Integrated and dynamic optimization of office building energy consumption with non-linear programming

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Abstract

An integrated approach was used for optimization of a RC-network model for a 5 zones (4 perimeters and 1 center zone) office building to control light ratio (ratio of current light power to maximum light power), shade position, inside air temperature, and outside air flow rate. Parameters considered in this model were: 1) heat transfer, solar heat gain and illuminance from window; 2) heat transfer from internal and external walls, 3)external walls heat storage, 4) internal heat gain from occupants and equipment, 5) ventilation rate 6) cooling and heating system, and 7) illuminance and heat gain from artificial lights. Total energy consumption of artificial light, ventilation fan, heating and cooling systems was considered as objective function for optimization. The dynamic optimization included minimizing total energy use and cost considering optimization for single- or several-hour periods. Our analysis shows significant energy saving potentials by using building integrated dynamic optimization. Comparing total energy use of the building assuming fixed control schedules with that of the integrated control systems showed savings of up to 60% in electricity use for the simulated office building.

Keywords: integrated, dynamic, optimization, energy, building

1. Introduction

Optimal operation of a building's systems is critical for reducing energy and maintenance costs, ensuring occupant comfort and maintaining indoor air quality. Optimizing a building's energy consumption requires an approach that allows devices and systems to interact with each other and work together to meet occupant requirements. Parameters that influence indoor environment quality such as temperature, CO2 concentration and indoor lights can be adjusted through integrated operation of controllers. Figure 1 shows the relationship of zone controllers and indoor comfort parameters. Many buildings have multiple systems that typically work independent of each other. These systems include heating, cooling, lighting, ventilation, automated blinds, and domestic hot water. The control strategies of existing building systems are mostly based on local controllers or pre-defined relation between parameters. These control methods lead to poor energy management and comfort [1]. Several case studies have documented significant energy savings potential by application of integrated control systems ([2-4]). Dynamic integrated control algorithms for building energy management and their energy and cost savings potential are not completely investigated yet. In this paper RC-network model as an example of simplified model was used for building modeling. Previous works have mostly focused on application of integrated control on one zone rather than the whole building. Mathews, et al. [5,6] and Vakiloroaya et al. [7] focused on HVAC system integration. Daylighting and illuminance control integration was investigated by Pandharipande and Caicedo [8], Shen and Hong [9], Mukherjee et al. [10], and Rubinstein et al. [11]. Roche and Milne [12] investigated the effect of combining smart shading and ventilation.

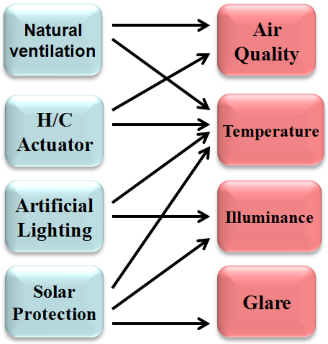

Figure 1: Relationship of zone controllers and indoor comfort parameters

Moreover, a variety of optimization methods have been applied in building control problems such as, linear and non-linear optimization (LP & NLP) [13,14], genetic algorithm optimization technique [15-17], and dynamic programming (DP) [18]. Gyalistras et al. [19] investigated the energy savings potential of simultaneous control of blinds, lighting, heating, cooling and ventilation in a single building zone. They compared whole-year hourly time step simulations with rule based control and model predictive control for several factors (such as comfort range, air quality controlled ventilation, and façade orientation). The largest energy savings potential was found for the use of CO2-controlled ventilation (average savings of 13%–28%).

Sun et al. [20] developed a methodology to get a near-optimal control commands for the blinds, natural ventilation, lights and HVAC system jointly. Numerical simulation results showed that both traditional and integrated strategies can effectively reduce the total energy cost and the integrated control can save more energy than the selected traditional non-integrated control strategies.Their methodology was tested for a fresh air unit (FAU) of two rooms.

Here, we investigate the energy savings potential by applying an integrated dynamic optimization for a 5-zone office building. RC-network model of the building is used for optimization of light ratio, blind position, inside air temperature, and outside air flow rate.

2. Methodology

2.1 Energy calculation equations

For each zone in a building, it is possible to apply energy, mass and momentum balances, depending on the type of analysis. In addition, the zones of the building are subject to many energy exchanges processes. At the basic level, a single control volume represented by a single node can be used to describe the volume of fluid inside the zone. This volume is bounded by solid constructions and is subject to heat transfer by convection, fluid exchange with its neighboring volumes and outside, heat and vapour gains from occupants, and solar energy transmitted through glazing, etc. The fundamental equation governing these exchanges is

$$\rho_i V_i c_i \frac{\partial \theta_i}{\partial t} = \sum_{j=1}^{n} q_{ij} + q_{in} \tag{1}$$

V_i is the volume (m^3) of the fluid volume *i*, ρ_i is its average density (kg/m^3), c_i is its average specific heat (J/kgK) and θ_i is the average temperature (℃). The left-hand side of Eq 1. represents the thermal capacitance of the fluid volume. In the right-hand side of the equation the $\sum_{j=1}^{n} q_{ij}$ is the sum of the energy rate (W) that interact with the control volume (surface to fluid heat transfer and fluid flow from other fluid volumes) and q_{in} is the rate of energy generation inside control volume.

Applying the convective heat transfer and fluid flow energy exchange equations to the building zone with convection to interior and exterior walls, also infiltration and ventilation and internal heat gain gives the following expression

$$\rho_i V_i c_i \frac{\partial \theta_i}{\partial t} = \sum_{j=1}^{n} h_{cij} A_{sj} (\theta_{sj} - \theta_i) + \sum_{k=1}^{m} \dot{m}_{ik} c_k (\theta_k - \theta_i) + q_i \tag{4}$$

For simplification it is possible to apply forward difference scheme to the partial derivative term, over some finite time interval:

$$\frac{\partial \theta_i}{\partial t} = \frac{\theta_i^{t+\Delta t} - \theta_i^t}{\Delta t} \tag{5}$$

This is the basic equation that can be used for the calculation of a fluid volume's temperature.

2.2 Building thermal RC-network modeling

In order to develop a thermal network and apply numerical techniques to its solution, it is necessary to subdivide the thermal system into a number of finite sub-volumes called nodes. The thermal properties of each node are considered to be concentrated at the central nodal point of each sub-volume. Each node represents two thermal network elements, a temperature (potential) and a capacitance (thermal mass).

The temperature, assigned to a node represents the average mass temperature of the sub-volume. The capacitance, C, assigned to a node is computed from the thermophysical properties of the sub-volume material evaluated at the temperature of the node and is assumed to be concentrated at the nodal center of the sub-volume. Conductors are the thermal mass modeling network elements used to represent the heat flow paths through which energy is transferred from one node to another node. Conduction conductors are computed from the equation: $R = \frac{kA}{L}$. Convection Conductors computed from the expression: $R = h\,A$

The conductive interaction in a mutli-zone building can be modeled with simple RC-networks as building blocks. In this formulation, the building is represented by a graph with nodes and edges. A node may represent a physical zone or point inside a wall. Edges represent pathways for conductive and convective heat transport. The resulting model of the building consists of a large electrical network of resistors and capacitors (figure 2).

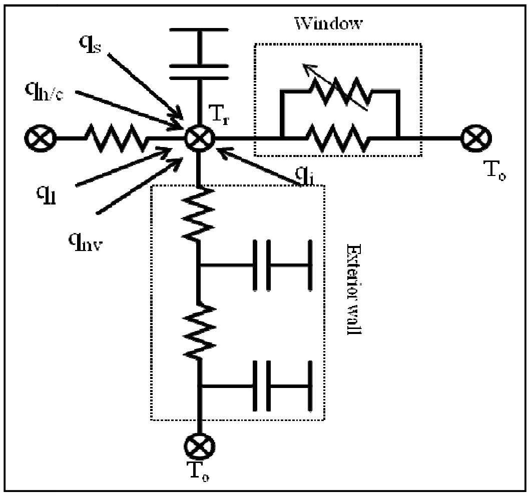

Figure 2: RC-Network model of one zone

3. Building and systems description

The prototypical building is a typical one-story office building with 5 zones. Detail of building construction and systems are shown in Table 1. Roof and floor were assumed adiabatic. Each external wall has shaded window that shading position affects conductance and emittance coefficient of the window. Occupancy and equipment schedule in addition to illuminance and heating and cooling set-point for occupancy and un-occupancy hours are shown in Table 2.

Table 1: Detail of building construction and systems

Building parameters	**Value**
Chiller COP	3.5
Electrical heater efficiency	1
Open shade window U value	2.3 W/m^2 K (0.4 Btu/hr ft^2 °F)
Close shade window U value	1.4 W/m^2 K (0.25 Btu/hr ft^2 °F)
Fluorescent lamp efficacy	70 lumens/W
Exterior wall U value	0.4 W/m^2 K (0.073 Btu/hr ft^2 °F)
Exterior wall specific heat	42 kJ/kg K (10 Btu/ °F lb)
Exterior wall outdoor surface convection heat coefficient	34 W/m^2 K (6 Btu/hr ft^2 °F)
Exterior wall indoor surface convection heat coefficient	8.5 W/m^2 K (1.5 Btu/hr ft^2 °F)
Interior wall U value	1.53 W/m^2 K (0.27 Btu/hr ft^2 °F)
Fan energy consumption	0.88 W (3 Btu/hr) per CFM of air
Maximum lamp power	15.8 W/m^2 (5 Btu/hr ft^2)

Table 2: Building schedule

Schedule	**Occupied**	**Un-occupied**
Minimum indoor illuminance	753.5 lux (70 Foot-candle)	430.5 lux (40 Foot-candle)
Occupancy heat generation	12.6 W/m^2 (4 Btu/hr ft^2)	1.6 W/m^2 (0.5 Btu/hr ft^2)
Equipment heat generation	10.7 W/m^2 (3.4 Btu/hr ft^2)	3 W/m^2 (1 Btu/hr ft^2)
Cooling Temperature set-point	25.5 °C (78 °F)	26.6 °C (80 °F)
Heating Temperature set-point	21 °C (70 °F)	18.3 °C (65 °F)
Minimum fresh air flow rate	0.01 m^3/s per m^2 (0.2 CFM per ft^2)	0.003 m^3/s per m^2 (0.05 CFM per ft^2)

4. Optimization model components

4.1 Optimization variables and constraints

Based on a simplified RC-network modeling methodology, the 5-zone (4 perimeters and 1 center zone) office building was modelled with 1) heat transfer and solar heat gain and illuminance from window, 2) heat transfer from internal and external walls, 3) internal heat gain from occupants and equipment, 4) outside air ventilation and heat gain, and 5) cooling and heating supplied by the systems. This model was used for integrated optimization of HVAC and artificial lighting systems. Table 3 shows effective variables and disturbance of optimization problem. Variables X_1, X_2, X_5, and X_6 are independent control variables and the other variables are dependent variables that were calculated based on independent variables.

The objective function is the sum of energy consumption of boiler, chiller, fan, and lighting

Objective Function: $Q_c/COP+Q_h/\eta+E_f+E_L=a_1X_1+a_2X_3+a_3X_4+a_4X_6$

Table 3: Effective variables and disturbance of optimization problem

Variables	**Disturbances**
X_1= Light ratio X_2= Blind position X_3= Cooling energy X_4= Heating energy X_5= Inside air temp. X_6= Outside air flow rate X_7= Exterior wall inside temp. X_8= Exterior wall outside temp.	V_1= outside air Temp. V_2= solar gain V_3= solar illuminance V_4= internal heat gain

Constrains of this optimization were developed according to relation between variables and their limitations. Nonlinear constrains were developed based on effect of thermal storage of external walls and limitation of these variables were developed based on visual and thermal comfort and air quality.

For dynamic optimization control variables of current hour and considered period of future hours were optimized together. Since, each hour affects future hours energy consumption because of the thermal storage of the walls, it is possible to increase energy savings potential by optimization of all the hours of considered time period simultaneously.

We used outdoor air temperature for current hour and future hours from meteorological weather data of Montreal. In addition, solar heat gain and solar illuminance from windows were obtained from the DOE2 (building energy simulation software) by modeling the same building.

4.2 Objective functions calculation

Two types of objective functions were used:

1. Energy consumption (over several time-interval span)
2. Cost function (over several time-interval span)

For calculation of energy or cost function first it is necessary to calculate total energy consumption of the building, Equation 7

$$E_{Total} = E_{Chiller} + E_{Boiler} + E_{Fan} + E_{Light} \tag{7}$$

energy consumption of chiller, boiler, and fan related to cooling and heating load of building zones. Heating and cooling load can be defined by the following equation

$$\mathrm{Q_{i,z}(x) = Q_{Cond,Ext}(x) + Q_{Fresh\ Air}(x) + Q_{Cond,Int}(x) + Q_{Light}(x) + Q_{Heat\ gain}(x) + Q_{Solar\ Trans}(x)} \tag{8}$$

In these equations “z” is zone number, “i” is optimization hour and “x” is vector of control variables. Energy objective function is defined as:

$$\text{Objective } Function\ of\ Energy = \sum_{i=1}^{n}\sum_{z=1}^{m} E_{i,z}(x) \tag{9}$$

The second summation adds energy consumption of all the zones inside the building from zone 1 to zone “m” and the first one considers energy consumption of current hour (n=1) and future hours. The cost objective function is defined as:

$$Objective\ Function\ of\ Cost = \sum_{i=1}^{n}\left[EP_i \sum_{z=1}^{m} E^{e}_{i,z}(x) + GP_i \sum_{z=1}^{m} E^{g}_{i,z}(x)\right] \tag{10}$$

where EP_i and GP_i are the electricity and gas price, respectively, at each hour base on time of use price.

5. Results and discussion

5.1 Effect of control variables

Energy consumption related to Lighting and HVAC systems are shown separately in Table 4, for three first days of each month for different strategies:

Integrated control: all control variables are optimized based on current hour outdoor conditions and building schedules;

Open shade: window shades are kept open for entire day while all other parameters are optimized;

Close shade: window shades are kept close for entire day while all other parameters are optimized;

Constant temperature: inside temperature set-point set to 23.8 °C during occupied hours and it can be changed from 18.3 °C to 26.6 °C during un-occupied hours;

Constant fresh air flow rate: fresh air flow rate is kept at minimum flow rate for entire day and all other parameters are optimized; and

Schedule: window shades are always closed, temperature is kept at 23.8 °C during occupied hours, and fresh air flow rate is kept at minimum flow rate for entire day.

In all strategies artificial lights illuminance are optimized to provide required illuminance set-point while it can go beyond this level to operate as a heat source.

The results showed the fresh air flow rate has less effect on building energy consumption, since using more fresh air increases fan energy consumption. Also, in most days outdoor air temperature is out of range of indoor set-point. Therefore, using fresh air increases heating or cooling energy consumption. The results also show that the shade position has a very significant effect on energy consumption, since it affects many parameters such as indoor illuminance, solar heat gain and windows conductance. Figure 3 shows integrated control and schedule control energy consumption, showing energy savings potential from 20% to 60% by using integrated control compared to schedule operations. Simulations indicate higher energy savings potentials in transient months such as March and April or October and November.

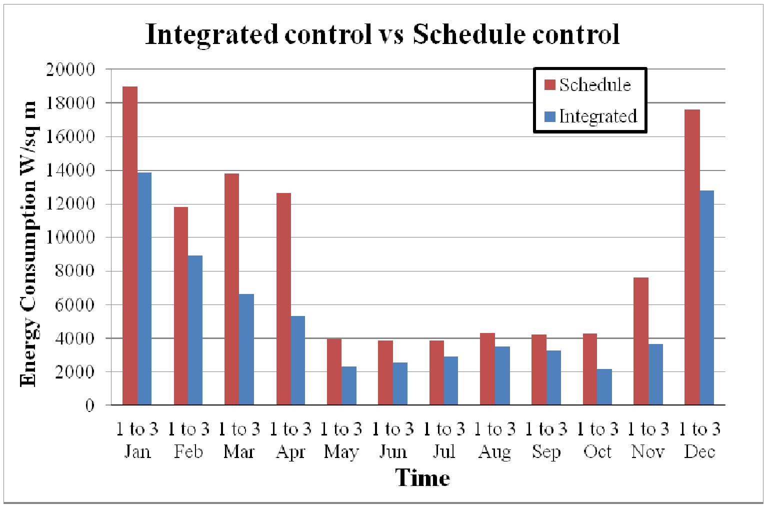

Figure 3: Integrated control and schedule control energy consumption

Table 4: Illuminance, HVAC system and total energy consumption (kJ/m^2) for three first days of each month for different strategies

Date	Energy	Integrated	Open Shade	Close Shade	Constant T	Constant CFM	Schedule
1 to 3 Jan	Light Energy	3396	3388	3688	3424	3412	3688
	HVAC Energy	10478	15292	13808	12148	10467	15286
	Total Energy	13874	18681	17495	15572	13879	18974
1 to 3 Feb	Light Energy	3284	3425	3617	3119	3298	3251
	HVAC Energy	5625	8775	6477	7489	5622	8599
	Total Energy	8909	12200	10094	10608	8920	11849
1 to 3 Mar	Light Energy	2738	2767	3688	2980	2766	3651
	HVAC Energy	3905	6723	8551	4843	3902	10117
	Total Energy	6643	9490	12238	7823	6668	13768
1 to 3 Apr	Light Energy	2660	2691	3688	2772	2698	3559
	HVAC Energy	2689	5151	7417	3714	2660	9119
	Total Energy	5349	7841	11105	6486	5358	12678
1 to 3 May	Light Energy	1627	1307	2134	1802	1812	2357
	HVAC Energy	695	2511	528	934	694	1618
	Total Energy	2323	3818	2662	2736	2505	3975
1 to 3 Jun	Light Energy	1753	1124	2113	1878	1857	2234
	HVAC Energy	816	4768	653	1157	915	1630
	Total Energy	2568	5892	2765	3035	2772	3865
1 to 3 Jul	Light Energy	1841	1124	2085	1951	1923	2158
	HVAC Energy	1094	5604	927	1606	1204	1704
	Total Energy	2935	6728	3012	3557	3127	3862
1 to 3 Aug	Light Energy	1972	1157	2095	2043	1981	2155
	HVAC Energy	1569	7733	1491	2052	1589	2158
	Total Energy	3541	8891	3586	4095	3571	4313
1 to 3 Sep	Light Energy	1979	1286	2113	2049	2000	2138
	HVAC Energy	1329	6815	1268	1880	1423	2062
	Total Energy	3308	8101	3381	3928	3423	4201
1 to 3 Oct	Light Energy	1693	1602	2197	1934	1835	2431
	HVAC Energy	468	1217	513	747	506	1814
	Total Energy	2160	2819	2710	2680	2341	4245
1 to 3 Nov	Light Energy	2513	2781	3029	2604	2547	2842
	HVAC Energy	1168	2439	2486	2687	1160	4773
	Total Energy	3681	5220	5515	5291	3707	7615
1 to 3 Dec	Light Energy	3437	3435	3688	3441	3457	3667
	HVAC Energy	9380	13844	12402	11117	9365	13902
	Total Energy	12817	17280	16090	14558	12823	17569

5.2 Effect of integrated control

In addition to schedule and integrated control strategies that explained before, three new control strategies were further investigated (Table 5).

Table 5: Illuminance, HVAC system and total energy consumption (kJ/m^2) for three first days of each month for different control strategies

Date	Energy	Schedule	Shade base on Illuminance	Shade base on Thermal	Individual Zone	Integrated
1 to 3 Jan	Light Energy	3688	1564	1647	3399	3396
	HVAC Energy	15286	13741	12999	10655	10478
	Total Energy	18974	15305	14646	14055	13874
1 to 3 Feb	Light Energy	3251	1821	1908	3251	3284
	HVAC Energy	8599	8340	7485	5768	5625
	Total Energy	11849	10160	9393	9019	8909
1 to 3 Mar	Light Energy	3651	1295	1364	2733	2738
	HVAC Energy	10117	6477	6203	4142	3905
	Total Energy	13768	7773	7567	6875	6643
1 to 3 Apr	Light Energy	3559	1294	1437	2646	2660
	HVAC Energy	9119	5325	5103	2989	2689
	Total Energy	12678	6619	6540	5636	5349
1 to 3 May	Light Energy	2357	1293	2049	1634	1627
	HVAC Energy	1618	1637	501	1066	695
	Total Energy	3975	2930	2550	2700	2323
1 to 3 Jun	Light Energy	2234	1095	2049	1748	1753
	HVAC Energy	1630	2656	589	1154	816
	Total Energy	3865	3751	2638	2902	2568
1 to 3 Jul	Light Energy	2158	1114	2061	1831	1841
	HVAC Energy	1704	3448	907	1406	1094
	Total Energy	3862	4562	2968	3237	2935
1 to 3 Aug	Light Energy	2155	1142	2072	1949	1972
	HVAC Energy	2158	4772	1445	1820	1569
	Total Energy	4313	5915	3518	3768	3541
1 to 3 Sep	Light Energy	2138	1279	2068	1981	1979
	HVAC Energy	2062	4038	1210	1517	1329
	Total Energy	4201	5317	3278	3498	3308
1 to 3 Oct	Light Energy	2431	1480	2029	1687	1693
	HVAC Energy	1814	859	394	871	468
	Total Energy	4245	2339	2423	2558	2160
1 to 3 Nov	Light Energy	2842	1716	1863	2477	2513
	HVAC Energy	4773	2265	2288	1468	1168
	Total Energy	7615	3981	4150	3945	3681
1 to 3 Dec	Light Energy	3667	1604	1679	3427	3437
	HVAC Energy	13902	12636	11909	9594	9380
	Total Energy	17569	14241	13588	13021	12817

Control of shade base on illuminance. In this control method shade position controlled with respect to outdoor illuminance without considering its effect on heating and cooling. Shade is closed during the night and it is open as much as it is required for indoor illuminance, i.e., if outdoor illuminance is less than the indoor set-point shade is completely open and if the outdoor illuminance is more than indoor set-point shade position equal to the ratio of set-point and outdoor illuminance.

Control of shade base on thermal effect. In this case shade position controlled with respect to heating and cooling without considering its effect on indoor illuminance for control.

Individual zone control. In this method control variables for each zone are optimized separately by considering temperature of previous hour on temperature of neighbor's zones for optimization. Building energy consumption is calculated based on applying these separate optimized control variables on each zone of the building and considering their heat transfer among each others.

The results show that the amount of energy saved by controlling the shade based on heating and cooling is more than the amount of energy saved by controlling the shade based on indoor illuminance. This effect is more important in hot months since shade opening has detrimental effect on cooling energy. Table 5 also shows that by using individual zone control energy savings will be reduced between 1% to 10%.

5.3 Dynamic optimization

Optimization base on effect of current hour control variables on future hours energy consumption are defined as dynamic optimization. A very important parameter in dynamic optimization is number of future hours to be modelled. Considering effect of more future hours increases potential of energy savings though, it decreases speed of optimization significantly also it increases possibility of divergence of the optimization. As a result, it is very important to find the best possible optimization period by investigating different time periods and comparing their energy consumptions. Table 6 shows optimization by considering effect of current hour on different future hours periods from next 2 hours to next 8 hours and optimizing entire day at same time.

Table 6: Total daily energy consumption (kJ/m^2) for dynamic optimization periods from next 2 hours to next 8 hours and optimizing entire day at same time

Date	Opt-current Hr	Opt-Dyn 2hr	Opt-Dyn 4hr	Opt-Dyn 8hr	Opt-Entire day
1-Jan	4214	4214	4214	4214	4214
1-Feb	1628	1616	1611	1606	1606
1-Mar	2199	2189	2180	2180	2180
1-Apr	1885	1858	1834	1826	1826
1-May	937	932	927	917	915
1-Jun	835	831	827	816	813
1-Jul	904	897	891	885	885
1-Aug	899	897	895	887	887
1-Sep	936	933	927	916	916
1-Oct	669	670	669	669	669
1-Nov	1123	1122	1121	1119	1119
1-Dec	2840	2840	2840	2840	2840

The simulations show that the dynamic optimization by considering next 2 hours have an small effect on building energy consumption. Increasing the hours under consideration in optimization process shows that considering next 8 hours is sufficient since there is no significant difference between this optimization, considering next 8 hours, and optimization of entire day. The results show up to 6% more energy savings by using dynamic optimization compared to using current hour optimization.

For dynamic optimization time of use price and energy cost should be investigated since different energy prices at different hours could affect on optimization results. Time-of-use price was considered by defining multiplier for different hours, as it is shown in Figure 4.

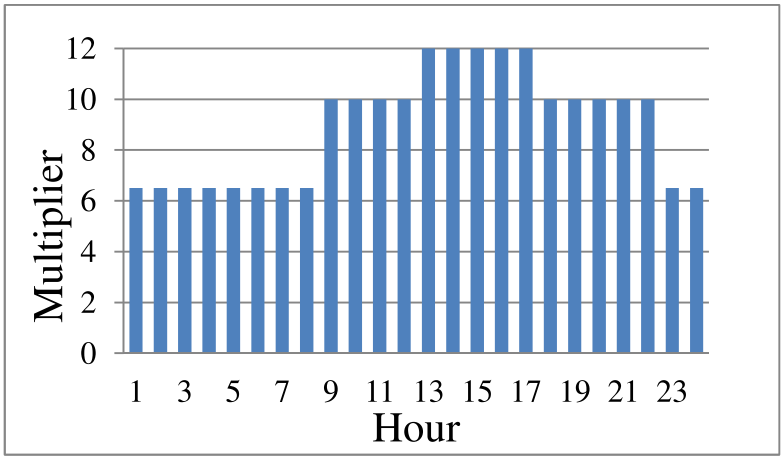

Figure 4: time of use price multiplier at different hours

The simulated building energy costs are shown in Table 7. This table shows energy cost for optimization base on current hour and dynamic optimization with considering effect on next 8 hours. Also it shows energy and cost savings for dynamic 8 hours optimization base on energy and cost.

Table 7: Energy cost for optimization base on current hour and dynamic optimization and percentage of cost and energy savings

Date	Opt-current Hr	Opt-Dyn 8hr	Energy savings %	Cost savings %
1-Jan	37330	37330	0.0	0.0
1-Feb	13568	13330	1.4	1.8
1-Mar	17680	17497	0.9	1.0
1-Apr	16196	15576	3.1	3.8
1-May	9362	9053	2.2	3.3
1-Jun	8337	8077	2.2	3.1
1-Jul	8915	8661	2.1	2.9
1-Aug	8898	8702	1.2	2.2
1-Sep	9335	9068	2.0	2.9
1-Oct	6131	6127	0.1	0.1
1-Nov	9081	9045	0.3	0.4
1-Dec	24204	24204	0.0	0.0

Dynamic optimization can save more energy because of two different energy storage effects. In cooling days, building can store cooling energy from night and early morning and use it during the hot hours; this process happens during May, Jun, July, and August. In heating days, building can store solar heating energy from morning to noon and use this heating energy during afternoon; this process happens during February, March, April, and November. Considering dynamic prices, dynamic optimization can lead to more savings. Considering different prices at different hours gives more flexibility to dynamic optimization for saving energy cost by shifting energy consumption from peak price hours to off-peak.

6. Conclusion

An integrated approach was used for optimization of a RC-network model for a 5 zones (4 perimeters and 1 center zone) office building to control light ratio (ratio of current light power to maximum light power), shade position, inside air temperature, and outside air flow rate. Parameters considered in this model were: 1) heat transfer, solar heat gain and illuminance from window; 2) heat transfer from internal and external walls, 3) external walls heat storage, 4) internal heat gain from occupants and equipment, 5) ventilation rate, 6) cooling and heating system, and 7) illuminance from artificial lights. In addition, the dynamic optimization included minimizing total energy use considering operation for a single- or several-hours period. Energy savings from 20% to 60% was achieved by using integrated control instead of scheduled control. The results show that the amount of energy saved by controlling the shade based on heating and cooling is more than the amount of energy saved by controlling the shade based on indoor illuminance. In addition by using individual zone control energy savings will be reduced between 1% to 10%. Also, dynamic optimization saved up to 6% of energy cost compare to optimization based on current hour.

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