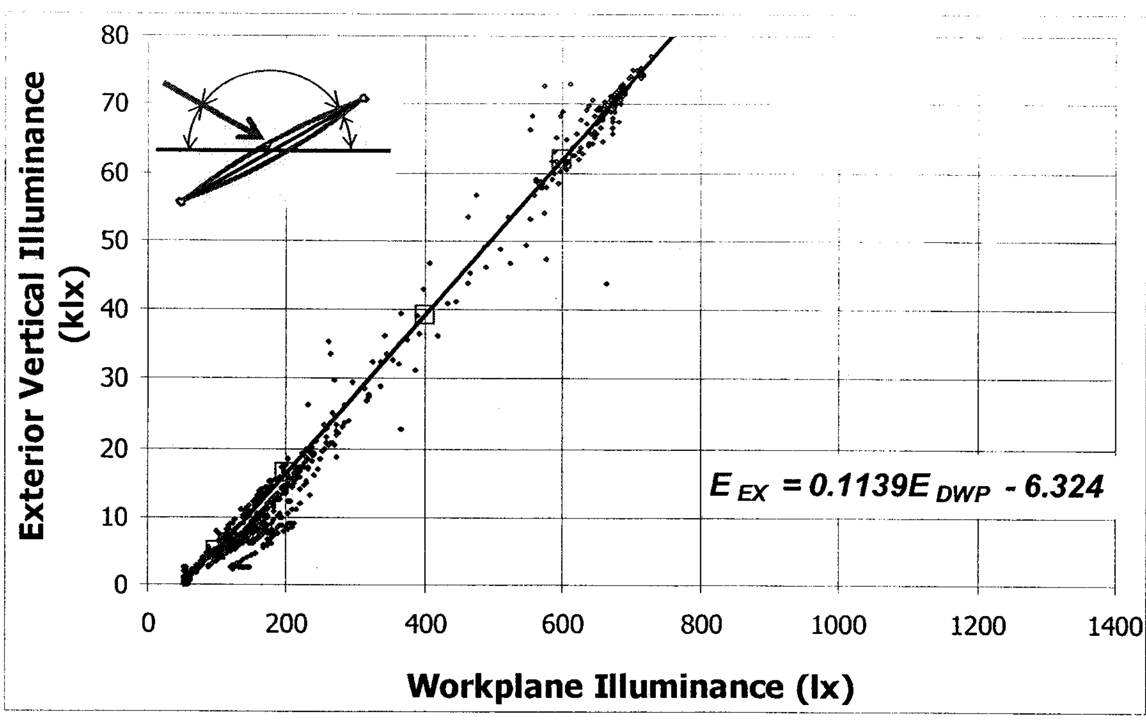


Figure 5-7(b) Correlation between the exterior vertical illuminance (E_{EX}) and the workplane illuminance (E_{DWP}) for the daylight angle $\omega = 90^{o}$

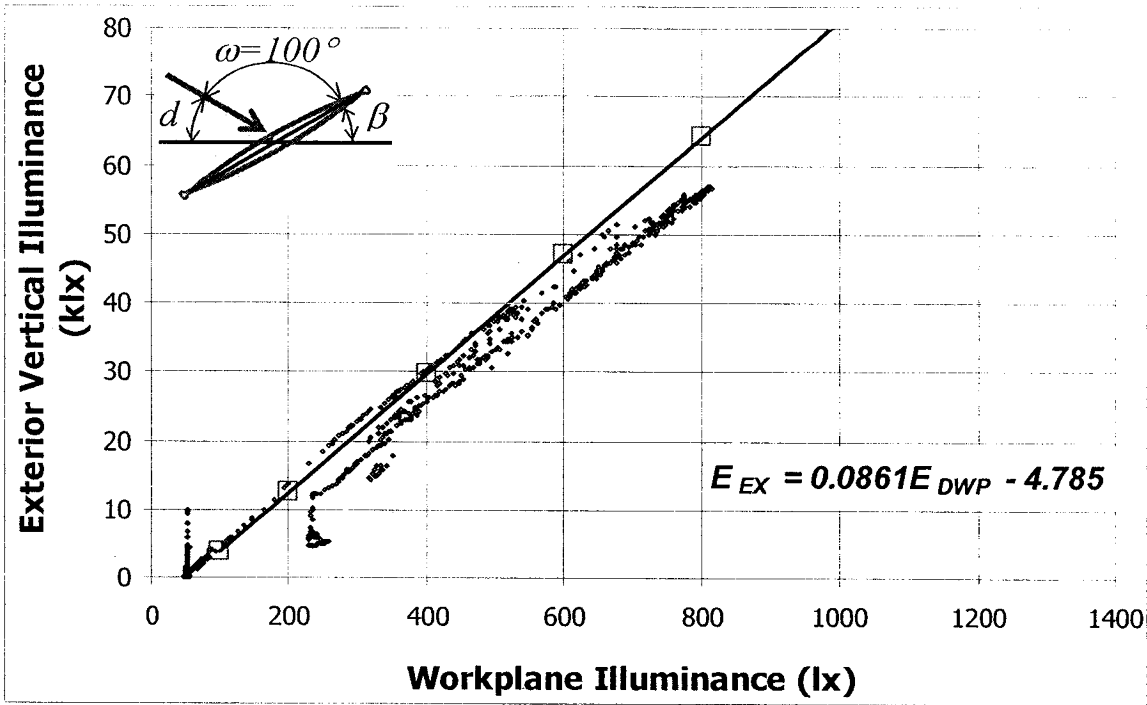


Figure 5-7(c) Correlation between the exterior vertical illuminance (E_{EX}) and the workplane illuminance (E_{DWP}) for the daylight angle $\omega = 100^{o}$

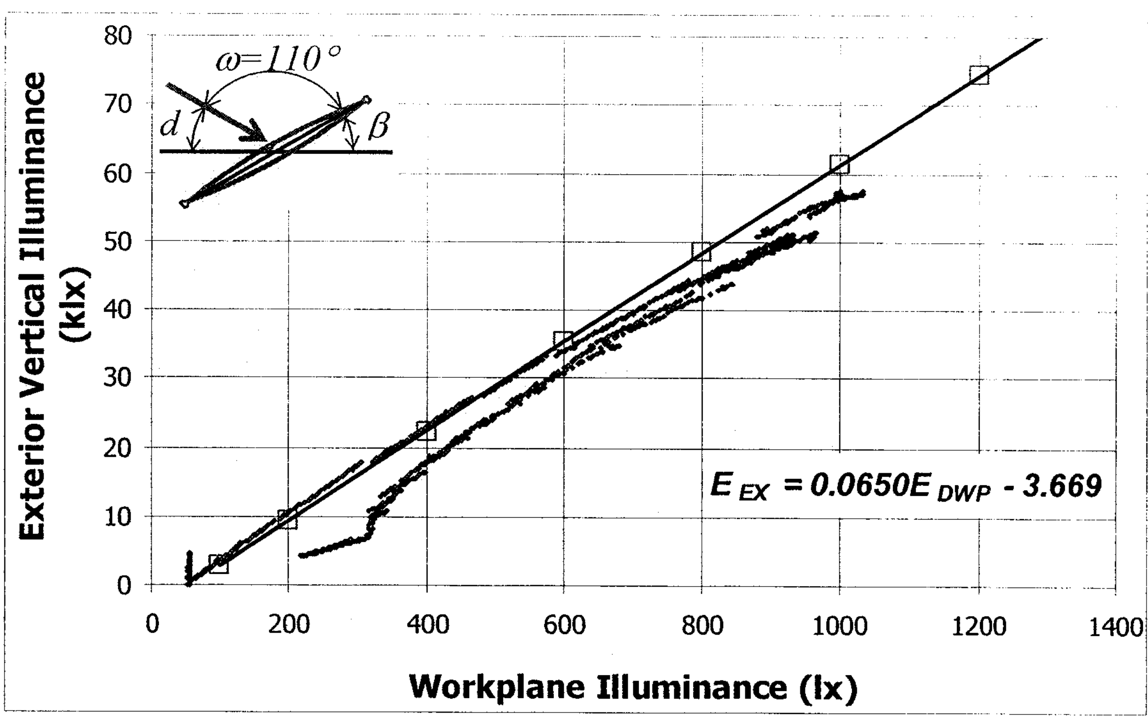


Figure 5-7(d) Correlation between the exterior vertical illuminance (E_{EX}) and the workplane illuminance (E_{DWP}) for the daylight angle $\omega = 110^{o}$

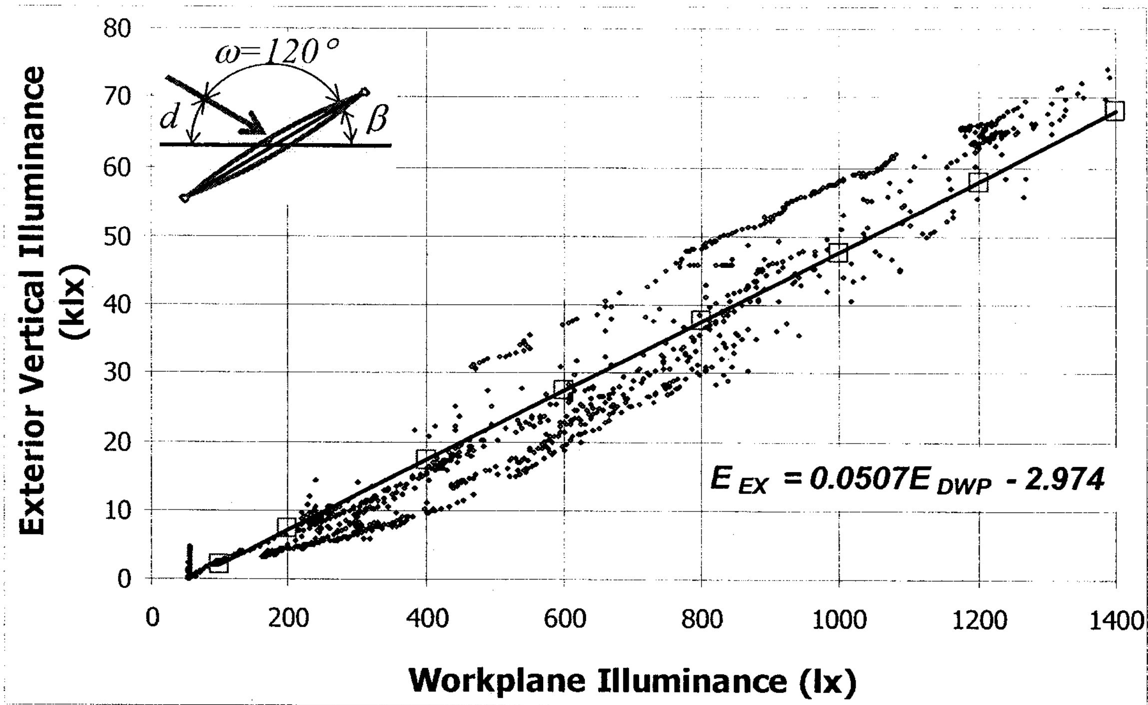


Figure 5-7(e) Correlation between the exterior vertical illuminance (E_{EX}) and the workplane illuminance (E_{DWP}) for the daylight angle ω = 120°

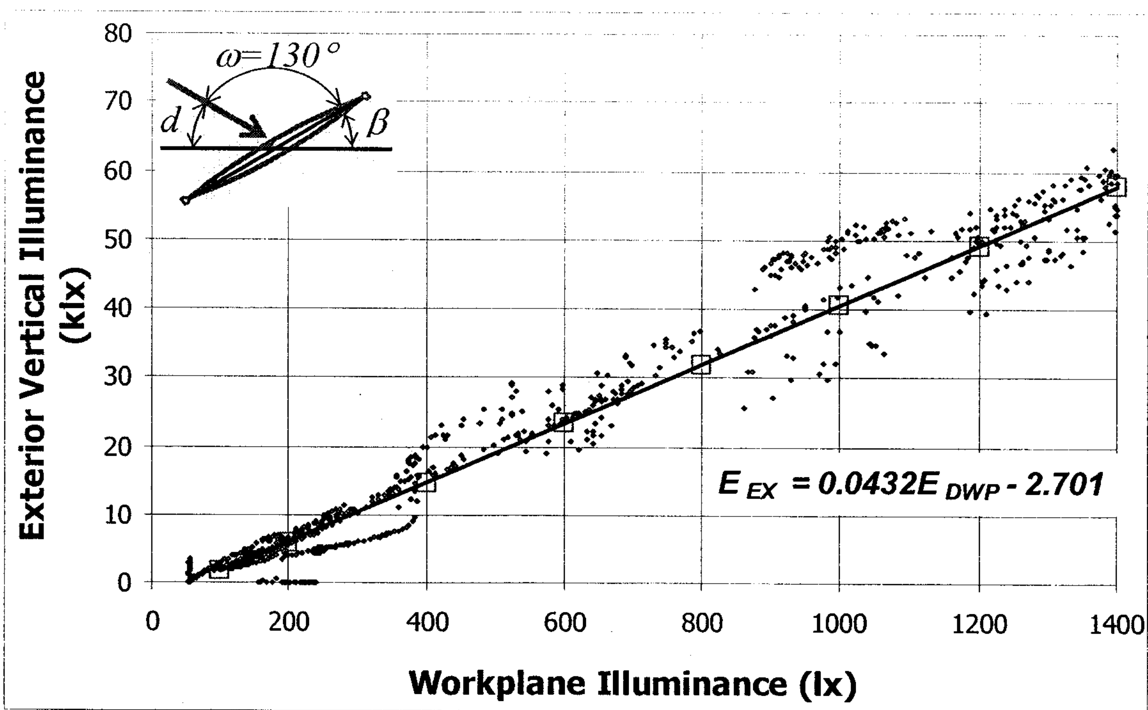


Figure 5-7(f) Correlation between the exterior vertical illuminance (E_{EX}) and the workplane illuminance (E_{DWP}) for the daylight angle ω = 130°

$$\omega = \frac{-B - \sqrt{B^2 - 4 \cdot A \cdot C}}{2 \cdot A} \tag{5-10}$$

where $A = 0.000034 \cdot E_{SP} - 0.00211$

$B = -0.009248 \cdot E_{SP} + 0.55479$

$C = 0.670864 \cdot E_{SP} - 39.16446 - E_{EX}$

With this daylight angle, a new blind tilt angle can be obtained with the profile angle (Eq. (4-1)) and undesirable excessive solar heat gains that may increase cooling load can be significantly reduced while keeping the workplane illuminance level around the design level. A control algorithm flow chart for the integrated daylighting system of light dimming control and blind tilt angle control is depicted in Fig. 5-8.

An integrated daylighting system to block excessive solar heat gains while complementing the design workplane illuminance level was calibrated with a workplane sensor control. It can be observed from Fig. 5-9 that the workplane illuminance profile shows unstable illuminance levels at from 8:30 to 9:10 and from 11:45 to 14:00, while it shows quite stable levels during the rest of the day, because of fast varying daylight sources at data sampling. The excessive daylight was blocked from around 9:10 to 14:00 by increasing blind tilt angles while keeping the workplane illuminance level near the design level (800*lx*) with the minimum light dimming (15%). It is observed that the deviations (around 100*lx*) from the design illuminance level around this period were caused by an inaccurate daylight angle prediction. This is mainly caused by the exterior vertical illuminance prediction errors.

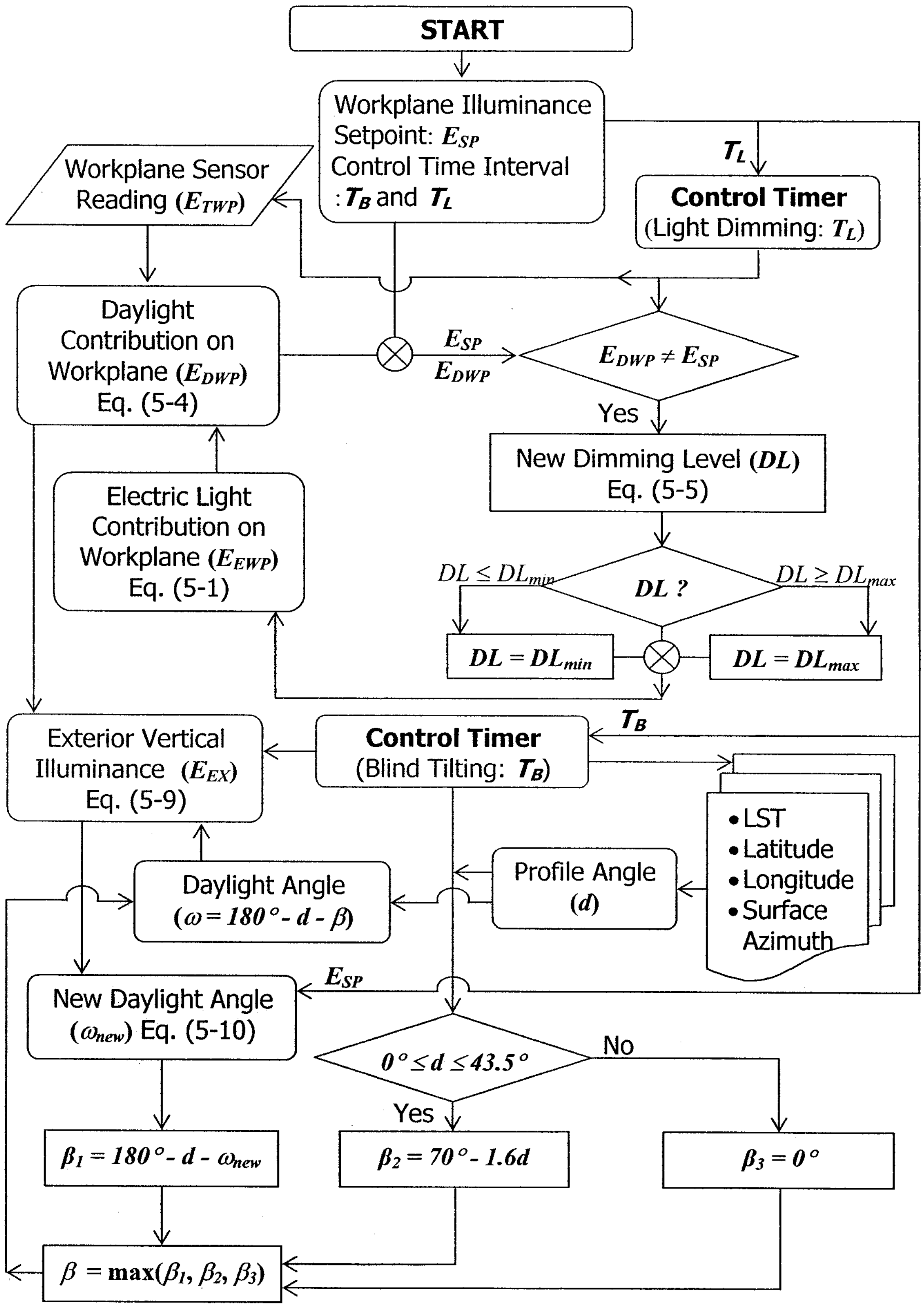


Figure 5.8 Algorithm for calibration of the integrated daylighting control system with a workplane sensor

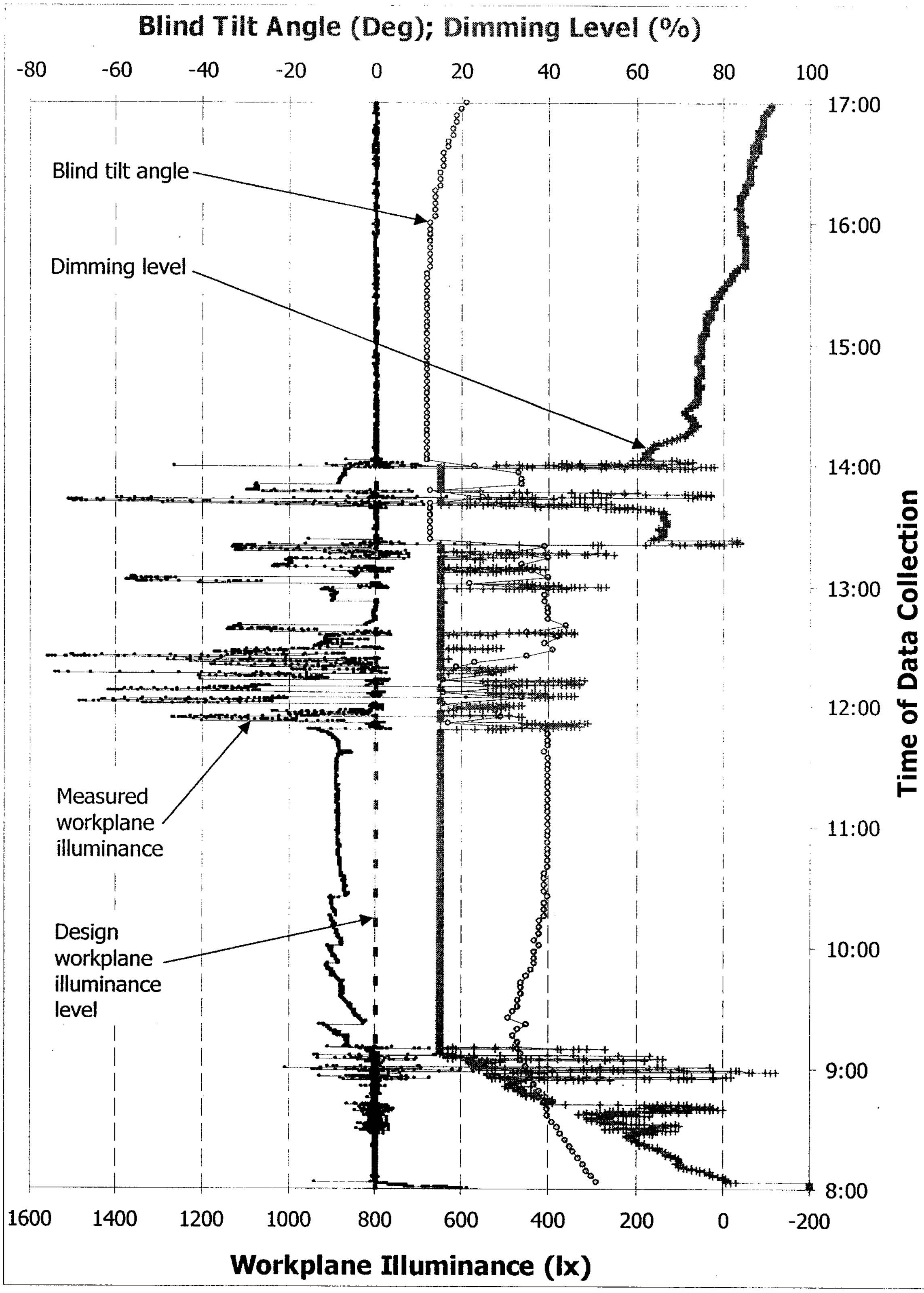


Figure 5-9 Daylighting control system performance with energy efficient blind control strategy under a variable sky condition day (workplane sensor control)

This control strategy is useful for reducing cooling loads during the cooling season and for preventing overheating during the mid seasons. During hot sunny afternoons in the summer, for example, daylight is usually completely blocked to reduce cooling loads and electric light is dimmed at the maximum level to complement the design workplane illuminance level. However, with the developed control strategy, daylight will be admitted around the design level and electric light will be dimmed to the minimum level. This will produce lower cooling loads and thus reduce peak demand, because daylight is more efficacious than electric light. The electricity cost at peak demand may be more expensive than at off-peak time of day and season.

5.3 Control with the Predicted Workplane Illuminance

An integrated daylighting control system calibrated with a workplane sensor proved efficient for complementing design illuminance level while preventing excessive solar heat gains. Based on this control strategy and control technique, an integrated daylighting control system with the illuminance prediction by a front wall sensor is developed. To control electric light dimming, daylight contribution to the workplane illuminance must be predicted with the measured sensor illuminance. The electric light contribution to the sensor illuminance can be obtained by using Eq. (5-2) with the current dimming level. The daylight contribution to the sensor is obtained as follows:

$$E_{DFW} = E_{TFW} - E_{EFW} \tag{5-11}$$

where E_{TFW} is the measured front wall sensor illuminance.

The workplane illuminance level contributed by daylight only can be predicted by using a correlation equation obtained from the previous chapter (Eq. (4-5)). The procedure to obtain the new dimming level is the same as the previous section (Eq. (5-5)). The external vertical illuminance must be predicted with the front wall sensor illuminance to perform an integrated system control. Equation (4-8) is used for prediction of the external vertical illuminance. The control algorithm flow chart for this system is the same as in Fig. 5-8, except for the workplane illuminance prediction by a front wall sensor as shown in Fig. 5-10.

An integrated daylighting control system with a front wall sensor control is developed based on strategy and technique achieved from the system with a workplane sensor control. The results of system performance show that the workplane illuminance can be achieved at near the design workplane illuminance level (800*lx*) while blocking undesirable excessive daylight as can be seen in Fig. 5-11. It can be observed that this system performed as well as the system controlled with a workplane sensor. Under steadily increasing daylight source conditions (from 8:00 to 9:00), the measured workplane illuminance levels were around 785*lx*; under steadily decreasing daylight source conditions (13:00 to 17:00), they were around 825*lx*. It can be shown that this was caused mainly by the workplane illuminance prediction errors (correlation errors).

The estimated deviations of the predicted workplane illuminance from the design workplane illuminance were found to be between –40*lx* and 50*lx* under mostly stable sky conditions (Fig. 5-12). Under unstable sky conditions, however, they were between –50*lx* and 120*lx*, which occurred between the periods of control action as well as because of slow blind angle movement. Note that after 13:00, window was shaded completely by an adjacent building so that the daylight steadily decreased.

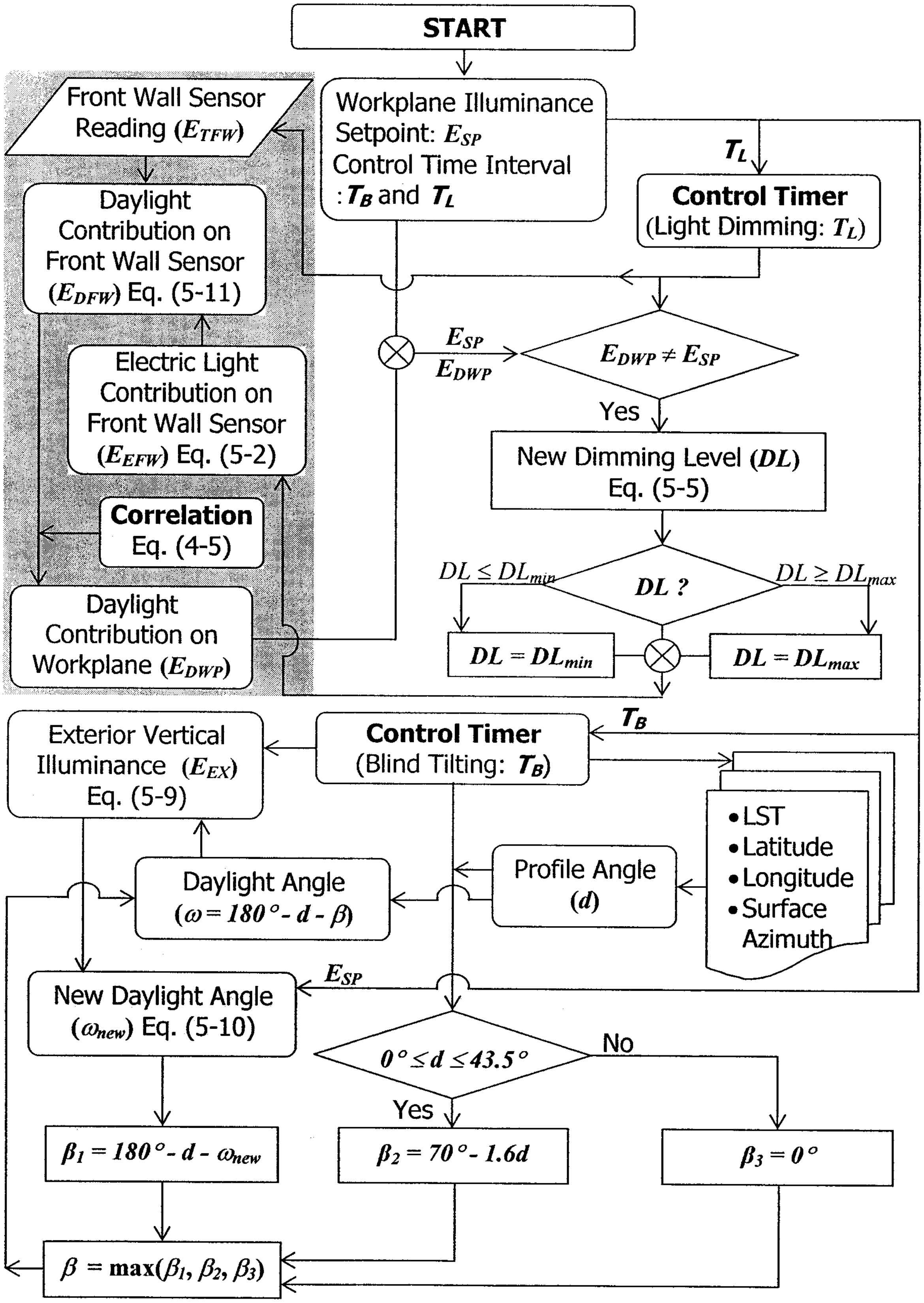


Figure 5.10 Integrated daylighting control system algorithm flow chart

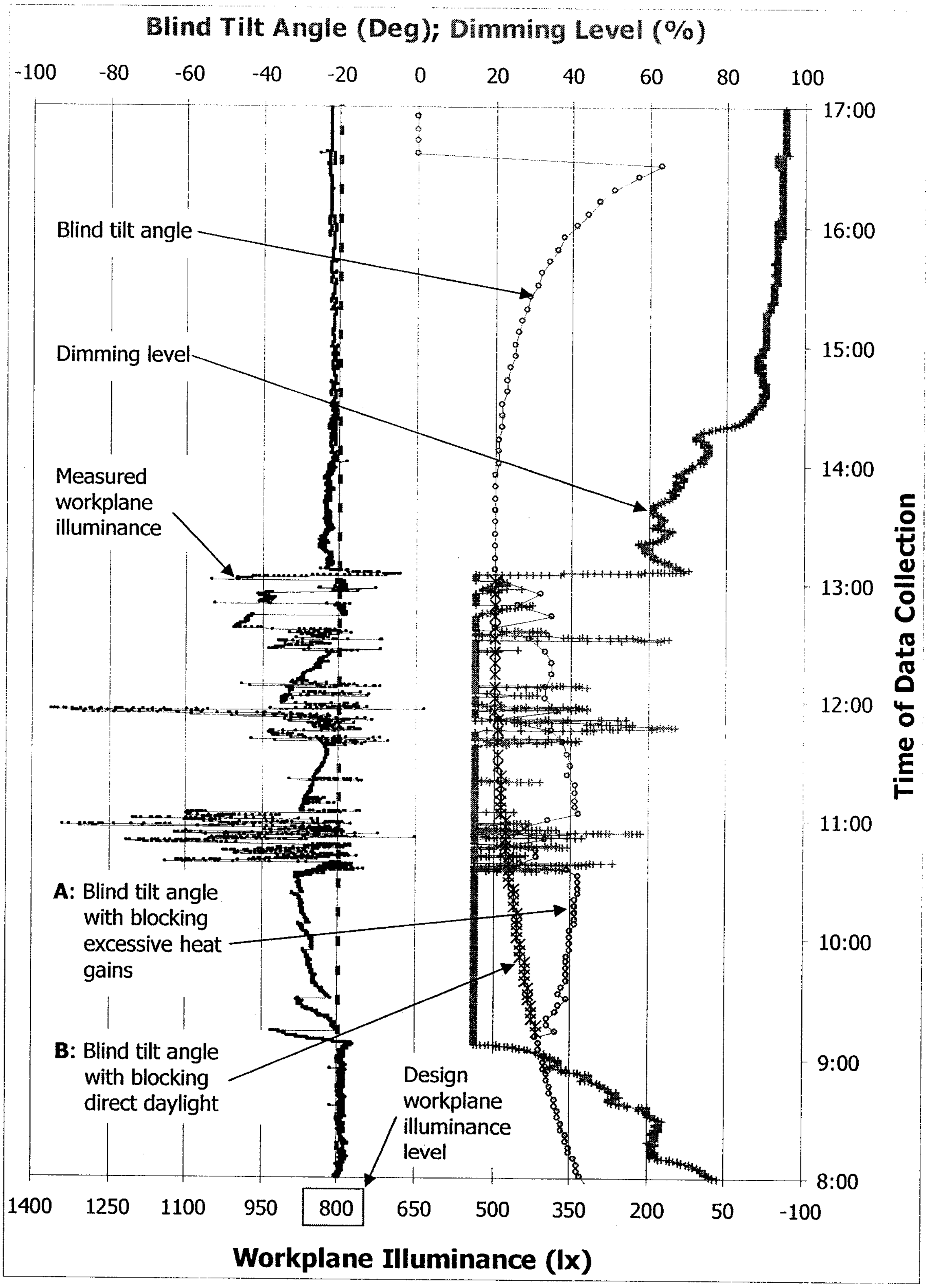


Figure 5-11 Daylighting control system performance with energy efficient blind control strategy under a variable sky condition day (front wall sensor control)

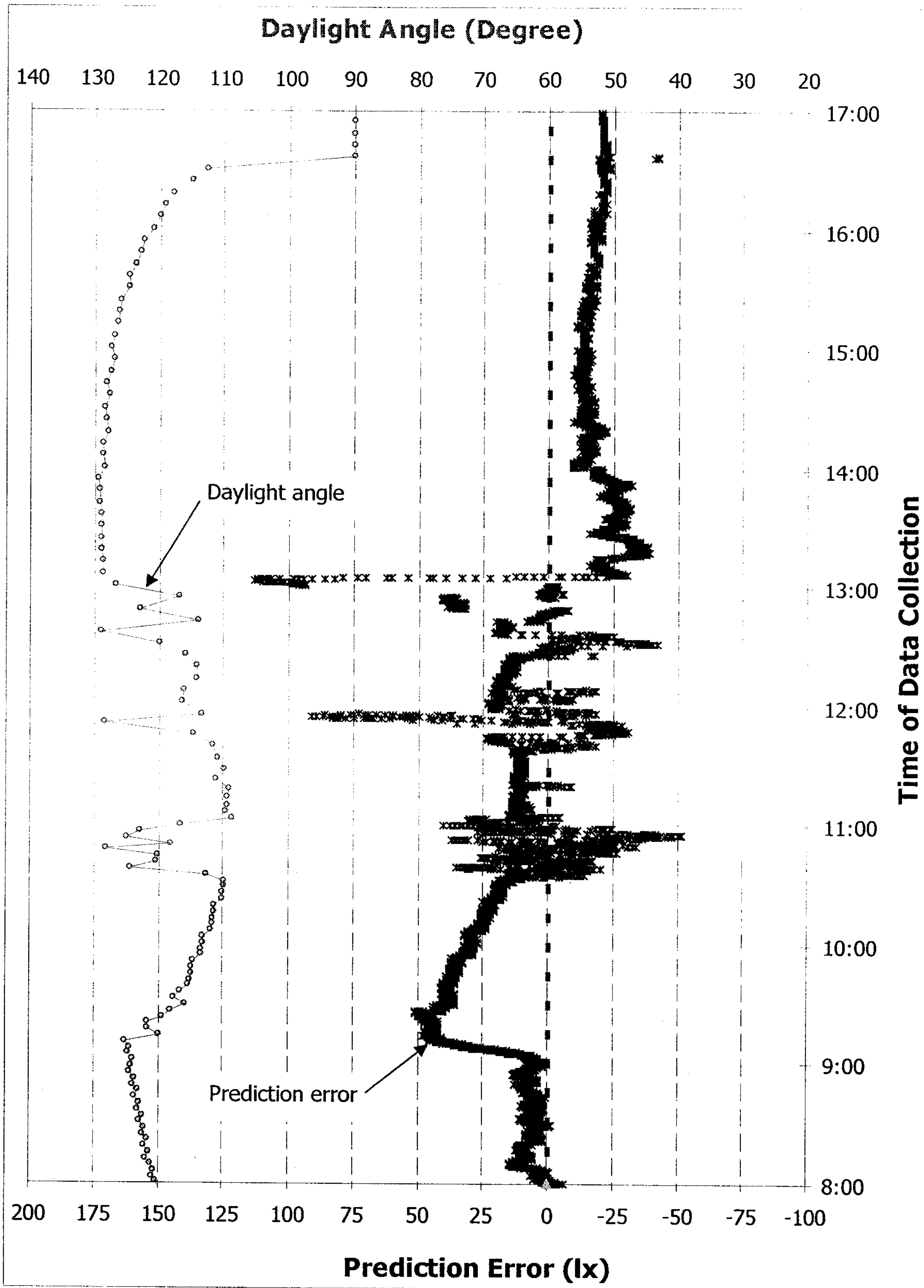


Figure 5-12 Variation of prediction error and the daylight angle under a variable sky condition day

From the profile of the daylight angle shown in Fig. 5-12, it can be observed that the system continuously adjusted the blind tilt angle and the light dimming level so that significant energy savings might be achieved. The estimation of energy savings can be obtained in terms of cooling load reductions; the solar irradiance admission difference by the decreased daylight angle (or the increased blind tilt angle). It is necessary to obtain the solar radiation transmittance as a function of daylight angle for this. However, the transmittance can be obtained with the exterior irradiance prediction similar to the exterior vertical illuminance prediction. With a front wall sensor illuminance, the solar irradiance through the window for any daylight angle can be predicted. Therefore, the energy savings due to cooling load reductions can be approximately estimated.

With the prediction of the exterior vertical illuminance, which was obtained with Eq. (4-8), the solar irradiance through the window using Eq. (4-11) was determined to calculate cooling load savings by blocking excessive daylight. Note that the exterior vertical illuminance can be converted to the exterior vertical solar irradiance by utilizing the spectral luminous efficacy of radiant flux. The cooling load savings due to control of the blind tilt angle to prevent excessive solar gains may be determined by comparing with the case where blind tilt angle is only controlled to exclude direct daylight (compare curve A and B in Fig. 5-11).

The solar irradiance through the window for two different blind control strategies were predicted using Eq. (4-11). Then the total irradiance (Watts) for both strategies were compared to obtain cooling load savings. It was found that the cooling load would be reduced by approximately 16% with the integrated daylighting control system. Note that the data in Fig. 5-11 was collected in early November when solar altitude is low so that the blind tilt angle varied from a minimum of 20 degrees to a maximum of 70 degrees to block direct daylight. It is therefore expected that higher savings can be achieved in the summer season during which the minimum blind tilt angle can be 0 degrees because the sun is at a high altitude angle.

Figure 5-13 shows the performance of the daylighting control system on a clear day. In this case, the design workplane illuminance level was set 600*lx*. The blind was controlled to prevent transmission of excessive quantity of daylight so that the workplane illuminance was kept between 600*lx* and 700*lx* most of time. Data between 12:00 and 13:00 were measured over 700*lx* because of exterior vertical illuminance prediction errors. Under a clear sky condition, the system performed well without any significant deviation of the design workplane illuminance level.

5.4 General Applications of IRP Method

It was shown that control of daylighting in buildings can be efficiently achieved with the IRP method. To apply this method in real applications, the window system with integrated shading devices must be treated as one light source similar to a luminaire. This is the basic condition to apply the IRP method. The consistency of daylight distribution in the room will become a factor affecting the correlation. With changing blind tilt angle, for venetian blind example, daylight distribution will be changed and thus the illuminance ratio between the workplane and the sensor will be different. However, it is expected that the illuminance ratio with a roller blind or with electrochromic glazing will be more easily considered as these are generally closer to a diffuse source.

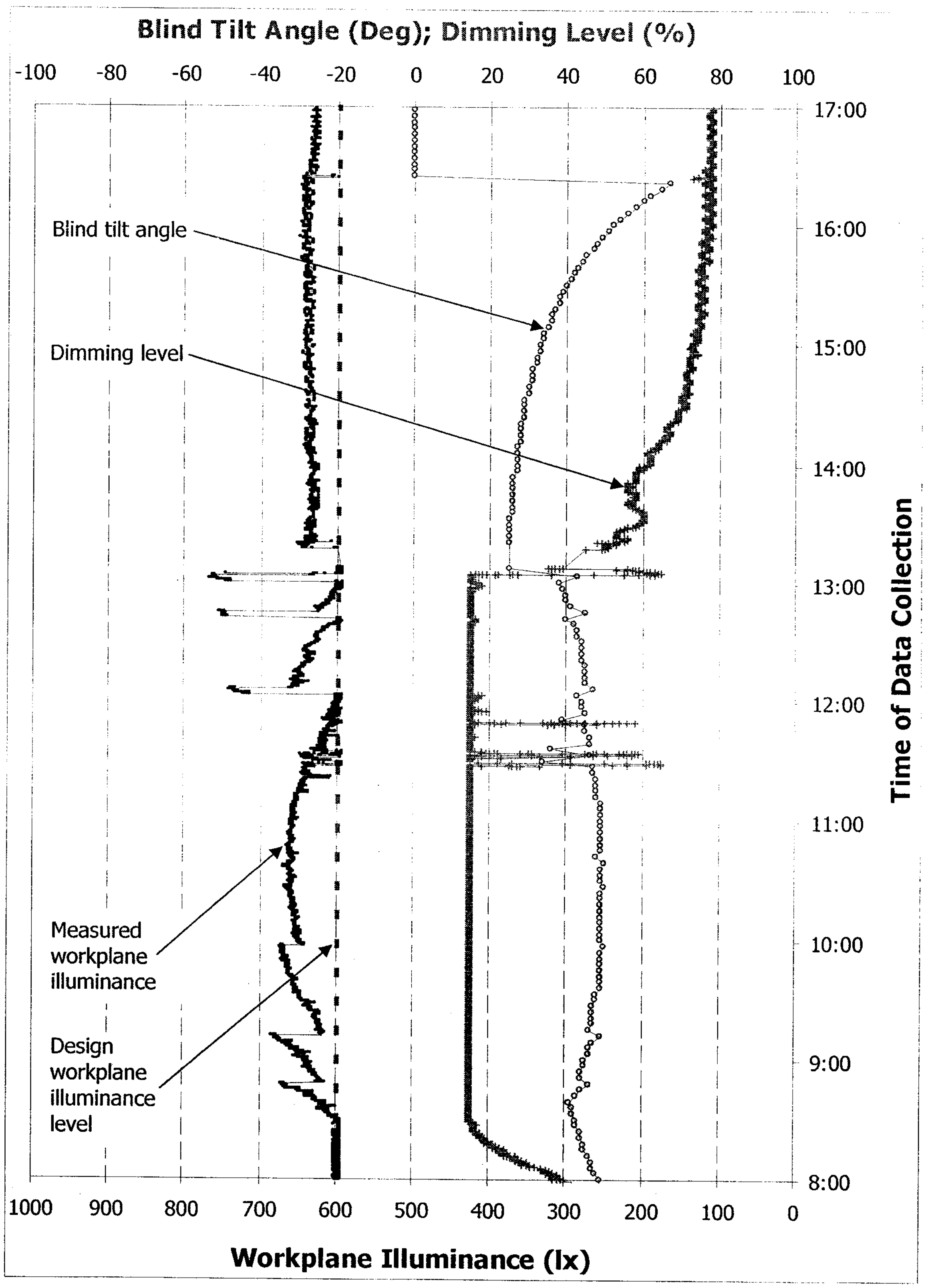


Figure 5-13 Daylighting control system performance with energy efficient blind control strategy under a clear day (front wall sensor control)

To obtain correlation between the workplane and the sensor, calibration must be carried out for both electric light and daylight. The electric light calibration can be done with only electric light source by completely covering the window. For daylight calibration, the data for the illuminance ratio(s) should be obtained on a clear sunny day. The sensor location can be anywhere in the room, but it is recommended to be on the front wall interior surface where admitted diffuse daylight is detected by reflection. It is also necessary to obtain correlation between the exterior vertical illuminance and the sensor for heat gain control.

With obtained correlations, the workplane illuminance and the exterior vertical illuminance can be predicted with one interior (front wall) sensor. Then the controls of electric light dimming to complement the design workplane illuminance level and blind tilt angle to prevent excessive heat gains can be achieved just like control with a workplane sensor.

5.5 Conclusion

An integrated daylighting control system was developed on the basis of the illuminance ratio prediction method. It was found that this system could maintain both the workplane illuminance level and the solar heat gains at the desirable levels by means of light dimming control and shading device control. Without explicitly determining daylight transmittance of window system, the desirable daylight amount was achieved with the controlled blind tilt angle, which was obtained from the predicted daylight angle with only one interior light sensor control. With active daylighting control, significant cooling loads can be reduced while keeping the design workplane illuminance level. The predictions of daylighting parameters are within acceptable ranges under mostly stable daylight conditions.

Keeping the workplane illuminance level at the desired level even with a workplane sensor control was difficult under unstable daylight source conditions. Appling fast ramp rate, slow fade rate and shorter control time interval could not overcome this problem. It is necessary to develop electric lamps, which rapidly compensate a desired illuminance level so that constant workplane illuminance will be maintained even under sudden daylight changes. However, it should be noted that the variability of daylight is psychologically satisfying for people and stimulating.

CHAPTER 6

CONCLUSION

6.1 Conclusion

The benefits of daylighting in buildings are obvious economically and with positive effects on occupants if daylight is controlled properly. Among the many daylighting systems, electric light dimming with shading device control has significant potential to achieve an efficient daylit building. However, the performance of the current systems is neither sufficiently reliable nor accurate, thereby reducing their potential for widespread adoption.

The uncertainty of the light dimming control is largely due to prediction of the workplane illuminance that causes system unreliability and complexity. To improve the performance of the system, prediction of the workplane illuminance must be considered primarily. Without thorough understanding of the systems, their control cannot be achieved efficiently. A new daylight prediction method, Illuminance Ratio Prediction (IRP) method, based on radiosity theory was proposed in this thesis for an integrated daylighting control system.

It was found theoretically and proved experimentally that the illuminance ratio of two arbitrary surfaces in a space in the presence of one initial light source with varying quantity at a fixed location is always constant. This finding can be applied to the predictions of daylighting parameters useful in integrated daylighting control systems such as the workplane illuminance, the exterior vertical illuminance and the solar heat gains through window systems. This also can be applied to any target workplane illuminance prediction of horizontal surfaces or near-vertical planes (e.g., Video Display Terminals: VDT).

The observed advantages of IRP Method are simplicity, accuracy and reliability. Compared to the current light dimming control systems, a photocell location and field-of-view are flexible for the given space conditions so that calibration, commissioning and maintenance of the system can be easily achieved. However, it is recommended that a location where photocell is directly facing the initial daylight source (window) must be avoided because of an occasional direct beam reflected from adjacent buildings. With one interior photocell, a linear correlation between photocell reading and target value can be easily obtained, hence, the control algorithm can be simplified.

Accuracy of the system was found to be dependent on the correlation, which can be obtained correctly under most climate conditions except a highly variable sky condition. However, it is believed that deviations from the correlation are mainly caused by measurement errors since two data cannot be measured simultaneously. With a higher accuracy system, more energy can be saved and a higher satisfaction and better productivity of occupants can be achieved.

Reliability of the system was achieved by control of motorized blinds based on the daylight angle, which facilitates admission of consistent diffuse daylight into the room. The obtained correlation equation as a function of the daylight angle can be applied to any time of a year and any location of a window. It was also observed that any lighting system and any room shape with any interior surface could be considered with the IRP method.

Based on control strategy and control technique calibrated with a workplane sensor control, an integrated daylighting control system with an interior front wall sensor prediction was developed. It was found that this system could maintain both the workplane illuminance level and the solar heat gains at the desirable levels by simultaneous control of the light dimming and the blind tilt angle. With active daylighting control, significant energy savings can be achieved by reducing electricity consumption, heating and cooling loads while improving occupants' comfort.

It was observed that it is difficult to keep the workplane illuminance level over the desired level under unstable light source conditions even with a workplane sensor control. This problem can be reduced if deviations from correlations are reduced. It is necessary to develop electric lamps, which rapidly compensate a desired illuminance level so that a constant workplane illuminance will be maintained even under sudden daylight changes.

6.2 Recommendation for Future Work

To improve and extend the illuminance ratio prediction method, the following research topics are recommended:

- The deviations from correlation between the photocell illuminance and the target value can be reduced by accurate and quick responding photocells and a data acquisition system, which scans data fast (small sampling interval) and accurately. Finding accurate correlation contributes to understanding of daylight distributions in buildings; this will improve the performance of the system significantly.

- Different shading devices for window systems such as motorized roller blinds or electrochromic coatings can be considered to obtain a linear correlation. Some passive daylighting systems such as anidolic zenithal openings, light pipe systems and translucent glazings would also be good applications. It is expected for these systems to have only one linear correlation for each system since consistent diffuse daylight will be transmitted through the systems just like a luminaire.
- More than two window systems are also an interesting case to obtain correlations. It is difficult to obtain one illuminance ratio with two different initial light sources but with a controllable photocell, which can change its location and field-of-view, correlations due to two daylight sources can be obtained.

To improve the performance of daylighting control systems, the following research issues need to be considered.

- In this research, simply on/off control strategy for heating and cooling systems was employed without predicting weather conditions. To maximize energy efficiency of daylighting buildings, the predicted daylight parameters can be fully utilized to control heating and cooling systems. Developing a new daylighting control system prototype, which controls electric light, shading devices, heating and cooling systems with active and interconnectable control strategy, is highly recommended.
- Control parameters such as control time intervals for light dimming and blind tilting must be studied considering physiological and psychological aspects of daylight. This must be a major consideration during the stage of development of control strategies with the integrated daylighting control system.

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