Optimizing Exterior Lighting Illuminance and Spectrum for Human, Environmental, and Economic Factors.

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Optimizing exterior lighting illuminance and spectrum for human, environmental, and economic factors.

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Abstract. With the recent widespread adoption of LED lighting in outdoor areas, numerous concerns have been raised about the potential for harmful effects on humans, animals, plants, and the night sky. These stem from the high blue light content of some LED bulbs and an incentive to increase lighting levels caused by higher efficiency and lower costs. While new lighting installations are often described as environmentally friendly due to their energy efficiency, factors such as light pollution are often neglected or not given enough weight. This research focuses on optimizing the design of exterior lighting for human, environmental, and economic factors using a multi-criteria decision analysis. Based on data in the literature and survey research, illuminance and spectrum alternatives were scored relative to each other using the analytic hierarchy process and multi-attribute utility theory. The findings of this study support the use of artificial illumination at levels similar to a full moon (0.01 fc) and a warm white spectrum (2700K or 2200K), with amber LED becoming a better choice if its energy efficiency and cost effectiveness improve in the future. This methodology can be used in the future as a framework for lighting design optimization in different settings.

1. Introduction

Modern lighting has improved the lives of people around the globe, from allowing society to function more effectively after dark to increasing comfort in the built environment. However, along with its benefits come costs. These include energy usage, which can contribute to climate change, and light pollution, which can negatively impact human health, plants, and animals. In recent years, the rapid transition to LED has revolutionized the lighting industry, but despite presenting new opportunities, this technology also brings the potential for making existing problems worse. While the efficiency and controllability of LEDs allow for the reduction of energy usage and light wastage, these attributes can result in excessive illumination due to decreased operational costs [1]. Additionally, the increased blue light emitted by many LEDs is associated with ill effects on human health [2, 3] and the night sky [4]. The good news is that LED lighting can lead to a reduction in light pollution if the right design choices are made [1, 5, 6]. To benefit both people and the planet, it is imperative that a lighting design considers the factors of human health, the night sky, animals, and plants, in addition to functionality, public perception, energy usage, and cost.

This research optimizes the design of an exterior pedestrian LED lighting system at the Missouri University of Science and Technology (Missouri S&T) campus for human, environmental, and economic factors. Several methods of optimizing lighting designs for multiple criteria already exist in the literature [7, 8, 9]. These all make use of different forms of a multi-criteria decision analysis (MCDA) to select an ideal solution among many possible design alternatives. While an exterior lighting design algorithm has been created that includes light pollution as a principal criterion [7], it does not address factors such as light spectrum. It also does not score alternatives for the illuminance and light pollution criteria, but instead simply eliminates those deemed unacceptable. This research addresses these shortcomings by utilizing the analytic hierarchy process (AHP) and multi-attribute utility theory (MAUT) to compare lighting alternatives in a quantifiable manner, as has previously been done for interior lighting [9], and by incorporating more criteria to cover all major light pollution impacts as well as public perception. The framework used for this case can be used for other exterior lighting design applications and can be modified as necessary to fit different design objectives.

2. Methodology

To create an optimized outdoor lighting design, all significant design criteria were defined and weighted according to their relative importance. After determining the weighted criteria, different alternatives for illuminance and spectrum were scored according to their performance relative to each other and to a baseline. On the condition that they provide an acceptable level of visibility, the alternatives scoring the highest were considered to represent ideal lighting specifications. While not pursued in this study, minimum standards for other criteria could be established as well.

2.1. Defining and weighting design criteria

The following eight design criteria were used in this analysis:

- Functionality—public safety, visibility
- Perception—feelings of safety, comfort and aesthetics
- Human health—melatonin suppression, linked to a multitude of ailments [2, 3]
- Night sky—veiling of stars due to skyglow
- Animals—interference with or harm of various species
- Plants—interference with growth, dormancy period, etc.
- Energy—estimated energy usage of a lighting system
- Cost—capital, operation, maintenance

These criteria were associated with three main objectives: utility (functionality, perception); light pollution reduction (human health, night sky, animals, plants); and economy (energy, cost).

The analytic hierarchy process (AHP) [10], a common method used in multi-criteria decision analyses [9, 11, 12, 13], was used in this study to weight the design criteria. This method involves setting each criterion against all others with pairwise comparisons and allowing decision makers to indicate how favorable one is over the other. The traditional scale of 1/9 to 9 was used, with a score of 1/9 indicating extreme unfavorability of the first criterion over the second, 1 indicating equal preference, and 9 indicating extreme favorability of the first over the second. Intermediate values indicate lesser degrees of favorability or unfavorability.

For this study, a survey containing pairwise comparisons of the design criteria was distributed to students in the university's Civil, Architectural, and Environmental Engineering department. The survey set items representing the criteria against each other—for example, "functionality vs. perception" was represented with the phrases "actually being safe" vs. "feeling safe." For each pair, respondents were asked to indicate which item they believed was more important, and to what degree. To provide simplicity and reduce survey fatigue, a 5-point Likert scale was used and converted to the 1/9 to 9 scale after collecting responses. The choices included the following: "equal importance," corresponding to a 1; "somewhat more important," corresponding to either 1/5 or 5; and "much more important," corresponding to 1/9 or 9. A sample survey question is included in figure 1. The average response among participants was used for the final analysis. It was assumed that if a criterion was ranked "much more important" by all respondents, this would truly indicate extreme importance and merit a 9 on the AHP scale.

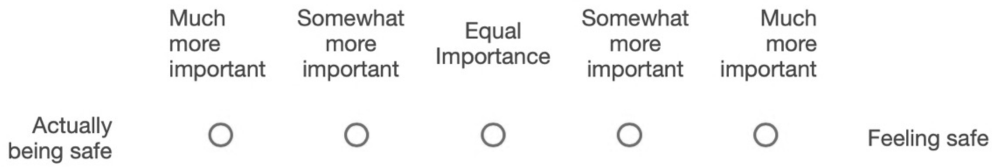

Figure 1. Sample survey question.

Survey responses were initially collected from members of a lighting design course within the department (n = 20, 50% female) as a pilot run, after which slight modifications to the wording were made to provide fairer representation of the criteria. Next, the survey was opened to all students in the department (~ 500 students) and received a response rate of around 10% (n = 53, 53% female). Participation was voluntary and anonymous, and no compensation or incentives were offered in exchange for participation. Responses were screened for credibility with the assistance of an interquartile range outlier analysis, and any spurious responses were removed. Using the average response from the final run of the survey, an AHP Excel template was used [14] to determine the weights of the three objectives, followed by the eight criteria independent of the objectives due to the design of the survey. The criteria were then grouped by objective, and their weights were adjusted in proportion to the objectives' weights. The final weights of the objectives and design criteria are given in table 1. In addition, functionality and perception were divided into subcriteria, the weights of which were approximated as detailed in appendix A.

There was greater than a 95% consensus between the pilot and final survey results. However, there were some noteworthy differences that could not be attributed to any wording changes that were made. Specifically, the weights of human health and functionality declined while those of energy and cost increased. This disparity could be due to differing values among students in the lighting class compared to the department in general. An assumption was made that the results of the final survey are a valid source for designing outdoor lighting for Missouri S&T's campus.

The calculated consistency ratio within the department's collective response was 0.076 for the three objectives and 0.174 for the eight criteria. Typically, a consistency ratio of 0.10 or lower is considered acceptable. However, the threshold is sometimes set at 0.20 [15]. In this case, since the results stem from the mean of more than 50 survey responses, the likelihood of inconsistency due to individual human error or poor judgment is lower. Rather, inconsistencies are more likely caused by the variation of items representing each criterion. For instance, the perception criterion was rated more favorably when represented by feelings of safety as opposed to comfort or aesthetics. Since great care was taken to ensure a balanced overall representation of all criteria, the results are considered acceptable. In addition, between-participant consistency was analyzed for all survey responses except for two that were incomplete (n = 51) using SPSS Statistics software (Version 28). The intraclass correlation coefficient (ICC) was calculated as 0.885 (95% CI: 0.818–0.937) based on a mean-rating, absolute agreement, two-way random model, representing good to excellent reliability [16].

Different methods of determining criteria weights, as well as the employment of this method towards other lighting applications and demographics, can be addressed in future research.

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Table 1. Calculated weights of objectives and final design criteria.

Utility		Light Pollution				Economy	
0.221		0.306				0.473	
Function-ality	Percep-tion	Human Health	Night Sky	Animals	Plants	Energy	Cost
0.156	0.065	0.120	0.042	0.073	0.071	0.249	0.224

2.2. *Quantifying relative performance of lighting alternatives*

The following lighting attributes and design alternatives were analyzed in this study:

- Illuminance—alternatives ranging from 0.01 fc (0.1 lx) to 10 fc (~100 lx)
- Spectrum—alternatives ranging from amber to 5000K correlated color temperature

Illuminance and spectrum alternatives are illustrated in figures 2 and 3.

(a) (b) (c) (d)

Figure 2. Illustrations approximating illuminance orders of magnitude: 0.01 fc (0.1 lx) (a), 0.1 fc (1 lx) (b), 1 fc (~10 lx) (c), and 10 fc (~100 lx), (d). Created with assistance of Missouri S&T lighting plans [37] and a LIFX brand light bulb which has a logarithmic dimming profile [48].

(a) (b) (c) (d) (e) (f)

Figure 3. Simulated spectrum alternatives, created using f.lux software as described in Appendix B: 5000K (a), 4000K (b), 3000K (c), 2700K (d), 2200K (e), and amber (f).

For each attribute, an MCDA was performed to compare several alternatives representing a wide range of possible design choices. In addition, significant interaction effects (i.e., variation in one attribute leading to altered performance of a different attribute) were studied. To score the alternatives relative to each other, multi-attribute utility theory (MAUT) [9, 17] was utilized. Utility indices were used to score alternatives with values ranging from 0 to 1, with 0 representing no utility and 1 representing an ideal alternative. Data were obtained from sources in the literature where possible or from other practical methods (e.g., survey research, analysis of market prices and specified product luminous efficiency), and regression models were used to estimate missing data points. Survey research was used to determine the perception utility for light spectrum, and is detailed in appendix B.

To assist in providing fair scoring across criteria and avoiding any bias from arbitrarily assigning utility values, the following scoring system was used:

Positive design criteria (e.g., visibility, feelings of safety, comfort) were scored using equation (1):

$$s_i = \frac{x}{x_{max}} \tag{1}$$

where s_i is the utility score of an alternative for criterion i, x is the value of the metric used to score the alternatives for that criterion, and x_{max} is the maximum value of this metric among all tested alternatives.

Negative design criteria (e.g., crime rate, light pollution impacts, cost) were scored using equation (2):

$$s_i = 1 - \frac{x}{x_{max}} \tag{2}$$

Finally, the total score of each alternative was calculated using equation (3):

$$S = \sum w_i s_i = w_1 s_1 + w_2 s_2 + \cdots + w_n s_n \tag{3}$$

where S is the total score, w_i is the weight of criterion i, s_i is the utility score of the alternative for criterion i, and n is the number of criteria ($n = 8$).

Using this scoring system, for positive criteria a score of 1 was assigned to the best case achievable within the range of alternatives (e.g., best visibility, feelings of safety and comfort, and energy efficiency within alternatives), and a score of 0 represents the theoretical worst case possible (e.g., zero visibility, feeling very unsafe/uncomfortable, zero energy efficiency); for negative criteria a score of 1 represents the theoretical best case possible (e.g., no crime/accidents, no light pollution, no cost) and a score of 0 was assigned to the worst values within the range of alternatives (e.g., highest crime/accident rate, largest light pollution impacts, and highest cost within alternatives). The possible scores for each criterion range from a maximum or minimum theoretically possible value to an extreme value found within the range of alternatives. In some cases, several subcriteria were combined to derive the final score for a criterion, and thus neither the 1 nor 0 point may appear among the alternatives. Due to the nature of this scoring system, the scores of each alternative should primarily be interpreted relative to other alternatives rather than as an absolute measure of utility. The formulation of different possible scoring systems for this analysis could be the topic of future research.

Following scoring by criterion, each alternative was given a total score by taking the sum of scores for each criterion multiplied by the criterion's weight. The results of this analysis are given in tables 2 and 3.

Table 2. Scores for illuminance alternatives.

Criteria	Function-ality	Percep-tion	Human Health	Night Sky	Animals	Plants	Energy	Cost	**Total**
Data Source	[19-23]	[24]	[20, 25-27]	[29-31]	[25, 26]	[28]	[32-37]	[32-39]	
Weight	0.156	0.065	0.120	0.042	0.073	0.071	0.249	0.224	
10 fc (~100 lx)	0.600	0.730	0.000	0.000	0.000	0.000	0.000	0.000	**0.141**
5 fc (~50 lx)	0.587	0.892	0.089	0.038	0.076	0.076	0.564	0.468	**0.418**
2 fc (~20 lx)	0.571	0.876	0.207	0.133	0.176	0.176	0.820	0.681	**0.559**
1 fc (~10 lx)	0.560	0.741	0.297	0.248	0.252	0.252	0.906	0.752	**0.612**
0.5 fc (5 lx)	0.555	0.627	0.386	0.398	0.328	0.328	0.950	0.789	**0.651**
0.2 fc (2 lx)	0.617	0.515	0.491	0.622	0.428	0.428	0.977	0.811	**0.701**
0.1 fc (1 lx)	0.599	0.446	0.556	0.775	0.504	0.504	0.986	0.819	**0.723**
0.01 fc (0.1 lx, approx. full moon)	0.462	0.255	0.772	0.973	0.697	0.697	0.994	0.826	**0.755**

Table 3. Scores for spectrum alternatives.

Criteria	Function-ality	Percep-tion	Human Health	Night Sky	Animals	Plants	Energy	Cost	**Total**
Data Source	[19, 21]		[27]	[27]	[27, 40]	[27]	[33, 41-45]	[38, 39, 46]	
Weight	0.156	0.065	0.120	0.042	0.073	0.071	0.249	0.224	
5000K	0.652	0.914	0.000	0.000	0.000	0.018	1.000	0.291	**0.476**
4000K	0.635	1.000	0.194	0.092	0.063	0.000	0.993	0.290	**0.508**
3000K	0.588	0.965	0.467	0.289	0.128	0.000	0.955	0.285	**0.534**
2700K	0.578	0.931	0.563	0.370	0.198	0.030	0.932	0.282	**0.546**
2200K	0.565	0.850	0.696	0.571	0.243	0.045	0.873	0.247	**0.545**
PC Amber	0.558	0.764	0.924	0.825	0.299	0.111	0.744	0.153	**0.531**
Narrowband Amber	0.558	0.764	0.971	0.921	0.491	0.435	0.461	0.000	**0.474**

3. Results

3.1. Illuminance

The illuminance alternative scoring the highest relative to the others is 0.01 fc (0.1 lx), or approximately the brightness of a full moon [18]. This lighting level is more than two orders of magnitude lower than typical illuminance values recommended for public lighting systems [47]. Levels below 0.01 fc were excluded from this analysis due to the potential for insufficient hazard detection at night [22], which is taken to be a critical factor for good quality lighting. An interaction effect between illuminance and lamp spectrum was found where visibility declined more steeply at low illuminances (< 0.2 fc) when warmer-colored lighting was used [21]. As 2000K HPS lighting was used to compute visibility vs. illuminance in the literature used for this analysis [22], use of a higher color temperature could result in lower illumination levels being required for acceptable visibility.

Despite having the highest score, a light level of 0.01 fc could present a design dilemma, as it provides a minimal level of obstacle detection capability [22] and, despite reduced illumination being associated with less crime [19], is associated with negative safety perception [24]. If a more acceptable level of visibility and perceived safety is deemed to be necessary, higher illumination levels may be called for. An interesting detail to note is that an illuminance of 0.2 fc (2 lx) scores highest for functionality in this analysis. In [21, 22], approximately 0.2 fc is identified as an inflexion point below which visual performance drops steeply, at least for a surface reflectance of 0.20. As certain assumptions were made in the calculation of the utility scores and surface reflectance can vary in real-world scenarios, this finding could be flawed to some extent, and the ideal illuminance could be different for specific cases. An interaction effect was also found in data from [21] where visibility dropped more significantly for elderly subjects than for younger subjects with reduced illuminance; however, this effect was only pronounced below 0.2 fc. A more precise study of how illuminance affects visibility and safety perception for case-specific conditions and demographics, as well as the determination of minimum acceptable illuminance, should be topics for future research.

3.2. Spectrum
The spectrum alternative scoring the highest is 2700K, but this alternative is virtually tied with 2200K (< 0.001 score difference). The interaction effect between illuminance and spectrum discussed in the previous subsection led to 2700K being favored slightly at low illuminances (~ 0.02 fc) and 2200K being favored slightly at higher illuminances (~ 2 fc). However, any slight differences between these two color temperature options are overshadowed by the estimated uncertainty in the criteria weights and from assumptions made in the calculations, as well as from a lack of complete and/or statistically significant data in the literature for some of the metrics. Benefits of choosing 2700K include better utility and economy, whereas 2200K better fulfills the objective of light pollution reduction. Color temperatures higher than 2700K increase light pollution significantly while not providing much benefit to utility or economics, whereas amber light would further reduce light pollution but bring drawbacks to utility and especially economics. If the energy efficiency and cost effectiveness of narrowband amber LEDs increase enough in the future, this alternative will score the highest.

3.3. Final Design Recommendation
Based on the results of this multi-criteria design optimization, the recommended LED lighting design for the exterior pedestrian areas of the Missouri S&T campus is an illuminance on the order of 0.01 fc at a color temperature of 2700K. If a higher illuminance is required for increased visibility and feelings of safety, 2200K may be more appropriate. Due to the interaction effect discussed above, if 2200K is selected at lower illumination levels (< 0.2 fc), a slight increase in illuminance may be appropriate to achieve the same visibility level. A lighting level above 0.2 fc is not recommended, as it is associated with a drop in functionality (due to a paradoxical potential for increased crime) as well as an increase in light pollution impacts.

3.4. Limitations
There are several limitations of this research that could be addressed in future studies. The survey data collected for weighting the design criteria and gauging public perception of different light spectra is limited in extent and represents the collective opinion of a specific group of people. The utility scoring system, while it provides consistency and objectivity through a mathematical model, scores alternatives in a relative manner to a certain degree. The data used to evaluate alternatives were often limited, and assumptions had to be made in several instances. This research also determined optimal lighting attributes independently of each other, potentially not accounting for certain interaction effects. Other lighting attributes such as color rendering index, uniformity, mounting height, distribution, and shielding were not accounted for as well.

4. Conclusion
This research addresses the lack of a comprehensive lighting design that adequately factors in people, the environment, and economics. Through a multi-criteria decision analysis consisting of AHP and MAUT methods, ideal illuminance and spectrum specifications for an exterior pedestrian LED lighting design were determined based on functionality, public perception, human health, environmental impacts, energy use, and cost. The findings of this study support a lower illuminance level than conventional recommendations prescribe, as well as the use of a warm white spectrum. This design is anticipated to be acceptable for visibility while minimizing light pollution, energy consumption, and cost. Future research should study the appropriateness of these findings for different lighting applications. This methodology can also be used as a framework for other design optimization problems.

Appendix A

Due to the limited extent of the survey, subcriteria weights for functionality and perception criteria used in the calculations were estimated using equation (A.1) instead of conducting separate AHP calculations.

$$w_k = w_i * \frac{\overline{a_k} * \overline{v_j}}{\sum(\overline{a_k} * \overline{v_j})} \tag{A.1}$$

where w_k is the weight of subcriterion k of criterion i, w_i is the final weight of criterion i, $\overline{a_k}$ is the average preference (from 1/9 to 9) of subcriterion k, and $\overline{v_j}$ is the average unadjusted weight of opposing criteria j in the pairwise comparisons containing subcriterion k. As an illustration, the feelings of safety subcriterion of the perception criterion was paired against functionality, human health, plants, and energy (average unadjusted weight = 0.152) in the survey and was preferred by a factor of 0.567. The other perception subcriterion, comfort/aesthetics, was compared against functionality, night sky, animals, and cost (avg. unadj. wt. = 0.118) and preferred by a factor of 0.275. The estimated weight of the feelings of safety (FoS) subcriterion is thus given as follows:

$$w_{FoS} = 0.065 * \frac{0.567 * 0.152}{0.567 * 0.152 + 0.275 * 0.118} = 0.047$$

which is about 73% of the weight of the entire perception criterion.

Appendix B

The perception utility scores for light spectrum were determined through a survey given to university students, predominately from the Missouri S&T Civil, Architectural, and Environmental Engineering department. Participation was voluntary, and no compensation or incentives were offered in exchange for participation. The survey consisted of three pictures, shown in figure A1, which were derived from one photograph taken of an area of campus at night (lighting has a known correlated color temperature (CCT) of 5700K). The photos were color corrected to a CCT of approximately 5000K, 2700K, and 1800K (simulating amber) by comparison with the original photo displayed on a screen running f.lux software, which allows for the screen to be set to a specific CCT. Pictures were displayed in a random order to prevent bias.

(a) (b) (c)

Figure A1. Simulated photos for the perception survey: 5000K (a), 2700K (b), and 1800K (c).

Respondents were asked to rate their agreement on a 5-point Likert scale with the following statements:

- "I would feel safe walking around in this area"
- "This lighting is aesthetically pleasing and comfortable to be around"

Next, the three pictures were shown side by side, and respondents were asked to indicate which light color would make them feel the safest and the least safe, as well as which color is most and least aesthetically pleasing and comfortable to be around. An opportunity to explain these preferences or indicate no preference was given. Responses were vetted for consistency, and any instances where the Likert scale ratings were inconsistent with the preferences given in the side-by-side comparison were removed. A total of 56 responses were received, of which six were removed for the feelings of safety (FoS) portion and nine for the comfort and aesthetics portion (FoS: n = 50, 55% female; Comfort: n = 47, 48% female). Between-participant consistency was measured by calculating the ICC for all responses with complete data for both portions (n = 42). The calculated ICC (0.858, 95% CI: 0.642–0.976) represents moderate to excellent reliability between participants.

Results were obtained by averaging the responses for each portion. In addition, a separate analysis was performed after separating data by gender to understand any differences that may be present based on this demographic. Results are assumed to provide a valid data source for designing lighting for Missouri S&T's campus. The overall and gender-separated results are shown in table A1 and figures A2 and A3.

Table A1. Color perception survey data. Scoring ranges from -2 to 2, with a value of 0 representing a neutral response.

	CCT	5000K	2700K	1800K
Feelings of Safety	Composite	1.080	0.980	0.480
	Male	1.182	1.091	0.636
	Female	1.000	0.852	0.296
Comfort/ Aesthetics	Composite	0.149	0.532	0.000
	Male	0.208	0.542	-0.250
	Female	0.091	0.500	0.182

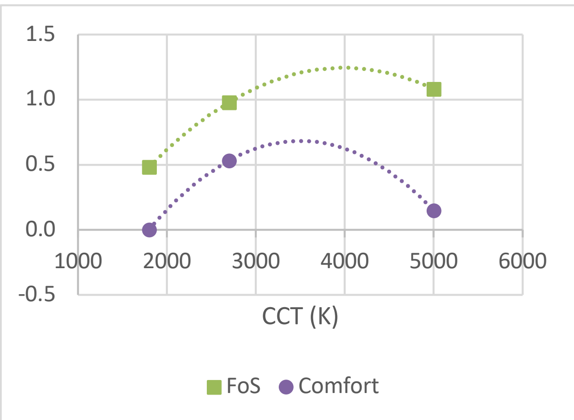

Figure A2. Composite scores.

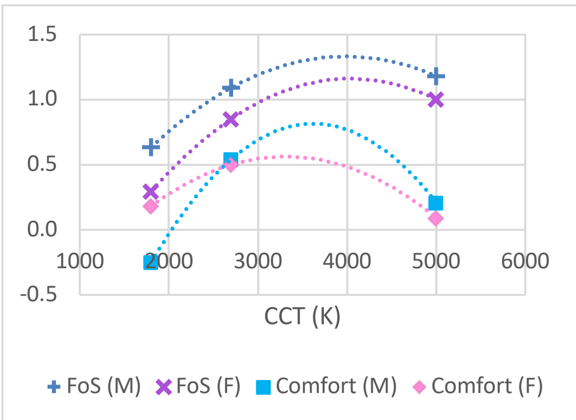

Figure A3. Results by gender.

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