The performance and energy saving potential of daylighting for an industrial building in Tianjin

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SUMMARY
It is important to predict the performance and energy saving potential of industrial buildings with electric lighting controls integrated with daylighting. This study presents the impacts of daylighting on the indoor environment and the energy saving potential of an industrial building in Tianjin, China, which is an elevator assemble factory. We simulated numerically indoor daylighting environment with Ecotect and Desktop Radiance and energy consumption with DesignBuilder and EnergyPlus. It has been found that the lowest indoor illuminance due to daylighting was 90 lux under a CIE overcast sky and 300 lux under a CIE clear sky. The electric lighting energy saving potential was 39.4% by using On/Off control integrated with daylighting. The largest potential could be 43.1% by using dimming control integrated with daylighting. The numerical simulation method can be used in predicting energy saving potential of industrial buildings and the use of skylight can improve indoor lighting environment and reduce the electricity consumption of artificial lighting effectively.

KEYWORDS
Industrial building, daylighting, energy saving potential, simulation, lighting control

1 INTRODUCTION
Rational use of daylighting can not only improve the visual comfort of the indoor environment, but also reduce energy consumption effectively in buildings. People desire good natural lighting in their living and working environments (Li and Lam, 2003). It has been proved that good daylighting can provide both a more pleasant and attractive indoor environment that can contributes to higher productivity and performance (Plympton et al. 2000). Electric lighting is one of the major electricity consuming parts in many non-residential buildings. It was found that artificial lighting consuming about 25-40% of the total electrical energy consumption for a typical US commercial building (Kharti, 2000) and about 20-35% of the total building electricity consumption for office buildings in Hong Kong (Lam et al. 2003). As the cost of energy continues to rise, increasing effort has gone into minimizing the energy consumption of lighting installations. Recently, there has been an increasing interest in the study of incorporating daylighting in architectural and building designs to save building energy consumption (Li and Lam, 2001; Atif and Galasiu, 2003). A variety of results have indicated that proper lighting controls integrated with daylighting have a strong potential for reducing energy consumption in non-residential building. Opdal and Brekke (1995) found that the energy saving potential by the utilization of daylighting of about 30% using the constant lighting system based on field measurements, while the simulation of the same offices and systems resulted in a saving potential of just over 40%. Embrechts and Van Bellegem (1997) revealed that an individual lighting dimming control system can offer 20-40% of lighting consumption savings. Li et al. (2006) found that energy savings in electric lighting were over 30% under the high frequency dimming control in the tested office. Also,
Ihm et al. (2009) compared measurements and simulated results and noticed that an annual energy use savings of up to 60% associated with lighting can be achieved using dimming control strategy. These indicate that the use of electric lighting controls integrated with daylighting can achieve 20-60% of lighting consumption savings.

However, the present studies are mainly concentrated on public buildings. There has been very little work on predicting energy saving potential of industrial buildings with electric lighting controls integrated with daylighting for the lack of an efficient method. Industrial buildings which are usually large space buildings with intensive energy consumption, high indoor environment quality requirements. An evaluation of the building performance and the effectiveness of the daylighting design strategies will create valuable knowledge and lessons to directly inform the design of similar buildings in the future. This study based on an industrial building case which is an elevator assemble factory in Tianjin of China. The factory has a complex fenestration and the electrical power consumption of lighting was about 30% of the total electricity consumption there. The objective of this research was to obtain the potential savings in power and energy which can be achieved through the integration of natural daylight and artificial lighting by means of numerical simulation. Additionally, we analyzed the impact of daylighting on the indoor environment.

2 METHODS
2.1 Simulation approach and building models
The elevator factory is located in Binhai Development District, Tianjin, China, (39.08°N,117.07°W), which covers an area of 156×160 m² and has a highest ceiling height of 14.5m and a lowest ceiling height of 11.0m. To predict the energy saving potential of the factory: Firstly, we simulated numerically indoor daylighting environment with Ecotect and Desktop Radiance to find whether there has the possibility of energy saving potential of the factory with daylighting; Then we simulated the factory energy consumption with DesignBuilder and EnergyPlus to get quantitative energy saving potential of the factory with electric lighting controls integrated with daylighting. Figure 1 summarizes the overall simulation approach and Figure 2 shows the building models used for simulation. The daylighting simulation was carried out using Desktop Radiance and the daylighting model was built and the results were visualized in Autodesk Ecotec. The energy simulation model was built in DesignBuilder and run using EnergyPlus.

![Figure 1. Daylighting and lighting energy consumption simulation approach](image)
2.2 Simulation conditions setting
In general, the time when the effect of natural light is best is noon of sunny summer day, while the worst effect of natural light is the morning or nightfall of cloudy winter day. Therefore, the time of indoor daylighting simulation were set as follow: CIE clear sky on June 22\textsuperscript{nd} (summer solstice) at 12 a.m. and CIE overcast sky on December 22\textsuperscript{nd} (winter solstice) at 9 a.m. The two days represent the most favorable and most unfavorable sky conditions, respectively. The reflectance of floor, interior wall and ceiling were set up as 30\%, 70\% and 80\%, respectively. And the visible transmittance of the side windows and skylight were set up as 60\% and 36\%, respectively.

For the simulation of electric lighting energy savings, the space was divided into ten parts (shown in Figure 3) and a illuminance reference point was set in the middle of every part to control the lamps of the part. The lighting control type was continuous/off (EnergyPlus
Documentation, 2010) a kind of continuous dimming control. All illuminance reference points detected and reflected illuminance of the work plane to provide a ‘close loop’ control dimming system. The target work plane illuminance was 300 lux (GB, 2004) and the plane was 0.75m above from the floor. The lighting power density of the factory is 11W/m². The space is occupied on weekdays for 24 hours.

3 RESULTS
3.1 Indoor daylighting environment under typical conditions

Figure 4 presents the indoor daylighting illuminance distribution of the factory under two kinds of typical conditions: CIE clear sky on June 22nd at 12 a.m. and CIE overcast sky on December 22nd at 9 a.m. It indicates that on sunny summer solstice, the illuminance of the yellow area can reach 10000lux, which is due to direct sunlight. The illuminance of the purple area around the skylight is between 600-800lux, and the blue area is also over 300lux. While on the cloudy winter solstice, only the illuminance of the yellow area near to the side window and the red area are over 300lux. However, the illuminance of the middle blue area is between 90-300lux. And the average indoor illuminances are 4295lux and 465lux, respectively.

Figure 4. The indoor daylighting environment of the factory under typical conditions. a) The illuminance distribution under a CIE clear sky on June 22nd at 12 a.m, b) The illuminance distribution under a CIE overcast sky on December 22nd at 9 a.m.

The two typical conditions represent the best and worst light climate through the whole year. Therefore, the indoor illuminance of the factory should be between the two extremes under natural lighting conditions. Hence the lowest illuminance of the factory under the skylight can reach 90lux and the maximum illuminance can reach 10000lux under natural lighting conditions. Sun glare and visual discomfort may occur for the latter, and some protective measures should be taken. But for the former, artificial lighting are needed to meet the target illuminance of the work plane. These are signs that the use of skylight can improve indoor daylighting environment effectively and there has energy saving potential for the factory by the use of daylighting.

3.2 Energy saving potential of daylighting

For comparison, we also simulated the energy saving potential of daylighting for the factory without skylight on the roof. Table 1 shows the daylight autonomy of the ten illuminance
reference points when the factory with or without skylight. Daylight autonomy is defined as ‘the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylit alone’ (Association Suisse des Electriciens, 1989). It indicates that 36.9%-40.4% and 11.3%-23.8% of the working time, a minimum illuminance threshold (300lux) for the work plane is met by daylit alone, for the factory with or without skylight, respectively. As shown in Table 2, the electric lighting energy consumption for dimming control integrated with daylighting are 974.9Mwh and 1121.1Mwh when the factory with or without skylight, and the electric lighting energy savings are 43.1% and 34.6% respectively. The electric lighting consumption for On/Off control integrated with daylighting are 1038.3Mwh and 1439.9Mwh when the factory with or without skylight, and the electric lighting energy savings are 39.4% and 16.0% respectively. Therefore we can conclude that rational use of daylighting can reduce the electricity consumption effectively and the dimming control has greater energy saving potential compared with On/Off control.

Table 1. The daylight autonomy of the ten illuminance reference points. (The total working times of the year are 6240 hours)

<table>
<thead>
<tr>
<th>Illuminance reference point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>With skylight (%)</td>
<td>36.9</td>
<td>37.0</td>
<td>39.8</td>
<td>39.2</td>
<td>40.0</td>
</tr>
<tr>
<td>Without skylight (%)</td>
<td>15.8</td>
<td>16.0</td>
<td>14.6</td>
<td>12.8</td>
<td>15.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Illuminance reference point</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>With skylight (%)</td>
<td>39.5</td>
<td>39.3</td>
<td>39.0</td>
<td>40.4</td>
<td>40.1</td>
</tr>
<tr>
<td>Without skylight (%)</td>
<td>14.5</td>
<td>11.8</td>
<td>11.3</td>
<td>23.2</td>
<td>23.8</td>
</tr>
</tbody>
</table>

Table 2. The electric lighting consumption for different lighting controls integrated with daylighting. (The total electric lighting consumption of the year was 1713.3Mwh when the lamps always being turned on during working time)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>With skylight</th>
<th>Without skylight</th>
</tr>
</thead>
<tbody>
<tr>
<td>On/Off control (Mwh)</td>
<td>1038.3</td>
<td>1439.9</td>
</tr>
<tr>
<td>Dimming control (Mwh)</td>
<td>974.9</td>
<td>1121.1</td>
</tr>
</tbody>
</table>

4 DISCUSSION
This study was based on the computer simulations. There were some differences between the real conditions of the factory and the conditions used for the computer simulations. Therefore, more effort should be done to reduce the differences between the real and simulated conditions. The field measurements for the real indoor daylighting environment and electric lighting consumption of the factory are needed. Additionally, daylighting and the reduction of artificial lighting have an influence on the heating, ventilation and air conditioning (HVAC) load. The quantitative relation between them also needs to be researched.

5 CONCLUSIONS
Rational use of daylighting has a significant impact on the indoor lighting environment and the electric lighting energy savings of the factory. It has been found that the reasonable utilizing of skylight can improve indoor lighting environment and reduce the electricity consumption of artificial lighting effectively. The lowest indoor illuminance due to daylighting was 90 lux under a CIE overcast sky on December 22nd at 9 a.m. and 300 lux under a CIE clear sky on June 22nd at 12 a.m. The electric lighting energy saving potential was about 39.4% by using On/Off control integrated with daylighting. The largest potential
could be 43.1% by using dimming control integrated with daylighting. The dimming control has greater energy saving potential than On/Off control.

The numerical simulation method used in this paper can be applied to predict the performance and energy saving potential of industrial buildings with electric lighting controls integrated with daylighting. Additionally, the results of this study can provide some operational and energy performance data, which would be useful and applicable to other industrial buildings with similar architectural designs.

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**6 REFERENCES**


