Optimal Demand Response Capacity of Automatic Lighting Control

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***Abstract*—Demand response programs seek to adjust the normal consumption patterns of electric power consumers in response to incentive payments that are offered by utility companies to induce lower consumption at peak hours or when the power system reliability is at risk. While prior studies have extensively studied the capacity of offering demand response in buildings by controlling the load at air conditioners, water heaters, and various home appliances, they lack to offer methods to also utilize the full demand response capacity of automatic lighting control systems. Since lighting systems consume a large amount of the total energy used in buildings, addressing this shortcoming is an important research problem. Therefore, in this paper, we propose to take a systematic optimization-based approach to assess demand response capacity of automatic lighting control systems in commercial and office buildings.**

***Keywords*: Demand response, automatic lighting control, commercial and office buildings, dimming control, user comfort, convex optimization.**

I. Introduction

To achieve a high level of reliability in power systems, the power grid is usually designed based on the peak demand rather than the average demand. This results in waste of resources and an increasing cost of expansion to meet the growing demand. To remedy this problem, different demand side management programs have been proposed to shape the energy consumption pattern of the users in order to use the available generating capacity more efficiently without installing new generation and transmission infrastructure. In particular, demand response programs are implemented by utility companies to encourage users to reduce their load at peak hours or when the power system reliability is at risk. Examples for recent studies to design efficient demand response programs for the smart grid include [1]–[6] that seek to control the electric load at air conditioners, water heaters, and various home and office appliances.

Recent studies have shown that about 14% of the electric usage in residential buildings and also about 35% of the electric usage in commercial buildings is for lighting purposes [7]. In particular, it was estimated that an annual total of 499 billion kilowatt-hours (kWh) electricity was consumed in various lighting systems in the year of 2010 [8]. Therefore, it is important to examine the capacity of building lighting systems in offering load conservation as well as demand response.

In [9], the authors identified the current market drivers and technology trends that can improve the demand responsiveness of commercial building lighting systems. They also provided an overview of the energy, demand, and environmental benefits of implementing lighting demand response and energy-saving controls strategies in the state of California. The promising results of implementing an automated light control system testbed for demand response in a large Southern California Edison's office space was reported in [10]. More recently, the authors in [11] examined the potential to reduce the load for lighting systems to offer demand response by deploying distributed lighting system controllers. The key idea is to shed load proportionally among multiple lighting control groups in a building. While the focus in [9]–[11] is to benefit from the load flexibility of lighting systems for the purpose of demand response, there is also a wide range of more general studies that focus on energy conservation of lighting systems using occupancy sensors and daylight dimming, e.g., in [12], [13].

In this paper, we propose to use optimization and utility theories to assess the demand response capacity of automatic lighting control systems in commercial and office buildings. Our system model significantly extends the one in [11] as it takes into account the exact building layout, the location, power consumption, and illumination level of luminaries, information collected from daylight and occupancy sensors, the minimum and maximum illumination requirements of each spot on the layout based on the type of usage, user comfort that is modeled in form of user-specific utility functions, the coefficient of daylight utilization, and dimming control capabilities of the installed luminaries. We show that the formulated optimization problems are convex; therefore, computationally tractable. Using computer simulations, we investigate the optimal demand response capacities for different demand response scenarios.

The rest of this paper is organized as follows. The system model and the techniques to calculate illumination as a function of lighting power consumption are explained in Section II. Our optimization-based demand

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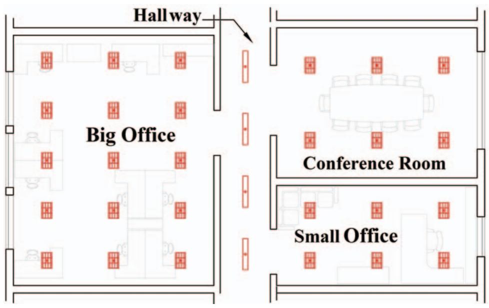
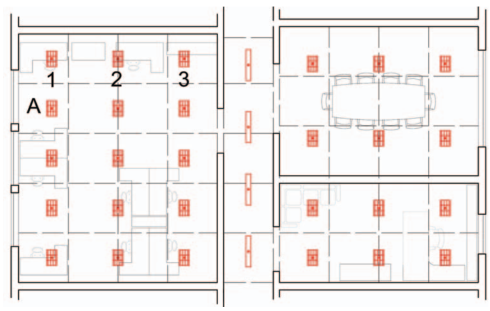


(a)



(b)

Fig. 1. An example office building. (a) The floor plan and layout. The electric lights in each room are shown in red rectangles. The natural daylight comes through the windows at both sides of the building. (b) Dividing the layout into several small square spots.

response framework for automatic lighting control is proposed in Section III. Numerical results are discussed in Section IV. The paper is concluded in Section V.

II. System model

Consider the floor plan in a commercial building, e.g., with research labs or office spaces with cubicles. An example is shown in Fig. 1(a). In this example, there are $3 \times 5 = 15$ electric lights in the larger room, 4 electric lights in the hall way, and $2 \times 3 = 6$ electric lights in each smaller room. For the ease of purpose of modeling illumination, we divide the layout into several small square spots, as shown in Fig. 1(a). As an example, each spot can be 2 meters by 2 meters. Let $\mathcal{L}$, with cardinality L, denote the set of all electric lights on each floor. For the example in Fig. 1, we have $\mathcal{L} = \{1, \ldots, 31\}$, where each number serves as an index for each of the $L = 15 + 4 + 6 + 6 = 31$ electric lights that we can see in this figure. We denote the power consumption for each light $i \in \mathcal{L}$ by P_i. Assuming that a dimming system is being used, for each electric light i, we have $0 \leq P_i \leq P_i^{\max}$, where $P_i^{\max} > 0$ denotes the light's power consumption at *full illumination*. Clearly, the total electric power consumption of the lighting systems in the whole building can be obtained as

$$P_{\text{total}} = \sum_{i \in \mathcal{L}} P_i. \tag{1}$$

Let $\mathcal{S}$, with cardinality S, denote the set of all square spots on the layout. If these square spots are small enough, we can assume that illumination is equal across the each spot. Therefore, for each square spot $A \in \mathcal{S}$, illumination can be represented by a single number I_A. Clearly, the illumination at each spot depends on the candle power and location of electric lights in the building (thus their power consumption) as well as the presence and amount of daylight. In this regard, we have

$$I_A = f_A(P_1, \ldots, P_L, w), \tag{2}$$

where f_A is an $S + 1 \times 1$ function and w is a daylight parameter indicating the exterior vertical illumination of sunlight. The exact shape of function f_A depends on the type of electric light that are installed in the building. However, for most practical lights, such as fluorescent, mercury vapor, metal halide, and light-emitting diode lamps, function f is linear [14]. Therefore, we have

$$f_A(P_1, \ldots, P_S, w) = \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A. \tag{3}$$

Next, we explain how $\alpha_{A,i}$ and β_A can be calculated for each layout spot $A \in \mathcal{S}$ and each electric light $i \in \mathcal{L}$.

First, we calculate parameter $\alpha_{A,i}$ using the *inverse square law* [15], which is a popular tool to calculate the illumination at a specific point. Consider Fig. 2 with one light source i and a small square spot A. Let $H_{A,i}$ and $D_{A,i}$ denote the vertical distance and the horizontal distance between the light source i and square spot A, respectively. Let C_i denote the light intensity, in *candle power*, of light source i. The illumination at square spot A caused by light source i can be calculated as

$$I_{A,i} = \frac{C_i \cos^3(\theta_{A,i})}{H_{A,i}^2} = \frac{C_i\, H_{A,i}}{(D_{A,i}^2 + H_{A,i}^2)^{1.5}}. \tag{4}$$

While the term $H_{A,i}/(D_{A,i}^2 + H_{A,i}^2)^{1.5}$ is constant, the light intensity C_i depends on the dimming position of the light source i. Therefore, it directly depends on the power consumption level P_i. The exact relationship depends on the type of lighting technology. An example intensity versus power consumption curve for a T-8 Fluorescent lamp is shown in Fig. 3. We can see that the curve is in fact linear. Therefore, we can write $C_i = \gamma_i P_i + \kappa_i$, where γ_i denotes the slop and κ_i denotes the y-intercept of the intensity versus power consumption curve for light source i. For the example in Fig. 3, we have $\gamma_i = 0.89$ and $\kappa_i = 14.87$. Together, from (3) and (4), we have

$$\alpha_{A,i} = \frac{\gamma_i\, H_{A,i}}{(D_{A,i}^2 + H_{A,i}^2)^{1.5}}. \tag{5}$$

We note that parameter $\alpha_{A,i}$ depends only on the type of light source i and the locations of the light source i and square spot A. From (3) and (4), we also have

$$\lambda_A = \sum_{i \in \mathcal{L}} \frac{\kappa_i\, H_{A,i}}{(D_{A,i}^2 + H_{A,i}^2)^{1.5}}. \tag{6}$$

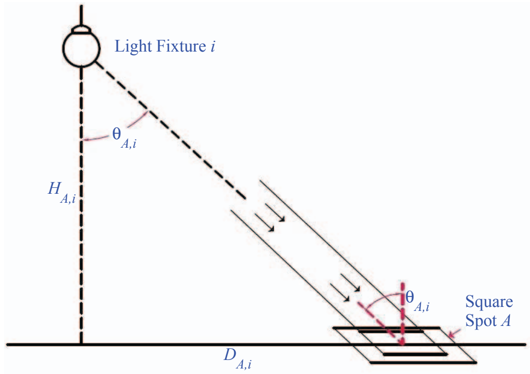


Fig. 2. The use of the inverse square law to calculate illumination at a specific point in presence of a single light source [15].

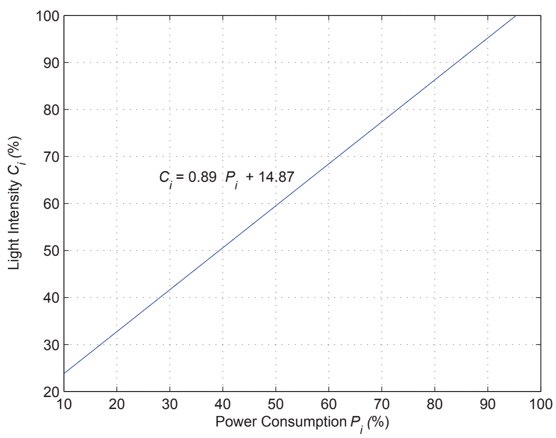


Fig. 3. An example light intensity versus power consumption for a T-8 Fluorescent lamp [14, Chapter 27]. Using automated dimming switches we can move along the line of this curve.

Next, we calculate parameter β_A. In general, buildings can get sun light from both roof top and side windows. However, since most buildings only have side windows, we focus on calculating the daylight illuminance of side lighting. Furthermore, for the ease of presentation, we assume that each room may have windows only on one side of the room. Recall that w denote the exterior vertical illumination of sunlight. This parameter can be measured using a single roof top daylight sensor. The illumination at square spot A that is caused by sun light through a side window can be calculated as

$$I_{A,w} = \tau_A\, \phi_A\, w, \tag{7}$$

where τ_A denotes the net transmittance of the window wall and ϕ_A is the coefficient of utilization that depends on the height and width of the side window and the depth of spot A from the side window. Clearly, if spot A is deeper inside the room or the height and width of the window are smaller, a lower coefficient of utilization is obtained. The exact value of the coefficient of utilization can be looked up using, e.g., Table I. In this table, the first column, with numbers ranging from 1 to 3, indicates the ratio between the room depth and window height. Given such ratio, the second column indicates the depth of spot A in percentage of the total room depth. The next five columns denote the ratio of the width to height of the window. As an example, consider a room which is 6 meters deep and has one window. The window is 2 meters high and 4 meters wide. At a spot which is 3 meters away from the side window, we have $\phi_A = 0.164$. From (3) and (7), and by using Table I, we have

TABLE I
COEFFICIENT OF UTILIZATION FOR DAYLIGHT [14, CHAPTER 8]

Room depth / Window height	Depth (%)	Windiw width/Window height .5	1	2	3	4
1	10	.503	.528	.536	.541	.544
	30	.359	.464	.514	.528	.534
	50	.261	.384	.471	.499	.508
	70	.204	.325	.432	.470	.485
	90	.179	.295	.412	.456	.475
2	10	.412	.477	.490	.492	.493
	30	.201	.304	.379	.402	.410
	50	.115	.192	.269	.304	.320
	70	.078	.136	.204	.241	.261
	90	.066	.117	.183	.221	.246
3	10	.331	.426	.458	.461	.462
	30	.121	.202	.275	.304	.316
	50	.062	.109	.164	.193	.209
	70	.041	.073	.114	.138	.154
	90	.035	.062	.099	.123	.141

$$\beta_A = \tau_A\, \phi_A. \tag{8}$$

We note that parameter β_A depends only on the size and type of spot A's nearby window and the distance between spot A and its nearby window.

By using equations (1) to (8), we can accurately map the vector of electric lights power consumption

$$\mathbf{P} = (P_i,\ \forall i \in \mathcal{L}) \tag{9}$$

to the matrix of square spot illuminations

$$\mathbf{I} = (I_A,\ \forall A \in \mathcal{S}). \tag{10}$$

We will use this mapping in the next section to formulate an optimization framework to calculate the demand response capacity of automatic lighting control systems.

III. Optimal Demand Response Capacity

Demand response programs seek to adjust the normal consumption patterns of electric power consumers in response to load reduction requests and incentive payments that are offered by utility companies to induce lower consumption at peak hours and when the power system reliability is at risk. Let ΔP denote the amount of load reduction that is requested by the utility company. In this section we seek to answer two questions:

- What is the feasible range of ΔP that an automatic lighting control in a building can support?

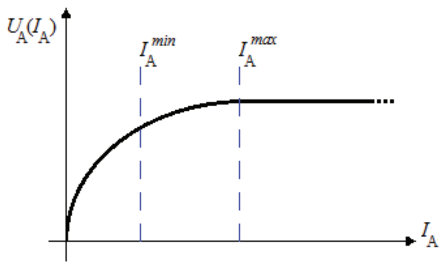


Fig. 4. An example for a utility function that describes the users lighting comfort in an occupied square spot A.

- What is the best way to reduce the power consumption of the lighting systems across the building to reduce the total building's load by ΔP?

The key to answer the above two questions is to understand the trade-off between users' comfort and power consumption in the lighting system. In this regard, we propose to obtain a quantitative measure to assess users' comfort in each square spot $A \in \mathcal{S}$ in the building based on the amount of illumination at that spot. This can be done by using the concept of utility functions from utility theory [16]. Let utility function $U_A(I_A) \geq 0$ denote a user's comfort level who is using square spot A, given the available illuminance at spot A. Of course, the utility function for each spot depends on what the user is doing in that spot and the room layout. If a square spot is not occupant at a time of day, then we have

$$U_A(I_A) = 0, \quad \forall I_A \geq 0. \tag{11}$$

The occupancy can be measured using various occupancy sensors that are commonly used in automated lighting systems in building [14, Chapter 27]. If a square spot is indeed occupied, then the utility function is expected to be an increasing and concave function of illuminance. An example is shown in Fig. 4. In general, as more illumination is provided, the user becomes more comfortable. However, in order to allow user to do its job, there is a *bare minimum* illumination that is needed to be provided, which is denoted by I_A^{min}. Yet, providing more illumination is still desirable for the user to give him/her more comfort. However, increasing illumination beyond a certain point, denoted by $I_A^{max} > I_A^{min}$ is no longer giving additional comfort level to the user as amount of illumination at this point is already enough. This is the point where the utility function is saturated.

To assure maximum comfort of users, the automated lighting control system should be designed such that for each occupied square spot $A \in \mathcal{S}$ in the building, we have $U_A(I_A) = I_A^{max}$. In order to achieve this goal, the power consumption of the lighting systems will be at

$$\begin{aligned} P_{total}^{max} = \underset{\mathbf{P}}{\textbf{minimum}} \quad & \sum_{i \in \mathcal{L}} P_i \\ \textbf{subject to} \quad & \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A \geq I_A^{max}. \end{aligned}$$

In fact, this is the amount of power consumed by the lighting system in the building in *normal* conditions, i.e., when the building is *not* offering demand response services. However, in case the building *does* receive a load reduction request from the utility company, it can choose to reduce its total lighting load to the following level while still maintaining the minimum required illumination at each occupied square spot in the building:

$$\begin{aligned} P_{total}^{min} = \underset{\mathbf{P}}{\textbf{minimum}} \quad & \sum_{i \in \mathcal{L}} P_i \\ \textbf{subject to} \quad & \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A \geq I_A^{min}. \end{aligned}$$

Therefore, a load reduction request ΔP from the utility company can be supported if and only if we have

$$0 \leq \Delta P \leq P_{total}^{max} - P_{total}^{min}. \tag{12}$$

The above expression answers the first question that we had raised at the beginning of this section.

Next, assume that the automated lighting control system in a building receives a load reduction request ΔP which *can* be supported. In particular, assume the non-trivial case where $\Delta P \neq P_{total}^{max} - P_{total}^{min}$. In that case, we propose to select $\mathbf{P}$ as the optimal solution of the following *aggregate utility maximization* problem:

$$\begin{aligned} \underset{\mathbf{P}}{\textbf{maximize}} \quad & \sum_{A \in \mathcal{S}} U_A \left(\sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A \right) \\ \textbf{subject to} \quad & \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A \geq I_A^{min}, \\ & \sum_{i \in \mathcal{L}} P_i = P_{total}^{max} - \Delta P. \end{aligned} \tag{13}$$

The above optimization problem answers the second question that we had raised at the beginning of this section. The second constraint in (13) assures that the total power consumption in the system will be reduced from its normal level by ΔP. The first constraint in (13) assures that all square spots will be provided will their minimum required illumination. The objective function in (13) can be interpreted as the *social welfare*, as far as users' comfort with respect to illumination is concert, across all square spots in the building. Therefore, maximizing the objective function in (13) means increasing illumination, and thus comfort level, across the building in a manner that is fair to all current occupants of the building. Of course, once the load reduction request from the utility company is withdrawn, the total power consumption and illumination levels can go back to the normal condition, where $U_A(I_A) = I_A^{max}$. To avoid any potential for frequent change of the illumination levels in the building, which could cause some extra discomfort for users, the system can be designed not to accept two load reduction requests that are less than a certain number of hours apart from each other.

As an example for the choice of utility function, we propose to use the following partly logarithmic function:

$$U_A(I_A) = \begin{cases} \log(1 + I_A), & \text{if } I_A < I_A^{max}, \\ \log(1 + I_A^{max}), & \text{if } I_A \geq I_A^{max}. \end{cases} \tag{14}$$

The above function is concave. It is increasing when $I_A \in [0, I_A^{max})$. It is saturated at $I_A = I_A^{max}$. After reordering the terms, we can rewrite the utility function in (14) as

$$U_A(I_A) = \min\left\{\log(1 + I_A),\ \log(1 + I^{m}ax_{A})\right\}. \tag{15}$$

From (15), if $I_A < I_A^{max}$, then $\log(1+I_A) < \log(1+I_A^{max})$ and we have $U_A(I_A) = \log(1 + I_A)$. If $I_A \geq I_A^{max}$, then $\log(1 + I_A) \geq \log(1 + I_A^{max})$ and we have $U_A(I_A) = \log(1 + I_A^{max})$. Therefore, the utility functions in (14) and (15) are indeed the same. By replacing (15) in (13), the aggregate utility maximization problem becomes

$$\begin{aligned} \underset{\mathbf{P}}{\textbf{maximize}} \quad & \sum_{A \in \mathcal{S}} \min\Bigg\{\log\Bigg(1 + \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i \\ & \qquad + \beta_A w + \lambda_A\Bigg), \log\left(1 + I_A^{max}\right)\Bigg\} \\ \textbf{subject to} \quad & \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A \geq I_A^{min}, \\ & \sum_{i \in \mathcal{L}} P_i = P_{total}^{max} - \Delta P. \end{aligned} \tag{16}$$

By introducing an auxiliary variable v_A for each square spot $A \in \mathcal{S}$, we can rewrite problem (16) as

$$\begin{aligned} \underset{\mathbf{P}, \mathbf{v}}{\textbf{maximize}} \quad & \sum_{A \in \mathcal{S}} v_A \\ \textbf{subject to} \quad & \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A \geq I_A^{min}, \\ & \sum_{i \in \mathcal{L}} P_i = P_{total}^{max} - \Delta P, \\ & v_A \leq \log\left(1 + \sum_{i \in \mathcal{L}} \alpha_{A,i} P_i + \beta_A w + \lambda_A\right), \\ & v_A \leq \log\left(1 + I_A^{max}\right), \end{aligned} \tag{17}$$

where $\mathbf{v} = (v_A,\ \forall A \in \mathcal{S})$. While problems (16) and (17) are *not* exactly the same, yet they are *equivalent*, i.e., they both lead to the *same* optimal solutions [17, Chapter 4]. Therefore, one can solve one problem and it readily gives the solution for the other problem. Since optimization program (17) is a *convex program*, it can be solved efficiently using various convex programming techniques such as the interior point method (IPM) [17].

IV. Numerical Results

In this section, we assess the performance of the proposed optimal demand response capacity planning for automatic lighting systems. Consider the layout in Fig. 1. First, we would like to obtain the feasible range for demand response parameter ΔP based on the model in (12), where P_{total}^{max} and P_{total}^{min} are as explained in

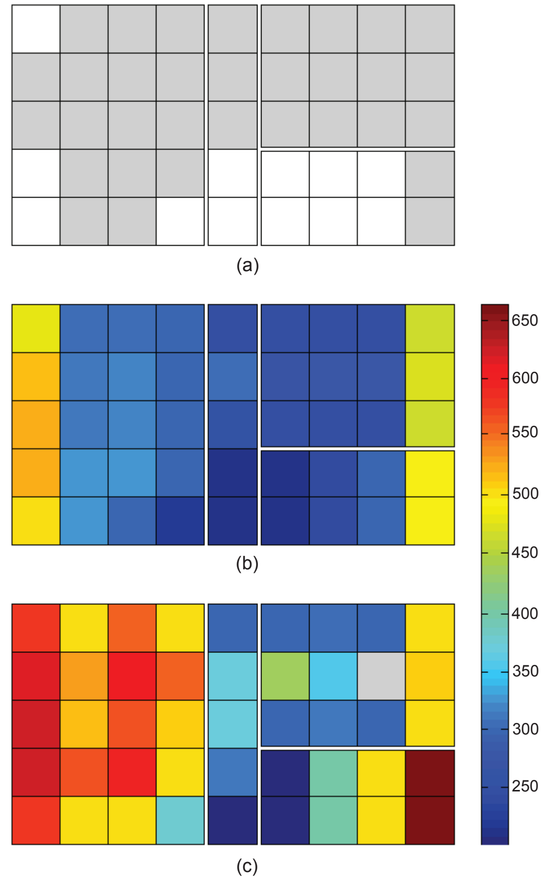


Fig. 5. Automatic lighting control for the layout in Fig. 1 with four rooms, one hallway, and a total of $5 \times 9 = 45$ square spots. (a) Floor occupancy where gray spots are occupied and white spots are not occupied. (b) Illumination I_A in lux at each spot $A \in \mathcal{S}$ where the total power consumption $P_{total} = P_{total}^{min}$. (c) Illumination I_A in lux at each spot $A \in \mathcal{S}$ where the total power consumption $P_{total} = P_{total}^{max}$. In this example, ΔP can be up to 267 watts.

Section III. For each square spot $A \in \mathcal{S}$ and each light fixture $i \in \mathcal{L}$, parameters $\alpha_{A,i}$, β_A, and λ_A are calculated following the detailed discussions in Section II. We assume that the exterior vertical illumination on the window wall from sunlight is $w = 750$ lux. The choice of parameters I_A^{max} lux and I_A^{min} lux follow the standards in lighting engineering and depend on the type of room [14, Chapter 10]. In our simulations, they are selected as follows. For any occupied spot in the big office, we have $I_A^{min} = 300$ lux and $I_A^{max} = 500$ lux. Similarly, for any occupied spot in the small office, we have $I_A^{min} = 300$ lux and $I_A^{max} = 500$ lux. For any occupied spot in the conference room, we have $I_A^{min} = 250$ lux and $I_A^{max} = 300$ lux. For any occupied spot in the hallway, we have $I_A^{min} = 150$ lux and $I_A^{max} = 200$ lux. For all lights $i \in \mathcal{S}$, we have $P_i^{max} = 96$ watts and $C_i^{max} = 1700$ candle powers. Assume that the floor occupancy, detected by the occupancy sensors, is as shown in Fig. 5(a). In that case, illumination at the $9 \times 5 = 45$ square spots on the layout can be calculated as shown in Fig. 5(b), where the total power consumption

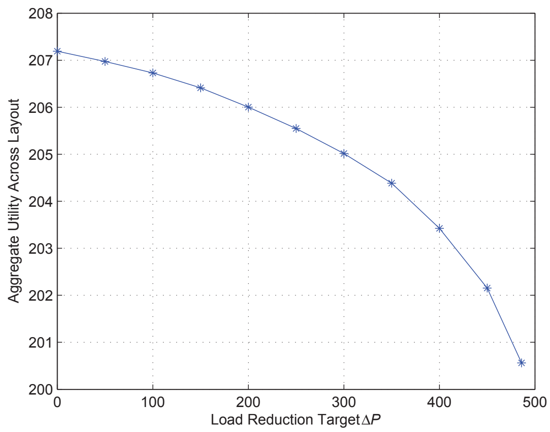


Fig. 6. Aggregate utility of all occupied spots across the layout in Fig. 1 versus the demand response load reduction target ΔP.

$P_{total} = P_{total}^{min}$, and in Fig. 5(c), where the total power consumption $P_{total} = P_{total}^{max}$. Note that, in this example, $P_{total}^{min} = 987$ watts and $P_{total}^{max} = 1,483$ watts. Therefore, we can conclude that the layout in Fig. 1 can support a demand response request in the following range:

$$0 \leq \Delta P \leq 496 \text{ watts.} \tag{18}$$

Comparing Fig.5(b) and (c), we can see that every square spot $A \in \mathcal{S}$, assuming that it is occupied, has at least I_A^{min} illumination for the case in Fig. 5(b) and has at least I_A^{max} illumination for the case in Fig. 5(c).

Next, we assess the trade-off between maximizing the users' comfort, in terms of utility functions, and fulfilling a higher demand response load reduction request. Again, we consider the layout in Fig. 1 and assume that all users have the modified logarithmic utility functions in (14). The results on the aggregate utility, i.e., the optimal objective of problem (17), versus the amount of load reduction ΔP are shown in Fig. 6. We can see that if $\Delta P = 0$, then aggregate utility is at its maximum level, i.e., the level that is expected in normal lighting when the automatic lighting control system does not receive any load reduction request. As ΔP increases, the aggregate utility decreases. This trend continues until ΔP reaches its upper bound in (18) at 496 watts. We note that if $\Delta P = 0$, then the illumination pattern will be as in Fig. 5(c). As ΔP increases, the illuminations will be decreases *fairly* across the layouts. Recall that the fairness property is a direct result of using the aggregate utility maximization approach. Once $\Delta P = 496$ watts, then the illumination pattern will be as in Fig. 5(b).

V. Conclusions

In this paper, we took a systematic approach, using utility theory and convex optimization, to assess the demand response capacity of automatic lighting control systems in commercial and office buildings. A wide range of design factors were taken into consideration, such as the building layout, the location, power consumption, illumination level, and dimming control capabilities of luminaries, information collected from daylight and occupancy sensors, the minimum and maximum illumination requirements of each spot on the layout based on the type of usage and user comfort according to existing lighting standards, and the coefficient of daylight utilization that depends on the building layout and the size of the side windows. The results show the significant potential of automatic lighting control systems in participating in demand response programs in form of responding to utilities' load reduction requests.

References

[1] H. Mohsenian-Rad and A. Leon-Garcia, "Optimal residential load control with price prediction in real-time electricity pricing environments," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 120–133, Sep. 2010.

[2] T. Masuta and A. Yokoyama, "Supplementary load frequency control by use of a number of both electric vehicles and heat pump water heaters," *IEEE Transactions on Smart Grid*, vol. 3, no. 3, pp. 1253–1262, Sep. 2012.

[3] K. Vanthournout, R. D'hulst, D. Geysen, and G. Jacobs, "A smart domestic hot water buffer," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, Dec. 2012.

[4] Y. Y. Hong, J. K. Lin, C. P. Wu, and C. C. Chuang, "Multi-objective air-conditioning control considering fuzzy parameters using immune clonal selection programming," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, Dec. 2012.

[5] M. Albadi and E. EI-Saadany, "A summary of demand response in electricity markets," *Electric Power Systems Research*, vol. 78, no. 2, pp. 1989–1996, Nov. 2008.

[6] H. Mohsenian-Rad, V. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Transactions on Smart Grid*, vol. 1, no. 3, pp. 320–331, Dec. 2010.

[7] Energy Information Administration, "Commercial Buildings Energy Consumption Survey," [Online] http://www.eia.gov/emeu/cbecs/cbecs2003/lighting/pdf/lighting_print.pdf.

[8] Energy Star, "Buildings & Plants, Chapter 6: Lighting," [Online] http://www.energystar.gov/ia/business/EPA_BUM_CH6_Lighting.pdf.

[9] F. Rubinstein and S. Kiliccote, "Demand responsive lighting: A scoping study," Berkelry, CA, 2007.

[10] California Energy Commission's Public Interest Energy Research Program, "Lighting the Way to Demand Response," Sacramento, CA, 2011.

[11] S. A. Husen, A. Pandharipande, L. Tolhuizen, Y. Wang, and M. Zhao, "Lighting systems control for demand response," in *Proc. of IEEE Conference on Innovative Smart Grid Technologies*, Washington, DC, Jan. 2012.

[12] Department of Energy - Federal Energy Management Program, "How to Select Lighting Controls for Offices and Public Buildings," [Online] http://www1.eere.energy.gov/femp/pdfs/light_controls.pdf, Dec. 2000.

[13] A. S. Choia, K. D. Songb, and Y. S. Kim, "The characteristics of photosensors and electronic dimming ballasts in daylight responsive dimming systems," *Building and Environment*, vol. 40, no. 1, pp. 39–50, Jan. 2005.

[14] M. S. Rea, *The IESNA Lighting Handbook Reference and Applications*, 9th ed. Illuminating Engineering Society of North America, New York, NY, 2000.

[15] J. L. Lindsey, *Applied Illumination Engineering*, 2nd ed. The Fairmont Press, Liburn, GA, 1996.

[16] D. Kreps, *Notes On The Theory Of Choice: Underground Classics in Economics*. Westview Press, May 1988.

[17] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.