Optimization of spatial lighting uniformity using non-planar arrays and photosynthetic photon flux density modulation

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Abstract

Planar, regularly spaced arrays of horticultural luminaires exhibit poor spatial uniformity due to a bullseye effect where photosynthetic photon flux density (PPFD) is higher at the canopy interior regions, and lower at the edges and corners. This can lead to uneven plant growth especially in sole-source lighting environments. Two different methods are presented to improve spatial uniformity: non-planar placement of luminaires, and PPFD modulation of individual luminaires in a planar regular array. A non-planar design is computed by an algorithm that models millions of possible layouts and selects the best design according to a statistical measure of uniformity. The algorithm was used to optimize both an HPS-lamp layout and an LED layout in a research greenhouse, with performance verified with PPFD mapping at canopy level.

Keywords: lighting uniformity, photometrics, PPFD modulation

INTRODUCTION

Horticultural luminaires may be used to provide supplemental light in greenhouses or in sole-source lighting applications in plant factories and growth chambers. Nearly all lighting designs in this application space employ regularly spaced planar layouts. This simplifies installation but has one major drawback: these designs exhibit poor spatial uniformity due to a bullseye effect where PPFD is higher at the canopy interior regions, and lower at the edges and corners. This occurs because interior areas are closer to more luminaires compared to areas on the perimeter.

In many commercial greenhouses this effect is diminished because of the sheer size of the building. With properly spaced luminaires, good spatial uniformity can be achieved even with planar designs since the edge effect will only be present on a very small portion of the total canopy area. The effect is also diminished by the presence of natural light for much of the year, as this tends to be more uniform than supplemental light.

In smaller commercial or research greenhouses, or indoor environments, the effect is present on a larger portion of the canopy. This can cause uneven plant growth which may have an impact on sales or data collection. Plant scientists can employ various strategies to mitigate the effect, such as only taking data from plants that receive similar amounts of light, or rotating plants to different positions in an attempt to deliver the same amount of light over time.

A different approach is described in this paper: modify the lighting design to improve spatial uniformity. The hypothesis is if the constraints on regular spacing and planar design are relaxed, a design exhibiting more uniformity can be achieved. In practice this is difficult, because moving even a single luminaire will affect the PPFD at every part of the canopy and changing all positions by trial and error is impractical due to the sheer number of combinations. A potential solution to this problem is presented in the next section.

Previous studies have investigated improving edge uniformity by relaxing the regular spacing constraint while keeping the design planar (Ciolkosz et al., 2001).

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MATERIALS AND METHODS

Photometric data

Photometric data for luminaires is represented in .ies files (IES, 2002) that describe the illuminance distribution. It is difficult to obtain .ies files for horticultural luminaires from manufacturers, in stark contrast to photometric data for luminaires used in commercial human lighting applications, which are freely available on manufacturer websites. An alternative is to have an .ies file created by an independent testing lab for a small fee, which was the method employed for this study. The lab must have a type-C goniophotometer (IES, 2001) in order to create the data set.

Spectral data

In general, .ies files are produced with units suitable for human vision (illuminance), so an additional post-processing step is required to convert the photometric data to photosynthetically active radiation (PAR) units as measured with PPFD (μmol m^{-2} s^{-1}). The conversion factor from lumens to PAR units depends on the spectrum of the luminaire, so a data set from a spectroradiometer is needed. The spectral power distribution is weighted with the photopic luminosity function to derive the conversion factor from illuminance to PAR units.

Photometric calculations

The converted .ies file can be input into any photometric software package, such as AGi32, and a particular layout of luminaires can be simulated in order to create a map of PPFD (photosynthetic photon flux density) at canopy level. In general, this calculation is highly accurate for greenhouse applications, because the distance from luminaire to surface is large compared to the largest dimension of the luminous opening (IES, 2019). Within that limitation, photometric calculations obey the inverse square law (Murdoch, 1981):

$$\mathrm{PPFD} = \frac{I \cos \varphi}{r^2}$$

where r is the distance from luminaire to calculation point, φ is the angle from vertical, and I is the photosynthetic photon flux per solid angle (μmol s^{-1} sr^{-1}) from the .ies file.

But the inverse problem, identifying a layout that optimizes some criteria (uniformity in this case) is not generally a feature available in commercial photometric software. In some cases, commercial photometric software can suggest layouts based on a metric known as the spacing criterion (LeVere et al., 1973), but these are generally limited to planar regularly spaced designs. For this study, custom photometric software was created that can search through many possible layouts where position constraints are relaxed in order to optimize some specified criteria.

Uniformity criteria

Both et al. (2002) describes several different quantitative metrics for evaluating uniformity of a luminaire design layout. For the case studies described in this paper, the maximum of min/mean and mean/max was used as the uniformity criterion, for simplicity. However, a marked improvement in multiple metrics is shown in the results.

Description of algorithm

The algorithm essentially functions as a brute force search of possible design layouts, subject to certain constraints. A regularly spaced grid of calculation points is established at canopy level. Symmetry assumptions are established for possible luminaire positions. For example, the layout is identical when reflected across the x- and y- axes, where the origin is the center of the layout. This helps to limit the possible combinations of luminaire position to a tractable number. Limits on (x, y, z) positions are given relative to the origin. Minimal spacing between luminaires is another input parameter.

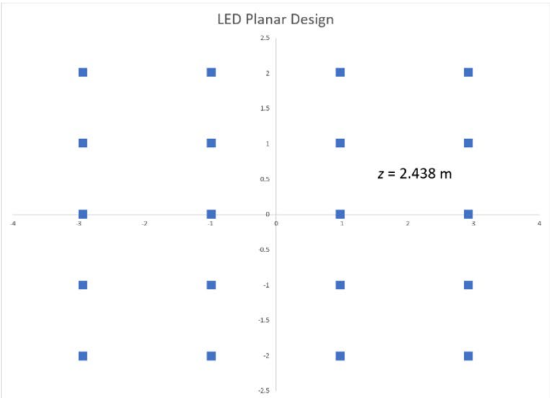
Based on these constraints, a grid of possible luminaire positions is constructed. Each iteration of the algorithm simulates a unique design layout of luminaire positions and evaluates the design against the established uniformity criteria. The optimal design according to the criteria is stored and output after all layout possibilities have been exhausted.

Case studies

The algorithm was tested for the design of two luminaire arrays in a research greenhouse. Each array illuminated a growing area of approximately 15 m^2, one with 200 W bar LEDs and the other with 600 W double-ended HPS lamps. Each growing area comprised nine ponds, with a walkway between each row of three ponds. A planar regularly spaced array was simulated for each area as a basis of comparison. The algorithm generated a design layout for each array, and then luminaires were mounted according to that design. PPFD measurements were taken with a quantum sensor at canopy level to verify the PPFD levels predicted by the algorithm.

RESULTS AND DISCUSSION

Figures 1 (LED) and 2 (HPS lamp) show layouts for the original planar designs and proposed designs, with notations for luminaire heights above canopy.



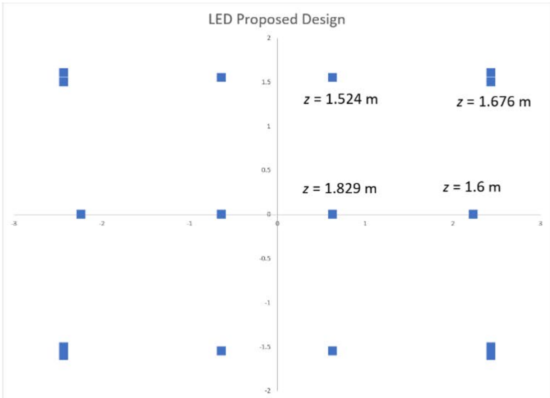
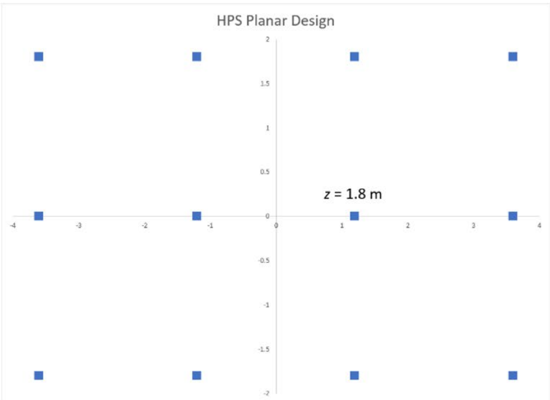


Figure 1. Luminaire layouts for planar (left) and proposed (right) LED designs. Each square represents the center point of a luminaire. Luminaire heights above canopy are noted.



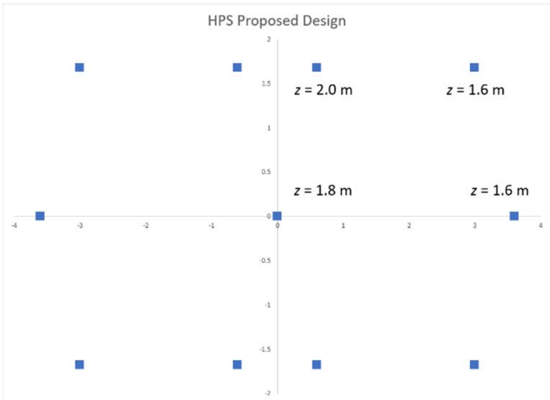


Figure 2. Luminaire layouts for planar (left) and proposed (right) HPS-lamp designs. Each square represents the center point of a luminaire. Luminaire heights above canopy are noted.

Figures 3 (LED) and 4 (HPS lamp) show calculated PPFD maps at canopy level for the planar regularly spaced array vs the layout chosen by the algorithm. The bullseye effect is clearly evident in the planar designs.

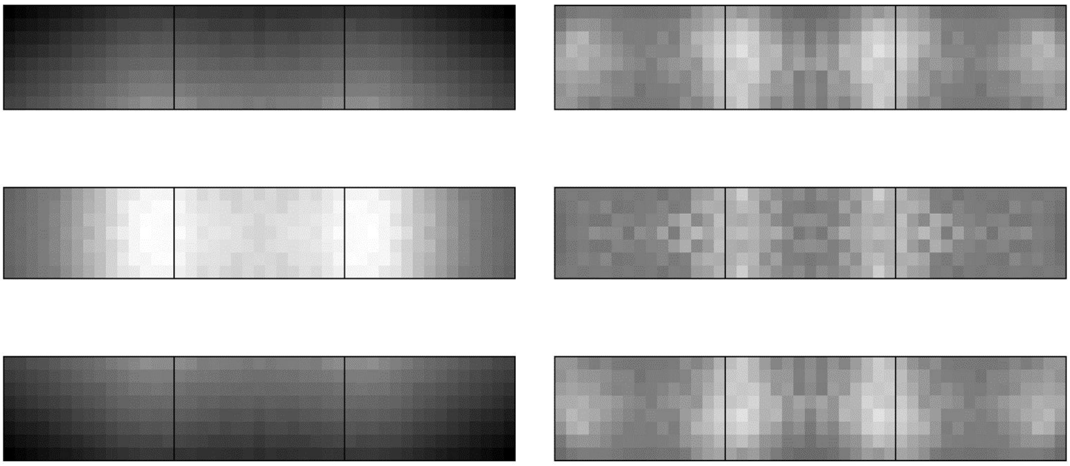


Figure 3. PPFD maps at canopy level for planar (left) and proposed (right) LED designs. PPFD in aisles between ponds is not shown, as it was not used in uniformity calculations.

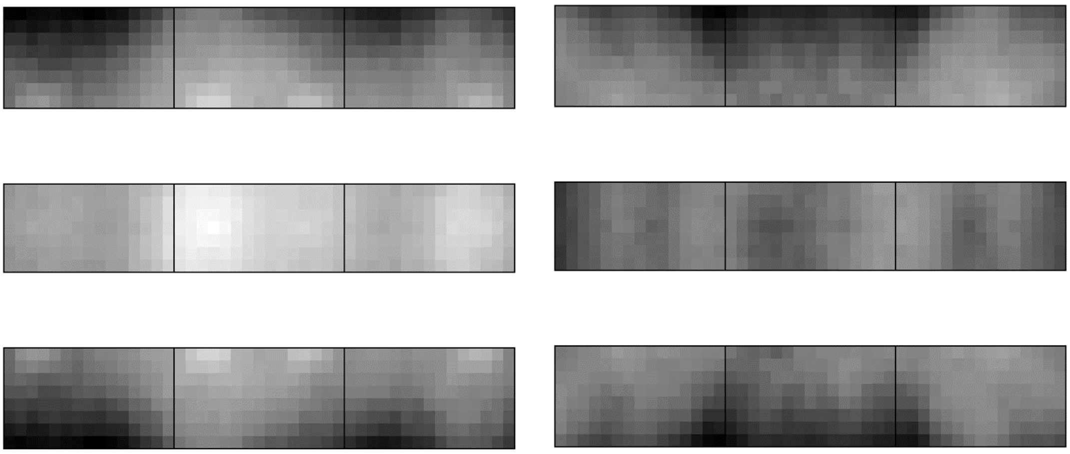


Figure 4. PPFD maps at canopy level for planar (left) and proposed (right) HPS-lamp designs. PPFD in aisles between ponds is not shown, as it was not used in uniformity calculations.

Note the proposed LED design in Figure 1 has two luminaires at each corner to provide additional light to the darkest parts of the planar design, and the two luminaires in the middle are raised higher to diminish the bullseye. Neither of these characteristics were hard-coded, they simply emerged from the design chosen by the algorithm. Figure 2 shows a very different solution for the HPS-lamp design, as the distribution of PPFD is very different for HPS lamps compared to an LED bar.

Table 1 quantifies the differences in uniformity for each design. Several of the metrics reported in the table correspond to uniformity criteria investigated in Both et al. (2002). The algorithm's LED design provided higher average PPFD, better uniformity, with fewer luminaires than the planar design, but this is not typical. In the HPS-lamp case, the algorithm's design provided better uniformity with one fewer luminaire, but the average PPFD was reduced. Based on other simulations, this seems to be a more typical result. Note that every uniformity criteria reported in Table 1 was improved with the proposed designs.

Figures 5 (LED) and 6 (HPS lamp) show frequency graphs of all PPFD sample points compared against the mean value and ±7% from the mean. The planar designs have many points outside of this range, while the proposed LED design has all points within this range, and nearly all for the proposed HPS-lamp design.

Table 1. Statistical results.

	LED planar	LED proposed	HPS planar	HPS proposed
Luminaires	20	16	12	11
x_{min}	136 μmol m^{-2} s^{-1}	175	172	172
x_{max}	201 μmol m^{-2} s^{-1}	196	225	204
$\bar{x}$	173 μmol m^{-2} s^{-1}	185	196	189
$\sum \frac{\lvert x_i - \bar{x}\rvert}{n}$	13 μmol m^{-2} s^{-1}	3	10	4
σ	16 μmol m^{-2} s^{-1}	4	12	5
$\frac{x_{min}}{x_{max}}$	68%	89%	76%	84%
$\frac{x_{min}}{\bar{x}}$	79%	95%	87%	91%
$\frac{\bar{x}}{x_{max}}$	86%	94%	87%	93%
$1 - \sum \frac{\lvert x_i - \bar{x}\rvert}{n\bar{x}}$	92%	98%	95%	98%
$1 - \frac{\sigma}{\bar{x}}$	91%	98%	94%	97%

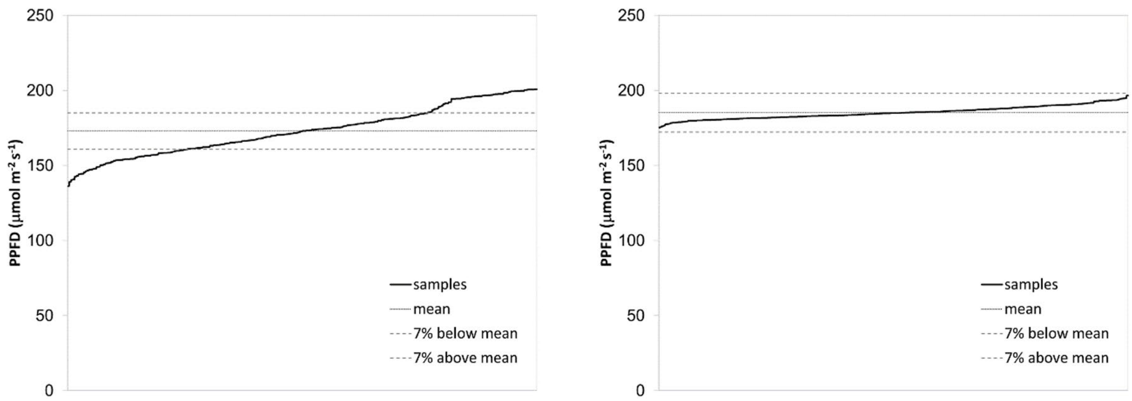


Figure 5. Frequency graphs of PPFD at canopy level for planar LED layout (left) and proposed design (right).

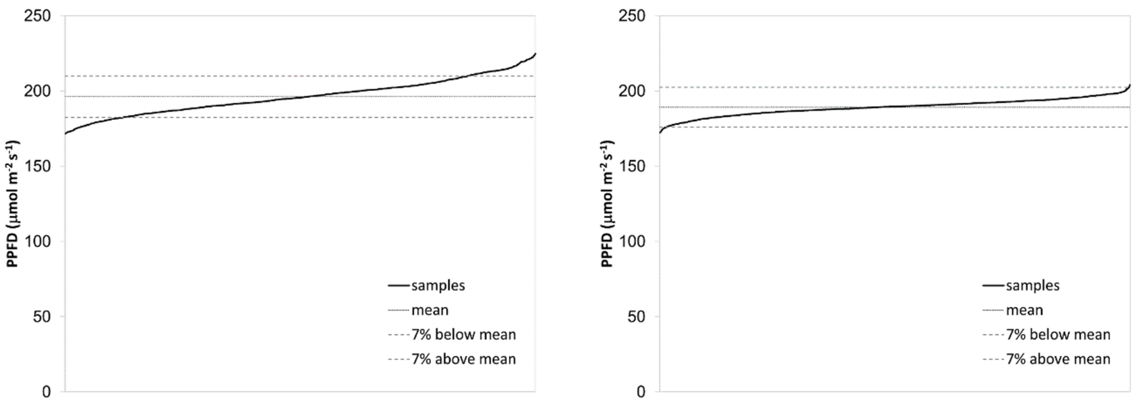


Figure 6. Frequency graphs of PPFD at canopy level for planar HPS-lamp layout (left) and proposed design (right).

Quantum sensor measurements at canopy level were shown to match predicted PPFD levels of the proposed designs to within 2 µmol m^{-2} s^{-1}.

CONCLUSIONS

This paper describes an algorithm for creating designs with improved spatial uniformity of supplemental PPFD at canopy level when compared with traditional planar regularly spaced designs. The algorithm is shown to be applicable to both HPS lamp and LED bar arrays.

As stated above, this technique is most practical for small greenhouse and indoor applications, where edge effects are more significant. More consistent yield should result from lighting with higher spatial uniformity. However, labor costs associated with mounting non-planar non-regular arrays may be a disadvantage in some cases.

ACKNOWLEDGEMENTS

The authors would like to thank A.J. Both at Rutgers University for providing spectral data on tested luminaires, and David deVilliers for assistance with light measurement and mapping. Funding for this research was received from the New York State Energy Research and Development Authority grant 40322.

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