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Experimental and Simulation Study on the Performance of Daylighting in an Industrial Building and its Energy Saving Potential

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Abstract

Proper use of daylighting cannot only improve the visual comfort in indoor environment, but also reduce building energy consumption effectively. Studies on this topic have been mostly conducted for office buildings, but were limited for industrial buildings, where lighting is a major electricity consumer. This paper presents a study of daylighting performance in a large space industrial building (Tianjin, China) by both field measurements and numerical simulations. The daylighting illuminance distribution was measured with 6m×6m grid size during four periods on a sunny spring day. The average daylighting illuminance during the four measurement periods (9:00-10:30, 11:00-12:30, 13:00-14:30, 15:00-16:30) were 373lux, 397lux, 360lux and 254lux, respectively. The daylighting illuminance simulations done by Ecotect and Desktop Radiance simulation program were applied for comparison with the field measurements. The simulated daylighting illuminance distributions matched well with the measurements. Furthermore, quantitative analysis of the energy saving potential of artificial lighting controls integrated with daylighting and the effect of reducing artificial lighting on the heating energy consumption were conducted with EnergyPlus simulation program. The electricity saving potential for the On/Off control and the dimming control integrated with daylighting were 36.1% and 41.5%, while the reducing of artificial lighting by the two strategies would lead to an increase of heating energy consumption by 7.1% and 8.7%, respectively.

Keywords: Large space building, Daylighting performance, Energy saving potential, Field measurement, Ecotect simulation

1. INTRODUCTION

Artificial lighting is one of the major electricity consumers in many non-residential buildings [1]. According to the United States Department of Energy, commercial buildings consumes 32% of the total electrical energy in the country, of which 33% go to artificial lighting [2]. For office buildings, artificial lighting consumes about 20-35% of the total building electricity consumption in Hong Kong [3]. For industrial buildings, the percentage varies widely depending on different manufacture process. A summary of seven factories showed that artificial lighting consumes about 1-34% of the total building electricity consumption in Dongguan, China [4]. To reduce the energy consumption therefore manufacture cost, increasing effort has been made to minimize the energy consumption of artificial lighting [5]. Proper use of daylighting cannot only reduce energy consumption effectively, but also improve the indoor visual comfort. People prefer natural lighting than artificial lighting as it gives the best color rendering and matches with human visual response [6]. It has been proved that good daylighting can provide a more pleasant and attractive indoor environment that can contributes to higher productivity and performance [7].

Recently, there has been an increasing interest in incorporating daylighting with architectural and building designs to save building energy consumption [8, 9]. A variety of results have indicated that proper lighting controls integrated with daylighting have a strong potential for reducing energy consumption in office buildings. Field measurements and simulation studies have showed that the energy saving potential by utilization of daylighting is about 30%-40% for constant lighting system [10] and 20-40% even up to 60% for dimming control system [11-13]. However, it is noted that the existing studies have mainly focused on office buildings, which are normally small room spaces. The study on the performance of daylighting for industrial buildings is limited, which are normally large spaces. Compared with office buildings, industrial buildings usually have more intensive energy use, and higher indoor illuminance requirement for some special manufacture process. For large space industrial buildings, there are more room spaces which can gain daylighting benefits due to the open floor planning. Therefore, quantitative analysis of the daylighting performance and the daylighting design effectiveness in the large space industrial buildings are needed and will help to improve the building performance through guiding the future design.

The study of daylighting performance can be achieved by experimental measurements and computer modeling. The experimental measurements can be either field measurements or scaled model tests. As the experimental measurements are usually expensive and time-consuming, computer modeling becomes increasingly popular. With the recent advances in computer technology, the application of Radiance becomes more attractive in modeling building daylighting performance. Radiance [14] is a ray-tracing daylight and electrical lighting analysis software developed by Lawrence Berkeley National Laboratory (LBNL) and has been successfully applied to the building lighting design. Researchers have used Radiance to predict various aspects of daylighting performance, including the illuminance distribution based on information of the incoming light [15, 16], the problem of glare [17], and sky luminance distribution [18]. Li and Tsang (2005) [19] measured and simulated the daylight illuminance in a daylit corridor and found that the indoor illuminance simulated by Radiance using daylight coefficient approach showed reasonably good agreement with measured data. However, Radiance can only predict the daylighting performance at a fixed weather condition and time point. It is not capable of predicting long term energy saving potential by lighting control integrated with daylighting. The building energy consumption simulation program EnergyPlus [20] has been validated for accuracy in predicting the performance of daylighting and lighting control systems in actual buildings [21, 22]. Therefore, EnergyPlus can be coupled with Radiance to predict the energy performance of daylighting.

This study conducted both field measurement and numerical simulation of the daylighting performance in a large space industrial building in Tianjin. The objective of this study is to: (1) evaluate the daylighting environment quality of the industrial building; (2) validate the accuracy of experimental method and procedure which was used in the daylighting environment evaluation; (3) evaluate the effectiveness of the integrated daylighting and lighting control system; (4) estimate the electricity saving potential of artificial lighting controls integrated with daylighting and the effect of reducing artificial lighting on the heating energy consumption for the industrial building.

2. METHOD

2.1 Investigated industrial building

This study was conducted in a single floor elevator factory building in Tianjin, China, (39.08°N, 117.07°W). The floor area is 156 (long) ×162 (wide) m^2 and the ceiling height is from 14.5m to 11.0m. Fig. 1 shows the factory building model and its fenestration. The factory has a hackle-shape roof and five spans (the width is 18m for one span, and 36m for the rest four spans). Three kinds of daylighting fenestration were designed: the side windows on the walls, the top daylighting panels and top vertical skylights on the roof. The window to wall ratio (WWR) and skylight to roof ratio (SRR) are showed in Table 1.

The factory has an electricity monitoring system, which can record electricity for different usages: production, lighting, heating, ventilation and air-conditioning (HVAC, which is used for the “office zone”; there is no HVAC system in the factory zone) and reserved (The electricity consumption which is reserved for additional sockets). By analyzing the history data of the year 2009 (see Fig. 2), it was found that the artificial lighting contributed to about 30% of the total electricity consumption, which is the second biggest electricity consumer following the production process in the factory.

2.2 Field measurement

The illuminance was measured by illuminance meters. TES 1330A (0-20000lux, TES Electrical Electronic Corp) was used for the measurement of indoor daylighting illuminance and TES 1332A (0-200000lux, TES Electrical Electronic Corp) was used for the measurement of outdoor illuminance.

The field measurement was conducted on Apr. 4, 2011, which was a sunny day. To separate the daylighting with artificial lighting, all the lamps were turned off during the measurement. To obtain the daylighting illuminance distribution in the whole indoor space accurately, the measurement grid size was set to be 6m×6m (702 points planned in total). As some areas of the factory were off limits or blocked by machines, totally 87-92% of planned points were measured. To reduce the influence of the changing solar angle during the measurement period, the measurement need to be finished in a short period time as much as possible. Therefore, the measurement points were divided into four zones and the measurement started simultaneously from positions P1, P2, P3, and P4 in an order of the arrow line indicated in Fig. 3. The measurement at each position lasted for 10s to get a stable illuminance reading and one complete measurement of the whole factory need to take about 1.5 hours. The measurements were conducted during the four time periods of the day: 9:00-10:30, 11:00-12:30, 13:00-14:30 and 15:00-16:30. The corresponding outdoor illuminance was recorded every 10 minutes. All the measurements were conducted in the horizontal plane at a height of 0.75m above the floor.

2.3 Illuminance simulation

As one complete measurement lasted for 1.5 hours, the measurement results represented an average daylighting illuminance distribution during the period. To validate the feasibility of the experimental method and procedure, the illuminance was simulated for the time period of 11:00-12:30 for comparison.

The building model was built by Ecotect (Autodesk) [23], and the daylighting simulation was then carried out using Radiance (Desktop). The analysis plane was set as 0.75m above the floor and the analysis grid size was set as 6m×6m, which was the same as the measurement. Four time points (11:00, 11:30, 12:00 and 12:30) were simulated for the measurement period of 11:00-12:30 on April 4. CIE clear sky condition [24] of Tianjin was used as the climate condition.

Table 2 shows the reflectance of the building envelope and the visible transmittance of the top daylighting panels, side windows and top vertical skylights used for the daylighting simulation. According to the Chinese lighting design standard of buildings (GB50034-2004) [25], the reflectance values of floors, interior walls, and ceilings are recommended to be 10%-50%, 30%-80%, and 60%-90%, respectively. Hence, the reflectance values of the floor, interior walls and ceilings for the simulation were estimated to be 35%, 70% and 80%, respectively. The design specification provided by the designer states a visible transmittance of 45% for the side windows and top vertical skylights and 25% of the top daylighting panels.

2.4 Energy consumption simulation

To predict the energy saving potential of daylighting and quantify the effect of reducing artificial lighting on the heating consumption for the factory, the energy consumption was simulated with EnergyPlus. Two lighting control strategies were studied: artificial lighting continuous/Off control integrated with daylighting and artificial lighting On/Off control integrated with daylighting. The building models with and without the top daylighting panels on the roof were simulated to investigate the effect of skylight on daylighting utilization. Since the factory only has radiator heating system in winter for the heating of work space, all the simulation cases were coupled with a heating system during the heating period (Nov.15th to Mar.15th) of Tianjin, China. The quantitative effects of reducing artificial lighting on the heating consumption were calculated. The effect on cooling load was not investigated here as there is no cooling system in the factory, and it's well expected that the reduced artificial lighting will decrease cooling load.

The building model built in Ecotect was exported to EnergyPlus for energy consumption simulation. The space was divided into ten zones and an illuminance reference point was set in the middle of each zone to control the lamps' operation status of the corresponding zone. The illuminance transducers were placed at the specified reference points to detect the illuminance levels and feedback the signals to the controller to control the overhead artificial lighting. The lighting control type was set as continuous/Off [26], which was a continuous dimming control strategy. For artificial lighting continuous/Off control, the overhead lights dim continuously and linearly from maximum electric power and maximum light output to minimum electric power and minimum light output as the daylight illuminance increases, the lights are switched off completely when the minimum dimming point is reached. For artificial lighting On/Off control, the lights are either switched on completely or switched off completely. The On/Off status of the artificial lighting was determined based on the simulation result of daylight autonomy (DA), which was defined as 'the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylit alone' [27]. Then the artificial lighting consumption for On/Off control was calculated based on the total artificial lighting power, the daylight autonomy, and the total occupied hours of the factory. The mathematical expression can be expressed as follows:

$$Elec = P_{total} \times h_{total} \times (1 - DA) \tag{1}$$

Where Elec (kWh) is the electricity consumption by artificial lighting for the On/Off control; P_{total} (kW) is the total artificial lighting power of the factory; h_{total} (h) is the total occupied hours of the factory; DA is the daylight autonomy, which is calculated as follows:

$$DA = h_{DA} / h_{total} \tag{2}$$

Where h_{DA} (h) is the total hours when a minimum illuminance threshold is met by daylit alone, which is calculated through the numerical simulation.

The target illuminance of the work plane (0.75m above the floor) was 300 lux. The lighting power density of the factory is 11W/m^2. The simulation was carried out for a whole year (24 hours on weekdays, 6240 hours per year in total). For evaluating the energy saving potential of daylighting, the benchmark of energy consumption was set as 1713.3Mwh, which was the total artificial lighting consumption of the year when all the lamps turned on during the whole working time.

For the calculation of heating energy consumption, the indoor design temperature was set as 18℃ and the thermal conductivities of the walls, windows, roof and ground were set as 0.35, 2.0, 0.35 and 0.56 ($W/m^2 \cdot K$), respectively, according to the design specification. The operation schedule of heating system was set as 24 hours on weekdays during the heating period. Our calculation assumed that the infiltration of the factory was 0.5ACH (the air change rate per hour).

3. RESULTS AND DISCUSSIONS

3.1 Experimental results

Fig. 4 shows the outdoor illuminance level on the measurement day. The outdoor illuminance increased gradually from 9:00 to 12:00 and reached the maximum of 1×10^5 lux at 12:00. Then the outdoor illuminance remained stable from 13:00 to 15:00, and decayed rapidly from 15:00 to the lowest value of less than 6×10^4 lux at 16:30.

Tecplot Focus 2009 was used to generate the indoor daylighting illuminance contours with the measurement data. Fig. 5 shows the measured indoor daylighting illuminance distribution during the four time periods. The areas that could not be measured were shown as blank in the figures. During 9:00-10:30, the average indoor illuminance was 373lux, while the outdoor illuminance was 88,400lux. The daylighting was mainly from the top daylighting panels and top vertical skylight on the roof, as indicated by the indoor strip light spots in y directions. With the increase of the outdoor illuminance, the average indoor illuminance increased during 11:00-12:30 to about 397lux. During 13:00-14:30, although the outdoor illuminance was a little bit lower, the indoor daylighting environment was still not bad; the average indoor illuminance was 360lux. After 15:00, the outdoor illuminance decayed rapidly which led to a rapid decrease of the indoor illuminance (the average indoor illuminance was 254lux).

Fig. 6 depicts the measured illuminance distributions during the four measurement periods. The first three measurement periods have similar illuminance distributions. The illuminance for more than 80% of the factory area was above 200lux; while after 15:00, the percentage reduced to just approximately 40%.

According to the Chinese lighting design standard of the buildings (GB50034-2004) [25], the work plane illuminance requirement of different process techniques are different. Table 3 summarizes the illuminance levels for different functional zones and corresponding standard requirements. During the four measurement periods, the percentage of illuminance above the standard level were 46.4%, 63.3%, 59.6%, and 33.3%, respectively. It means that at least the illuminance of more than 33.3% of the factory area can meet the requirement of GB50034-2004 during the daytime just by daylighting, which indicates significant energy saving potential by using daylighting.

3.2 Illuminance simulation results

The indoor daylighting performance of the factory was simulated and compared with the experimental data. Fig. 7 shows the simulated daylighting illuminance distributions during the period of 11:00-12:30. The illuminance distributions were pretty constant during this time period and the illuminance in most areas was above 200lux, which indicated good daylighting performance in the factory.

For quantitative comparison between the measured and simulated results, the similarity coefficient [28] was defined as:

$$SIM_{ij} = \frac{\sum_{k=1}^{m} x_{ik} x_{jk}}{\sqrt{\sum_{k=1}^{m} x_{ik}^2 \sum_{k=1}^{m} x_{jk}^2}} \tag{2}$$

Where, SIM_{ij} is the similarity coefficient; i and j represent the experiment and simulation images, respectively; k is the index of sample points; x is the illuminance of sample points. The value of SIM_{ij} is between [-1, 1], $SIM_{ij} = 1$ represents the two images are most similar, while $SIM_{ij} = -1$ represents the two images do not match at all.

As shown in Table 4, all the similarity coefficients at the four time points were similar and close to 1, which means a good match between the measurement and the simulation results. The maximum similarity coefficient was 0.90 at 11:00. The results could validate the experimental method used in this study: the experimental method and procedure is applicable and accurate enough for the measurement of daylighting performance in large space buildings. Also the good agreement between the measurement and the simulation results in the indoor daylighting illuminance distribution indicated that the numerical simulation was correct in predicting the indoor daylighting illuminance distribution.

For further comparison between the measurement and the simulation results, we compared the illuminance values of positions on Line1 and Line2 (in Fig. 3). The data in Fig. 5b and Fig. 7a were used for the comparison, and the comparison along the lines was plotted in Figure 8. The relative error (RE) between the measurement and the simulation results was calculated as:

$$RE = \left| (MI-SI)/MI \right| \times 100\% \tag{3}$$

Where, MI is the measured illuminance value at each measurement point and SI is the corresponding simulated illuminance value. As shown in Fig. 8, the RE values for most of the measurement points were below 20%. The maximum RE value was 44% and the minimum RE value was 0.9%. The RE was considered to be acceptable as the errors might be caused by the following reasons: (1) The measurement results represented the overall daylighting performance during the 1.5 hours measurement period, while the simulation results were only for the simulated moment; (2) The material reflectance and the visible transmittance used in the simulation might have some difference with the reality; (3) The sky condition might be different between the measurement and the simulation.

3.3 Energy consumption simulation results

The energy consumption of the factory was simulated, and the energy saving potential by using daylighting and the effect of reducing artificial lighting on the heating consumption were analysed.

Fig. 9 shows the daylight autonomy of the ten illuminance reference points with or without the top daylighting panels. It indicated that with the top daylighting panels, for 32.5%-37.7% of the total working time of the whole year, a minimum illuminance threshold (300lux) for the work plane could be satisfied by daylighting alone. While the satisfactory time reduced to 11.3-23.8% without the top daylighting panels. This difference indicated that the designed top daylighting panels were very effective in introducing daylight into the factory and improving the indoor lighting environment. As shown in Table 5, the energy saving potential with the top daylighting panels was higher than without the top daylighting panels. And the two lighting control strategies with the top daylighting panels had similar energy saving potential. On the other hand, when there were no top daylighting panels, the dimming control method performed much better than the On/Off control method. It demonstrated that different lighting control strategies could have little influence on the artificial lighting consumption when the building already had a good daylighting design. In addition, the daylight autonomy values at different reference points were not consistent (see Fig. 9) and different production processes also required different illuminance levels (see Table 3). Thus, the artificial lighting controlled based on production process may be a better way for the energy saving designs of industrial buildings.

Contrarily, as shown in Table 6, the heating load increased with the reduction of artificial lighting. For the case of with the top daylighting panels, the heating consumption increase for the On/Off control was slightly lower than for the dimming control, and the difference value was 25.7MWh (account for 22.4% of the On/Off control). While for the case of without top daylighting panels, there was an enormous difference between the heating consumption increase for the two artificial lighting control strategies, the difference value was 85.3MWh (nearly three times of the On/Off control). Either way, the heating consumption increases were much lower than the electricity saving of reducing artificial lighting.

4. CONCLUSIONS

This study investigated the indoor illuminance distribution caused by daylighting in a large space industrial building by both experimental measurements and numerical simulations. The measurement results showed that the average daylighting illuminance during the four measurement periods, 9:00-10:30, 11:00-12:30, 13:00-14:30, 15:00-16:30, were 373lux, 397lux, 360lux, 254lux, respectively. More than 33.3% of the factory area could meet the standard requirements for work spaces on the sunny day. The simulated distributions of daylighting illuminance agreed well with the measured data. The experimental method presented in this study was proved and could be used for the measurement of daylighting illuminance distribution in large space buildings.

The quantitative electricity saving potential of daylighting and the effect of reducing artificial lighting on the heating consumption were simulated using EnergyPlus. It showed that the heating consumption increased with the reduction of artificial lighting. The electricity saving potential of the On/Off control and the dimming control integrated with daylighting were 36.1% and 41.5% for the present daylighting design, while the increase of the heating consumption due to the On/Off control and the dimming control were 7.1% and 8.7%, respectively. Either way, the heating consumption increases were much lower than the electricity saving of reducing artificial lighting. As a whole, the dimming control integrated with daylighting has a greater energy saving potential than the On/Off control for industrial building.

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Figure Captions

Fig.1 Structure and fenestration of the building: (a) Schematic view, (b) Top view, (c) Side view

Fig. 2 The energy (electricity) consumption of the elevator factory in 2009

Fig.3 The distribution of measurement points

Fig.4 The outdoor illuminance on Apr.4, 2011

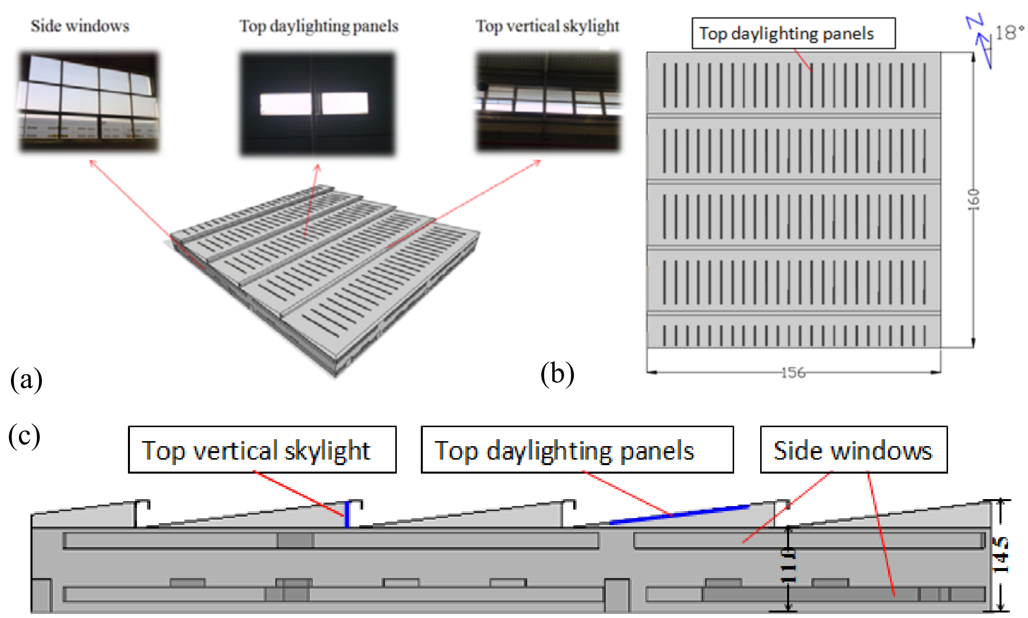
Fig.5 The measured daylighting illuminance distribution on Apr.4, 2011: (a) 9:00-10:30, (b) 11:00-11:30, (c) 13:00-14:30 and (d) 15:00-16:30

Fig.6 The illuminance distribution of the measured points in the four time periods on Apr.4, 2011

Fig.7 The simulated daylighting illuminance distribution on Apr.4, 2011: (a) 11:00, (b) 11:30, (c) 12:00 and (d) 12:30

Fig.8 The comparison of measurement and simulation results for Line 1 and Line 2

Fig.9 The simulated daylight autonomy of the ten illuminance reference points



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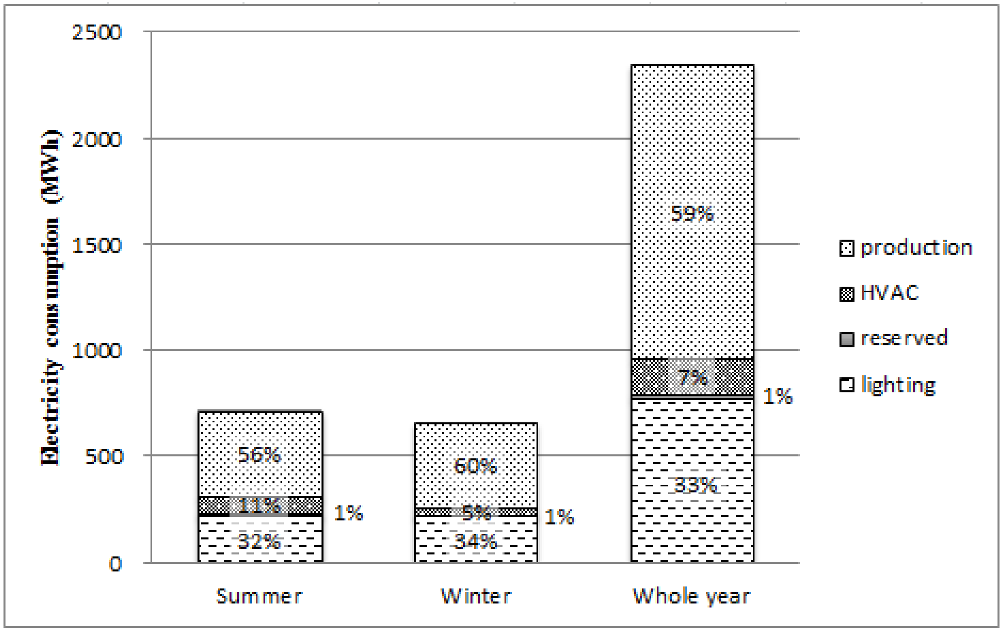

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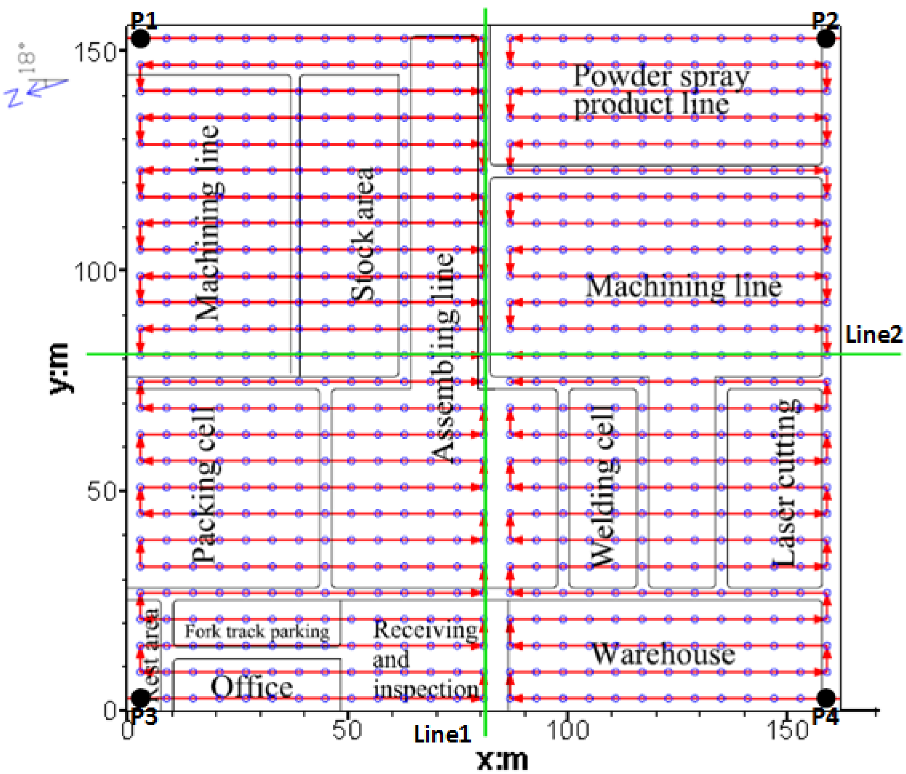


Fig.3 The distribution of measurement points

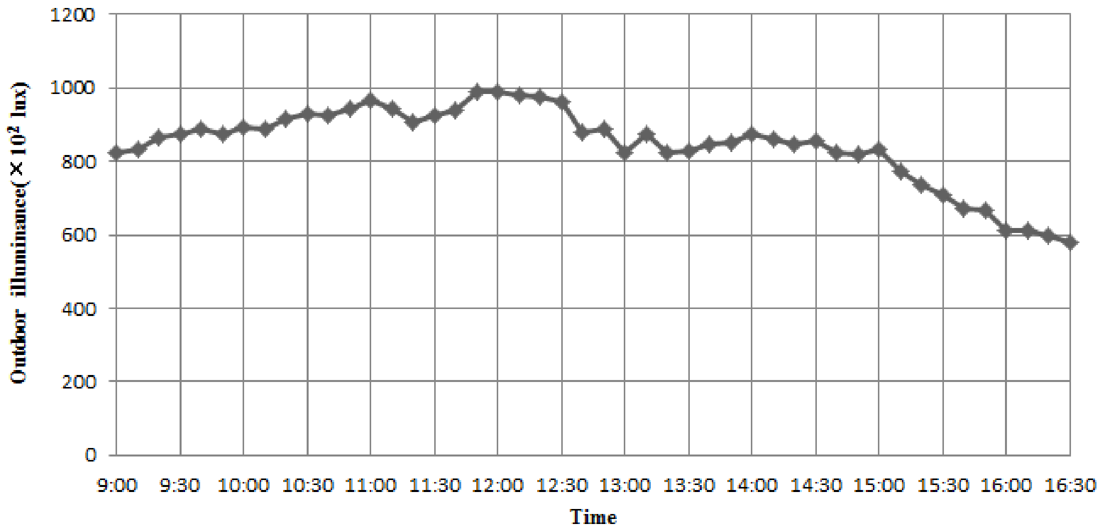


Fig.4 The outdoor illuminance on Apr.4, 2011

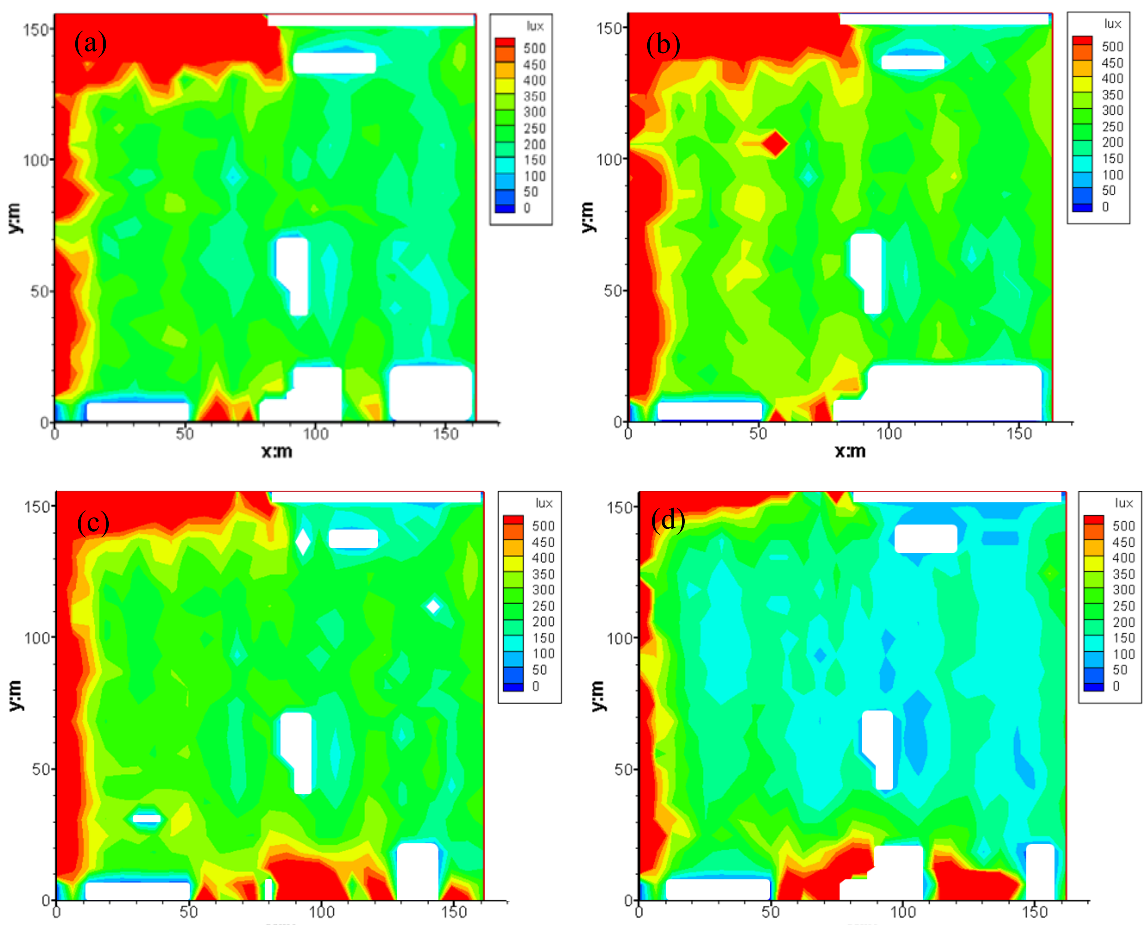


Fig.5 The measured daylighting illuminance distribution on Apr.4, 2011: (a) 9:00-10:30, (b) 11:00-11:30, (c) 13:00-14:30 and (d) 15:00-16:30

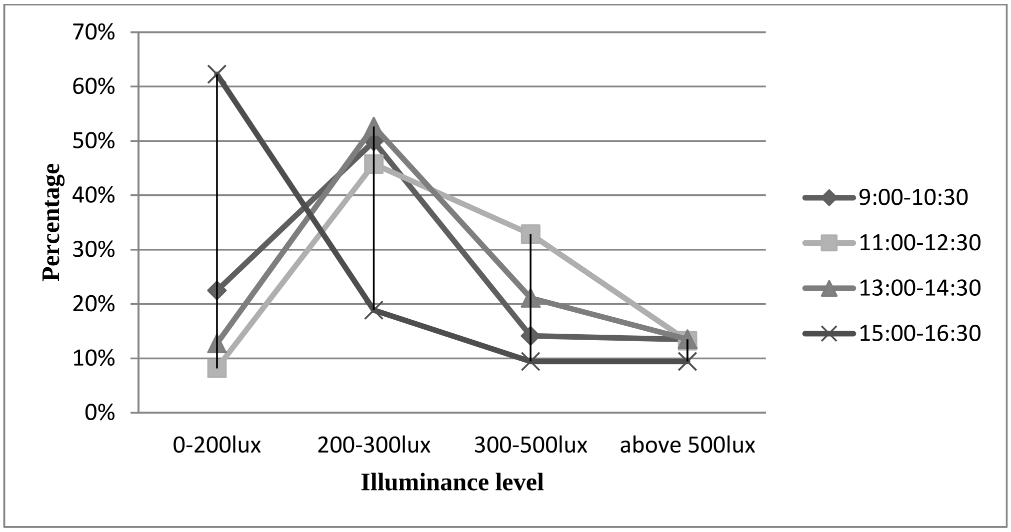


Fig.6 The illuminance distribution of the measured points in the four time periods on Apr.4, 2011

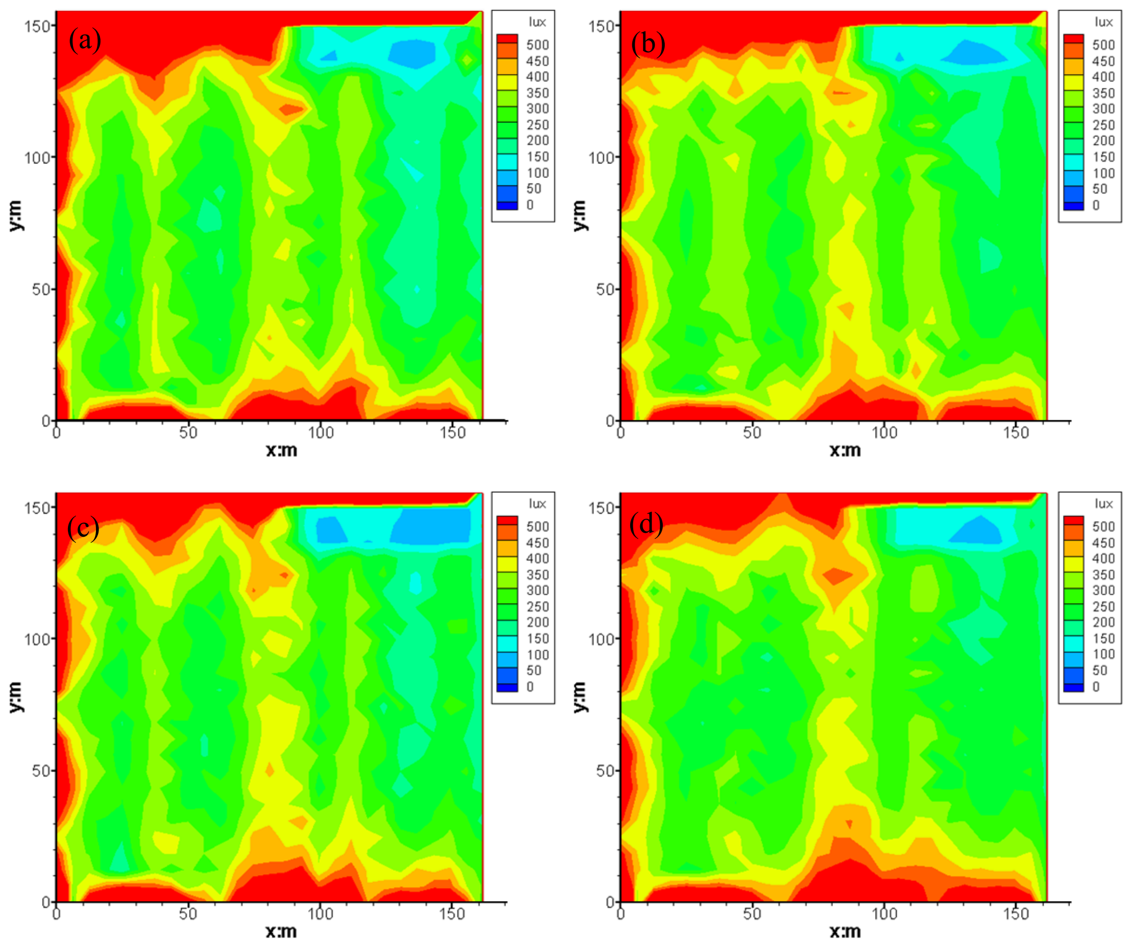
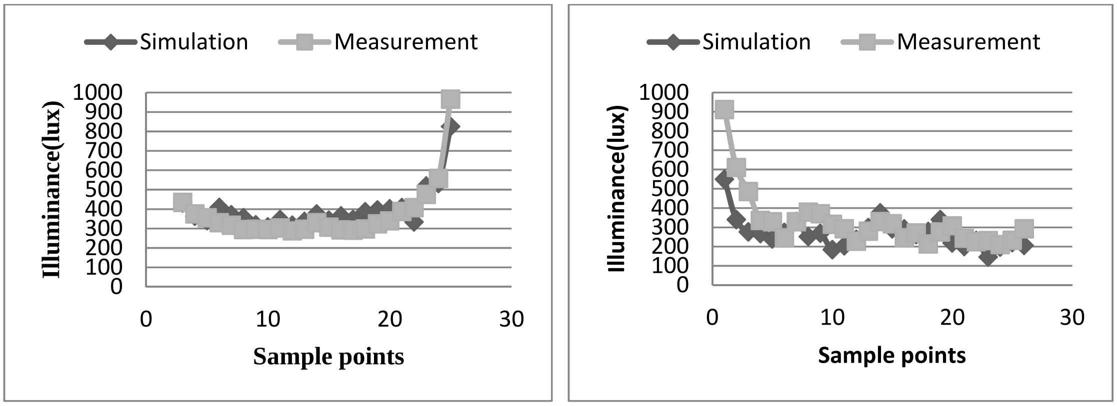


Fig.7 The simulated daylighting illuminance distribution on Apr.4, 2011: (a) 11:00, (b) 11:30, (c) 12:00 and (d) 12:30



(a) Line 1 (b) Line 2

Fig.8 The comparison of measurement and simulation results for Line 1 and Line 2

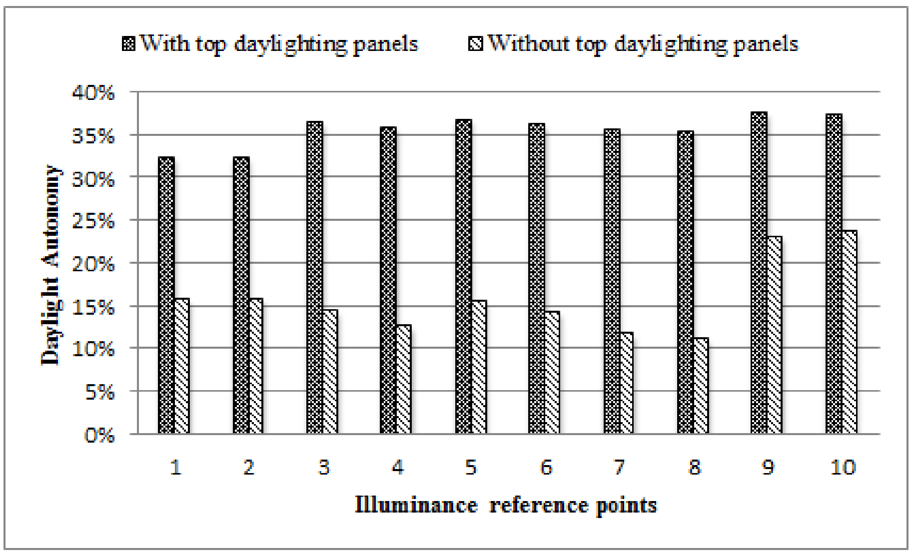


Fig.9 The simulated daylight autonomy of the ten illuminance reference points

Table 1

Window to wall ratio (WWR) and skylight to roof ratio (SRR)

Orientations	North	East	South	West	Roof
WWR/SRR	37.5	31.1	0	29.1	8.2

Table 2

Parameters used for the illuminance simulation

	Reflectance*[1]		Visible transmittance*[2]
Floor	35%	Daylighting panel	25%
Interior wall	70%	Side window	45%
Ceiling	80%	Top vertical skylight	45%

*[1]These values determined with the reference of corresponding Chinese lighting design standard of the buildings (GB50034-2004); *[2]These values determined with the reference of corresponding design specification provided by the designer.

Table 3
The illuminance distributions of the measured points in each work area

Work area	Illuminance range (lux)				Illuminance above the standard level				Standard level of GB50034 -2004 (lux)
	9:00-10:30	11:00-12:30	13:00-14:30	15:00-16:30	9:00-10:30	11:00-12:30	13:00-14:30	15:00-16:30	
Warehouse	160-437	193-459	163-1850	86-1630	100%	100%	100%	93.3%	100
Fork track parking	205-373	211-376	245-402	186-325	100%	100%	100%	100%	100
Stock area	211-1280	273-1096	227-561	139-315	100%	100%	100%	100%	100
Receiving and inspection	219-1281	263-895	270-1142	215-1925	65.0%	90.0%	90.0%	90.0%	300
Packing cell	177-1237	253-1505	244-1232	162-1148	95.9%	100%	100%	65.3%	200
Assembling line	94-467	110-666	127-487	64-308	76.4%	97.2%	87.5%	22.2%	200
Welding cell	105-233	141-257	135-262	74-220	42.9%	64.3%	50.0%	7.2%	200
Laser cutting	112-232	147-271	120-296	88-191	28.6%	52.4%	61.9%	0%	200
Machining line	120-1324	117-1294	127-1382	73-1035	27.7%	49.1%	30.1%	12.7%	300
Power spray product line	95-503	118-476	95-381	56-308	14.5%	23.6%	12.7%	1.8%	300

Table 4
The similarity coefficient between measured and simulated illuminance during 11:00~12:30(Fig. 5b and Fig. 7a-d)

Time points	11:00	11:30	12:00	12:30
SIM_{ij}	0.90	0.89	0.86	0.84

Table 5
The electric lighting consumption for different lighting control strategies integrated with daylighting.

Parameter	With top daylighting panels		Without top daylighting panels	
	On/Off control	Dimming control	On/Off control	Dimming control
Electricity consumption (MWh)	1094.5	1002.7	1439.9	1121.1
Electricity saving (MWh)	618.8	710.6	273.4	592.2
Energy saving potential (%)	36.1	41.5	16.0	34.6

Table 6
The heating consumption for different lighting control strategies integrated with daylighting.

Parameter	With top daylighting panels			Without top daylighting panels		
	Benchmark	On/Off control	Dimming control	Benchmark	On/Off control	Dimming control
Heating consumption (MWh)	1611.3	1726.1	1751.7	1369.8	1399.6	1484.9
Heating consumption increase(MWh)	_	114.7	140.4	_	29.8	115.1
Increasing proportion (%)	_	7.1%	8.7%	_	2.2%	8.4%