Energy saving effects of integrated lighting utilizing daylight

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This paper presents the energy saving effects in a building having automatically controlled lighting utilizing daylight inside perimeter zone.

We have developed a computer program that enables to calculate capital and energy cost of a building in order to estimate the energy saving effects, and calculated many cases under various conditions, such as four types of window ratio to wall (20%, 35%, 50%, 65%), three operation types of venetian blind, etc.

Finally we estimated these energy saving effects by using a two-dimensional vector on a graph, on which the abscissa shows capital cost required and ordinate energy cost. By means of this vector on the graph, building owners can easily understand the energy saving effects of an automatically controlled lighting system utilizing daylight.

1. Introduction

The energy consumption increases in a building which has large window area. As the large window area causes increased summer heat gain and winter heat loss, small window area buildings are usually recommended. However this may be changed if the artificial lighting inside perimeter zone is turned off or controlled automatically utilizing daylight.

Some papers about daylight utilization in interiors have been published^{1)~5)}. We have developed a computer program which enables us to calculate capital and energy cost of a building in order to estimate the energy saving effects, and many cases have been calculated under various conditions, such as four types of window area ratio to outside wall (20%, 35%, 50%, 65%), three operation types of venetian blind, etc.

Finally we estimated these energy saving effects using a two-dimensional vector on a graph, on which the abscissa shows capital cost required and ordinate energy cost.

2. Evaluation method of energy conservation techniques using two-dimensional vectors on a graph

In order to evaluate various energy conservation techniques, the effect of each technique is shown as a two-dimensional vector on a graph, where the abscissa shows the capital cost required and the ordinate energy cost. Therefore we call this vector a thermal economics vector.

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A part of this paper was described in J. Illum. Engng. Inst. Jpn. 65-4 (1981).

2.1 Steps of procedure to show economics vector on a graph

- (1) First, we calculate the capital cost required I_0 , and energy cost R_0 , of the building in which no energy conservation techniques are adopted, using the computer program which we have developed.

Fig. 1 Evaluation procedure using thermal economics vector.

- (a) Assignment of the original building to the origin.
- (b) Evaluation of the effect of each technique.
- (c) Evaluation of the accumulated effect of some selected techniques.

This original building is assigned to the origin on the graph (Fig. 1 (a)).

(2) Secondly, in order to evaluate each energy conservation technique individually, we calculate both costs, I_i and R_i , of the building in which each technique is adopted, as well as the original building. The cost differences between each energy conservation building and the original building are calculated as follows,

$$\Delta IC_i = I_i - I_0, \quad \Delta RC_i = R_i - R_0 \quad \dots\dots\dots(1)$$

i : suffix showing each energy conservation technique and each vector is drawn on the graph as Fig. 1 (b).

(3) Finally, in order to evaluate the accumulated effect of some selected techniques, we calculate both costs of the building in which some techniques are adopted, and the cost differences are as follows,

$$\Delta IC_j = I_j - I_{j-1}, \quad \Delta RC_j = R_j - R_{j-1} \quad \dots\dots\dots(2)$$

where, j : suffix showing the number of adopted techniques

and the combined vector is drawn on the graph as Fig. 1 (c).

2.2 Evaluation method using depreciation period

When an energy conservation technique is adopted in a building, the increase of the average annual expenditure ΔI , is calculated using the average interest model of engineering economy as eq. (3). Similarly, the decrease of the average annual expenditure ΔR , is calculated as eq. (4).

$$\Delta I = \Delta IC \cdot (1-r) \frac{1}{T} + \Delta IC \cdot r \cdot i + \Delta IC \cdot (1-r) \cdot \frac{i}{2} \left(\frac{T+1}{T} \right) \quad \dots\dots\dots(3)$$

$$\Delta R = \Delta RC \cdot \frac{(1+j)^T - 1}{T \cdot j} \quad (\text{when } j=0, \Delta R = \Delta RC) \quad \dots\dots\dots(4)$$

where, i : the salvage value rate
 j : energy price increase rate
 i : interest rate of loan
 T : depreciation period

$r=0$ and $\Delta I = \Delta R$ yields,

$$\Delta IC \left\{ 1 + \frac{i(T+1)}{2} \right\} = \Delta RC \cdot \frac{(1+j)^T - 1}{j} \quad \dots\dots\dots(5)$$

Depreciation period T , can be calculated from eq. (5), and the gradient $\Delta RC/\Delta IC$, can be calculated for any value of T . By drawing the depreciation line with calculated gradient on the graph, as Fig. 1 (a), depreciation period of each energy conservation technique can be found easily.

3. Calculation of energy consumption within a building⁶⁾

According to the results of research for the amount of annual energy consumption within commercial buildings, the composition of annual energy consumption within a building is shown as Fig. 2.

Utilizing daylight inside perimeter zone decreases lighting and cooling energy consumption in summer, but increases heating energy consumption in winter. Therefore, to evaluate daylighting system, building total energy consumption (especially air-conditioning and lighting energy consumption) must be analyzed.

For this purpose building total primary energy consumption in a year can be calculated using computer program which we have developed as follows.

3.1 Air-conditioning

(1) Energy consumption of refrigerator and boiler⁹⁾

Using hour-by-hour thermal loads calculated by response-factor and weighting-factor method, the primary energy consumption of refrigerator and boiler in a year E_c and E_h , is calculated as follows,

$$E_c = \sum_i \frac{L_{ci}}{COP_i \cdot \eta_e} \quad (\text{kcal/a}) \quad \dots\dots\dots(6)$$

$$E_h = \sum_i \frac{L_{hi}}{\eta_B} \quad (\text{kcal/a}) \quad \dots\dots\dots(7)$$

where, i : suffix showing time
 L_{ci} (kcal/h): cooling load
 L_{hi} (kcal/h): heating load
 COP_i : coefficient of performance of

Fig. 2 Composition of energy consumption within a conventional commercial building.

- Each number is the primary energy consumption divided by the gross floor area.
- The suffix "*" shows the results by Ref. (7), (8).
- The suffix "**" shows the results obtained from the analysis of several selected commercial buildings.

chiller (3.0 in all season)
 η_g : efficiency of generator (0.351)

(2) Secondary HVAC distribution energy consumption

Assuming that the energy consumption of fans and pumps for air-conditioning is in proportion to the summer peak load, D_0 and E_0 in Fig. 2 are corrected as follows,

$$D_1 = \frac{L_1}{L_0} \cdot D_0 (\text{Mcal/m}^2 \cdot \text{a}) \dots\dots\dots(8)$$

$$E_1 = \frac{L_1}{L_0} \cdot E_0 (\text{Mcal/m}^2 \cdot \text{a}) \dots\dots\dots(9)$$

where, L_0 (kcal/m²·h) : the standard peak summer load (assumed to be 100)

L_1 (kcal/m²·h) : the actually calculated peak summer load

Ultimately, the primary energy consumption of distribution system is calculated by multiplying C_0 , D_1 and E_1 by the gross floor area.

3.2 Lighting

The primary consumption for lighting E_l , is calculated as follows,

$$E_l = \sum_i \sum_j W_i \times 10^{-3} \times AR_i \times r_{ij} \times CF \dots\dots\dots(10)$$

where, i : suffix showing zone

j : suffix showing time

W_i (w/m²) : lighting output in i zone

AR_i : floor area of i zone

r_{ij} : fraction of lights turned on when lighting is controlled automatically utilizing daylight

CF (kcal/kWh) : coefficients of converting electric power energy into the primary energy consumption (2,450).

3.3 Elevator, plumbing system and others

The primary energy consumption of elevator, plumbing system and others is calculated by multiplying G_0 in Fig. 2 by the gross floor area.

4. Calculation of the capital cost and energy cost

4.1 The capital cost of architectural elements

The unit costs of elements such as roof wall, outside wall, window surroundings, inside wall, eaves, and so on are prepared in the computer program as Table 1.

The capital cost of each element is calculated by multiplying its unit cost by its area.

4.2 The capital cost of air-conditioning equipments

The unit costs of elements of air-conditioning equipments are prepared in the computer program

as Table 2, and corrected by thermal loads calculated by the program and the gross floor area of the building. The capital cost of each element is calculated by multiplying the corrected unit cost by its zone floor area.

Table 1 Some examples of material composition and unit cost of architectural elements

Element	Material composition	Unit cost (yen/m ²)
Roofing	Lightweight concrete Asphalt water proofing Heavyweight concrete Expanded polystyrene (25mm) Plaster board Rockwool board	21,490
Outside wall	Heavyweight concrete Expanded polystyrene (25mm) Plaster board	24,120
Inside wall	Cement mortar Heavyweight concrete	19,150
Window surroundings	Glazing Aluminum sash Venetian blind	59,730
Eaves	Heavyweight concrete	10,000

Table 2 Some examples of unit cost of conventional air-conditioning system's elements

Element	Standard load	Unit cost 1 (yen/m ²)	Unit cost 2 (yen/m ²)
Plant for cooling	Summer peak load (kcal/m ² ·h)	100	5,681
		150	7,142
Plant for heating	Winter peak load (kcal/m ² ·h)	80	1,047
		150	1,553
Secondary AHU system	Maximum blowing volume (m ³ /m ² ·h)	13.6	9,794
		20.5	11,864
Secondary FCU system	Summer of winter peak load (kcal/m ² ·h)	112.5	18,737
		168.8	21,390

* Unit cost 1 is the cost in the case of gross floor area 10,000 m².

* Unit cost 2 is the cost in the case of gross floor area 50,000 m².

* The unit, m², in each dimension shows the unit air-conditioning floor area in the case of Plant for cooling and heating, the unit floor area of interior zone in the case of secondary AHU system, and the unit floor area of perimeter zone in the case of secondary FCU system.

Table 3 Some examples of unit cost of electrical equipment

Element	Unit cost (yen/kVA)
Transformation work	15,180
Feeder work	7,038
Mechanical work	12,719
Lighting fixture and wiring work	175,916

4.3 The capital cost of electrical equipments

The unit costs of electrical equipments are shown in Table 3. The cost of artificial lighting controller equipped near the each window is two hundred and fifty thousand yen and the increase of ballast cost for step light control is four thousand yen.

4.4 The annual energy cost

The primary energy consumption of boilers calculated in section 3 is converted into the kerosene consumption, and the primary energy consumption of other equipments is converted into the electric power consumption. The building total annual energy cost E_t , is calculated as follows,

$$E_t = E_{kt} + E_{et} \quad \dots\dots\dots (1)$$

$$E_{kt} = \sum_j \frac{E_{kj}}{CF_k} \times C_k$$

$$E_{et} = \sum_j \left(\frac{E_{ej}}{CF_e} \times C_{ej} + W \times CE \right)$$

where, E_{kt} (yen/a) : the annual cost of the kerosene consumption
 E_{et} (yen/a) : the annual cost of the electric power consumption
 E_{kj} (kcal/month) : the primary energy consumption of boilers
 E_{ej} (kcal/month) : the primary energy consumption of other equipments
 CF_k (kcal/l) : calorific value of kerosene (8,900)
 CF_e (kcal/kWh) : coefficient of converting electric power energy into the primary energy consumption (2,450)
 C_k (Yen/l) : the unit cost of kerosene (66)
 C_{ej} (Yen/kWh) : the unit cost of electric power (26.88 in summer, 24.42 in other seasons)
 W (kW) : contract demand
 CE (Yen/kW/month) : power rate of contract demand
 j : suffix showing month

5. Simulation procedure of artificial lighting control inside perimeter zone

5.1 Control procedure of artificial lighting

The procedure of artificial lighting control inside perimeter zone utilizing daylight is shown in Fig. 3. We assumed the daylight illuminance E_d is equal to the average illuminance in the case that all luminaires in a room are turned on.

Fig. 3 Control procedure of artificial lighting inside perimeter zone.

A, B: Controlled luminaires utilizing daylight (two 40-w fluorescent lamps)

D1 : selected point in the case of one row turning on/off or turning on/off plus step light control (the distance from window is 2 m)

D2 : selected point in the case of two rows turning on/off or turning on/off plus step light control (the distance from window is 4 m)

Control procedure of artificial lighting inside perimeter zone: (Turning on/off system)

* If the daylight illuminance at point D1 exceeds E_d lux, luminaire A is turned off in the case of one row turning on/off.

* If the daylight illuminance at point D1 exceeds E_d lux, luminaire A and B are turned off in the case of two rows turning on/off.

(Turning on/off plus step light control system)
 * If the daylight illuminance at point D1 exceeds E_d lux, luminaire A is turned off and in the case exceeding a half of E_d the light output of luminaire A is reduced to a half.

* If the daylight illuminance at point D1 exceeds E_d lux, luminaire A and B are turned off and in the case of exceeding a half of E_d the light output of luminaire A and B is reduced to a half.

where, E_d : the daylight illuminance deciding turning on or off.

If we use coverless recessed luminaires using two 40 W fluorescent lamps, we can calculate utilization factor U approximately as follows,

$$U = 0.505 + 0.674 \log RI - 0.258 (\log RI)^2 \quad \dots\dots (12)$$

RI : Room index

The above formula was derived by applying least square method to the curve shown in Fig. 4.

Fig. 4 The utilization factor of coverless recessed luminaire (40 W x 2).

5.2 Calculation method of daylight illuminance in the interior

We supposed three operation types of Venetian blind, of which slat reflection factor is about 60% and the ratio of slat width to slat pitch is 1.17, for the shading device.

(1) Automatically controlled operation

Venetian blinds are driven down automatically when direct sunlight is incident in interiors. The angle of the slats is constantly set to 30°.

(2) Manual operation once a day

Venetian blinds are manipulated by building occupants at certain time once a day in accordance with window orientation. The angle of slats is set to 90° when direct sunlight is not incident. The example of manipulation is shown in Fig. 5.

Fig. 5 Manual operation pattern of venetian blind.

(3) No up/down manipulation in the daytime

Venetian blinds are kept down in the daytime. The angle of slats is adjusted to 30° for sunny days and to 90° for cloudy days.

The weather, sunny or cloudy, is distinguished by direct normal sunlight illuminance.

We used 18,000 lux⁽¹⁰⁾ as this distinguishing illuminance.

The daylight illuminance in interiors was calculated as follows,

(a) Cloudy day⁽¹¹⁾⁽¹²⁾

In the case of cloudy day daylight factor was very convenient to predict daylight illuminance at the selected point. Therefore we calculated daylight factor under next conditions.

* The luminance ratio of venetian blind to the sky luminance is 0.08.

* The luminance ratio of eaves to the sky luminance is 0.03. (concrete reflection factor is 30%)

(b) Sunny day

In the case of sunny day we can't use daylight factor. The calculation method enabling daylight illuminance in interiors with venetian blind under direct sunlight is not developed. Then we calculated as shown below.

* Effective luminance of venetian blind is calculated by using luminance coefficient studied by Matsuura⁽¹³⁾

* Direct daylight illuminance at the selected point is calculated by using effective luminance of venetian blind and configuration factor of window.

We assumed that the direct sunlight illuminance of window surface is six times as much as skylight illuminance⁽¹⁴⁾.

* Indirect daylight illuminance is uniform in in-

teriors. The upper component of daylight passing through slats of venetian blind is one and half times as much as lower component.

5.3 Annual daylight illuminance data⁽¹⁵⁾⁽¹⁶⁾

Daylight illuminance data throughout a year doesn't exist in Japan. We corrected solar radiation data called as HASP/ACLD/7302 which is prepared by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, because original sky radiation data is considerably smaller than actual state. Then we converted sky radiation into daylight illuminance using conversion coefficient shown below.

(1) Conversion coefficient C_D from direct solar radiation into direct sunlight illuminance

$$C_D = 27.8 \sin h + 95 \quad (\text{lm/W}) \dots \dots \dots (13)$$

h : solar altitude

(2) Conversion coefficient C_a from sky radiation into skylight illuminance

$$C_a = 7.18 \sin h + 115.5 \quad (\text{lm/W}) \dots \dots \dots (14)$$

Also we assumed that solar radiation data during a month distributes uniformly evenly between $R_t - \sigma_t$ and $R_t + \sigma_t$ in order to reduce calculation time of computer. R_t is mean value of solar radiation and σ_t standard deviation.

5.4 The annual reduction of electric energy consumption caused by integrated lighting

We can calculate the annual reduction of electric energy consumption by artificial lighting using previously mentioned procedure. The calculating formula is shown below.

Energy saved by daylight

$$= \sum_i \sum_j (\sum S_o \times W_o) \times D_w \times R_{off} \times 1.15 \times 10^{-3} \quad (\text{kWh}) \dots \dots \dots (15)$$

where, $S_o (\text{m}^2)$: total area of perimeter zone connected with artificial lighting control utilizing daylight

$W_o (\text{w/m}^2)$: lighting output in perimeter zone

D_w : working days per month (25 days)

R_{off} : ratio of turned off or dimmed hours to full turned on hours

1.15 : ballast loss factor of fluorescent lamp

j : suffix showing month

i : suffix showing time (9-17 o'clock)

6. The simulated example of energy consumption and saved energy by utilizing daylight

We examined annual energy consumption and saved energy by daylighting in a model building of

Table 4 Conditions for the simulation

Varying conditions				
Window area ratio to wall (%)*	20 (28)	35 (49)	50 (70)	65 (91)
Pattern of venetian blind operation	(A)	Automatically controlled operation		
	(B)	Manual operation once a day		
	(C)	No up/down manipulation in the daytime		
Control type of artificial lighting inside perimeter zone	(A)	Turning on/off system for a full year		
	(B)	Turning on/off plus step light control for a full year		
Bound of controlled luminair	(A)	One row from window		
	(B)	Two rows from window		
Fixed conditions				
Glazing thickness (mm)	8			
Length of eaves (mm)	900			
Air-conditioning period	cooling : July - September heating : December - March			
Working plane height (m)	0.75			
Considered conditions of thermal load calculations				
	Design temperature and relative humidity		Operating time of equipment for air-conditioning	
Summer (July-September)	27°C, 60%		8 precooling 9 ~ 17 ~	
Winter (December-March)	21°C, 40%		7 preheating 9 ~ 17 ~	
Perimeter depth: 3m		Occupant density: 0.2 person/m²		
Flow rate of outside air: 20 CMH/person		Weather data: HASP/ACLD/7302		

* This is the window area ratio to outside wall. The value inside parenthesis is the window area ratio viewed from the inside of the room.

Fig. 6 Model building

Location: Tokyo

Outline of architecture:

10 stories, gross floor area 15,000 m²,

rentable ratio 80%

(outside wall)

heavyweight concrete 150 mm

expanded polystyrene 25 mm

plaster board 12 mm

(core inside wall)

cement mortar 25 mm

heavyweight concrete 120 mm

cement mortar 25 mm

Luminair: Coverless recessed type using two 40-w fluorescent lamps, lighting output without ballast loss 20 w/m², average illuminance on the working plane 1,000 lux at lamp flux 6,000 lumen per luminair and maintenance factor 0.75

which outline is shown in Fig. 6. The various conditions for the simulation of a model building is shown in Table 4. The calculated results, such as total energy consumption, cooling load, heating load, saved energy of artificial lighting and thermal economics vector, are shown in Fig. 7 and Fig. 8.

We assumed that the type of operation of the blind is no up/down when automatic control of artificial lighting inside perimeter zone is not adopted.

7. Results

(1) Energy saving effect of artificial lighting inside perimeter zone increases as a building has large window. However there is little difference between 50% and 65% of window area ratio to wall area. Because the effective height at the window area ratio 65% is the same as the case of 50%. In addition, the automatically controlled blind operation is most effective in three operation types. The second is manual operation type once a day.

(2) Cooling load is reduced and heating load is increased by artificial lighting control inside perimeter zone utilizing daylight.

(3) When the artificial lighting is turned off utilizing daylight, the total primary energy consumption of a building decreases. Also the primary energy consumption increases in proportion to the window area even though the artificial lighting inside perimeter zone is turned off. However there is an exception in the case that two rows of luminaires inside perimeter zone are turned off and blind is automatically controlled.

Fig. 7 Simulated results of a model building

- (a) Turning on/off system (one row)
- (b) Turning on/off system (two rows)
- (c) Turning on/off plus step light control system (one row)
- (d) Turning on/off plus step light control system (two rows)
- Automatically controlled operation of venetian blind
- · - Manual operation once a day of venetian blind
- No up/down manipulation of venetian blind
- No control of artificial lighting
- Control of artificial lighting utilizing daylight

In this exceptional case the total primary energy consumption of a building with window area ratio 50% to wall is less than 35% because of the large difference of saved energy for artificial lighting utilizing daylight. (see Fig. 7) However a building with window area ratio 50% to wall is much expensive than 35% because the cost of window surroundings and air-conditioning equipment increases. The difference of capital cost is about twenty-seven million yen.

(4) In the case of turning on/off plus step light control system of artificial lighting, saved energy for artificial lighting becomes larger than turning on/off system. Also the reduction of the total primary energy consumption using step light control system is about 0.2–0.8% in the case of one row control of luminaire and 0.7–1.7% in the case of two rows control of luminaire.

(5) We got next results by thermal economics vectors.

(a) The automatically controlled operation type of venetian blind is most effective as for energy conservation, but most expensive as for capital cost.

The increase of capital cost in the case of manual

operation type once a day and no up/down manipulation type in the daytime is small, therefore daylight utilization in interiors should be considered.

(b) If we add the step light control system to the turning on/off, the increase of capital cost is three million yen in the case of one row control and six million yen in the case of two rows control. When the window of a building is small, we can take the advantage of the addition of the step light control because of large increase of saved energy for artificial lighting. On the other hand we don't take the advantage in the case of large window.

(c) We can say that the most economical method of energy saving is the reduction of window area and the second is the construction of eaves. The third economical method is turning on/off system of artificial lighting inside perimeter zone utilizing daylight and the last is turning on/off plus step light control system. However it's evident that the turning on/off system or the same system plus step light control of artificial lighting inside perimeter zone utilizing daylight is also effective in a existing building.

Fig. 8 The analysis of energy conservation effects using thermal economics vectors.

→ Vector of window area

--- Vector of eaves

— Vector of turning on/off system

→ Vector of step light control

Interest rate of loan: 8%

Controlled luminair: one row from window

Length of eaves: 900 mm

energy price increase rate: 10%

A, A' : Automatically controlled operation of venetian blind

B, B' : Manual operation once a day of venetian blind

C, C' : No up/down manipulation of venetian blind

Ref. There are eaves in the case of A', B' and C'.

8. Conclusion

This paper has described about the energy saving effect and economical comparison of turning on/off system and the same system plus step light control of artificial lighting inside perimeter zone using the simulation program. We have a plan to study about occupant psychology under these control and estimate the optimum method of artificial lighting control utilizing daylight.

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Received 6 Sep. 1982; Revision Received 3 Feb. 1983