Smart Indoor Lighting Control:

Power, Illuminance, and Colour Quality

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Abstract—This paper investigates the correlation between color quality and energy efficiency of indoor lighting control. The color quality, in terms of visual performance and comfort, is quantified using three measurements: illuminance, Color Rendering Index, and Correlated Color Temperature. Several experiments have been conducted to evaluate the potential energy savings of using different portions of light spectrum to obtain the optimal color quality. In particular, Light-Emitting Diodes are used as the lighting sources of the experimental luminaire. Moreover, the above quantification method and experimental results have been incorporated into a previously developed simulation framework for Building Automation and Control Systems, and smart lighting is used to adjust the tradeoff between comfort and energy consumption based on the presence of occupants. The results can be used to evaluate the viability of advanced lighting automation.

Keywords—BACS; LED; colour temperature; colour rendering index; colour quality; CCT; visual comfort; IEC 61499

I. INTRODUCTION

Lighting systems play an important role in modern buildings. In particular, for indoor work places, appropriate lighting conditions are essential for people's visual comfort and working efficiency [1, 2]. Moreover, illumination as the second largest end use consumes over 20% of total energy of office buildings in USA [3]. This means efficient lighting control can significantly improve the energy efficiency of buildings. When profiling or evaluating the energy efficiency of indoor lighting system, the power consumption and illuminance are usually the two primary factors considered. It is well appreciated that while providing the minimum illuminance acceptable for visual performance, a lucrative lighting system also should conserve the energy usage as much as possible. The common practices in smart lighting system often involve the detection of room occupants, the utilization of daylight, and optimization of artificial light sources. For example, the EN 12464 [4] standard comprehensively specifies the minimum illuminance required for various indoor work areas.

Along with the reference values provided for each specific area and type of building, it is possible to estimate the relatively accurate energy consumption of indoor lighting systems. It can be envisaged that such virtual metering function can significantly facilitate the design of lighting control

system; especially when specific energy efficiency is required. In our previous work [5], a simulation framework based on such virtual metering concept has been developed. Specifically, a smart lighting control taking room occupancy and daylight density into account has been demonstrated.

In this paper, the above framework is further extended to incorporate recent research correlating color quality and energy usage. The color quality as controllable factor can affect the energy consumption as well. However, as a quality property it is always difficult to quantify it. Especially the color quality is closely bound with users' perception of comfort, which can be quite subjective. Previous works have identified that, in general, people prefer working environments with higher illuminance, *Color Rendering Index* (CRI), (also abbreviated R_a) and *Correlated Color Temperature* (CCT) [6, 7]. In order to satisfy the minimum degree of acceptable visual performance and comfort, there are certain requirements on the illuminance, R_a , and CCT for the lighting system. One possible way of achieving such lighting conditions is by using a luminaire consisting of light sources with different colors. Different light colors have different power consumption rates, so while satisfying the required lighting conditions, different color combinations will use different amounts of energy. It is, consequently, necessary to investigate whether the energy savings as a result of using different light colors is sufficient enough to motivate the adoption of such a composite luminaire with smart control.

In this work, a methodology has been proposed to incorporate data from the aforementioned type of studies to the building automation system, in order to achieve an intelligent tradeoff between color quality and power consumption. A further research goal of this work is to investigate whether the energy savings from varying CCT keeping R_a value above minimum requirement are sufficient enough to be implemented in the lighting control.

As compared to a traditional incandescent or fluorescent lamps, a white light generated by mixing different colored LEDs in appropriate proportions has advantages such as longer lifespan, excellent durability, absence of mercury content and greater electrical efficiency; further, the different color LEDs give numerous options for varying color quality and power consumption while satisfying minimum requirements for

illuminance. The experiments conducted in this work were therefore primarily focused on the applications of LEDs for indoor lighting.

The remainder of this paper is organized as follows. First of all, Section II provides an overview of enabling technologies for this work. Section III first outlines the experimental setup used in this work then elaborates the methodology proposed to correlate energy consumption and color quality. The results obtained in the experiment will be analyzed in Section IV with a discussion on the effectiveness of the proposed correlation. The paper will finally conclude in Section V with perspectives of further research.

II. ENABLING TECHNOLOGIES

A. Measurement of Color Quality

Color quality is important characteristic to be considered in using light sources for indoor lighting [8,9]. In current practice, the color of light sources is usually described by two properties: chromaticity of light itself (measured by Correlated Color Temperature (CCT)) and color rendering performance (measured by color rendering index R_a) of light source describe the color quality of light source [10]. The R_a is most widely used metric to evaluate the color-rendering performance of light sources. However, a number of questions have arisen as to whether or not the R_a should be used to evaluate the color-rendering performance of white LEDs due to several flaws in the CIE (Commission Internationale de l'Eclairage) test sample method [11, 12, 13, 14, 15]. Hence, CIE has formed a technical committee to recommend a new metrics or metrics for assessing the color rendition of light sources. Till date work is still underway to recommend the new metric or metrics and despite of having shortcomings, R_a is still in use.

While standards for indoor lighting set requirements in terms of illuminance and the R_a [4], there are several other characteristics of light sources that may still be varied, and these have an impact on comfort, productivity and power consumption. Kruithof [16] showed the comfortable illuminance zone related to the color temperature of light sources called Kruithof curves. However, many studies [17, 18, 19] which tested the Kruithof curve showed that people's preference of illuminance and CCT might vary depending upon different environments and purposes and could not be completely explained by the Kruithof curve. Park et al [20] evaluated the impact of varying CCT on personal preferences and productivity and suggested that changeable CCT lightings are better than fixed CCT for occupants in a space. Juslan [21] found that the productivity of the workers is significantly higher when the higher color temperature is use in an industrial work area and suggest that for a lower use of energy as well as for higher productivity, the color temperature of the dimmable task lighting system should be around 4400 K rather than around 3500 K. Ohno [9] proposes an approach for seeking an ideal combination of color quality and minimal power consumption in terms of color rendering index and luminous efficacy. In this research, the approach is to incorporate data from such lighting studies to an intelligent building automation system, and to integrate the automation system to a simulation of a building and a virtual smart metering system, in order to

obtain results pertaining to the type of building under consideration.

B. Component-Based Design and Virtual Metering System

The lighting simulation system developed in this work is designed following the component-based approach previously proposed in [22, 23]. As illustrated in Fig. 1, the lighting system is modeled in a plant-controller closed-loop manner using the IEC 61499 Function Block (FB) standard [24]. The BuildingModelFB models the environment data, such as occupant presence and daylight luminance in each room of the building. It also simulates operations of the lighting system, which provides status data for the virtual meter implemented in the BACFB. The BACFB consists of three component FBs: the higher-level HLC FB analyzes the environment data and assigns appropriate control policies for the lower-level LLC FB, which interacts with the lighting system. Once the operation status data from the lighting system are evaluated, the VirtualMeter FB can produce the energy usage data, which will be analyzed and visualized in the SimulatorFB. The theory of this virtual metering approach is quite straightforward: by continuously monitoring the operation time of lighting system, the energy consumption can be estimated as:

$$Energy = Nominal Power \times Operation Time \quad (1)$$

Fig. 1. Lighting Control Simulation and Virtual Metering System.

III. EXPERIMENTAL SETUP AND EVALUATION METHODOLOGY

A. Experimental setup

12-Channel LED-based SPD Simulator System (LED simulator) as shown in Fig. 2 is used for the purpose of the research. The LED simulator is built using three main parts: (a) LED panels – 12-channel LED panels (LightingMetrics Kft.), (b) Power supply Unit (PSU) - 24- channel DMX/RDM compatible power supply unit (IST Ltd), (c) Interface- PC DMX/RDM USB Interface (Dezelectric Kft.)

The LED panel of the LED simulator has twelve independent LED strings of different LED types. Each LED string had nine LEDs connected in series. In this study, only four LEDs string (among twelve strings) are used: blue, cool-white, amber and green. Each LED type was controlled by a PC DMX/RDM USB interface and a 24-channel DMX/RDM

compatible power supply unit. The master dimmer function of the power supply which was at constant setting for the experiments.

Measurement was done inside the lighting booth of height 1m, length and depth both of 0.5m (Fig. 3). The LED panel was concealed at top of the booth by a Plexiglas GS WHO2 diffuser, which blended the light well, thus providing homogeneous illumination at the base of the booth. The inner surface of the booth was coated with matt grey paint (IN2-NCS-S2500N), maintaining the surface reflectance at 50%.

Fig. 2. Experimental setup (a) LED panel, (b) Power supply unit and (c) Interface

Fig. 3. lighting booth where measurement was done

The power consumption of the luminaire is calculated in Table I. The forward voltage and forward current of LED was specified in the respective LED data sheet. The “Power” row is for 1 LED and “Total power” for the LED string (each LED string had nine LEDs of same type). These values are for the case when all LEDs are fully on all the time, without dimming. In this study Pulse Amplitude modulation (PAM) technique is used instead of dimming to control current for each type of LED. The actual power consumption per LED type, ρ^c , is calculated as:

$$\rho^c = Total\ power \times \frac{PAM\ control\ value}{255} \quad (2)$$

where the superscript, c, denotes the LED type. For example if PAM control signal value 127 is given to cool-white LED, then the actual power consumption of cool-white is calculated as below:

$$\rho^{White} = 10.08 \times \frac{127}{255} W = 5.02W \quad (3)$$

Fig. 4 is a visualization of the user interface of Fig. 2c, showing PAM control values for each LED in the blue, cool white, green and amber strings.

0	0	0	127	127	127
0	0	0	127	127	127
0	0	0	127	127	127
48	48	48	0	0	0
48	48	48	0	0	0
48	48	48	0	0	0

Fig. 4. User interface visualizing PAM (Pulse Amplitude Modulation) control values to the amber, blue, green and cool white LEDs

TABLE I. TOTAL POWER CONSUMPTION CALCULATION OF DIFFERENT LED TYPES BASED ON LED SPECIFICATIONS

	Blue	Cold White	Amber	Green
Forward current (IF) [mA]	350	350	350	350
Forward Voltage (VF) [V]	3.2	3.2	2.2	3.3
Power [W]	1.12	1.12	0.77	1.16
Total power [W]	10.08	10.08	6.93	10.44

B. Methodology

LED spectral power distributions (SPDs) with desired CCT and R_a keeping horizontal illuminance at 330 Lux were generated, by varying some LED types (among four LED types used) and then adjusting the remaining one as shown in Table II. Standards require different minimum illuminance for rooms with different purposes, so another constant value instead of 330 Lux could have been used.

The illuminance meter LMT Pocket- Lux- 2A was used to measure horizontal illuminance levels. The meter was calibrated by the LMT Lichtmesstechnik GmbH Berlin. The light source SPDs and color quality were measured with a calibrated Spectroradiometer Konica-Minolta CS 2000. The spectroradiometer was calibrated at Aalto University before the measurement. The SPDs were measured by focusing the

Spectroradiometer at a 45° *measuring* angle onto a white spectralon tile (Gigahertz-Optik-BN-R98-SQ2C) placed at the center of the booth floor. In order to avoid increasing the cost of the building automation system, such a device will not be required, and this no feedback control is desired, as the data is constant for the luminaire type.

The columns Blue, White, Amber and Green in Table II are the PAM control values to the LEDs. The columns Lux, R_a and CCT are measurement data obtained with the spectroradiometer. There are 9 LEDs of each color, and the same control is sent to all of them. The “Power” column is calculated using equation (3) as:

$$Power = \rho^{Blue} + \rho^{White} + \rho^{Amber} + \rho^{Green} \quad (4)$$

where all superscripts refer to the columns in Table II. For example, when PAM control signal of 0 is given to blue LED, 127 to cool-white LED, 48 to amber LED and 0 to green LED, (to generate LED SPD having R_a of 91 at 2900K CCT) then the total power consumption is

$$Power = (0 + 5.02 + 1.30 + 0)W = 6.324 W \quad (5)$$

TABLE II. MEASUREMENT DATA RELATING PAM CONTROL VALUES TO LEDs (BLUE, WHITE, AMBER, GREEN) TO COLOR QUALITY AND POWER CONSUMPTION

Blue	White	Amber	Green	Lux	R_a	Power (W)	CCT (K)
0	127	48	0	333	91	6,324706	2904
4	127	43	0	328	91	6,346941	3065
37	0	72	209	331	62	11,976	6224
23	0	91	181	329	54	10,79259	4098
8	0	121	149	331	51	9,704824	2645
0	164	0	0	331	64	6,482824	4576
9	61	64	52	333	82	6,635294	3294
14	67	50	52	329	85	6,689647	4004
0	63	89	31	331	82	6,178235	2385
0	106	58	7	331	90	6,052941	2844
21	121	25	15	331	87	6,906706	4910

Our methodology aims to incorporate information from studies relating some of the color quality data in Table II to occupant comfort or productivity. Our approach is general and any study relating CCT or R_a to comfort or productivity may be used. In order to demonstrate our approach, we use [6], but our method is general and data from other studies could be used instead. Fig. 5 is adapted from [6] by using linear interpolation.

Fig. 5. Occupant comfort as a function of CCT. Adapted from [6].

Using the function in Fig. 5, the comfort rating for each row in Table II can be obtained. This rating is one metric of comfort. The color rendering index R_a is another such metric. Both metrics should be maximized. In Fig. 6, each measurement in Table II is plotted as a dot, based on its comfort rating and R_a values. These two are uncorrelated, but since both should be optimized, the ideal measurements are on the Pareto front shown as a red line.

Fig. 6. Correlation between comfort rating based on CCT and R_a . Dots correspond to rows in Table II.

However, Fig. 6 does not consider power consumption. Our goal is to maximize both the comfort rating and R_a , but minimize consumption. If both our color quality based comfort metrics are given equal weight, the problem can be simplified to two dimensions: maximize the product (comfort rating * R_a) and minimize power consumption. This two dimensional space is shown in Fig. 7, and each measurement in Table II is plotted as a dot in this space.

Fig. 7. Comfort metric versus power consumption. Dots correspond to rows in Table II.

The Pareto optimal settings for maximizing comfort and minimizing power consumption are on the Pareto front shown as a red line in Fig. 7. Table III is an excerpt of Table II focusing on the four points on the Pareto front in Fig. 7. The user will be presented with an interface for selecting any of these settings (setting 1 has best power saving and setting 4 has best quality). This table is also all the specification that is required for the building automation control system engineer: based on the user setting, the system will output the corresponding PAM control values as specified in the columns Blue, White, Amber and Green.

TABLE III. AN EXCERPT OF TABLE II FOCUSING ON THE FOUR POINTS ON THE PARETO FRONT IN FIG. 7

Blue	White	Amber	Green	Power (W)	Quality	Setting
0	106	58	7	6,052	280,08	1
0	127	48	0	6,324	285,92	2
4	127	43	0	6,346	293,24	3
14	67	50	52	6,689	313,57	4

IV. RESULT ANALYSIS AND DISCUSSION

As previously shown in Fig. 1, the BuildingModelFB provides data corresponding to sensor measurements of occupant presence. The building has 5 floors and each floor has 5 rooms, with different occupancy data for each room. Fig. 8 shows data for one room.

Fig. 8. Occupant profile for one of the rooms in the BuildingModelFB.

The simulation was run for 24h twice with the exact same occupant profiles. The first run was using intelligent control: the settings in Table III were chosen so that higher settings (with higher comfort and energy consumption) were chosen when occupants per room exceeded certain thresholds; lights were off when there were no occupants. The settings were set separately for each room, and results are shown as “smart lighting” in Fig. 9. The second run used the maximum comfort setting 4 in Table III whenever there was at least one person in the room; otherwise the lights were off. Results are shown as “maximum comfort” in Fig. 9.

In Fig. 9, it should be noted that the “maximum comfort” is also optimized, as it uses a setting from the Pareto front of Fig. 7. However, this is an optimization that can be done offline. The “smart lighting” requires additional investments to infrastructure, so these may not be justified under current energy efficiency incentives, since the saving according to Fig. 9 is clearly under 10%. However, the offline optimization that takes into consideration color quality aspects can make significant energy efficiency savings, as can be seen by comparing the power consumption of different color combinations in Table III, even though all have the same illuminance.

Power Consumption of Smart Lighting VS Pareto Front Setting

Fig. 9. Power consumption.

V. CONCLUSIONS

In this research, data from lighting studies relating various color quality metrics to comfort and productivity has been incorporated to an intelligent building automation system. The automation system has been integrated to a simulation of a building and a virtual smart metering system, in order to obtain results pertaining to the type of building under consideration.

Our methodology is general, but the data that has been used is specific to the comfort study [6] as well as the luminaire that has been used. In Fig. 7, the two comfort metrics (comfort rating based on [6] and R_a) were combined to one metric to be maximized. An alternative would have been to keep the three dimensional optimization problem and to obtain a three dimensional Pareto front, but it is unclear if the users want to see that much complexity. Our data is sufficient for demonstrating the methodology, but not sufficient for drawing definitive conclusions on the percentage of power savings that may be attained by the approach. The contribution of the paper is thus the methodology and not the numerical result, which is only presented as proof-of-concept.

Finally, it may be asked that are there other color quality based metrics in addition to R_a and comfort based on CCT. Numerous potential metrics indeed exist; for example, it would be possible to consider productivity instead of comfort as a function of CCT. If such a study is published, the function in Fig. 5 could be replaced, and the methodology in this paper would be otherwise useful.

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REFERENCES

- [1] R.-H. Huang, Y.-A. Chiu, Y. Sun, Y. Hsu, T.-T. Kao, T.-C. Shen, et al., "Effects of Color Temperature of LED Desk Lights on Working Attention," in 2013 International Conference on Business and Information (BAI 2013), Bali, Indonesia, 2013, pp. F125-F143.
- [2] S. W. Smith and M. S. Rea, "Relationships between office task performance and ratings of feelings and task evaluations under different light sources and levels," in Proceedings of 19th CIE Session, Kyoto, Japan, 1980, pp. 207-211.
- [3] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy and Buildings*, vol. 40, pp. 394-398, 2008.
- [4] European Committee for Standardization (CEN), "EN 12464-1: 2011: Light and lighting. Lighting of work places. Indoor work places," ed, 2011.
- [5] C. Pang, V. Vyatkin, Y. Deng, and M. Sorouri, "Virtual Smart Metering in Automation and Simulation of Energy-Efficient Lighting System," in 18th IEEE Conference on Emerging Technologies and Factory Automation (ETFA 2013), Cagliari, Italy, 2013, pp. 1-8.
- [6] R. F. Lin, C. Chou, Y.-T. Wang, and H.-W. Tu, "Effects of LED Color Temperature on Office Workers," in 2nd Southeast Asian Network of

- Ergonomics Societies Conference (SEANES 2012), Langkawi, Malaysia, 2012.
- [7] S. A. Fotios, "Lamp colour properties and apparent brightness: a review," *Lighting Research and Technology*, vol. 33, pp. 163-178, 2001.
- [8] U.S. Department of Energy, Energy Efficiency & Renewable energy "Building Technologies Program, Solid-state lighting Technology". [Online]. <http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf>. Accessed on 2013 December
- [9] Y. Ohno, "Color rendering and luminous efficacy of white LED spectra," in Proc. of SPIE Vol. 5530, Bellingham, 2004, pp. 88-98.
- [10] L. Halonen, E. Tetri and P. Bhusal, "Annex 45 - Guidebook on Energy Efficient Electric Lighting for Building. Summary Report" pp. 16, International Energy Agency, 2010. [Online]. http://www.ecbcs.org/docs/ECBCS_Annex_45_Guidebook.pdf [Accessed Dec 2013]
- [11] W. Davis, Y. Ohno, "Approaches to color rendering measurement", *Journal of Modern Optics* 2009; 56(13): 1412-1419.
- [12] J. Scanda, "Color Rendering of Light Sources" in J. Scanda, Ed., "Colorimetry: Understanding the CIE System", New York: John Wiley and Sons, Inc., 2007, pp. 207-215
- [13] Commission Internationale de l'Eclairage, "Colour Rendering of White LED Light Sources, CIE Publication 177", Vienna, Austria: CIE, 2007.
- [14] X. Guo, K.W. Houser, "A review of colour rendering indices and their application to commercial light sources", *Lighting Research and Technology* 2004; 36 (3): 183-197.
- [15] Commission Internationale de l'Eclairage, "Colour Rendering, CIE Publication 135/2 (TC 1-33 closing remarks)", Vienna, Austria: CIE, 1999.
- [16] A. Kruthof, "Tubular luminescence lamps for general illumination", *Philips Technical Review*, 1941. 6(3): pp. 65-96.
- [17] M. M. Sinoo, J. van Hoof, and H.S.M. Kort, "Light conditions for older adults in the nursing home: Assessment of environmental illuminances and colour temperature" *Building and Environment*, vol. 46 (10), pp. 1917-1927, 2011
- [18] P. R. Boyce, and C. Cuttle. "Effect of correlated colour temperature on the perception of interiors and colour discrimination performance." *Lighting research and Technology*, 22(1), 19-36,1990
- [19] R.G. Davis and D.N. Ginthner, "Correlated color temperature, illuminance level and the Kruthof curve", *Journal of the Illuminating Engineering Society*, 19 (1), 27-38,1990.
- [20] B. C. Park, J. H. Chang, Y. S. Kim, J. W. Jeong, and A. S. Choi, "A Study on the Subjective Response for Corrected Colour Temperature Conditions in a Specific Space" *Indoor and Built Environment*, vol. 19(6), pp. 623-637, 2010
- [21] H. Juslén. "Influence of the colour temperature of the preferred lighting level in an industrial work area devoid of daylight." *Ingenieria Illuminatului* 8 (2006): 25-36.
- [22] V. Vyatkin, H. M. Hanisch, C. Pang, and Y. Chia-Han, "Closed-Loop Modeling in Future Automation System Engineering and Validation," *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 39, pp. 17-28, 2009.
- [23] C. Pang and V. Vyatkin, "Systematic Closed-Loop Modelling in IEC 61499 Function Blocks: A Case Study," in 13th IFAC Symposium on Information Control Problems in Manufacturing (INCOM09) Moscow, Russia, 2009, pp. 199-204.
- [24] "Function blocks - Part 1: Architecture," IEC 61499-1: 2012, p. 245, 2012.