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Intelligent Commercial Lighting: Demand-Responsive Conditioning and Increased User Satisfaction

Final Report Submitted to the UC Energy Institute, California Energy Studies Program

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1.0 Abstract

Energy efficiency has recently come to the forefront of energy debates, especially in the state of California. This focus on efficiency has been driven by the deregulation of electrical-energy distribution, the increasing price of electricity, and the implementation of rolling blackouts. Currently, buildings consume over 1/3 of primary energy, and 2/3 of all electricity produced in the U.S. Commercial buildings consume roughly half of this, and lighting is responsible for approximately 40% of commercial building energy use. These numbers indicate that research in lighting efficiency has great potential to positively impact energy efficiency.

Efficient lighting controls proven to save up to 45% in electricity consumption *are* commercially available. In practice however, these systems are poorly received and greatly under-leveraged, resulting in a missed opportunity for impressive energy savings. Accordingly, we proposed the three-phase extension of an intelligent decision framework that addresses two major shortcomings of today's energy-efficient lighting controls – user satisfaction, and lost energy savings stemming from naïve decision algorithms. The first phase of research was directed at enhancement of an existing preference-balancing control algorithm, in order that it accommodate demand-responsive control as well as the desires of the building manager. The second phase was devoted to identifying user preferences through empirical occupant testing. In the third phase, the resulting algorithms were simulated and evaluated.

Several facilities managers were interviewed and surveyed in order to identify appropriate variables and control policies to represent their desires within the decision algorithm. The preferred demand response strategy was found to be specific to the particular manager. Across all managers, energy was the most commonly selected indicator of the quality of lighting decisions. Automated occupant preference testing was conducted to demonstrate the feasibility of collecting such data in office environments, and to provide realistic occupant perceptions for use in simulation.

Simulated results indicate that the intelligent decision algorithm and framework present a promising control paradigm, and should be further expanded for the explicit inclusion of solar variables. Preliminary assessment showed that energy pricing can be factored into the control algorithm without significantly compromising occupant perceptions of lighting quality. Further energy savings are garnered by curtailing consumption during times of elevated pricing. Provided that curtailment is implemented with a slow enough dimming rate, reductions of up to 30% in illuminance are detected by roughly half of all occupants. Leveraging this research, the intelligent controller implements the specific demand response policy chosen by the facilities manager.

1.0 Introduction to Influence Diagrams

As the objective of this research was to refine and evaluate the influence diagram shown in Figure 1, we provide an overview of such decision models before reviewing the completion of the deliverables associated with each phase of research.

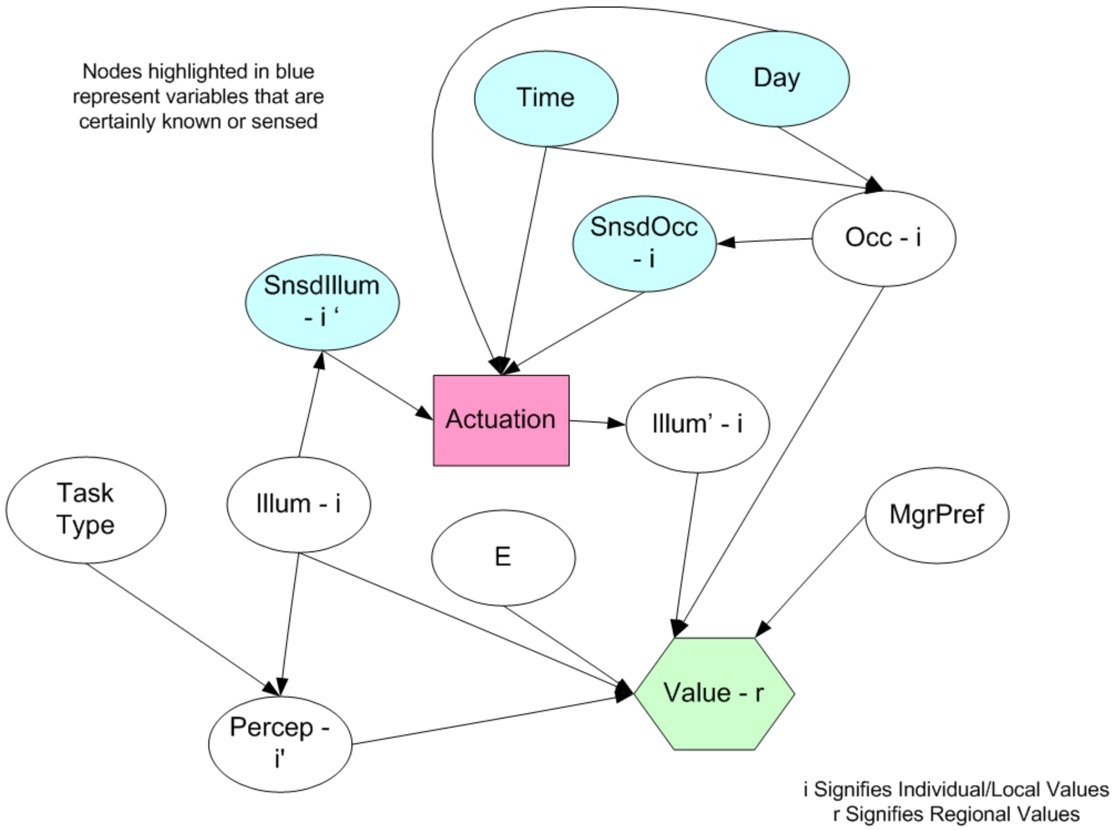

Figure 1: Initial Influence Diagram Lighting Model – Simplified Representation

An influence diagram is an acyclic directed network with nodes representing variables critical to the problem and arcs that represent their interrelationships. The general influence diagram model consists of three types of nodes: state, decision/control, and value nodes. Any variable in the system can be represented by a state node, shown graphically with an ellipse. In our model, state nodes include illuminance, occupancy, electricity rates, etc...

A decision, or control node represents the various decision options that are available, and is depicted as a square or rectangle. Here, the decisions correspond to voltages between zero and ten that are applied to the ballast to effect different dimming levels. The value node, shown as a hexagon, represents the value/cost function associated with the problem being modeled. In our case, the value function attempts to balance occupant and manager preferences, while improving energy efficiency. Ultimately, the optimal decision is that which maximizes the expected value of the cost function.

The interpretation of the relationships represented by the arcs in an influence diagram depends on the type of the nodes they connect. Arcs pointing to a decision node represent information available to the controller at the time the decision is to be made – i.e., all sensor values. Arcs going into state nodes represent potential *conditional influences*, while the lack of an arc states strongly that *no dependency* exists. Arcs entering the value node signify variables that appear in the value function, directly influencing the value of any decision. Any variable's value can be inferred from probabilistic knowledge of the parent nodes with arcs pointing into it. For example in the lighting model, knowledge of the day and time can be used to infer the state or value of occupancy – occupied or vacant.

2.0 Phase I: Facilities Manager Preferences and Energy Efficiency

The Phase I deliverables were motivated in part by a desire to ensure that the system have demand-responsive capabilities in alignment with current trends in building energy management and electricity pricing. Demand responsiveness refers to the ability to limit energy consumption during times of peak demand. As energy is most expensive when demand is at a maximum, implementing load shedding strategies that reduce consumption during these times of peak demand, can generate significant cost savings with respect to exiting daylighting systems. Limiting peak demand also has the potential to positively impact the environment, as most of the energy used in commercial buildings derives from fossil fuels, principally coal and natural gas. In addition, this set of deliverables is intended to increase user satisfaction with respect to existing daylighting systems, by specifically addressing the concerns of the facilities manager who is responsible for energy consumption, costs, and management.

Upon beginning the research detailed in this report, the topology of the influence diagram and the structure of the value function were defined with respect to balancing occupant preferences only. The portion of the decision problem concerning electricity rates and the desires of the building manager was yet to be formulated, and the model contained *placeholder* nodes for manager preference and electricity; their states and values were not yet determined. Similarly, the value function contained placeholder terms for energy consumption and building manager preferences. Accordingly, the first set of deliverables in Phase I involved expansion of the existing model to include the preferences of the facilities manager and a consideration of energy consumption.

The initial value function that was expanded throughout the course of this research is shown in below in Equation 1. The algorithm executed with this mathematical expression is summarized in the following 3 steps: 1) if the occupant perceives the lighting quality to be 'ideal,' her vote is to maintain the current setting; 2) if the occupant does *not* perceive the lighting to be ideal, her vote is to set the lights so that the resulting worksurface illuminance meets her 'ideal,' as determined in preference testing; 3) sum the votes over all occupants present, and minimize the collective deviation from the favored illuminance for each occupant. The reader is referred to Section 3.0 for a detailed discussion of occupant preference testing. Here it is noted that occupancy is assigned values of $\{0, \pm 1\}$ to provide a means of discarding the preferences of occupants who are not present at the time of the decision. Similarly, perception is assigned values of $\{0, \pm 1\}$ to ensure votes of maintain-current and match-ideal when the occupant's perception is ideal and non-ideal, respectively.

$$v = \lambda_o \sum_{i=1}^{Nocc} \lambda_i v_i \text{ , where}$$

$$v_i(O_i, I_i, I_{i+1}, P_i) = -O_i(1-|P_i|)|I_i - I_{i+1}| - O_i|P_i||pref_i - I_{i+1}|$$

Equation 1: Initial value function – occupant preference balancing

$$Setting^* = ArgMax\{vi(O_i, I_i, I_{i+1}, P_i)P(O_i, P_i, I_i, I_{i+1} | Evidence, Setting)\}$$

Equation 2: Optimal ballast setting - occupant preference balancing

2.1 Efficiency and Manager Preferences: Methods

In order to ascertain the form of the nodes for manager preference and electricity rate, a questionnaire was designed, and individual facilities managers were interviewed. The interviews were conducted so that general feedback was gathered through an unstructured conversation, with specific, directed feedback coming from the questionnaire. Three references [2,4] informed the design of the questionnaire and the structuring of interviews.

To be able to ask meaningful questions regarding load shedding and demand response, a literature review of current demand response programs, and the effects of load shedding on occupants was conducted. The literature review revealed that there is wide variety in the type of demand response programs that are offered by utility companies. As this research was conducted in the San Francisco Bay Area, the following discussion is based on the specific programs offered by Pacific Gas and Electric (PG&E), as of February, 2005.

Eligibility for each of PG&E's six distinct programs is based on the customers' current tariff or average/maximum monthly billed demand, where a customer may generally participate in one program at a time. PG&E's demand response programs are distinguished by the magnitude and type of reductions that customers agree to implement. Reductions vary in terms of the amount of warning time provided; whether they are mandatory, voluntary, or bid upon; duration; and whether they are figured in absolute terms or with respect to a baseline. Incentives for participation generally take the form of additional savings through reduction in electricity prices.

Given the variety of programs offered by PG&E, and the eligibility requirements, one time of use (TOU) tariff for smaller commercial customers was selected as a representative program to inform the structure of the DR question in the facilities manager survey and to structure the influence diagram. In contrast to full-building Energy Management Systems (EMS) that are for day-ahead pricing or demand bidding strategies [6], the intelligent daylighting controller is modeled to consider less complex representations of pricing in order that every-day decisions might take into account energy efficiency.

In response to the popularity of demand response and TOU tariffs, researchers within the lighting community have recently begun to investigate the impact of dimming on occupant perceptions of lighting quality. In Kryszczuk and Boyce's 2001 investigation, occupants were found to be *insensitive* to reductions in illuminance below 20%, independent of initial illuminance or dimming rate [3]. The following year, Newsham et. al. showed that provided that the dimming rate is slow enough (.5% per minute), occupants did not opt to increase illuminance with manual controls, until the illuminance had fallen 40-50% [5]. Most recently, Akashi and Neches determined that: 50% of occupants could *detect* reductions in illuminance of 15%; 50% of occupants were satisfied with reductions up to 40%, and; 80% of occupants were satisfied with reductions up to 20% [1].

The literature review of demand response programs and occupant responses to dimming, was used to inform the design of the 15-question survey issued during facility manager interviews. Those questions most relevant to defining the influence diagram topology and the structure of the value function are provided below in Table 1. Please refer to Appendix A to access the full survey.

Table 1: Facilities Manager Preferences – Selected Survey Questions

Q13. Which of the items below are your top two preferred measures for *lighting* decisions? ***Please mark your most preferred measure with a '1', and your second most preferred measure with a '2'*** a) __ Power (kW) b) __ Energy (kWh) c) __ Cost ($) d) __ Electricity rates e) __ Occupant perceptions f) __ Standards/regulations g) __ no preferred measures h) __ Other ***Please specify***_______________	Q14. As you may know: ▪ If dimmed slowly, most people cannot detect a 30% reduction in lighting intensity. ▪ Electricity rates can quadruple or even quintuple depending on demand, pricing plan, and time of day. ▪ 'Load shedding' strategies are used to reduce consumption and thereby expense, during times of elevated pricing. <u>Which would you most desire from an intelligent automatically dimming lighting controller?</u> ***Please choose one.*** a) ☐ Perform *undetectable* load shedding, but only during times of *elevated* electricity pricing b) ☐ Perform *undetectable* load shedding *regardless* of pricing c) ☐ Perform *detectable* load shedding, but only during times of *elevated* electricity pricing d) ☐ Perform *detectable* load shedding *regardless* of electricity pricing e) ☐ *Never* perform load shedding, independent of pricing and detectability f) ☐ Other ***Please specify:***__________________

2.2 Efficiency and Manager Preferences: Findings

Eleven facilities managers from the City of Oakland, Government Services Agency, University of California campuses, and the private sector were interviewed in this study. Four of the eleven comprised two special cases in which: A) the manager was responsible for a *very* large office building (hundreds of thousands of square feet) with lots of occupants and a high 'churn rate' (speed at which occupants change workstations) and; B) the manager was responsible for a hospital and medial research facility in which there was not much freedom to implement lighting control strategies. Table 2 summarizes the responses to selected questions from the survey, excluding managers of the two medical facilities. When the managers were asked to identify their top two preferred measures for the quality of lighting decisions, energy, followed by cost and occupant perception were the quantities most commonly selected.

Managers' preferences with respect to load shedding strategy were quite varied, preventing formulation of a strategy for the 'average' manager. Of the nine respondents to the load shedding question, three would perform undetectable load shedding during times of elevated electricity pricing, and three would perform undetectable load shedding *regardless* of rate. The remaining three managers' responses were evenly spread over the remaining choices.

Table 2: Facilities Manager Preferences – Survey Results, Questions 13 and 14

Preferred Measure	Responses	DR Preference	Responses
Power	XX	Undetectable when elevated	XXX
Energy	XXXXXX	Undetectable regardless of rate	XXX
Cost	XXXX	Detectable when elevated	X
Occupant Perception	XXXX	Detectable when elevated, else undetectable	X
Standards/Regulations	XX	Never regardless of rate	X

Based upon the unstructured portions of the interviews in which general feedback was collected, it was ascertained that a demand response or load shedding program would be most realistically and appropriately implemented as a supervisory control strategy. Within such a framework, local decisions are defined as those that would result under 'normal' conditions. Under exceptional circumstances, the supervisory controller is activated, and local decisions are trumped by the supervisory control strategy.

The supervisory controller is EMS or as presented here, the personal desires of the building manager. For the intelligent lighting problem the local decisions are those that would result from balancing occupant perceptions with a measure of consumed energy. The local decision making preference to minimize energy is assumed constant across all building mangers. The supervisory control strategy however, is particular to a specific manager and defines their load shedding preferences. Alternatively, the building EMS might serve as the supervisory controller.

2.3 Model Expansion: Efficiency and Manager Preferences

The combined findings from the investigation of manager preferences, occupant perceptions, and demand response programs permitted expansion of the influence diagram model. As it was determined that most managers use energy as a measure of the quality of lighting decisions, the expanded value function contains a term for the ballast setting (*Setting*). The states of Setting are control voltages, which are proportionate to the energy consumed. This finding does not result in a change in model topology since the initial model already contained a node for the ballast setting, which arced into the value function. The value function for the influence diagram balances occupant preferences with energy consumed, and is provided in Equation 3 below. Similar to the case of initial value function in Equation 1, the 'λ' terms in the expanded value function are scaling constants to constrain v to values in the range {-1,0}. Equation 4 represents the optimal decision after combining energy efficiency with occupant preferences.

$$v = \lambda_o \sum_{i=1}^{Nocc} \lambda_i v_i + \lambda_E v_E \text{ , where}$$

$$v_E = -Setting$$

Equation 3: Value function - energy efficiency and occupant preference balancing

$$Setting^* = ArgMax\{v(O_i, P_i, Setting, I_i, I_{i+1},)P(O_i, P_i, I_i, I_{i+1} \mid Evidence, Setting)\}$$

Equation 4: Optimal decision - energy efficiency and occupant preference balancing

The interviews and surveys also revealed that the manager's preferences with respect to demand responsive load shedding could be expressed using a control strategy in which the electricity rate determines whether or not to reduce the illuminance an additional percent beyond that resulting from the influence diagram decision ($Setting^*$). Since illuminance is very nearly directly proportionate to voltage, or ballast setting no change in diagram topology was required. Equation 5 contains the value function for the decision regarding demand responsive load reductions, while Equation 6 represents the optimal ballast actuation (A^*). In summary, $Setting^*$ is the recommended ballast setting when balancing occupant preferences with energy consumption. A^* is the optimal ballast actuation after implementation of the supervisory load shedding policy.

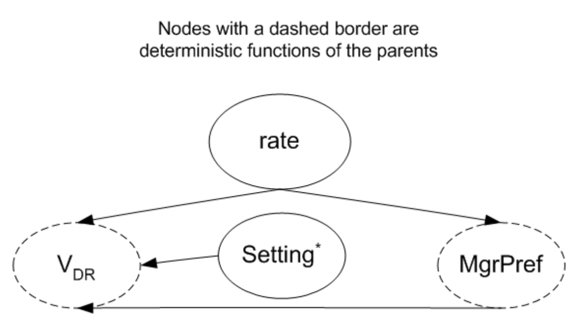

Figure 2: Schematic representation - demand response value function

$$v_{DR} = -(1 - Rate)((Mgrpref)\,Setting^{*} - A) - (Rate)((Mgrpref)\,Setting^{*} - A)$$

Equation 5: Value function - demand responsive decisions

$$A^{*} = ArgMax\,\{-(1 - Rate)((Mgrpref)\,Setting^{*} - A) - (Rate)((Mgrpref)\,Setting^{*} - A)\}$$

Equation 6: Optimal ballast actuation

3.0 Phase II: Occupant Preference Identification

As Phase III was to be devoted to the simulation and evaluation of the influence diagram decisions, the *second* phase of research focused on quantifying the personal preferences of the occupants of the simulated office space. In addition, a transition model describing the change in perception with respect to illuminance and task type (paper- or computer-based) was developed. Phase II therefore, comprised the final set of deliverables that had to be completed before the influence diagram decisions could be simulated and evaluated.

3.1 Occupant Preference Testing: Methods

Empirical occupant preference testing was conducted over a 4-week period. The experimental hardware included: a dedicated workstation containing a desktop PC running Matlab software, a four-lamp dimmable fluorescent fixture suspended above the workstation from a portable PVC truss, a wireless programmable actuator to vary the lighting intensity, and two photodiode light sensors. A calibration procedure was used to determine the relationship between incident illuminance and the corresponding sensor value. This calibration was used to process the preference data.

Upon beginning a testing session occupants were asked to open a Matlab program stored on the PC hard drive. This program was developed in order to minimize the demands on the participant so that they might work as freely as possible during testing. At the start of each testing the occupant set the lights to a comfortable level that would serve as the setpoint for the remainder of the session. As the participants conducted their work the Matlab program would periodically perturb the lights to a level different from the setpoint. An audio alert would sound, and the occupant was asked to record their perception of the lighting quality (comfortable, too dark, or too bright) using the PC keyboard. Following entry of a perception, the lights were returned to the setpoint.

Participants were asked to conduct only paper-based or computer-based tasks during any given session, with each session lasting an hour. Occupants were asked to participate in eight sessions over the four-week period allotted for testing. Participants joined the study under conditions of informed consent, and were informed that they could interrupt testing or withdraw from the study at any time, for any reason.

3.2 Occupant Preference Testing: Results

The reader is reminded that perception nodes for each individual (P_i)have three states, dark ideal and bright, and that its parent nodes are task type (T_i, paper or computer) and worksurface illuminance. The 'preferred' illuminance for any occupant ($pref_i$) is assumed to be constant over time, and is taken as the median ideal illuminance for each task. As such, the influence diagram uses human subjects data in the form of the probability of perception, conditioned on task type and worksurface illuminance, $P(P_i| T_i, I_i)$.

Following empirical occupant testing a two-way type III Analysis of Variance (ANOVA) was performed to determine the significance of the perception-task data for each individual. In the ANOVA, perception is considered the dependent variable, while task type and worksurface illuminance are the independent variables. Three f-values were considered: that for the influence of task type on perception, that for the influence of illuminance on perception, and that for the interaction between illuminance and task type. Significance in the task type and illuminance f-values confirm the validity of the conditional perceptions gathered during preference testing.

A total of six occupants from the target office space to be simulated were tested. The following table summarizes the results for each of the six occupants.

Table 3: Occupant preference testing ANOVA results

Occupant ID	F_{crit}(df, alpha)	Task f, p-value	Perception f, p-value
1	2x2	p =.09	p =.00
2	3x2	p =.10	p =.00
3	2x2	p =.94	p =.00
4	3x2	p =.01	p =.00
5	2x2	p =.00	p =.00
6	(I only)	n/a	n/a

For two of the six participants, occupants two and four, the ANOVA revealed significant differences in illuminance between computer and paper perceptions, and significant differences in the illuminances for each perception, at the alpha =.1 and .05 levels respectively. Occupant five yielded significant results at the alpha=.05 level for dark and ideal perceptions, however there were no paper conditions for which the occupant perceived the lighting to be bright. Occupant five's data was used assuming that the P(bright|paper)=0 for all possible illuminances. This is supported in the fact that testing showed P(ideal|paper, max illuminance) =1.

Two of the six participants, occupants five and one, 'maxed out' the experimental lighting equipment. That is, the lighting system was not able to not able to provide a high enough illuminance to elicit bright perceptions. In these cases a 2x2 ANOVA (dark/ideal, computer/paper) rather than a 3x2 ANOVA (dark/ideal/bright, computer/paper) was considered. For these two occupants, the results were significant, at the alpha =.05 and .1 levels, respectively. As these occupants two, four, and five comprised the best three results based on statistical significance, their data was used in subsequent simulation and evaluation of the decisions for the intelligent controller. Occupant six did not report any dark perceptions for paper tasks, or bright perceptions for computer tasks, therefore, the associated data is not used in the simulation.

4.0 Phase III: Model Simulation and Evaluation

Following formulation of the value function and quantification of manager and occupant preferences, use of the intelligent decision model within the target space was simulated, and a preliminary evaluation of its decisions was conducted. Throughout Phase III performance was judged relative to the electricity consumption and user satisfaction that would be found using existing commercial daylighting controls. These evaluation and simulation efforts are critical to the proposed research on a whole, in that they culminate in critical conclusions regarding the feasibility of the proposed model for daylighting control.

4.1 Model Instantiation

PI Agogino's research lab was selected as the first target space because it contains no windows. This permits isolation of the satisfaction and load shedding aspects of the decision problem, independent of natural lighting and outdoor influences. The physical layout of this space is shown below in Figure 3. Similarly, to control for the effects of sensor and ballast inaccuracies, the simulation treats sensor and actuator input as perfect indicators of illuminance before and after the decision. That is, the sensor information certainly determines the illuminance at the time of the decision, while the decision certainly determines the illuminance *following* the decision.

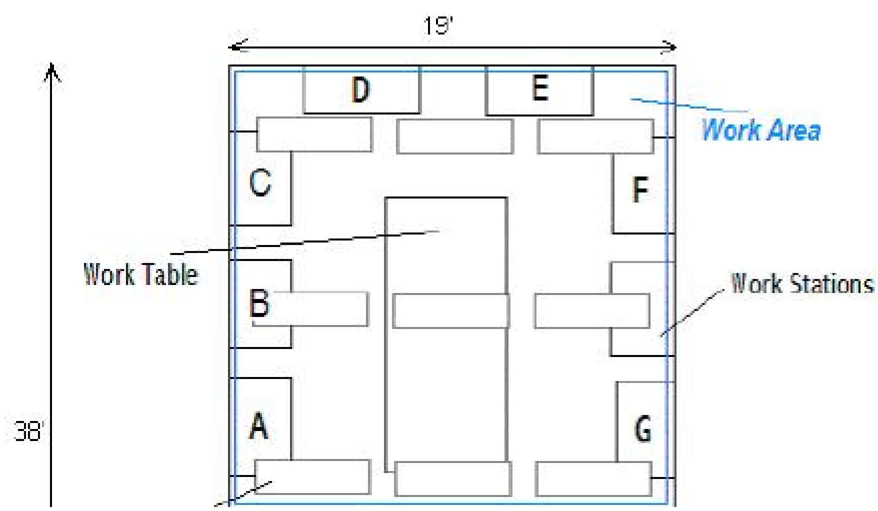

Figure 3: Physical layout - simulated research laboratory

The three most significant sets of occupant preference data were instantiated during simulation and evaluation. Paper based tasks are defined as those that take place without light from the computer monitor contributing to the worksurface illuminance. The average ideal illuminances for each occupant simulated are provided below in Figure 4. Please refer to Appendix B for the complete probability tables of perception conditioned on task type and illuminance

Figure 4: Simulated occupant preferences

Occupant2:	
Paper Avg Ideal	Comp Avg Ideal
551.77	303.41
Occuant4:	
Paper Avg Ideal	Comp Avg Ideal
352.81	526.27
Occuant5:	
Paper Avg Ideal	Comp Avg Ideal
683.37	488.18

Occupancy state nodes are removed from the model for simulation, as occupant improved occupant satisfaction is one of the system goals. The initial worksurface illuminance is unknown, and assumed to be uniformly distributed. As the target space contains evenly distributed lighting, that the illuminance at each workstation is assumed equal, and controllable to within +/- 25 lux up to 825 lux. While a commercial controller actuates to a static setpoint, the decisions from the intelligent controller vary with task and electricity rate. Simulation assumes that the commercial controller maintains 525 lux at the worksurface, corresponding to 64% ballast output.

Sources of uncertainty in the simulated model are the initial illuminance, and occupant perception. The model is tightly constrained with respect to sources of uncertainty in order to demonstrate that the intelligent control algorithm performs well in the absence of mechanical uncertainty (largely attributed to sensors). Once this capability has been established, the intelligent algorithms is to be further examined for robustness under increased levels of uncertainty that reflect the current state of the sensor technology, and the impact of sunlight on system performance.

Simulations assumed that the office is continuously occupied Monday through Friday from 8:00AM-6:00PM. In addition, based on the results of the literature review of demand response utility programs (Section 2.1), PG&E's A6 TOU tariff was selected for simulation. Under the A6 TOU tariff, winter service runs six months a year, from November 1 through April 30, and summer service includes use from May 1 through October 31. Summer rates are divided into on peak hours, 12:00-18:00 M-F; partial peak hours, 8:30-12:00, 18:00-21:30 M-F; and off peak hours, 21:30-8:30 M-F, Sat, Sun. Winter rates are divided into partial peak hours, 8:30-21:30 M-F; and off peak hours, 21:30-8:30. Figure 5 below provides the A6 TOU rates in dollars per kilowatt hour, for each seasonal peak category.

Figure 5: A-6 TOU tariff

Summer	On peak	$0.27322
	Part Peak	$0.12878
	Off Peak	$0.08212
Winter	Part Peak	$0.14004
	Off Peak	$0.09581

The manager preference to minimize consumption (see Section 2.2) is represented in the v_E term in the value function provided in Equation 3. The manager of the target space simulated was interviewed, and the results were used in the instantiation of the particular demand response strategy. Namely, the manager prefers to load shed up to 30%, but only in cases of elevated pricing. Balancing the general consumption preference of the manager with the preferences of the occupants results in an intermediate decision. During on peak summer hours the optimal intelligent decision is 30% below the intermediate decision. During all other times the optimal intelligent decision is the intermediate decision, without reduction.

Section 4.2 Evaluation and Simulation Results

Several cases combining different occupant tasks and λ_E weights were simulated in order to evaluate the performance of the intelligent controller with respect to a commercial controller. Combinations of four task cases were considered with three values for λ_E. Task cases include one instance of all three occupants performing computer tasks, and three instances of one occupant performing paper tasks. The number of occupants performing paper tasks is limited to one, as most office work is conducted with the computer monitor on, contributing to the worksurface illuminance, and requiring less illuminance from the overhead system. Simulated values for λ_E were 1/100, which weights the energy and occupant preference portions of the value function equally, 1/250 which weights occupant preference more heavily than energy, and zero. Setting λ_E equal to zero forces the algorithm to consider occupant preferences without energy consumption, allowing assessment of.

For each case simulated the actuation decision from the intelligent system, with and without demand responsive load shedding was determined and expressed as a percentage of the maximum output. For each decision from the commercial and intelligent systems the perception probabilities for each occupant were calculated based on the statistically significant preference testing data. In addition, the energy and cost savings resulting from the intelligent system were calculated as a percentage of those that would result from a commercial system. These results are summarized in Tables 4 and 5 below. Table 4 reports the results associated with the intelligent system and Table 5 contains the results from a representative commercial system.

Table 4: Occupant satisfaction, cost and energy savings: simulation results

Case	λ_E	% Output No DR	Perc(A*) No DR	% Energy Savings	% Cost Savings
All comp	1/100	33	P(occ4=ideal)=.5 P(occ4=dark)=.5 P(ideal) = 1 for occs 2,5	62	57
	1/250	46	P(ideal) = 1 for all occs	35	35
	0	58	P(occ2=ideal)=.5 P(occ2=bright)=.5 P(ideal) = 1 for occs 4,5	25	25
Occ2 p	1/100	39	P(occ2,4=ideal)=.5 P(occ2,4=bright)=.5 P(ideal) = 1 for occ 5	47	44
	1/250	58	P(ideal) = 1 for all occs	25	25
	0	64	P(occ4=ideal)=.8 P(occ4=bright)=.2 P(ideal) = 1 for occs 2,5	18	23
Occ4 p	1/100	33	P(ideal) = 1 for all occs	62	57
	1/250	39	P(occ2=ideal)=.5 P(occ2=bright)=.5 P(ideal) = 1 for occs 4,5	47	44
	0	46	P(ideal) = 1 for all occs	34	37
Occ5p	1/100	27	P(occ2=ideal)=.33 P(occ2=dark)=.67 P(dark) = 1 for occs 4,5	60	72
	1/250	46	P(ideal) = 1 for all occs	34	37
	0	64	P(occ4=ideal)=.8 P(occ4=bright)=.2 P(ideal) = 1 for occs 2,5	18	23

Table 5: Occupant satisfaction with commercial control

<table>
<tr><th>Case</th><th>Comm. % Out</th><th>Comm. P(perception)</th></tr>
<tr><td>All comp</td><td rowspan="4">64</td><td>P(Occ4=ideal)= .8
P(Occ4=bright)=.2

P(ideal) = 1 for occs 2,5</td></tr>
<tr><td>Occ2 paper</td><td>P(ideal) = 1 for all occs</td></tr>
<tr><td>Occ4 paper</td><td>P(ideal) = 1 for all occs</td></tr>
<tr><td>Occ5 paper</td><td>P(occ4=ideal)=.8
P(occ4=bright)=.2

P(occ5=ideal)=.67
P(occ5=bright)=.33

P(ideal) = 1 for occ 2</td></tr>
</table>

4.2.1 Energy and Cost Savings

The yearly conditioning cost under each system is calculated by multiplying the total wattage of all fixtures by the TOU rate, the number of conditioning hours per year, the percent maximum output at the control setting, and summing the product over each TOU. For example, the yearly conditioning cost during on peak hours is calculated as: $Cost = (on-pkrate)(wattage)(\%Max)(onpkhrs/yr)$. The ratio comparing yearly energy consumption of the intelligent controller with respect to a commercial controller was calculated by removing the rate term from the previous calculation for cost, and again summing over each TOU rate. For example, the yearly energy consumption during peak hours is calculated as: $Consumption = (wattage)(\%Max)(onpkhrs/yr)$.

As expected, decreasing values of lead to decreasing energy and cost savings in every case simulated. The results from each of the simulation cases with λ_E greater than zero indicate that the decisions from the intelligent lead to a 25-62% increase in energy savings compared to a commercial system under the same TOU electricity pricing program. While the intelligent system does not attempt to minimize cost per se, the energy reductions it can achieve translate into cost savings between 25-72% under the particular tariff simulated. These savings and improvements over commercial systems are attributed to the energy consumption and demand response portions of the value function used in the intelligent decision algorithm.

4.2.2 Occupant Satisfaction

To estimate the degree to which occupant preferences are satisfied, the ideal dark and bright perceptions resulting from the decisions from both types of controllers were compared. Table 4 shows that for λ_E equal to 1/100 the number of non-ideal perceptions resulting from intelligent decisions is 6 out of a possible 12. For λ_E equal to 1/250, the performance of the intelligent system improves drastically with respect to occupant satisfaction, as the number of non-deal perceptions decreases to just 1 out of a possible 12. Table 5 shows that for the commercial system, the number of non-ideal perceptions is

3 out of a possible 12. These simulation results indicate the intelligent control system is as good, if not better than commercial systems in terms of effecting lighting conditions that would satisfy occupants.

4.2.3 Facilities Manager Satisfaction

Similar to the assessment of the intelligently derived decisions with respect to occupant satisfaction, assessment with respect to facilities manager satisfaction is also based on preference data. In the case of the occupants, the data came from empirical testing under fluctuating lighting conditions, while in the case of the facilities manager, the data comes from survey results and interviews (see Section 2.2). Returning to the results from the survey, the top measures of the quality of lighting decisions were energy consumption, followed by cost and occupant perception.

The analysis of energy consumption and cost in Section 4.2.1 revealed that on a representative time of use electricity tariff, the intelligent system is capable of improving energy consumption and expense with respect to a commercial controller. Specifically, the simulation revealed that with λ_E set to 1/00 the intelligent system generates between 47-62% energy savings and between 44-72% in cost savings. With energy consumption weighted less importantly than occupant perception the intelligent system generates between 25-47% in energy savings and between 25-44% in cost savings.

The analysis of occupant satisfaction in Section 4.2.2 provides further insight to the analysis of facility managers' satisfaction with the intelligent control decisions. With λ_E set to 1/250, only one out of twelve perceptions simulated was non-ideal for the intelligent system. With a representative commercial system, the number of non-ideal perceptions rose to three out of twelve.

The intelligent controller always implements the manager's preferred demand response strategy, clearly outperforming commercial controllers with respect to load shedding. Taken together, the energy, cost, occupant satisfaction, and demand response analyses support the initial conclusion that the interests of facilities managers are better met with the intelligent system than with existing commercial controllers. Please refer to the Section 5 for a discussion regarding the further assessment of facility manager satisfaction.

Taken together, the energy, cost, occupant perception analyses with the demand responsive capabilities indicate that facilities managers would be more satisfied with the intelligent system than with a commercial system. However, this is only the case, provided that λ_E is appropriately weighted with respect to the occupant perception portion of the value function.

5.0 Discussion

The analysis of potential energy and cost savings achieved with the intelligent decision algorithm that was presented in Section 4.2 was based on a simulation space that contained no windows. Therefore, rather than reporting absolute improvements in consumption and expense, the performance of the intelligent system was reported as a percentage of that of a commercial system.

The weighting on the energy consumption term has a significant effect on both occupant satisfaction and facility manager satisfaction. As detailed in Section 4.2.3, changing the weight from 1/100 to 1/250 raises the intelligent system's actuation level, greatly improving occupant satisfaction and presumably improving manger satisfaction for the cases that were simulated. This result is largely due to the large range of illuminances over which each occupant found the lighting to be ideal with one hundred percent probability. It is possible that the form of the value function could be improved with respect to occupant preferences. For example, rather than setting the target illuminance in non-ideal cases to the midpoint of the ideal perception range, the algorithm could be altered to target any illuminance for which the perception is ideal with probability one.

More informed assessment of the facility manager's satisfaction, and refinement of the energy consumption component of the intelligent control algorithms is possible with further questioning of facilities managers. Interviews might, for example attempt to identify appropriate ratios of occupant perception and energy consumption weightings, or minimum acceptable conditioning levels.

6.0 Conclusion

Each of the four phases planned for this one-year research project was carried out successfully with results encouraging further pursuit of the proposed system. It was shown that statistically significant occupant lighting preferences can be gathered using an automated sensor-based system connected to a dimmable lighting controller. Data can be entered and stored using a personal computer, and collected during the course of a typical workday, with minimal restrictions and disruption to the user.

A set of eleven facilities mangers were surveyed and interviewed in order to identify their preferences with respect to demand responsive load shedding, and the judgment of the quality of lighting decisions. The intelligent model and decision algorithm were expanded to include these findings. Preliminary evaluations indicate that occupant and manager satisfaction are increased with the intelligent system, compared to a representative commercial system. The intelligent system was also found to decrease energy expense and consumption. The analyses presented in this report serve as encouragement that the intelligent system is capable of outperforming existing commercial systems. However, in order to ensure a high level of occupant and manager satisfaction the algorithm should bound the weighting on the energy consumption term in the value function.

The next set of evaluations will use these results as a baseline to determine whether the intelligent system is able to make good decisions in the face of uncertainty due to sensor and actuator hardware, and imperfect knowledge of occupant tasks. Future research will also focus on the inclusion of solar contributions to worksurface illuminance, and the ability of the algorithm to make reliable daylighting decisions. In addition, a sensitivity analysis will be conducted to quantify the impact of uncertainty in occupant perception, task type, and worksurface illuminance on the quality of the intelligent decisions.

7.0 References

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8.0 Appendix

8.1 Appendix A: Facilities Manager Questionnaire

I. Background

1. What is your job title?
   Please specify: ____

2. Do you participate in the management of a commercial building?

	Agree	*Disagree*	*Don't know*
Yes, an office space			
Yes, a retail space			
Yes, a school/educational space			
No, I don't have any commercial building management responsibilities			

Other
Please specify: ____

3. Are the following included in your job responsibilities?

	Yes	*No*	*I don't know*
Building security – for example, guards, door/window locks, keys			
Building safety – for example, chemical, fire, emergency matters			
Building maintenance – for example, leaks, plumbing, electrical			
Equipment upkeep/contracts – elevators, HVAC, water heating, lights			
Maintenance and operations accounting			
Recruitment and retention of building/facilities staff			

Other
Please specify: ____

4. Are you responsible for managing the energy costs, consumption, or efficiency in a *commercial* building?
   a) ☐ Yes
   b) ☐ No

5. Do you manage at least one building of the following size?

	Yes	*No*	*I don't know*
1-1,000 ft^2			
5,001-10,000 ft^2			
Greater than 10,000 ft^2			

Other
Please specify: ____

6. Have occupants in your building(s) expressed the following with respect to the perceived quality of indoor lighting?

	Yes	*No*	*I don't know*
It is too dark			
It is too bright			
The distribution of light is uneven			
There is a disturbing amount of glare			
There is poor contrast with the outdoor light			
Occupants' have not expressed their lighting perceptions			
	True	***False***	
Occupant lighting feedback is not made known to those with my job responsibilities			

Other
Please specify: ____

II. Energy Management

7. Which of the items below are your top two preferred measures for *building energy management*?
   Please mark your most preferred measure with a '1', and mark your second most preferred measure with a '2'

   a) ___ Power (kW)

   b) ___ Energy (kWh)

   c) ___ Cost ($)

   d) ___ Electricity rates (peak, partial-peak, off-peak hours)

   e) ___ Occupant perceptions of environmental conditioning quality

   f) ___ Industrial regulations/standards – for example, OSHA's recommended office temperature range

   g) ___ I have no preferred measures for building energy management

   h) ___ Other

   Please specify: ____

8. Given your answer to Question 7, which quantity would you *most like* to monitor for energy management in your building(s)? For example, if you chose power (kW), would you most like to monitor the average kW, total kW, maximum kW, or the kW as a percentage of the average for buildings similar to yours?
   Please choose one.

   a) ☐ Averages

   b) ☐ Totals

   c) ☐ Maximums

   d) ☐ Percent averages with respect to buildings of similar size/occupancy/type

   e) ☐ I have no preference regarding monitored quantities for building energy management

   f) ☐ Other
   Please specify: ____

9. Given your answer to Question 8, which time period would you rather consider for energy management in your building(s)? For example, if you chose “averages,” would you rather consider yearly, monthly, or weekly averages?
Please choose one.

   a) ☐ Yearly

   b) ☐ Monthly

   c) ☐ Weekly

   d) ☐ I have no preference regarding time periods to consider for building energy management

   e) ☐ Other
   Please specify: ____

10. Which of the following indicators of consumption are you *most likely* to use for decisions regarding energy management in your building(s)?
Please choose one.

   a) ☐ Percent of the baseline/average for the particular building

   b) ☐ Percent of the baseline/average for buildings of similar size, type, occupancy

   c) ☐ Totals ($, kW, kWh) below an absolute limit set by my managers or by myself

   d) ☐ I have no preference regarding indicators of consumption for building energy management

   e) ☐ Other
   Please specify: ____

III. Energy Efficient Lighting

11. As you may know:
    - lighting comprises 40-45% of a building's electricity consumption.
    - automatic dimming controllers can reduce electricity consumption up to 45% in areas with significant amounts of daylight.

    Would you install such a system in your building(s)?
    Please choose one.

    a) ☐ Yes

    b) ☐ No

    c) ☐ I don't know

12. If you answered 'No' or 'I don't know' to Question 11 above, did the following statements contribute to your response?
    If you answered yes to the previous question, please skip this question

	Yes	***No***	***Don't know***
The controllers are too expensive			
I've heard that the controllers don't work well			
I've had bad experiences with automatic dimming controllers			
I have no experience using automatic dimming controllers			
My building(s) don't receive enough daylight			
Lighting expense is not a concern in my building(s)			

Other
Please specify: ____

13. Which of the items below are your top two preferred measures for *lighting* decisions?

Please mark your most preferred measure with a '1', and mark your second most preferred measure with a '2'

a) ____ Power (kW)

b) ____ Energy (kWh)

c) ____ Cost ($)

d) ____ Electricity rates (peak, partial-peak, off-peak hours)

e) ____ Occupant perceptions of lighting quality

f) ____ Industry standards/regulations – for example, OSHA's minimum lighting power density

g) ____ I have no preferred measures for lighting decisions

h) ____ Other
Please specify: ____

IV. Load Shedding and Intelligent Lighting Control

14. As you may know:
    - If dimmed slowly, most people cannot detect a 30% reduction in lighting intensity.
    - Electricity rates can quadruple or even quintuple depending on demand, pricing plan, and time of day.
    - 'Load shedding' strategies are used to reduce consumption and thereby expense, during times of elevated pricing.

    <u>Which would you most desire from an intelligent automatically dimming lighting controller?</u>
    Please choose one.

    g) ☐ Perform *undetectable* load shedding, but only during times of *elevated* electricity pricing

    h) ☐ Perform *undetectable* load shedding *regardless* of pricing

    i) ☐ Perform *detectable* load shedding, but only during times of *elevated* electricity pricing

    j) ☐ Perform *detectable* load shedding *regardless* of electricity pricing

    k) ☐ *Never* perform load shedding, independent of pricing and detectability

    l) ☐ Other
    Please specify: ___________________________________

15. How would you prefer to interface with (adjust/override) an *automatic dimming system*?
    Please choose one.

    a) ☐ Through software

    b) ☐ With a manual switch such as a dial-knob dimmer, or slider

    c) ☐ Other
    Please specify: ____

8.2 Appendix B: Occupant Perception Probabilities Conditioned on Worksurface Illuminance (lux)

Occupant 2

	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450-499	500-549	550-599	600-649	650-699	700-749	750-799	800-849
Paper dark	1.00	1.00	1.00	1.00	0.75	0.67	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Paper ideal	0.00	0.00	0.00	0.00	0.25	0.33	0.00	1.00	0.83	1.00	1.00	1.00	1.00	0.75	1.00	0.00	1.00
Paper bright	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00
Comp dark	0.00	0.25	0.33	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comp ideal	0.00	0.75	0.67	1.00	0.67	1.00	0.50	1.00	0.75	0.50	1.00	0.00	0.00	0.33	0.00	0.00	0.00
Comp bright	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.25	0.50	0.00	1.00	1.00	0.67	1.00	1.00	1.00

Occupant 4

	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450-499	500-549	550-599	600-649	650-699	700-749	750-799	800-849
Paper dark	0.00	1.00	0.67	1.00	0.50	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Paper ideal	0.00	0.00	0.33	0.00	0.50	1.00	0.50	1.00	0.33	0.50	1.00	0.33	0.00	0.00	0.00	0.00	0.00
Paper bright	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.67	0.50	0.00	0.67	1.00	1.00	1.00	1.00	1.00
Comp dark	0.00	1.00	1.00	0.00	1.00	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comp ideal	0.00	0.00	0.00	1.00	0.00	0.50	0.50	1.00	0.50	1.00	0.80	1.00	0.33	0.67	0.33	0.33	1.00
Comp bright	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.20	0.00	0.67	0.33	0.67	0.67	0.00

Occupant 5

	0-49	50-99	100-149	150-199	200-249	250-299	300-349	350-399	400-449	450-499	500-549	550-599	600-649	650-699	700-749	750-799	800-849
Paper dark	0.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00
Paper ideal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.67	1.00	1.00	0.00	1.00	1.00	1.00
Paper bright	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comp dark	0.00	1.00	1.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comp ideal	0.00	0.00	0.00	0.00	0.25	1.00	1.00	1.00	1.00	1.00	1.00	0.67	1.00	1.00	0.50	0.67	0.20
Comp bright	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.50	0.33	0.80

8.3 Appendix C: Cost and Energy Savings Calculations

Commercial Energy Cost = (on-pk-smr-rate $/kWhr)(525/825)(total wattage)(on-pk-smr-hr/yr) + (pt-pk-smr-rate)(pctoupt)(525/825)(on-pt-pk-smr-hr/yr) + (off-pk-smr-rate)(525/825)(total wattage)(on-off-pk-smr-hr/yr) + (pt-pk-winter-rate)(525/825)(total wattage)(on-pt-pk-winter-hr/yr) + (off-pk-winter-rate)(525/825)(total wattage)(on-off-pk-winter-hr/yr)

The yearly lighting cost is calculated as the rate ($/kWhr) multiplied by the percent ballast output corresponding to the decision, the system wattage, and the number of operation hours per year at the rate. This product is then summed over each rate in the tariff. For the A-6 TOU tariff offered by PG&E, there are five rates in the tariff. A commercial daylighting system is assumed to actuate to 525 lux independent of the rate.

$$Cost = \sum_{i=1}^{Nrates} (rate_i)(PctOutpt_i)(W)(hrs / yr_i)$$

Summer on-peak hours per day: noon-6, 6 hours
- Per week = 30 hours
- Per summer = 780, (30*26)

Summer on-part-peak hours per day: 8:30-noon, 3.5 hours
- Per week = 17.5
- Per summer = 455

Summer on-no-peak hours per day: 8-8:30, .5 hours
- Per week = 3.5
- Per summer = 91

Winter on-part-peak hours per day: 8:30am-6pm, 9.5 hours
- Per week = 47.5
- Per winter = 1235

Winter on-no-peak hours per day: 8-8:30, .5 hours
- Per week = 3.5
- Per winter = 91

Total hours per year = 2652

The cost ratio of the intelligent system to a commercial system is calculated as the cost with the intelligent system divided by the cost with a commercial system.

$$CostRatio = \frac{\begin{array}{l}(.273 * 780 * PctOut_{smrpk}) + (.129 * 455 * PctOut_{smrptpk}) + (.082 * 91 * PctOut_{smroffpk}) \\ + (.140 * 1235 * PctOut_{wtrptpk}) + (.096 * 91 * PctOut_{wtroffpk})\end{array}}{.636\begin{bmatrix}(.273 * 780) + (.129 * 455) + (.082 * 91) + \\ (.140 * 1235) + (.096 * 91)\end{bmatrix}}$$

The ratio of energy savings is calculated by removing the rate terms from the equation for the cost ratio.

$$EnergyRatio = \frac{\left(780 * PctOut_{smrpk}\right) + \left(455 * PctOut_{smrptpk}\right) + \left(91 * PctOut_{smroffpk}\right) + \left(1235 * PctOut_{wtrptpk}\right) + \left(91 * PctOut_{wtroffpk}\right)}{.636\left(2652\right)}$$

Cost Ratio, 3 occupants on computer, equal occupant and energy weights:
(.273)(.21)(780)+(.129)(.33)(455) +(.082)(.33)(91)+(.140)(.33)(1235)+ (.096)(.33)(91)/ (.273)(.636)(780)+(.129)(.636)(455) +(.082)(.636)(91)+(.140)(.636)(1235)+ (.096)(.636)(91) = 44.7+19.4+2.5+57.1+2.9/135.4+37.3+4.7+110+5.6=126.6/293=.43

→ resulting in a 57% cost savings for a year

Energy Ratio, 3 occupants on computer, equal occupant and energy weights:
(.21)(780)+(.33)(455) +(.33)(91)+(.33)(1235)+ (.33)(91)/ (.636)(2652)= 163.8+14.9+30.0+407.6+30.0/1686.7=646.3/1686.7=.38

→ resulting in a 62% savings in energy for a year

Cost ration, 3 occupants on computer, demand response only:
(.273)(.39)(780)+(.129)(.58)(455) +(.082)(.58)(91)+(.140)(.58)(1235)+ (.096)(.58)(91)/ (.273)(.636)(780)+(.129)(.636)(455) +(.082)(.636)(91)+(.140)(.636)(1235)+ (.096)(.636)(91) =83.0+34.0+4.3+100.3+5.1/135.4+37.3+4.7+110.0+5.6=226.7/293=.77

→ resulting in a 23% savings in cost per year

Energy Ratio, 3occupants on computer, demand response only:
(.39)(780)+(.58)(455) +(.58)(91)+(.58)(1235)+ (.58)(91)/ (.636)(2652)= 304.2+263.9+52.8+716.3+52.8/1686.7=1390/1686.7=.82

→ resulting in an 18% savings in energy for a year, with a TOU tariff, energy minimization, and demand reductions during times of peak elevated pricing.

Cost Ratio, occupant 4 on paper, demand response only, equal occupant and energy weights:
(.273)(.21)(780)+(.129)(.27)(455) +(.082)(.27)(91)+(.140)(.27)(1235)+ (.096)(.27)(91)/ (.273)(.636)(780)+(.129)(.636)(455) +(.082)(.636)(91)+(.140)(.636)(1235)+ (.096)(.636)(91) =44.7+15.8+2.0+46.7+2.4/135.4+37.3+4.7+110.0+5.6=111.6/293=.38

→ resulting in a 72% savings in cost per year

Ratio Energy = (.21)(780)+(.27)(455) +(.27)(91)+(.27)(1235)+ (.27)(91)/ (.636)(2652)=163.8+122.9+24.6+333.5+24.6/1686.7=669.4/1686.7=.40

→ resulting in a 60% savings in energy for a year

Cost Ratio, all occupants on computer, occupant weight 2.5 times energy weight:
(.273)(.33)(780)+(.129)(.46)(455) +(.082)(.46)(91)+(.140)(.46)(1235)+ (.096)(.46)(91)/ (.273)(.636)(780)+(.129)(.636)(455) +(.082)(.636)(91)+(.140)(.636)(1235)+ (.096)(.636)(91) = 70.3+27.0+3.4+79.5+4.0/135.4+37.3+4.7+110+5.6=184.2/293=.63

→ resulting in a 37% cost savings for a year

Energy Ratio, all occupants on computer, occupant weight 2.5 times energy weight:
(.33)(780)+(.46)(455) +(.46)(91)+(.46)(1235)+ (.46)(91)/ (.636)(2652)= 257.4+209.3+41.9+568.1+41.9/1686.7=118.6/1686.7=.66

→ resulting in a 34% savings in energy for a year

Actuation decisions with occupant 2 on paper, are the same as for all occupants on the computer

Cost ratio, occupant 4 on paper, occupant weight 2.5 times energy weight:
(.273)(.27)(780)+(.129)(.39)(455) +(.082)(.39)(91)+(.140)(.39)(1235)+ (.096)(.39)(91)/ (.273)(.636)(780)+(.129)(.636)(455) +(.082)(.636)(91)+(.140)(.636)(1235)+ (.096)(.636)(91) = 57.5+22.9+2.9+67.4+3.4/135.4+37.3+4.7+110+5.6=154.1/293=.53

→ resulting in a 47% cost savings for a year

Energy Ratio, occupant 4 on paper, occupant weight 2.5 times energy weight:
(.27)(780)+(.39)(455) +(.39)(91)+(.39)(1235)+ (.39)(91)/ (.636)(2652)= 210.6+177.5+35.5+481.7+35.5/1686.7=940.8/1686.7=.56

→ that translates into a 44% savings in energy for a year, with a TOU tariff, energy minimization, and demand reductions during times of peak elevated pricing.

Energy Ratio, occupant 5 on paper, occupant weight 2.5 times energy weight:
(.273)(.33)(780)+(.129)(.46)(455) +(.082)(.46)(91)+(.140)(.46)(1235)+ (.096)(.46)(91)/ (.273)(.636)(780)+(.129)(.636)(455) +(.082)(.636)(91)+(.140)(.636)(1235)+ (.096)(.636)(91) = 70.3+27.0+3.4+79.5+4.0/135.4+37.3+4.7+110+5.6=184.2/293=.63

→ resulting in a 37% cost savings for a year

Energy Ratio, occupant 5 on paper, occupant weight 2.5 times energy weight:
(.33)(780)+(.46)(455) +(.46)(91)+(.46)(1235)+ (.46)(91)/ (.636)(2652)= 257.4+209.3+41.9+568.1+41.9/1686.7=1118.6/1686.7=.66

→ resulting in a 34% savings in energy for a year