Ground Factors and Lighting Design in an Urban Area: Daylight Availability and Light Pollution Risk

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Abstract

In urban areas the daylight available to a building directly from the sky may be compromised, and the contribution from reflected daylight can become more significant. The influence of external obstructions and façade configurations has received some attention, but the impact of daylight reflected from the external ground surrounding an urban building has not been widely examined. This study implemented a lighting simulation analysis of the influence of ground reflection configurations on the daylight availability and the light pollution risk in a typical urban courtyard in Beijing, China. Based on the simulated data, some design strategies are suggested to support landscape and lighting design in a similar urban context.

Introduction

The design of lighting has generally been divided into two types in terms of light sources: daylighting and artificial lighting (Tregenza & Loe, 2013). Daylighting is important in buildings for various reasons, including energy savings, enhancing working efficiency and improving human health and well-being (Boyce et. al., 2003). In urban buildings the daylight illuminance received at a vertical window surface consists of two components: direct light from the sun and sky, and indirect light reflected from obstructions and external ground surfaces (Tregenza & Wilson, 2011). Reinhart, 2014) noted that deep plan working areas in a ground floor office with side windows will clearly benefit from ceiling-reflected light, that will distribute daylight towards the back of the office. For ground floor offices, this ceiling-reflected light will mainly come from the light reflected from ground in front of the office window. Thus, a reflective ceiling combined with a reflective ground could be adopted as a design strategy to support daylight utilization in deep plan, ground floor rooms (Reinhart, 2014). This ground effect has previously been observed in atrium buildings (Sharples & Lash, 2007). Several earlier studies (Cole, 1990; Iyer, 1994; Boubekri, 1995) indicated that the improvement of daylighting in the adjoining ground floor could be achieved through increasing the reflectivity of the atrium floor and enlarging the window size. Iyer (1994) pointed out that the edge areas of an atrium floor play a key role in reflecting daylight in to adjoining rooms. Boubekri, (1995) found that increasing the floor reflectance from 0.1 to 0.85 could result in 90% more vertical daylight illuminance for the low level façades of adjoining spaces. Tregenza & Wilson (2011) have highlighted the significance of a bright external surface beneath a window in an urban area. According to the studies discussed above, the ground effect on daylighting has been investigated either within a simple space or under an overcast sky. In current daylighting practice the external ground is generally simplified as a uniform surface with a typical reflectance of around 0.2 (Li et.al, 2014; Reinhart, 2014), even though various ground reflections are available (BSI, 2008). Therefore, more investigation of ground reflection factors could still be required in order to help enhance daylighting design in complicated urban environments dominated by non-overcast sky conditions.

On the other hand, the increase of artificial outdoor lighting at night has created a new environmental problem of light pollution in cities (Falchi et.al, 2011). Light pollution complaints about outdoor lighting can be categorized into three groups: sky glow, light trespass and glare (LRC, 2007; SLL, 2012). Figure 1 illustrates the fundamental ways of lighting pollution from a pole-mounted outdoor luminaire (LRC, 2007). Sky glow, a luminous background of sky at night, is produced by the light either emitted upwards from a luminaire or reflected from the ground. When unwanted spill light enters into a room and illuminates an indoor space, light trespass occurs. Similar to the indoor lighting space, glare from outdoor lighting is also caused by a higher brightness or contrast, which can be uncomfortable or disabling.

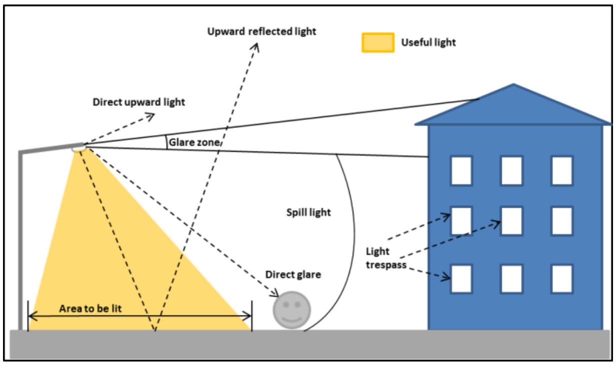

Figure 1: Example of useful light and light pollution from an outdoor luminaire (LRC, 2007) (source: adapted from Institute of Lighting Engineers).

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According to Fig1, only the light cast within the yellow triangular zone can be regarded as useful light. However, the reflected useful light from the ground surface will become a new source of light pollution, contributing to sky glow and light trespass (Cabelloa & Kirschbauma, 2001). The remote sensing images of urban areas at night provide proof of the effect of ground albedo in respect of this issue (Katz & Levin, 2016). Currently, most studies and design strategies relating to light pollution focus on how to reduce the direct upward light from the lighting equipment (lamp and luminaire) (IDA-IES, 2011). This type of light pollution can be effectively controlled via the adjustment of the spatial light distribution of the luminaire. In contrast to the direct light, controlling the reflected light from the ground seems more difficult (Cabelloa & Kirschbauma, 2001). Therefore, it is necessary to carry out more investigations to expose the influence of environmental factors (e.g. ground and building surfaces) on the light pollution risk in cities.

Based on the two ground surface-related aspects of daylight availability and light pollution lighting design, this study presents a simulation study in an urban courtyard in Beijing, China. The impact of various ground surface reflectances and configurations on the daylight availability and light pollution risk were investigated, and several design strategies have been developed to support both landscape and lighting design in urban areas with similar environmental conditions.

Methods

This section includes an urban model and various ground configurations, as well as methods used for the assessment of daylight availability and lighting pollution risk in the model.

Location, urban model and ground configurations

Beijing (39.9167° N, 116.3833° E), a megacity in China, was the location for this study. A 4-sided enclosed square courtyard was selected as a typical building layout in Beijing to be modelled (Figure 2). The courtyard had a plan dimension of 40×40m, and was enclosed by a seven-storey, 21m high building. The courtyard surface was modelled as, in total, 15 ground configurations of bands of different materials. Three typical ground surface materials were used: green grass (reflectance 0.1), grey earth (reflectance 0.25), and white sand (reflectance 0.4) (BSI, 2008). The three materials were set as diffuse surfaces. With a uniform ground surface, the uniform models were labelled U0.1 (green grass), U0.25 (grey earth), and U0.4 (white sand). Based on the mixed grass and sand surfaces the band grounds (see Figure 2) were M2-1 & M2-2 (two bands), M4-1 & M4-2 (four bands), and M8-1 & M8-2 (eight bands). In each band model, the thickness of each black band equalled that of each grey band. Thus, each band model had the same area-weighted average surface reflectance of 0.25. Two groups of band grounds were divided in terms of orientation: horizontal band (long axis: east-west) and vertical band (long axis: north-south). For the horizontal band models, '-1' and '-2' mean the external neighbouring band of the studied room are black and grey respectively. Nevertheless, the vertical band models have the names of '-1' or '-2' depending on the black or grey band bordering with the right adjacent building. In order to focus on the reflection of ground, the reflectance of the external building surface was set as zero.

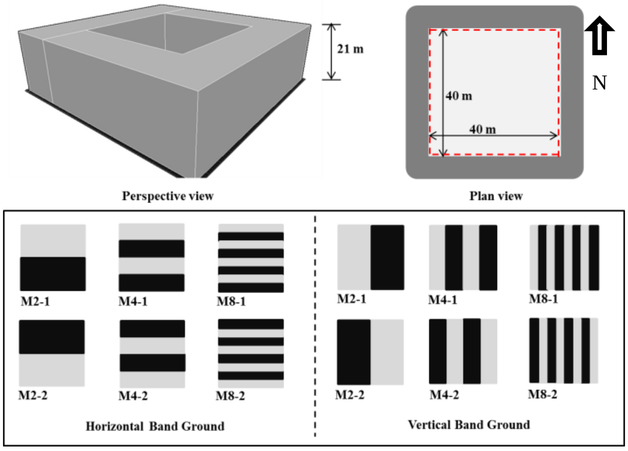

Figure 2: Building model and ground configurations (black band: grass surface; grey band: white sand surface).

Daylight availability

At each adjacent building surface, a room (Figure 3) was used for daylighting analysis, based on a suggestion by Tregenza (1995). The room was vertically placed along the centre of each internal façade (marked with red dash line in the plan view of Figure 2) from the ground floor to the 6th floor. With one side window (8×1.5m) facing the courtyard, the room had a dimension of 8×6×3m. The photometric properties of the room surface were floor reflectance 0.3, wall reflectance 0.6, ceiling reflectance 0.8, and window transmittance 0.8. At the working plane of the room (0.8m above the floor), six positions were studied along the centre line in terms of the distances from the window wall: 0.5m, 1.5m, 2.5m, 3.5m, 4.5m, 5.5m (Figure 3).

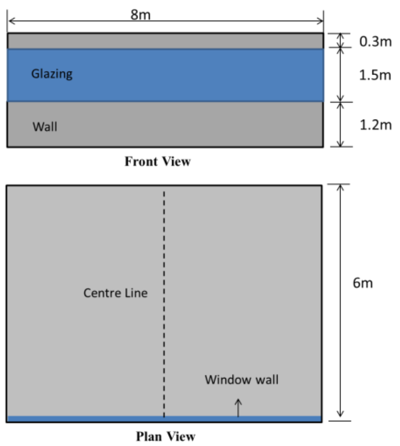

Figure 3: Configurations and dimensions of the room used for the daylighting simulation.

As a climate-based daylight modelling (CBDM) tool (Mardaljevic, 2006), DAYSIM (Reinhart and Herkel, 2000) was adopted here to assess the Daylight Autonomy (DA) in the adjacent buildings under Beijing's climate conditions. Daylight autonomy (DA) is the percentage of the time-in-use that a certain user-defined lux threshold is reached using just daylight. The required indoor illuminance was set at 300 lux (BSI, 2008). For each room on the seven floors the DA was calculated at the six positions using DAYSIM, taking into account the impact of the four room orientations and the ground reflectance configurations (Reinhart et al. 2006).

Artificial lighting and light pollution risk

In this study, five outdoor pole-lightings were evenly distributed in the courtyard to provide the area with lighting at night (Figure 4). One pole-lighting was centrally located (no.1), whilst four pole-lightings were placed along the vertical axis (no.4 & 2) and horizontal axis (no.5 & 3), each at a distance of 10m from the centre pole. All five pole-lightings had a height of 4m above the ground, and this outdoor lighting system produced an average illuminance of 14.3 lux across the courtyard ground.

At night, the building façades surrounding the courtyard would receive direct and reflected light from the artificial lighting system. Such lighting could put the building at risk from urban light pollution (SLL, 2012). In general, the maximum vertical illuminance at building facades should be less than 2 lux after 11pm (SLL, 2012).

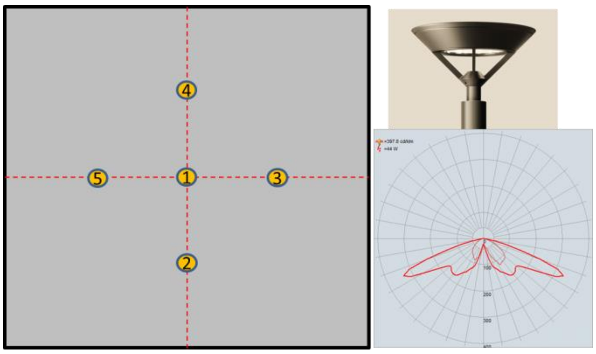

Figure 4: Outdoor artificial lighting layout (right), luminaire and light distribution curve (left) in the courtyard.

Radiance (v3.9), a backward ray-tracing software package, was the simulation tool used to assess the artificial lighting system in this courtyard. In the field of lighting simulation, Radiance has been broadly applied in various spaces to produce quantitative results and photorealistic renderings (Ward & Shakespeare, 1998). In order to simulate artificial lighting this study used a sub program of Radiance, IES2RAD, to convert IES files of the pole luminaires (Figure 4) into Radiance scene descriptions. The vertical illuminances at the internal façades (marked with a red dashed line in Figure 2) from the five pole-lightings were calculated by Radiance along the centre line of each internal façade (Figure 2). Seven calculation positions were selected at heights above the ground of 1.5m, 4.5m, 7.5m, 10.5m, 13.5m, 16.5m and 19.5m.

Ground impact on daylight availability

This section includes the analysis of the 15 ground configurations and daylight availability in the courtyard.

Uniform grounds and orientations

The three uniform ground models were analysed here. According to Figure 2, the adjacent rooms at seven floors had four cardinal orientations: south, north, east and west. Taking the model U0.1 as a reference, the relative average Daylight Autonomy (R_{ADA}) in one room of model U0.25 or U0.4 can be calculated via the following equation:

$$R_{ADA} = \frac{ADA_i - ADA_{U0.1}}{ADA_{U0.1}} \times 100\% \quad (1),$$

where $ADA_{U0.1}$ is the average DA of the six positions in one room with a specific orientation and at a specific floor for model U0.25 or U0.4; ADA_i is the average DA in the same room for model U0.25 or U0.4. Table 1 shows the R_{ADA} values in rooms for the seven floors and the four orientations. According to the variations of R_{ADA} value, increasing ground surface reflectance will increase the average Daylight Autonomy in the adjacent rooms, especially for the lower floors. The increase tends to be lower towards the top floor. In addition, the north facing rooms have the highest R_{ADA} values while the lowest values are found in the south facing rooms. Both east and west facing rooms see values in between. These variations demonstrate that rooms facing north and facing south have the highest and lowest sensitivities to the ground surface respectively. This could be explained by the fact a room facing north mainly receives diffuse light from sky and the reflected sunlight and skylight from the ground, while the direct sunlight and skylight dominate in the south facing rooms. In general, the significant ground impact can be found in the rooms as follows: ground floor to 1st floor (south facing), ground floor to 3rd floor (north facing), ground floor to 2nd floor (east and west facing).

Horizontal band grounds

This part includes models with the horizontal bands of reflectance and uniform ground reflectance. First, the south facing rooms have been analysed. The discussion above meant that only the variations of DA at the ground floor and the first floor have been presented, since only they receive a significant ground impact (see Figure 5). The DA value decreases with the position moving towards the rear of rooms for any ground configuration. From the window to the back wall, in addition, U0.4 has the maximum DA values whilst the lowest DA values were achieved for U0.1. U0.25 and the six horizontal band models show DA values in between U0.4 and U0.1. For the area near a window (distance<2.5m from window), no big differences of DA can be seen between the various models. A clear divergence of DA occurs at the middle area (distance= 2.5m), and then achieves the peak in the back half of the room (distance = 4.5m). Interestingly, the divergence tends to drop towards the back wall. These could well confirm the view of Reinhart, (2014) that the deeper positions receive the daylight reflected from ceiling and external ground and the higher ground reflectance would enhance the daylighting level in a deeper room. Furthermore, the band models have other special variations that are associated with band number and position. Having a black band adjacent to the south facing facade, the band models ('-1' model) will generally achieve lower DA than U0.25 in the middle and back of the room. Conversely, the '-2' band models give rise to higher DA than U0.25, due to a grey adjacent band. Increasing the band number will reduce the DA divergence between band models and U0.25. This could be explained by the reflection of the external ground beneath the window (Tregenza & Wilson, 2011). Since this ground area takes a significant role in reflecting light in to the deeper room, more band numbers will make its area-weighted reflectance approach 0.25. When comparing the DA variations between two floors, it could be clearly seen that the divergences between various models at the ground floor are bigger than those of the first floor.

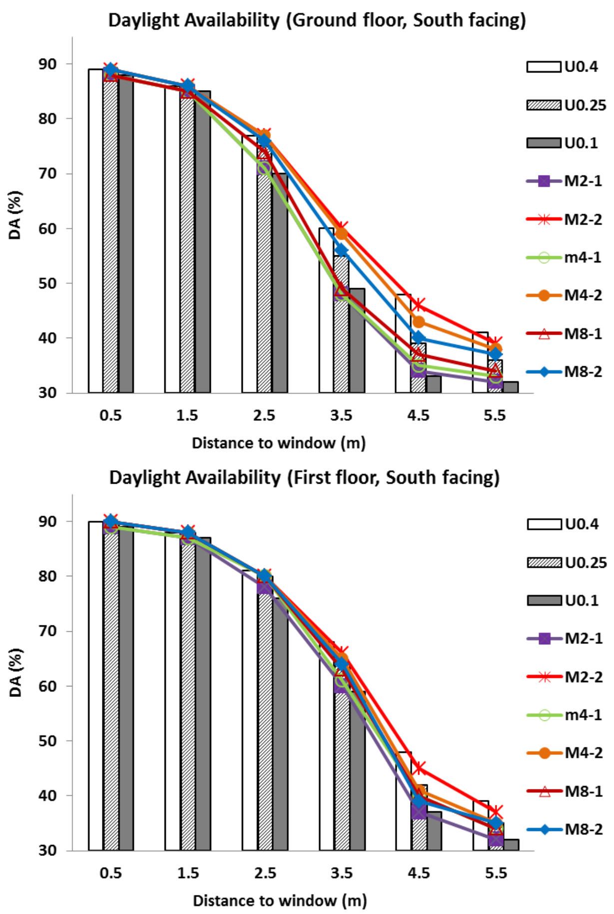

Figure 5: The variations of Daylight Autonomy at six positions in the south facing rooms (uniform and horizontal band grounds, top: ground floor, bottom: first floor).

Second, the north facing rooms have also been assessed. Regarding the analysis in the uniform ground models, a clear impact of ground material can be found from the bottom four floors. Therefore, this part just presents the DA variations of these floors (Figures 6 and 7).

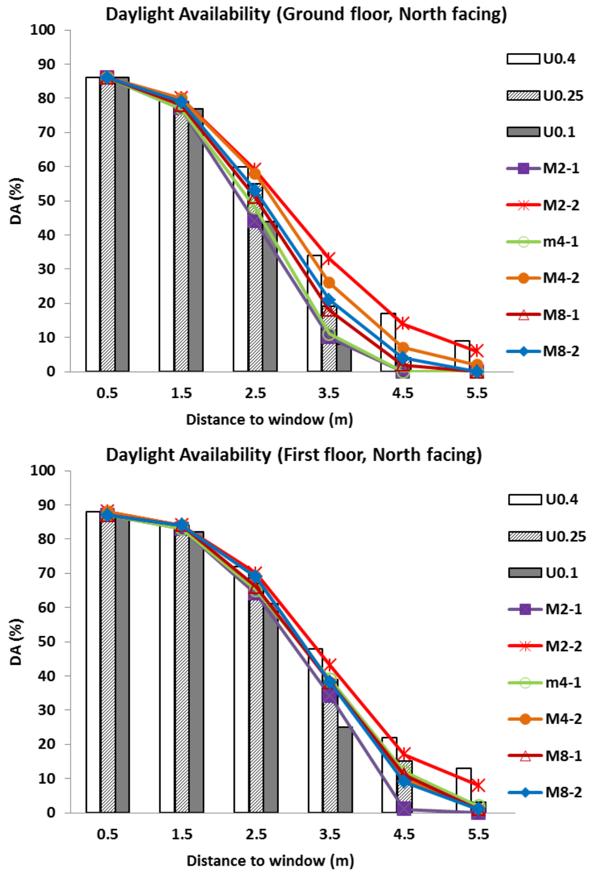

Figure 6: The variations of Daylight Autonomy at six positions in the north facing rooms (uniform and horizontal band grounds, top: ground floor, bottom: first floor).

Figure 6 gives the variations of DA in the north facing rooms with uniform and horizontal band grounds. Compared with the south facing rooms in Figure 5, the north facing rooms have similar general varying trends of DA across the room centre. However, it can be seen that the differences of DA values between front, middle and back areas are much bigger in the north facing rooms. For the average DA of all models at the ground floor, the reduction of DA between position 0.5m and position 4.5) is around 80% in the north facing room while for the south facing room the figure is around 50%. At the first floor, north facing and south facing rooms see reductions of 76% and 48% respectively. For the north facing rooms (Figure 6), the band models have more clear divergences of DA when compared with U0.25. Similarly, the divergences have become lower at the first floor. The highest divergence occurs at the position 3.5m on the ground floor whilst the peak value on the first floor can still be found at the back area (4.5m). In contrast to south-facing rooms, the reflectances and configurations of the ground band make a more clear impact on the DA at the middle and back room areas.

Figure 7 displays the variations of DA of the second floor and the third floor in north facing rooms. Clearly, no big differences of DA are evident in the band models, even though various uniform grounds can still bring in different DA values for the middle and back areas, as shown in Table 1.

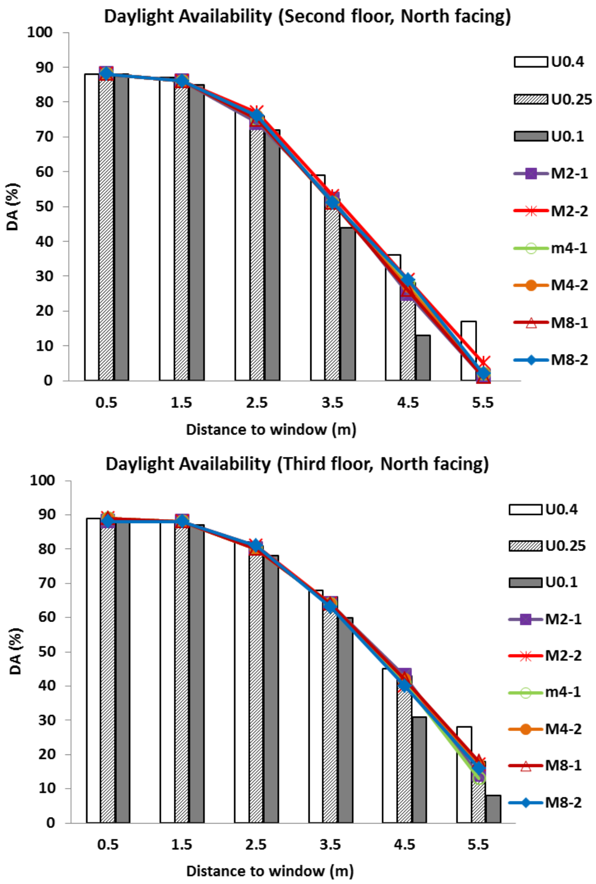

Figure 7: The variations of Daylight Autonomy at six positions in the north facing rooms (uniform and horizontal band grounds, top: second floor, bottom: third floor).

In the north facing rooms, the window area still receives higher daylighting availability due to exposure to the north sky, which can explain the relatively higher DA values at lower floors. Little penetration of direct sunlight will lead to a much lower daylighting in the middle and deeper parts. On the two bottom floors, the deeper room is dominated by the diffuse daylight reflected from the ceiling and ground, which could justify the higher sensitivity of DA variations to the ground configurations. For the second or third floors, moreover, the increased direct skylight would become the main daylighting source and the ground-reflected daylight levels are very small.

Vertical band grounds

This part discusses models with the vertical band (see Figure 2) and uniform ground reflectances.

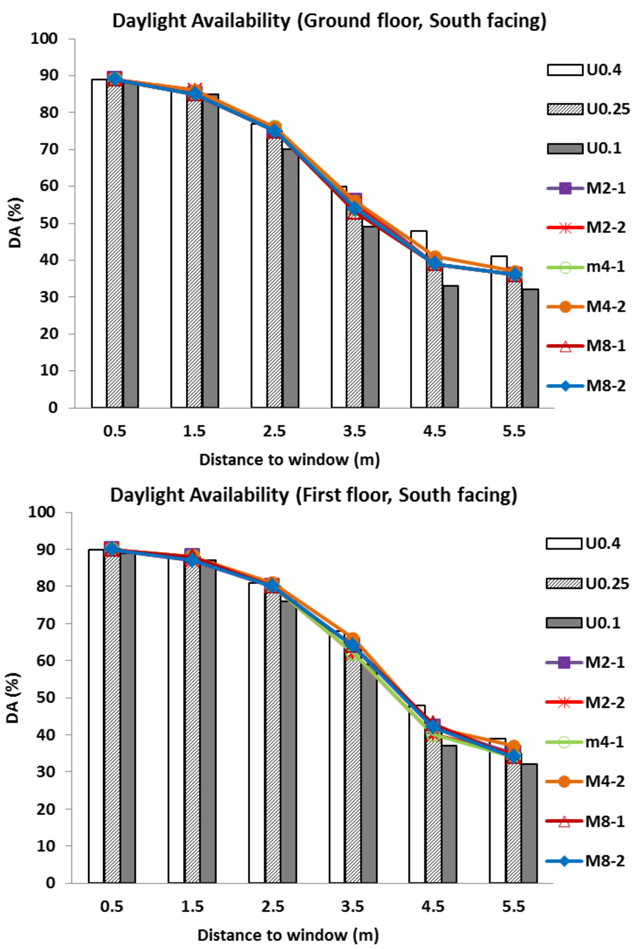

Figure 8: The variations of Daylight Autonomy at six positions in the south facing rooms (uniform and vertical band grounds, top: ground floor, bottom: first floor).

Figures 8 and 9 display the variations of DA at the two bottom floors in the north and south facing rooms respectively. Unlike the varying trends in Figures 5 and 6, the vertical band configurations make little impact on the daylight availability in rooms. In general, the band models achieve similar DA values to U0.25 at any positions for both north and south facing rooms. Since the vertical band configurations will not change the area-weighted reflectance of the zone (i.e. 0.25), there will be no significant differences between band models and the uniform ground reflectance U0.25.

In terms of the discussions above, a highly reflected ground near buildings will enhance the indoor daylight availability. On the other hand, this design strategy should be cautiously applied, since it will also increase the glare risk for the occupants sitting near the window.

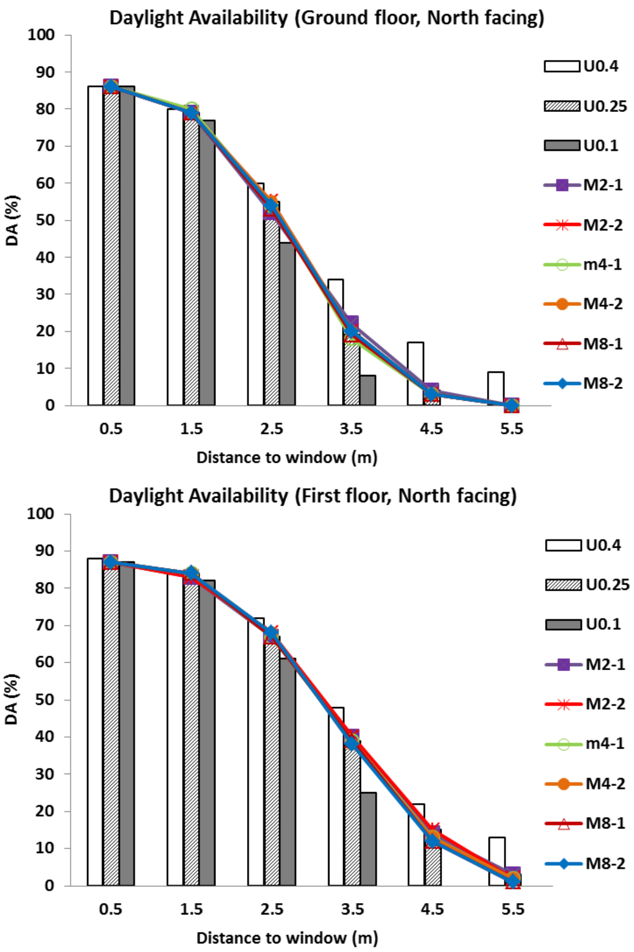

Figure 9: The variations of Daylight Autonomy at six positions in the north facing rooms (uniform and vertical band grounds, top: ground floor, bottom: first floor).

Ground impact on light pollution risk

According to the layout in Figure 4, orientation will not take clear effect on the lighting level from the artificial lighting system. Thus, this study only adopts the south facing façade as a studied case.

With the artificial lighting system (five pole-lightings) used at night, Figure 10 indicates the impact of ground surface reflectances and horizontal band configurations on the vertical illuminances at seven façade positions. Similar to the daylight analysis (see Table 1), the higher ground reflectance will lead to a higher vertical illuminance at the façade. In this courtyard, the higher vertical illuminance means a higher light pollution risk, especially when the illuminance is greater than 2 lux (SLL, 2013). However, the ground effect tends to be attenuated with increasing façade height. The vertical illuminances achieve their maxima at the ground floor and then dramatically drop towards the second floor. Interestingly, no clear variations of vertical illuminance can be found at the area around the middle floor (from 7.5m to 10.5m). When the position is moving up above the middle level facade, vertical illuminances start to decrease again.

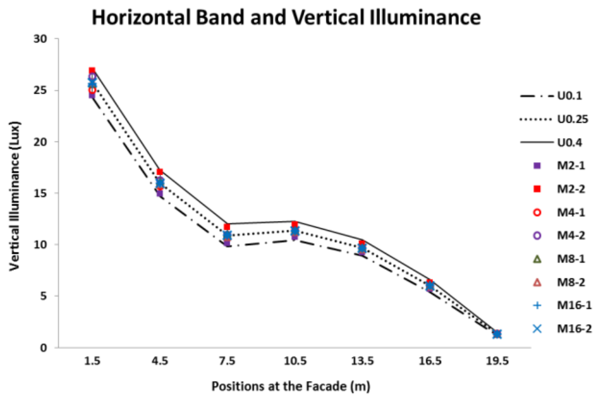

Figure 10: The variations of vertical illuminance at seven façade positions (horizontal band ground).

Based on the average horizontal illuminance across the courtyard floor (14.3 lux), the relative difference of vertical illuminances (R_{VI}) can be calculated by the following:

$$R_{VI} = \frac{VI_i - 14.3}{14.3} \times 100\%, \qquad (2),$$

where VI_i is the vertical illuminance (lux) at various façade positions of all the models. Table 2 gives the R_{VI} values of the uniform and horizontal band models. Apparently, both the ground and first floors receive higher illuminances than the ground surface. The ground floor has the largest impact from the pole-lightings at night, which indicates the highest risk of experiencing light pollution. Compared with U0.1, U0.25 and U0.4 see a 10% and 20% increase of the R_{VI} value at the ground floor respectively. The two values for the first floor are 9% (U0.25) and 18% (U0.4). Increasing the ground reflectance will significantly increase the light pollution risk for the lower part of the building façade. As for the band models, the band configurations clearly affect the variations of R_{VI} values, particularly at the low facade. The '-1' band models will give rise to a lower R_{VI} than U0.25, whilst the '-2' band models result in a higher value. The divergences of R_{VI} between band models and U0.25 tend be smaller with an increasing band number. This means that various ground configurations will create different light pollution risks. Similar to the analysis of daylighting, the areas of ground near the building take a key role in reflecting the light to the low levels of the façade.

Figure 11 demonstrates the variations of vertical illuminances across the façade for uniform and vertical band ground models. Similarly, the relative differences of vertical illuminance are achieved using Equation (2) (see Table 3). The varying vertical band configurations do not have a substantial effect on the vertical illuminances. With the same area-weighted reflectance as U0.25, the building facades for different vertical band models will have the same light pollution risk. This could suggest that the orientation of ground band configurations might be critical with respect to the protection from light pollution in this courtyard.

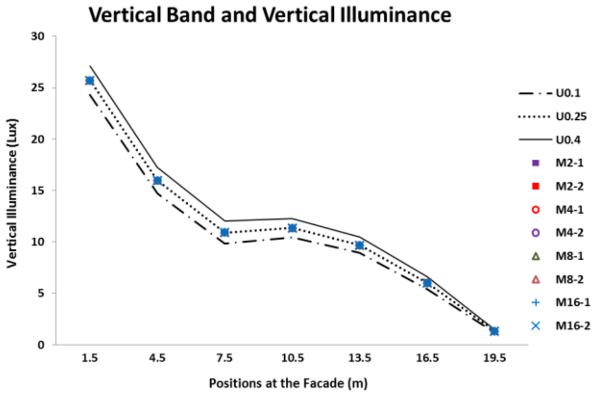

Figure 11: The variations of vertical illuminance at seven façade positions (vertical band ground).

Given the analysis of artificial lighting above, increasing the ground reflectance could possibly increase the vertical illuminance of surrounding builds. In addition, ground configurations will affect the vertical illuminance received at the lower facade. However, this impact might be limited to the ground area near the buildings. This study has found that such a zone has a width of around 5m. Clearly, the size might be associated with properties of the artificial lighting system, such as distance to façade, spatial light distribution, luminaire height, etc. Combined with the analysis of daylighting above, a proper landscape design might need to have a balance between the two different lighting requirements.

Conclusion

This study has presented a simulation analysis of the impact of ground reflectances and configurations on the daylight availability and light pollution risk in a typical urban courtyard in China. Some conclusions that can be drawn from this investigation include:

1) In an urban area, it could be necessary to take into account the ground factors in the process of daylighting/lighting design, due to the fact that the ground surface could make a substantial contribution to the reflected light.

2) The daylight availability in the adjacent rooms of the courtyard building could be improved through increasing the ground surface reflectance, in particular at lower floors. The improvement tends to be negligible towards the top floor. On the other hand, the increase of ground reflectance would also increase the risk of glare problems at the indoor window area.

3) Rooms facing north have the highest sensitivity of daylighting availability to the ground reflectance and band configurations, whilst rooms facing south will receive the least impact of ground reflectance and band configurations.

4) The ground band configuration can influence the daylight availability for rooms of low floors of buildings, as long as the band varies along the normal direction of the façade. The magnitude of the influence could be decided by the average reflectance of a limited ground zone bordering the façade. The increasing band density could decrease this influence. Nevertheless, a variation of ground band configuration along the direction parallel to the façade would not bring in any significant change according to the daylighting availability.

4) Increasing the ground reflectance could significantly increase the risk of light pollution from outdoor artificial lightings at the low and middle levels of building facades.

5) With the occurrence of outdoor artificial lighting, the ground band configuration varying along the façade normal would have a clear impact on the light pollution risk at the ground floor. Similarly, the impact is only associated with a limited neighbouring ground zone by the façade. The varying band configuration horizontally parallel to the façade would not give rise to any big change in terms of this issue.

6) It could be found that the ground configurations might have both positive and negative effects on the lighting environment. Therefore, it would be necessary to find a balance between daylighting, artificial lighting and environmental considerations when planning a landscape plot in a highly dense urban area.

Limitations and future work: these conclusions are obviously limited to simple urban building models and ground materials, one typical outdoor lighting system and a specific location and climate. Other urban models with various architectural configurations, complicated photometric properties of ground materials, and under more complicated conditions of night lightings should be investigated to find the general findings of the relationship between the ground factors, daylighting utilization and light pollution risk. These issues will be studied in future work.

Nomenclature

ADA: average daylight autonomy in the room (%);
BSI: British Standard Institute;
CBDM: climate-based daylight modelling;
DA: daylight autonomy (%);
R_{ADA}: the relative value of ADA of U0.25 or U0.4, taking U0.1 as a reference, (%);
R_{VI}: the relative difference of vertical illuminance (%);
SLL: Society of Light and Lighting (UK);
VI: vertical illuminance (lux).

U0.1: urban model with a ground reflectance of 0.1;
U0.25: urban models with a ground reflectance of 0.25;
U0.4: urban models with a ground reflectance of 0.4;
M2-1&M2-2: urban model with a two-band ground configuration;
M4-1&M4-2: urban model with a four-band ground configuration;
M8-1&M8-2: urban model with an eight-band ground configuration.

References

Boyce, P., Hunter, C. and Howlett, O. (2003). The benefits of daylight through windows. Report of Lighting Research Centre, USA, www.lrc.rpi.edu/programs/daylighting/pdf/Daylight Benefits (retrieval date: Nov 9, 2011).

Boubekri, M. (1995). The effect of the cover and reflective properties of a four sided atrium on the behaviour of light. *Architectural Science Review* 38(3), 3–8.

BSI (2008). Lighting for Buildings – Part 2: Code of Practice for Daylighting. UK: British Standards Institute.

Cabelloa, AJ. and Kirschbauma, CF. (2001). Modeling of Urban Light Pollution: Seasonal and Environmental Influence. *Journal of the Illuminating Engineering Society*. 30, 142-151.

Cole, R. J. (1990). The effect of the surfaces enclosing atria on the daylight in adjacent spaces. *Building and Environment* 25(1), 37–42.

Falchi, F., Cinzano, P., Elvidge, C.D, Keith, D.M., Haim, A. (2011) Limiting the impact of light pollution on human health, environment and stellar visibility. *Journal of Environmental Management* 92(10), 2714-2722.

IDA – IES. (2011). Model lighting ordinance - with useers' guide. http://darksky.org/our-work/public-policy/mlo (retrieval date: July 10, 2015).

Iyer, R.U. (1994). Daylighting in atrium spaces. *Architectural Science Review* 37, 195–208.

Katz,Y. and Levin, N. (2016). Quantifying urban light pollution — a comparison between field measurements and EROS-B imagery. *Remote Sensing of Environment* 177, 65-77.

Li, DHW., Lam, TNT. and Wu, TKK. (2014). Estimation of average daylight factor under obstructed CIE Standard General Skies. *Lighting Research and Technology* 46, 187–97.

LRC (Lighting Research Centre). (2007). Lighting answers: lighting pollution. Troy, New York. USA.

Mardaljevic, J. (2006). Examples of climate-based daylight modelling. CIBSE National Conference 2006: Engineering the Future, London, UK.

Reinhart, C.F. and Herkel, S. (2000). The simulation of annual daylight illuminace distributions – a state-of-the-art comparison of six RADIANCE-based methods. Energy and Buildings 32,167–187.

Reinhart, C.F., Mardaljevic, J. and Rogers, Z. (2006) Dynamic daylight performance metrics for sustainable building design. LEUKOS 3, 7-31.

Reinhart, C. (2014). Daylighting Handbook I: Fundamentals, Designing with the Sun. USA.

Sharples, S. and Lash, D. (2007). Daylight in atrium buildings: a critical review. *Architectural Science Review 50*(4), 301–312.

SLL (Society of Light and Lighting). (2012). Guide to limiting obtrusive light. Lavenham, Suffolk, UK.

Tregenza, P. (1995). Mean daylight illuminance in rooms facing sunlit streets. *Building and Environment* 30, 83-89.

Tregenza, P. and Wilson, M. (2011). Daylighitng: Architecture and Lighting Design. Routledge. London and New York.

Tregenza, P. and Loe, D. (2013). The Design of Lighting. Routledge. London and New York.

Ward G L and Shakespeare R. (1998). Rendering with Radiance: the Art and Science of Lighting Visualization. Morgan Kaufmann Publishers, Inc. San Francisco, California, USA.

Table 1: Relative differences of average daylight autonomy (R_{ADA}, %) between U0.25, U0.4 and U0.1 for the seven floors and with four orientations.

	South Facing		**North Facing**		**East Facing**		**West Facing**	
Models / Floors	**U0.25**	**U0.4**	**U0.25**	**U0.4**	**U0.25**	**U0.4**	**U0.25**	**U0.4**
Ground	6.16	12.32	11.98	32.26	9.57	17.49	10.88	20.00
1st	5.00	8.95	15.23	27.73	9.76	16.57	10.09	16.09
2nd	3.11	5.74	10.26	19.87	7.03	11.72	5.80	11.05
3rd	2.81	4.33	8.88	14.61	3.84	5.87	3.93	7.37
4th	1.20	1.79	3.18	6.85	1.21	3.22	2.02	4.48
5th	0.38	0.57	2.35	3.42	0.75	1.31	1.04	2.30
6th	0.56	0.94	1.01	1.01	0.37	0.55	0.80	1.41

Table 2: Relative differences of illuminance levels (VI_i, %) between the façade positions and the ground surface (uniform and horizontal band ground).

Model / Position	**U0.1**	**U0.25**	**U0.4**	**M2-1**	**M2-2**	**M4-1**	**M4-2**	**M8-1**	**M8-2**	**M16-1**	**M16-2**
1.5m	70.4	80.1	89.7	71.5	88.3	75.4	84.7	79.4	80.3	79.5	80.5
4.5m	2.8	11.9	21.0	4.6	19.2	9.7	14.0	13.0	10.8	11.7	11.9
7.5m	-31.3	-23.6	-15.8	-29.1	-18.2	-24.2	-23.0	-22.6	-24.7	-23.8	-23.6
10.5m	-27.0	-20.6	-14.0	-24.7	-16.5	-20.3	-20.9	-20.0	-21.5	-20.5	-20.5
13.5m	-37.6	-32.3	-26.9	-35.4	-29.5	-31.9	-32.8	-31.9	-33.1	-32.4	-32.5
16.5m	-62.2	-57.9	-53.5	-60.0	-55.9	-57.4	-58.4	-57.5	-58.4	-57.8	-58.1
19.5m	-91.9	-90.8	-89.7	-91.3	-90.3	-90.7	-90.9	-90.7	-90.9	-90.8	-90.8

Table 3: Relative differences of illuminance levels (VI_i, %) between the façade positions and the ground surface (uniform and vertical band ground).

Model / Position	**U0.1**	**U0.25**	**U0.4**	**M2-1**	**M2-2**	**M4-1**	**M4-2**	**M8-1**	**M8-2**	**M16-1**	**M16-2**
1.5m	70.4	80.1	89.7	80.1	79.9	80.0	80.0	80.1	79.9	80.0	79.9
4.5m	2.8	11.9	21.0	11.8	11.8	11.8	11.8	11.8	11.7	11.9	11.8
7.5m	-31.3	-23.6	-15.8	-23.7	-23.6	-23.6	-23.7	-23.7	-23.7	-23.6	-23.6
10.5m	-27.0	-20.6	-14.0	-20.6	-20.6	-20.6	-20.6	-20.6	-20.6	-20.6	-20.6
13.5m	-37.6	-32.3	-26.9	-32.3	-32.4	-32.4	-32.4	-32.3	-32.3	-32.4	-32.4
16.5m	-62.2	-57.9	-53.5	-57.9	-57.9	-57.9	-57.9	-57.9	-57.9	-57.9	-58.2
19.5m	-91.9	-90.8	-89.7	-90.8	-90.8	-90.8	-90.8	-90.8	-90.8	-90.8	-90.9