Real-time Control of Indoor Lighting to Minimise Energy Use

Joy Dassgupta and Peter Pudney

Abstract—**Indoor lighting is responsible for around 15 percent of the energy use in commercial buildings. Requirements for illumination vary during the day, depending on how much daylighting is available and on the occupancy and use of various parts of the space. With modern lighting and control systems, light sources can be controlled to respond to these varying requirements. The problem is to calculate the most energy-efficient way to meet the lighting requirements, in real time. This problem can be solved using linear programming for dimmable light sources, and integer linear programming for switchable light sources. This paper proposes a new technique to control indoor electric lighting intensity with the optimisation of a linear program or integer linear program that considers the occupancy and the level of illumination at any points in different environmental conditions**

Index Terms—**Indoor lighting control, optimisation, illumination, linear programming, integer programming, daylight, lighting efficacy, energy efficiency.**

I. Introduction

Indoor lighting is responsible for around 15 percent of the energy use of commercial buildings (1; 2; 3). Many work places use indoor lighting continuously during working hours, without considering how much light is available from natural daylighting, or the occupancy and lighting requirements of individual work spaces.

(4) describe a system that uses wireless sensor networks to track individual users with known background and local lighting requirements as they move around a space that contains local and area lighting devices. (5) extend this work to remove the need for an external system to track user locations. Both papers use a combination of linear programs and heuristic methods to find lighting combinations that meet the user requirements. In the case where user satisfaction is binary, energy can be minimised within the user satisfaction constraints. When users have continuous utility functions, total utility is maximised and energy is not considered. Both systems require users to carry light sensors, which is a limitation.

Manuscript received on January 15, 2019; revised on April 16, 2019.

J. Dassgupta is an Professional Electrical Engineer (NER) and Registered Professional Engineer of Queensland (RPEQ) in Australia, and EIT in APEGS, Canada. He is also a member of IEEE, IAENG and Engineers Australia.

P. Pudney is an Associate Research Professor of Industrial and Applied Mathematics in University of South Australia. He is the current Director of the Mathematics in Industry Study Group and also the Deputy Director of the Centre for Industrial and Applied Mathematics, a member of the Barbara Hardy Institute, and Node Leader at UniSA for the Industry Doctoral Training Centre. In 2013, Assoc Prof Pudney was awarded the "Unsung Hero of South Australian Science Communication" by the Australian Science Communicators (SA) and National Science Week (SA).

(6) formulate a lighting control problem with multiple light sources as a linear programming problem, but do not consider the control of non-dimmable light sources, and do not describe how the control can be integrated with occupancy sensors and daylighting.

(7) consider a scenario where each work plane has a light sensor and the contribution of light from each light source to each work plane is known. They use a non-optimal heuristic method to determine the intensity of each light source to achieve specified illumination at each work plane.

We build on this work by formulating the problem of finding the most energy-efficient light source intensities to meet illumination requirements as linear program for dimmable light sources and as an integer linear program for non-dimmable light sources, and illustrate the method for an example problem. We also describe a algorithm that can use a network of activity sensors to determine where light is required, and light sensors to determine the contribution of daylighting, to adjust lighting in real time to meet changing requirements during a day. This is primarily set to project lighting energy savings by achieving the necessary illumination required in any situation and omitting the additional intensities. This will subsequently increase the lifetime of lamp by controlling illumination means limiting the heat increase and reducing the amount of switching on a light.

II. Problem formulation

Our aim is to find the most efficient combination of light source intensities to meet illumination requirements on a set of work surfaces. Illumination requirements will vary during the day, particularly if daylighting is taken into account, and so we wish to vary the light source intensities during the day, either by dimming or by switching light sources on and off.

The illuminance E_j on a work surface j is found by summing the contributions of each of the light sources, and is given by

$$E_j = \sum_{i=1}^{n} c_{ij} a_i I_i \quad (1)$$

where n is the number of light sources, I_i is the maximum intensity of light source i, a_i is the controlled proportion of maximum intensity for light source i, and the coefficient c_{ij} determines the contribution of light source i to the illumination of work surface j. The coefficients c_{ij} should take into account both direct and reflected illumination, and can be found using typical lighting design software such as DIALux (8).

ISBN: 978-988-14048-6-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Suppose we know how much illuminance is required on each work surface. We wish to control the intensity of each light source to provide the necessary illumination with minimum power.

We assume that the lamps have constant luminous efficacy, so that the power, in watts, required for each light source is proportional to its intensity, in lumens; minimising power is then equivalent to minimising the total intensity of the lamps. (9) show that the luminous efficacy of example white phosphor-coated LEDs controlled with pulse width modulation is almost constant until dimming drops below about 20%, and that that luminous efficacy can increase as the LED is dimmed using constant current control.

The objective is

$$\text{minimise} \sum_{i=1}^{n} a_i I_i \tag{2}$$

subject to the constraints

$$\sum_{i=1}^{n} a_i c_{ij} I_i \geq \hat{E}_j \quad j \in \{1 \ldots m\} \tag{3}$$

where $\hat{E}_j$ is the illuminance required on work surface j. The illuminance requirements will depend on whether the work surface is in use or not, and the tasks for which it is being used. We assume that the lighting has been designed so that any reasonable set of illuminance requirements can be met. In the case where the room is also illuminated by daylight, the parameter $\hat{E}_j$ represents the additional illuminance required on a work surface to supplement the existing daylight.

If the light sources are dimmable then the variables to be determined are $a_i \in [0, 1]$. The other factors in Equations (2) and (3) are known parameters, and so the problem is a linear program.

If the light sources are non-dimmable then they can be either on or off, and we have $a_i \in \{0, 1\}$. In this case the problem is an integer linear program.

III. Simulation and results

To simulate the problem we choose a real-time office platform which has three office desks and six lighting fixtures. The desks, equipped with computers, are the most relative work surfaces for the working personnel. Light sources are used to provide light to various work surfaces in the room. Let the lighting source denotes as LS and the each work surface denotes as WS. Each work surface WS has an illumination requirement that is met by the light coming from various light sources. Each work surface is 0.75 m above the floor. The light sources are in the ceiling, 2.4 m above the floor. Figure 1 shows the plan view of the open-plan office, showing three work surfaces (WS) in square shape and six light sources (LS) in circle shape. 3x14W OSRAM DEDRA plus T5 DALI WIELAND lighting fixture is considered in developing the solution, which will have a maximum intensity of 1000 lumens. The lamps will have a maximum intensity of 1000 lumens. We will consider both dimmable and non-dimmable lamps.

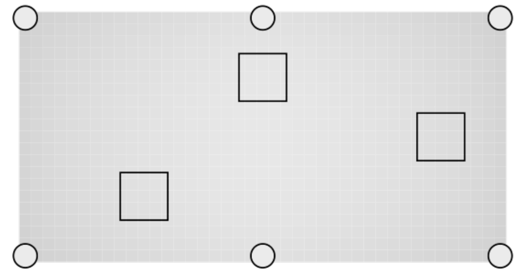

Fig. 1. Example office layout, with three work surfaces (squares) and six light sources (circles).

The light sources are numbered 1–3 along the southern wall from west to east, and 4–6 along the northern wall from west to east. A set of 3D coordinates is assumed to describe the location of each LS

(0, 0, 2.8) (2, 0, 2.8) (4, 0, 2.8)
(2, 2, 2.8) (2, 2, 2.8) (4, 2, 2.8).

The work surfaces (WS) are numbered 1–3 from west to east, and have coordinates

(1, 0.5, 0.75) (2, 1.5, 0.75) (3.5, 1, 0.75).

The coefficients of illumination for the example office are given in Table I.

Table II gives the illuminance requirements for three different scenarios. The first scenario has all three work surfaces in use, with an illumination requirement of 250 lux at each work surface. The second and third configurations each correspond to a partially occupied office. We assume that there is no sunlight in the office, so these illumination requirements must be met from the six artificial light sources only.

We solved the linear and integer linear programs using the Excel LP Simplex solver. Each problem solved in a few seconds—fast enough for a real-time control system.

Figure 2 shows the illuminance of the room at a height of 0.75 m for each of the scenarios, with optimal dimmming. Table III summarises the results with optimal dimming.

Figure 3 shows the illuminance of the room at a height of 0.75 m for each of the scenarios, with optimal switching instead of dimming. Table IV summarises the results with optimal switching. These solutions are not necessarily unique.

IV. Implementation and automation

The optimal control of the lighting for an office could be automated using the following components:

- controlled lights (dimmable or switchable)
- sensors to detect the occupancy of different zones within the space
- light sensors to detect the amount of daylight illumination in different zones within the room
- a controller that monitors the activity sensors and light sensors, then controls the lights accordingly.

ISBN: 978-988-14048-6-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE I
ILLUMINANCE COEFFICIENTS FOR SIX LIGHT SOURCES AND THREE WORK SURFACES.

	WS1	WS2	WS3
LS1	0.16101	0.06066	0.02812
LS2	0.16101	0.12507	0.10076
LS3	0.04155	0.06066	0.16101
LS4	0.10076	0.08342	0.02812
LS5	0.10076	0.21820	0.10076
LS6	0.03375	0.08342	0.16101

TABLE II
ILLUMINATION REQUIREMENTS FOR THREE SCENARIOS.

scenario	$\hat{E}_1$	$\hat{E}_2$	$\hat{E}_3$
1	250	250	250
2	0	250	250
3	0	0	250

TABLE III
OPTIMAL ILLUMINATION WITH DIMMING.

scenario	a_1	a_2	a_3	a_4	a_5	a_6	lumens	E_1	E_2	E_3
1	0.66	1.00	1.00	0.00	1.00	0.22	2327	250	277	250
2	0.00	0.65	0.55	0.00	1.00	1.00	1923	157	250	250
3	0.00	0.00	1.00	0.00	0.94	1.00	1764	102	209	250

TABLE IV
OPTIMAL ILLUMINATION WITH SWITCHING.

scenario	a_1	a_2	a_3	a_4	a_5	a_6	lumens	E_1	E_2	E_3
1	1	0	1	1	1	1	3000	263	304	287
2	0	0	1	1	1	1	2400	166	267	271
3	0	1	1	0	0	1	1800	142	161	254

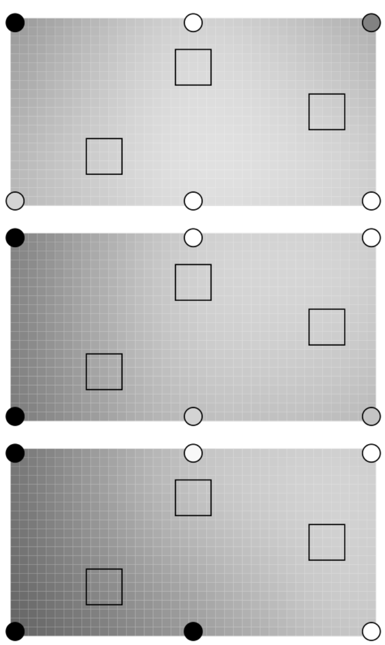

Fig. 2. Illuminance for scenarios 1–3 with optimal dimming.

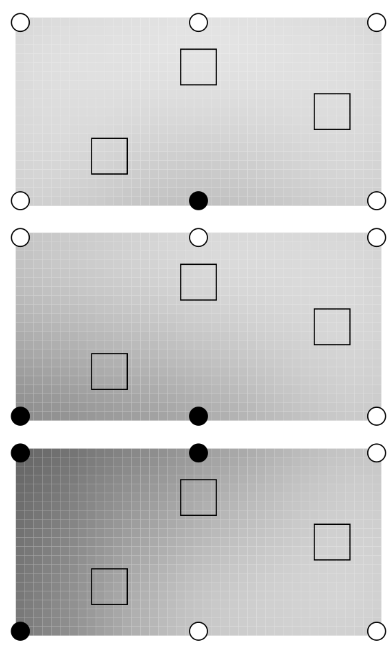

Fig. 3. Illuminance for scenarios 1–3 with optimal switching.

ISBN: 978-988-14048-6-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Ideally, each work surface would have an individual occupancy sensor and an individual light sensor. In practice, this may not be feasible.

Activity sensors in the space should be arranged so that activity at any of the work surfaces in the space will be detected. On the other hand, we want to minimise the number of work surfaces detected by any given activity sensor to avoid including inactive work surfaces in the lighting calculations. We also want to minimise the number of sensors that detects activity at a given work surface, once again to avoid including inactive work surfaces in the lighting calculations.

We assume that the space has n_{a} activity sensors, and that A_k is the set of work surface numbers covered by activity sensor $k \in \{1, \ldots, n_{\mathrm{a}}\}$. Every work surface number must be included in at least one of the sets A_k. For our example office with three work surfaces, we might have two activity sensors with

$$A_1 = \{1, 2\},\ A_2 = \{3\}.$$

Light sensors can be used to measure the amount of light in various zones of the room, and can be used to correct for daylighting. As with activity sensors, there will not always be an individual light sensor for each work surface.

In our problem formulation, the parameter $\hat{E}_j$ represented the additional illumination required on work surface j, given the daylight illumination. We cannot directly measure daylight illumination if there are lights on, but we can detect whether there is too much illumination on a work surface due to unexpected daylight and then reduce $\hat{E}_j$.

Unlike an activity sensor, a light sensor will provide some measure of how much light there is in a zone. If the work surfaces in a zone will receive different amounts of daylight, the light sensor should be focussed on the work surface in the zone that will receive the least daylight. This will ensure that all active work surfaces in the zone receive at least the required illuminance, though some may receive more than required.

As with activity sensors, we assume that the space as n_{l} light sensors and that L_l is the set of work surface numbers in the zone l covered by light sensor l. For our example office with three work surfaces, we might have two light sensors with

$$L_1 = \{1\},\ L_2 = \{2, 3\}.$$

The lighting control algorithm must have the following information:

- the maximum intensity I_i of each light source i
- the illumination $\hat{E}_{j1}$ required at each work surface j when there is activity at the work surface
- the illumination $\hat{E}_{j0}$ required at each work surface j when there is no activity at the work surface
- the coefficient c_{ij} that specifies the contribution of light source i to work surface j
- the set $A = \{A_1, A_2, \ldots, A_{n_{\mathrm{a}}}\}$, where the set A_i specifies the work surfaces detected by movement sensor i.
- the set $L = \{L_1, L_2, \ldots, L_{n_{\mathrm{l}}}\}$, where the set L_l specifies the work surfaces in light sensor zone l.

Given this information, the Algorithm 1 continuously estimates the daylight on each work surface and adjusts the lighting to ensure that each desk has the required illuminance:

Algorithm 1 Lighting control

```
for each work surface j do
  set the initial daylight estimate D_j = 0
end for
loop
  for each work surface j do
    if there is activity at work surface j then
      set Ê_j = Ê_j1
    else
      set Ê_j = Ê_j0
    end if
  end for
  solve the (integer) linear program to determine the required intensity for each light source i
  for each light sensor zone l do
    measure the illuminance E*_l from light sensor l
    determine the excess illuminance E_l in zone l
    subtract E_l from D_j for all work surfaces j in zone l
  end for
end loop
```

There is activity at a work surface j if $j \in A_k$ for any activity sensor k that is measuring activity.

The excess illuminance E_l in zone l is

$$E_l = \min\{E_l^* - \hat{E}_j | j \in L_l\}$$

The lighting control algorithm could be implemented using any microcontroller that can solve the linear program. For example, it could be implemented on a small Linux microcontroller, such as a Raspberry Pi, using a solver such as GLPK or MiniZinc. The application software could be written in any standard language supported by the Linux hardware.

V. Related Literature

Other authors have considered the problem of how to control indoor lighting to reduce energy use while still meeting user requirements for illumination.

(10) describe a rule-based controller that controls a window blind and a single indoor light source to manage heat and light in an office.

(11) use wireless sensor networks for a lighting system designed to meet user preferences and reduce energy use. They noted that occupant's lighting preferences change as their activities change, and with changes in daylighting during the day. They formulate a problem where the 'utility' of every combination of lamp intensities is known for each user and for the building operator, and use a distributed optimisation method to maximise the sum of user and building utilities. A difficulty with this method is constructing the utility functions.

(12) suggest the use of wireless work-plane illuminance sensors as a cheaper alternative to wired sensors when retrofitting

daylighting systems to existing buildings, and estimate lighting energy savings of 30% by using daylighting.

The integration of daylighting is also explored by (13). They also found that retrofitting wired control systems was not viable, and that poorly-positioned photosensors resulted in inaccurate measurement of work surface illumination. They propose a system based on a dense network of distributed desktop sensors which are used to control lamps to keep the desktop illumination at the required levels, but they do not describe a method for deciding how lamps should be dimmed to achieve the desired illuminance on each desk.

Prediction and modelling of daylighting is discussed by several authors (14; 15; 16).

(17) describe a system where each lighting unit has sensors for measuring occupancy and illumination of the area to be illuminated by the lamp. If a lighting unit is unable to provide sufficient illumination in an area, it communicates with adjacent units to turn on adjacent lamps.

(18) report that around 30% of office building lighting energy used in USA is wasted energy. They describe a wireless tool—LightWiSe (Lighting Evaluation through Wireless Sensors)—which measures occupancy and lighting and calculates energy waste, but does not control the lights.

(19) surveyed projects that use occupant sensing for building control. They report that interior lighting consumes 25% of office energy in the USA, and 19% in Japan. They review a list of projects related to energy savings in offices and discuss different systems that take into account and user preferences and occupancy, but do not provide detailed analysis of control techniques. They do acknowledge the necessity for more research on lighting control techniques for energy-efficient buildings.

VI. Conclusion

Energy used for office lighting can be reduced by taking into account illumination from daylight and occupancy of work surfaces, and then optimising the intensity of light sources to meet the illumination requirements with minimum energy. Illumination requirements for each work surface are required for two scenarios: when the work surface is occupied, and when it is not occupied. Illumination requirements for an occupied work surface could potentially be varied by the user as their requirements change.

Our problem formulation takes into account the contribution of each light source to each work surface. We use a linear program to solve the optimisation problem with dimmable light sources, and a integer linear program to solve the problem with non-dimmable light sources.

We have also described a real-time algorithm, suitable for implementation on a small microcontroller, that measures occupancy, estimates daylighting, and calculates the optimal light source intensities.

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ISBN: 978-988-14048-6-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

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ISBN: 978-988-14048-6-2
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