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Life-cycle cost analysis for constant-air-volume and variable-air-volume air-conditioning systems

Mehmet Azmi Aktacir, Orhan Büyükalaca *, Tuncay Yılmaz

Department of Mechanical Engineering, University of Çukurova, 01330 Adana, Turkey

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Abstract

This study presents a life-cycle cost analysis using detailed load profiles and initial and operating costs to evaluate the economic feasibilities of constant-air-volume (CAV) and variable-air-volume (VAV) air-conditioning systems. The present-worth cost method for life-cycle cost analysis is applied to a sample building located in Adana, Turkey which can be conditioned with CAV or VAV systems. In the analysis, two different uses of the building (as a school or as an office center), two different operating scenarios for air-conditioning system (scenario 1 and scenario 2) and two different economic measures (developed and developing economy) are considered. It is found, for all the cases considered, that although initial cost of the VAV system is higher than that of the CAV system, the present-worth cost of the VAV system is lower than that of the CAV system at the end of the lifetime due to lower fan-operating costs.

Keywords: Air-conditioning; Life-cycle cost; Present-worth cost; Constant-air-volume; Variable-air-volume

1. Introduction

Selecting the most suitable and economic air-conditioning system among the available many alternatives is one of the important problems that engineers usually

* Corresponding author. Tel.: +90 322 3386485; fax: +90 322 3386126.
E-mail addresses: orhan1@cu.edu.tr, orhan1@cukurova.edu.tr (O. Büyükalaca).

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Nomenclature

AHU	air-handling unit
CAV	constant-air-volume
COP	coefficient of performance
LCC	life-cycle cost
M	air-mass flow rate under real operating conditions
$\overline{M}$	seasonal average value of M
M_{dsg}	design air-mass flow rate
P_{chil}	power consumption of chiller at part load
$\overline{P_{\mathrm{chil}}}$	seasonal average value of P_{chil}
$P_{\mathrm{chil,full}}$	power consumption of chiller at full load
P_{fan}	power of electric motor of fan under real operating conditions
$\overline{P_{\mathrm{fan}}}$	seasonal average value of P_{fan}
$P_{\mathrm{fan,dsg}}$	design power of electric motor of fan
PLR	hourly part-load ratio
$\overline{\mathrm{PLR}}$	seasonal average value of PLR
PWC	present-worth cost
Q	annual heating-energy requirement of building
Q_{chil}	hourly cooling-demand on chiller
$\overline{Q_{\mathrm{chil}}}$	seasonal average value of Q_{chil}
$Q_{\mathrm{chil,full}}$	hourly cooling-capacity of chiller at full load
$\overline{Q_{\mathrm{chil,full}}}$	seasonal average value of $Q_{\mathrm{chil,full}}$
Q_{coil}	hourly cooling-coil capacity
$\overline{Q_{\mathrm{coil}}}$	seasonal average value of Q_{coil}
$Q_{\mathrm{coil,dsg}}$	design capacity of the cooling coil
Q_{max}	maximum allowed annual heating-energy requirement of building
RTS	radiant time series
ST	hourly operating step of compressor
$\overline{\mathrm{ST}}$	seasonal average value of ST
U	overall heat-transfer coefficient
VAV	variable-air-volume
VSD	variable-speed drive
YTL	new Turkish lira
ρ	density of air
ρ_{dsg}	density of the air for design condition

face. An air-conditioning system that saves operating costs usually requires a higher initial investment. In this case, engineers should decide whether it is worth paying the extra first cost for a system that has lower operating cost [1].

Air-conditioning systems can be categorized according to the transfer of heating and cooling energy between central plants and conditioned building-spaces. There are four basic system categories: all-air systems, air- and water-systems, all-water systems and packaged unitary equipment systems. All-air systems have been widely used in air-conditioning system applications. Air movement is one of the biggest areas of energy use in these systems. Two main air-distribution systems associated with all-air air-conditioning systems are constant-air-volume and variable-air-volume systems. Different types of these two approaches are available, such as single-duct, dual-duct, reheat and multi-zone systems. CAV systems have been used since the introduction of air-conditioning, while VAV systems have been utilized since the 1960s. Energy saving is one of primary reasons that VAV systems are very popular design choices today for some commercial buildings and many industrial applications. With these systems, the volume of the air delivered is reduced whenever operating loads are less than design loads [1,2].

The purpose of this study is to compare CAV and VAV systems considering initial and operating costs together. For this purpose, a sample building located in Adana, which can be air conditioned with a CAV or VAV system, was selected. Two different uses of the sample building (as a school or as an office center) and two different operating scenarios for the air-conditioning system were considered. The operating time of the building and the air-conditioning system is between 8:00 and 17:00 h for scenario 1 and between 8:00 and 24:00 h for scenario 2. Life-cycle cost (LCC) analysis was performed using detailed load-profiles, and initial and operating costs to evaluate the economic feasibility of CAV and VAV systems. The present worth cost (PWC) method for LCC [3–7] was used to evaluate total costs. Two different sets of economic measures (interest rate and inflation rate) were used in the LCC analysis, one for a developed economy (ecoset 1) and one for a developing economy such as Turkish economy (ecoset 2). The current exchange rate is 1$ ≅ 1.5 New Turkish Lira (YTL).

2. Description of the sample building

The sample building is located in Adana, Turkey (36.59 latitude, 35.18 longitude and 20 m altitude) and it has 3 almost identical floors. The cooling period for Adana, which has a hot and humid climate during summer, covers 184 days between April 21 and October 21. The gross area of the building is 1628 m^2 and the outside surfaces of the walls are light colored. Fig. 1 shows the architectural plan of the first floor of the sample building. Long sides of the building face to the north and the south. It was assumed that the sample building can be used as an office center or a school building. If it is used as a school, the building has 14 classrooms, 3 laboratories, 5 offices, 1 library, 1 computer room and 3 corridors. In the case of office center, all the rooms are used as offices (i.e. 24 offices).

The indoor-air conditions desired are 26 °C dry bulb temperature and 50% relative humidity. Description of the internal heat-gain parameters (number of people inside, lighting, internal heat gain and related diversity factors) that were used in the calculation of the cooling load are given Table 1 for the school and the office center.

The Thermal Insulation Regulation [8] for buildings effective in Turkey classifies buildings as “A type”, “B type” or “C type” according to the ratio of annual heat-

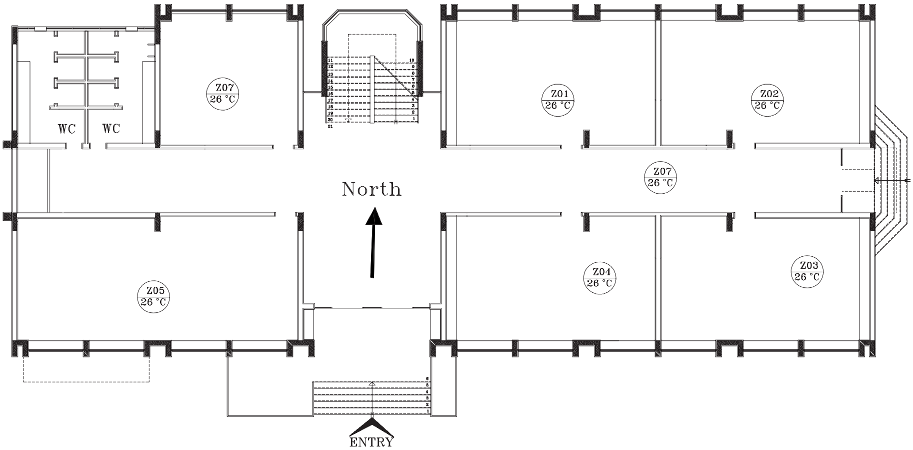

Fig. 1. Architectural plan of the first floor of the sample building.

ing energy requirement of building (Q) to the maximum allowed annual heating energy requirement (Q_{max}). Table 2 presents a classification of the energy efficiency index of buildings according to the regulations. If Q/Q_{max} is higher than 0.99, insulation should be applied to reduce the annual heating-energy requirement of the building [9].

The sample building is thermally insulated and it is a "B type" building according to the insulation regulations. Table 3 shows the overall heat-transfer coefficients of the sample building-envelope.

3. Description of the air-conditioning system

The first step in the design of air-conditioning systems is the calculation of the cooling loads of the building that depend on its characteristics, the indoor conditions to be maintained, and on the outside weather conditions.

3.1. Cooling load

In this study, Radiant Time Series method (RTS) was used for the calculation of the cooling load. The RTS method introduced by Spitler et al. [10] and 2001 ASHRAE Handbook-Fundamentals [11] is a new simplified means for performing design cooling-load calculations and it was derived from the "heat balance method".

Hourly cooling-loads of the sample building were calculated to size the air-conditioning system using hourly outdoor weather-data. The load calculations were performed for the 21st of each month during a whole cooling season (between April and October). Hourly cooling loads of the building may be affected by a different schedule of internal heat sources (i.e., operating period of the building). However, it was found that the total cooling-load of the building for scenario 1, which covers an operation

Table 1
Description of the internal heat-gain parameters for the school building and the office center

Room code	People in school		People in office		Lighting in office and school		Equipment in school		Equipment in office	
	No.	Diversity factor	No.	Diversity factor	Heat gain (W)	Diversity factor	Heat gain (W)	Diversity factor	Heat gain (W)	Diversity factor
Z01	1	0.90	5	0.85	480	0.50	2000	1.0	1766	0.8
Z02	16	0.20	5	0.85	480	0.30	1366	1.0	1766	0.8
Z03	16	0.20	5	0.85	480	0.30	2000	1.0	1766	0.8
Z04	16	0.20	5	0.85	480	0.30	2000	1.0	1766	0.8
Z05	16	0.50	5	0.85	640	0.30	6040	1.0	1766	0.8
Z07	2	0.90	5	0.85	320	0.50	1766	1.0	1766	0.8
Z08	60	0.15	10	0.50	1120	0.50	–	–	–	–
101	16	0.30	5	0.85	480	0.30	–	–	1766	0.8
102	20	0.30	5	0.85	480	0.50	1366	1.0	1766	0.8
103	16	0.80	5	0.85	480	0.30	500	1.0	1766	0.8
104	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
105	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
106	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
107	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
108	15	0.50	5	0.85	480	0.30	1000	1.0	1766	0.8
110	2	0.90	5	0.85	320	0.50	1766	1.0	1766	0.8
111	110	0.15	10	0.50	1120	0.50	–	–	–	–
201	24	0.80	5	0.85	480	0.30	500	1.0	1766	0.8
202	24	0.80	5	0.85	480	0.30	500	1.0	1766	0.8
203	16	0.80	5	0.85	480	0.30	500	1.0	1766	0.8
204	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
205	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
206	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
207	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
208	16	0.80	5	0.85	320	0.30	500	1.0	1766	0.8
210	2	0.90	5	0.85	320	0.50	1766	1.0	1766	0.8
211	140	0.15	10	0.50	1120	0.50	–	–	–	–

Table 2
Classification of buildings according to the thermal-insulation regulation of Turkey

Type	Q/Q_{max}	Energy efficiency
A	$\leqslant 0.80$	Very good
B	$\leqslant 0.90$	Good
C	$\leqslant 0.99$	Normal

Table 3
Values of the overall heat-transfer coefficient (U) of the sample building's envelope

	Wall	Roof	Floor	Window
U (W/m^2 K)	0.783	0.508	0.757	2.8

period between 8:00 and 17:00, is approximately equal to that for scenario 2 for 8:00–17:00. Therefore, scenario 2 was considered for the sizing of the air-conditioning system.

Hourly cooling loads of the office center and the school building are given in Figs. 2 and 3, respectively. It can be seen, from the figures, that maximum cooling load of the sample building is obtained in August. Therefore, the cooling system should be designed using the cooling load obtained in August. The maximum (design) cooling load for the school and the office center is 131.1 and 117.7 kW at 13:00, respectively. The ratio of sensible to total cooling load is called the sensible-heat ratio. At the peak hour, the sensible-heat ratios for the school and the office center are 0.89 and 0.94, respectively. The sharp increases in the cooling load at 8:00 and the sharp decrease at 24:00 is due to the change in the number of the occupants.

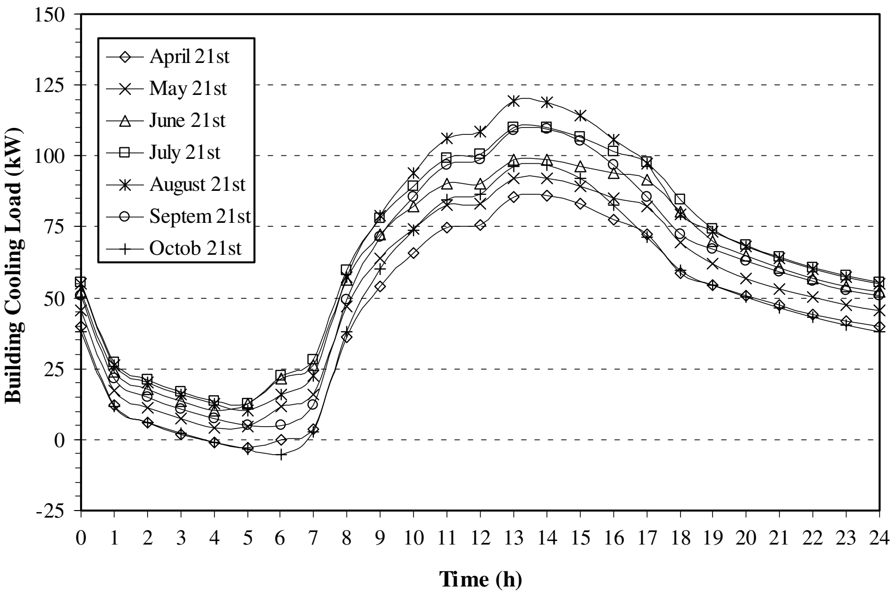

Fig. 2. Building cooling-load profile of the office center for scenario 2 (operating hours are between 8:00 and 24:00).

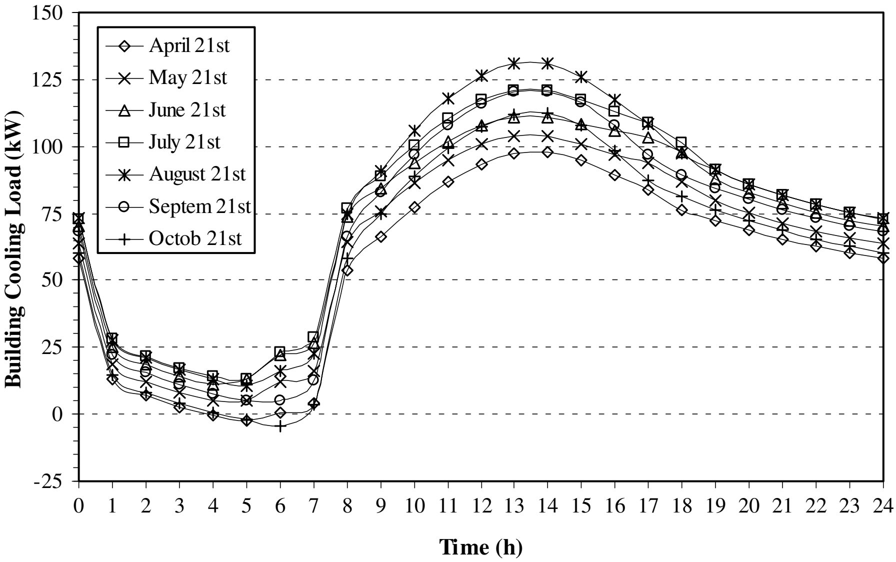

Fig. 3. Building cooling-load profile of the school building for scenario 2 (operating hours are between 8:00 and 24:00).

3.2. Air-conditioning system

Fig. 4 shows a schematic of the all-air air-conditioning systems considered. Since the aim of the study is to compare CAV and VAV systems, both approaches are indicated in the figure.

It can be seen, from Fig. 4, that the CAV and the VAV air-conditioning systems commonly consist of an air-handling unit (AHU), an air-cooled chiller system, supply and return fans, a duct, and control units. The VAV system includes additional two variable-speed drive (VSD) units for the supply and return fans and 27 VAV boxes in addition to the other common units. One VAV box, which regulates the amount or volume of cold air discharged into the conditioned space in order to maintain the desired comfort conditions, is used for each room in the building.

According to ASHRAE Standard 62 ventilation-rate procedure [12], the office rooms and the classrooms should be supplied with fresh air at a flow rate of 28 m^3/h per person. Fresh-air requirements for laboratories and corridors are 36 m^3/h per person and 1.8 m^3/h per square metre, respectively. These resulted in minimum total ventilation rates of 7001 m^3/h for the school building and 3359 m^3/h for the office center.

In the calculation of the design value for the cooling-coil capacity, temperature of the air supplied to the air-conditioned volumes was selected to be 15 °C for the VAV system. Air is supplied to the room by mixing the minimum amount of fresh air for ventilation with the return air, so that maximum energy saving can be obtained. Using the maximum building-cooling load (131.1 kW), a sensible-heat ratio (0.89), minimum fresh-air ventilation requirement (7001 m^3/h) and fixed-supply air temper-

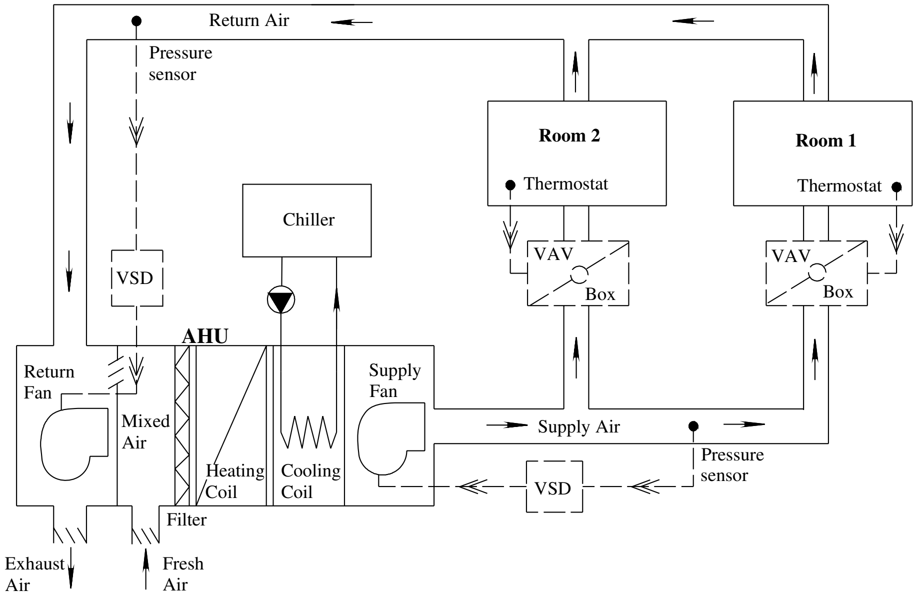

Fig. 4. Schematic of CAV and VAV (for which additional units are shown with dashed lines) air-conditioning systems.

ature (15 °C) as input parameters, the maximum (design) cooling-coil capacity and the maximum (design) supply air-flow rate were found, respectively, to be $Q_{\mathrm{coil,dsg}} = 166.2$ kW and $M_{\mathrm{dsg}} = 37{,}348$ kg/h for the school building when the VAV system was considered. Calculation procedure required an iterative approach, therefore a computer program was written.

Flow rate of the supply air is constant for a CAV system, whilst it is variable for a VAV system. A VAV system operates identically to a CAV system under peak-cooling conditions, with the AHU operating at maximum supply flow-rate. The supply airflow is reduced under part-load conditions. Therefore for a fair comparison, the maximum (design) supply air-flow rate obtained for the VAV system ($M_{\mathrm{dsg}} = 37{,}348$ kg/h) was selected for the CAV system. Since the maximum building's cooling-load and the flow rate of the supply air are the same, the cooling-coil capacity of the CAV system is obtained to be the same as that of the VAV system ($Q_{\mathrm{coil,dsg}} = 166.2$ kW). It should be noted that, the same diversity factors were used for both the CAV and the VAV systems (Table 1) when the cooling load due to internal heat-gains was calculated. The most serious problem when calculating internal heat-gains is lack of information on the exact schedule of occupancy, light usage and equipment operation. For example, it may not be reasonable to assume that all the occupants are present, all lights are on, and all equipment is operating [13]. The diversity factor reflects the less than full presence of people or utilization of lighting and equipment.

The air-handling unit and chiller were selected from a local supplier (Alarko-Carrier). The total power of the electric motors of the supply and return fans in the AHU that provide air for the CAV or the VAV system is $P_{\mathrm{fan,dsg}} = 26$ kW. Net cooling capacity and electricity consumption of the chiller unit selected are $Q_{chil,full}$ = *185 kW and* $P_{chil,full} = 80$ kW under nominal operating conditions (38 °C condenser air-inlet temperature, 10 °C evaporator inlet and 6 °C outlet water temperature), respectively. The compressor in the chiller unit is controlled by a five-stepped proportional-control system for part-load operations.

For the case of the office center, after similar calculations, the design cooling-coil capacity of the CAV or VAV systems and the design mass flow rate of the supply air were found to be $Q_{coil,dsg} = 136.1$ kW and $M_{dsg} = 36{,}240$ kg/h, respectively. The total power of the electric motors of the supply and return fans is $P_{fan,dsg} = 26$ kW. Net cooling capacity and electricity consumption of the chiller unit are $Q_{chil,full} = 146$ kW and $P_{chil,full} = 66$ kW under nominal conditions, respectively. The compressor in the chiller has four-stepped proportional-control for part load.

4. Costs analyses of air-conditioning systems

For a fair comparison of two alternative air-conditioning systems, all the costs (initial and operating costs) that will be incurred over the lifetime of the systems should be taken into account.

4.1. Initial costs

Initial costs of the CAV and the VAV systems include those of the AHU, chiller system, ducts, and control units. Table 4 shows the estimated initial costs of the systems considered. As can be seen from Table 4, initial cost for the school building is approximately 7% higher than that for the office center. When the initial costs of the CAV and the VAV systems are compared, it is seen that, initial cost of the VAV system is 21% and 23% higher than that of the CAV system for the school building and the office center, respectively.

Table 4
Comparison of initial costs of the VAV and the CAV systems

Unit	Initial cost ($)			
	School building		Office building	
	CAV	VAV	CAV	VAV
AHU	20,355	20,355	20,355	20,355
Duct	20,000	20,000	20,000	20,000
Chiller	47,495	47,495	40,710	40,710
Automation	6785	11,696	6785	11,649
VSD	0	4150	0	4150
VAV Box	0	10,877	0	10,754
Total	94,635	11,4573	87,850	10,7618
Extra investment for the VAV	–	19,938	–	19,768

4.2. Operating and maintenance costs

Operating costs include the costs of electricity, wages of employees, supplies, water and materials. Electrical operating costs for the systems considered comprise those for the chiller and AHU including supply and return fans. Electrical costs of the chiller, supply and return fans were calculated separately for the CAV and the VAV systems. Maintenance cost depends on many parameters, such as local labor rates, their experience, the age of the system, length of time of operation, and therefore, it is difficult to quantify. Complexity of the air-conditioning system and the relative ease of access to plant play an important role on the maintenance cost [3]. A proper estimation of the maintenance cost requires a detailed analysis, which is beyond the scope of this study. Maintenance cost for the CAV and the VAV systems can be considered approximately to be the same. In the calculations, therefore, maintenance costs and other operating costs such as wages of employees, supplies, etc., were neglected.

Two electricity-consuming units in the air-conditioning systems are the fans and the chiller unit. Electric consumption of the other unit such as chilled-water pumps will be the same for both systems, and, therefore, they are neglected in the cost analysis. For the CAV system, mass-flow rate is constant through the operation of the system, therefore even for the part-load conditions the fans consume the maximum power. Under peak-cooling conditions, the VAV system operates identically to a CAV system with AHU operating at maximum flow and maximum cooling coil capacity. However, at reduced cooling load, the system airflow is reduced by the combined action of the closing of the zonal VAV box dampers and the fan speed controller [1]. Therefore the electricity consumption of the fans may vary greatly through the day or cooling season depending on the cooling load. For determining the total operating cost of the fans for a cooling season in the VAV system, the power of the fan's electric motor under the real operating conditions (P_{fan}) was calculated using the following equation:

$$P_{\text{fan}} = P_{\text{fan,dsg}} \left(\frac{M/\rho}{M_{\text{dsg}}/\rho_{\text{dsg}}} \right)^3, \tag{1}$$

where M is the air-mass flow rate under the real operating conditions, and $P_{\text{fan,dsg}}$ and M_{dsg} are the design fan-power (total capacity is 26 kW for both buildings) and the design air-mass flow rate (37,348 kg/h for the school building and 36,240 kg/h for the office center), respectively; ρ is the density of air. Since the density of air will be approximately same for both the design and actual operating conditions, Eq. (1) can be written as follows:

$$P_{\text{fan}} = P_{\text{fan,dsg}} \left(\frac{M}{M_{\text{dsg}}} \right)^3. \tag{2}$$

As seen from Eq. (2), the power required for running a fan is proportional to the cube of the air-mass flow rate. In this study, fan powers at part load (P_{fan}) for the school building and the office center were determined hourly during a cooling season using Eq. (2).

Hourly total mass flow rate requirement (M) and hourly cooling-coil capacity (Q_{coil}) for the 21st day of each month during the cooling season were computed using the variable hourly cooling-loads given in Figs. 2 and 3. For these purposes, two computer programs, one for the VAV and the other for the CAV system using FORTRAN programming language were prepared. Details of the calculation procedure can be found in [14]. Hourly total mass-flow rates for 21st day of each month during the cooling season for the VAV and the CAV systems are given in Fig. 5 for the school building. Fig. 6 shows hourly cooling-coil capacity for the 21st day of each month for the VAV system for the school building.

It is seen, from Figs. 5 and 6, that the fans and the compressor in the chiller unit usually operate at part load under real operating conditions because of the varying cooling load. Whenever the operating load is less than the design load, the capacity of the compressor in the chiller unit should be reduced by the five-stepped proportional controller and the total flow rate should be reduced in the VAV system to save energy. The minimum values of total mass flow rate and coil capacity occur in April, whilst the maxima are seen in August.

The total mass-flow rate and the coil capacity for days other than 21st day of each month were not calculated. Therefore, the results obtained for 21st day of each month were integrated on an hourly basis by the Simpson Integral Method and seasonal average values of hourly total mass-flow rate ($\overline{M}$) and hourly coil capacity ($\overline{Q_{coil}}$) were obtained. The seasonal average mass-flow rate ($\overline{M}$) and coil capacity ($\overline{Q_{coil}}$) are also shown in Figs. 5 and 6, respectively.

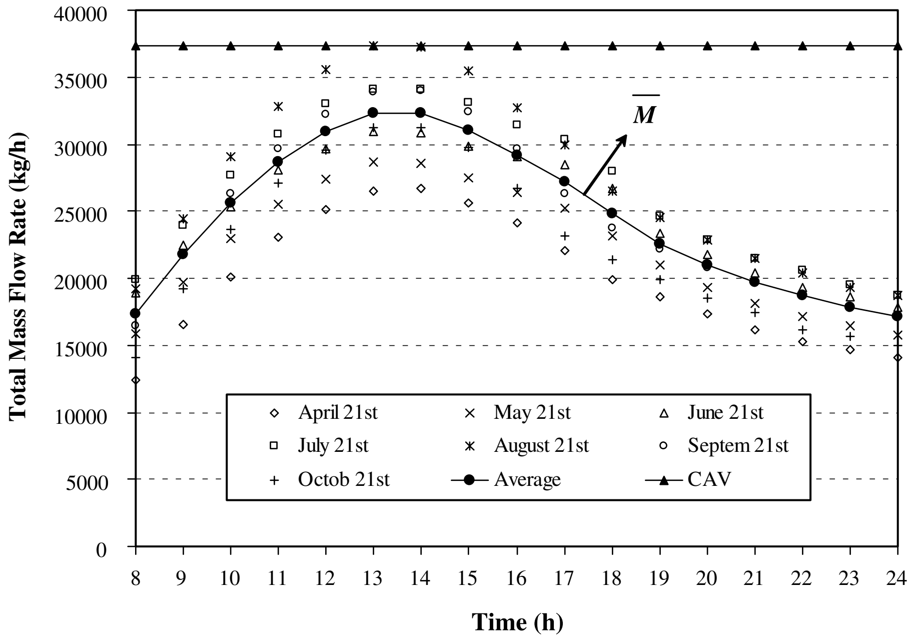

Fig. 5. Hourly total mass-flow rate for the VAV and the CAV systems for the school building.

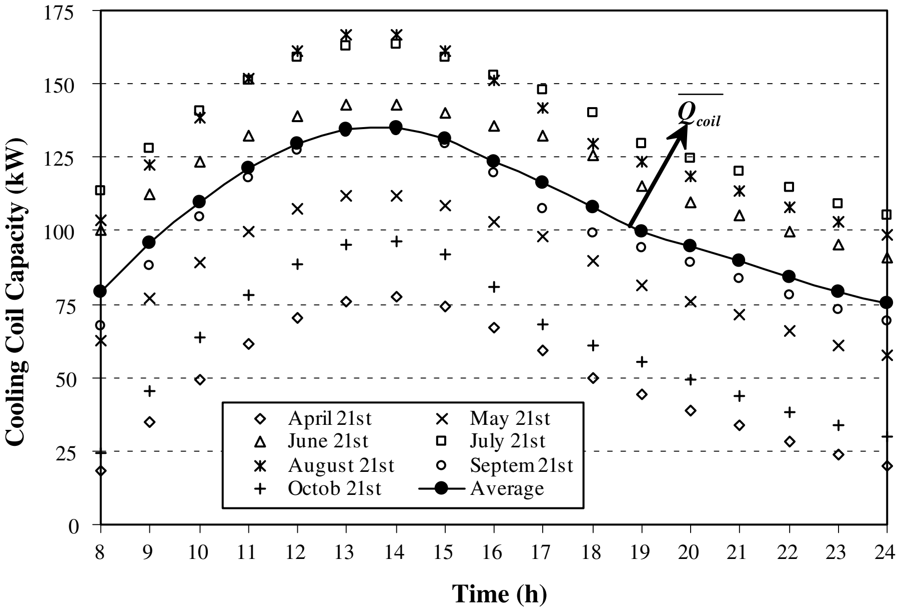

Fig. 6. Hourly cooling-coil capacity for the VAV system for the school building.

By inserting the seasonal average mass flow rate ($\overline{M}$) in Eq. (2), the seasonal average hourly fan-power for the VAV system ($\overline{P_{\mathrm{fan}}}$) was obtained. Total electric consumption of the fans in a cooling season can be calculated by multiplying the average hourly fan power with the operating period. Utilizing an electric price of 0.11 \$/kWh, the annual operating costs for the fans were determined for the CAV and the VAV systems.

In the study, two different operating scenarios (8:00–17:00 operating hours for scenario 1 and 8:00–24:00 operating hours for scenario 2) were considered. Table 5 shows the estimated annual (for 184 days of operation) operating costs of the fans for the VAV and the CAV systems in the school building according to the scenarios considered. As seen from the table, the annual operating cost of the fans in the VAV system is 56% less than that of the CAV system for scenario 1. In the case of scenario 2, the saving is higher (≈66%), due to the longer operating hours.

A similar approach was followed for the calculation of the seasonal operating cost of the chiller unit. In the analysis, variation of the coefficient of performance (COP) of the chiller unit with the outside-air temperature and variation of COP with part-load ratio were considered. Part-load ratio (PLR) was defined as;

$$\mathrm{PLR} = Q_{\mathrm{chil}}/Q_{\mathrm{chil,full}}, \tag{3}$$

where Q_{chil} is the hourly cooling-demand on the chiller, which is approximately equal to the hourly coil-load (Q_{coil}), and $Q_{\mathrm{chil,full}}$ is the full cooling-capacity of the chiller. The automatic control-system of the chiller unit will select a suitable operating step for the compressor depending on the value of PLR.

Table 5
Annual operating costs of the fans for the school building

Scenario[a]	System	Operating time	Power (kW)	Electric consumption (kWh/year)	Operating cost ($/year)
I	VAV	08:00–09:00	2.59	475.98	52
		09:00–10:00	5.12	942.75	104
		10:00–11:00	8.34	1535.41	169
		11:00–12:00	11.72	2156.62	237
		12:00–13:00	14.71	2706.39	298
		13:00–14:00	16.78	3087.82	340
		14:00–15:00	16.77	3085.19	339
		15:00–16:00	14.85	2733.10	301
		16:00–17:00	12.33	2268.29	250
		Total operating cost of the fans ($/year)=			2089
	CAV	08:00–17:00	26	43056	4736
		Total operating cost of the fans ($/year)=			4736
II	VAV	08:00–09:00	2.59	475.98	52
		09:00–10:00	5.12	942.75	104
		10:00–11:00	8.34	1535.41	169
		11:00–12:00	11.72	2156.62	237
		12:00–13:00	14.71	2706.39	298
		13:00–14:00	16.78	3087.82	340
		14:00–15:00	16.77	3085.19	339
		15:00–16:00	14.85	2733.10	301
		16:00–17:00	12.33	2268.29	250
		17:00–18:00	10.04	1846.70	203
		18:00–19:00	7.65	1407.53	155
		19:00–20:00	5.71	1049.99	115
		20:00–21:00	4.59	844.48	93
		21:00–22:00	3.80	699.56	77
		22:00–23:00	3.26	600.52	66
		23:00–24:00	2.85	523.66	58
		Total operating cost of the fans ($/year)=			2856
	CAV	08:00–24:00	26	76544	8420
		Total operating cost of the fans ($/year)=			8420

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.

Using the data provided by the manufacturer and the hourly outside air-temperature, hourly values of the cooling capacity (Q_{chil}) and power consumption (P_{chil}) of the chiller at full load and at part load (for each of the five steps of the chiller) were obtained for the 21st day of each month during the cooling season. As an example of the results, Q_{chil} and P_{chil} are shown in Figs. 7 and 8 for full capacity and compressor step 3, respectively. The trends observed in these figures are due to the variation of COP of the chiller system with outdoor-air temperature, since the chiller has an

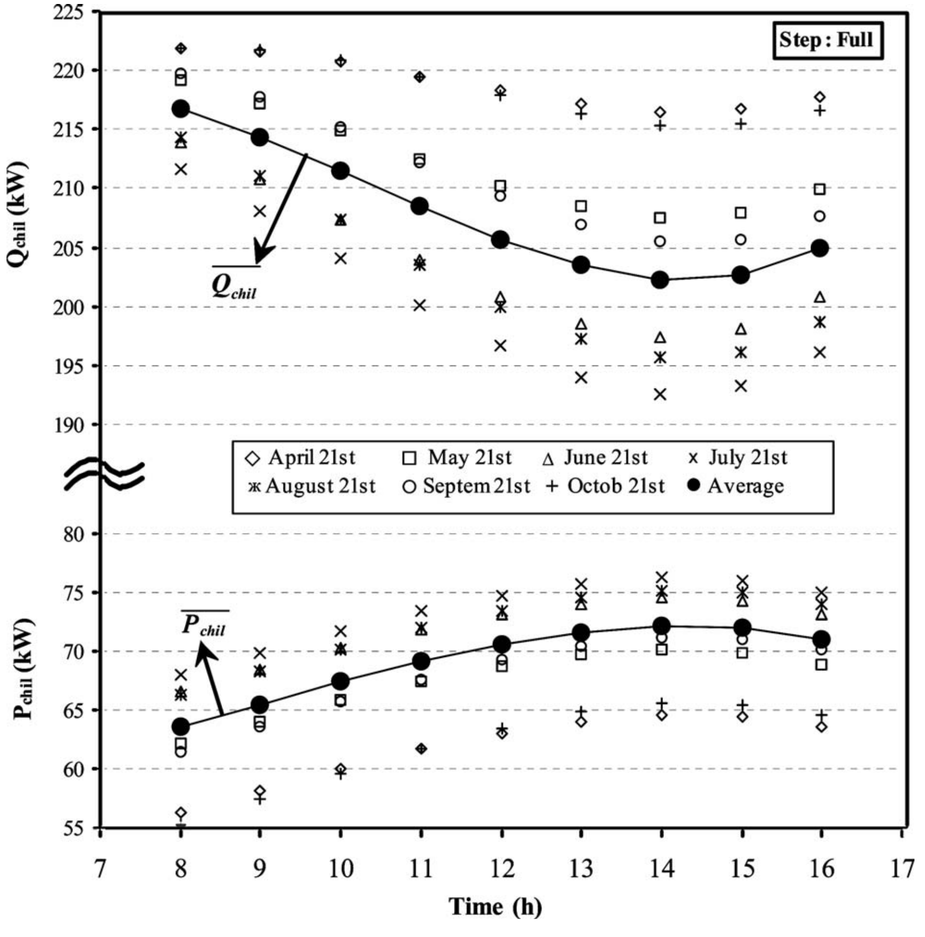

Fig. 7. Hourly cooling-capacity and power consumption of the chiller unit at full load.

air-cooled condenser unit. Q_{chil} decreases and P_{chil} increases with the increase of outdoor air-temperature, as expected. Seasonal average hourly values of Q_{chil} and P_{chil} ($\overline{Q_{chil}}$ and $\overline{P_{chil}}$) were then calculated utilizing the Simpson Integral Method. Figs. 7 and 8 also show $\overline{Q_{\text{chil}}}$ and $\overline{P_{\text{chil}}}$.

Using the seasonal average hourly values of the coil load ($\overline{Q_{\text{coil}}}$) obtained previously and chiller capacity at full load ($\overline{Q_{\text{chil,full}}}$), the seasonal average hourly part-load ratio ($\overline{\text{PLR}}$) and then seasonal average hourly operating step of the compressor ($\overline{\text{ST}}$) were determined.

From the corresponding part load $\overline{Q_{\text{chil}}}$ and $\overline{P_{\text{chil}}}$, and operating time it was possible to calculate seasonal work consumption and then the operating cost of the chiller unit.

It should be noted that annual operating-cost of the chiller unit is the same both for the CAV and the VAV systems. Table 6 shows the annual operating cost of the chiller for the school building. As seen from the table, the annual operating cost of

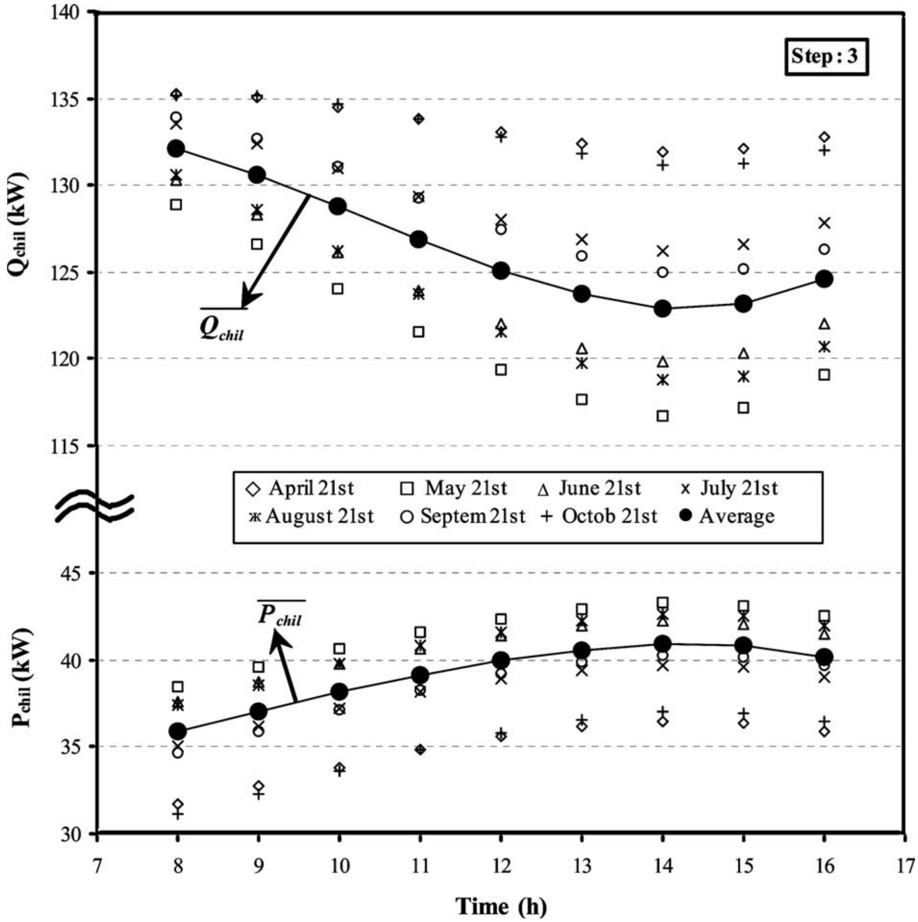

Fig. 8. Hourly cooling-capacity and power consumption of the chiller unit at compressor step 3.

the chiller for scenario 2 is 70% higher than that of scenario 1 due to the longer operating hours.

Similar calculations were performed for the office center. A summary of the results obtained for the operating cost analysis is given in Table 7. Also shown are the annual operating-cost savings due to use of VAV system. For the school building, the annual total saving of the VAV system is 21% and 25% for scenarios 1 and 2, respectively. In the case of the office center, slightly higher savings were obtained (24% for scenario 1 and 30% for scenario 2).

5. Life-cycle cost analyses of air-conditioning systems

Analyses of overall initial and operating costs for two air-conditioning systems were developed in this study. A LCC analysis was carried out to compare the

Table 6
Annual operating cost of the chiller unit for the school building

Scenario[a]	System	Operating time	Power (kW)	Electric consumption (kWh/year)	Operating cost ($/year)
I	CAV and VAV	08:00-09:00	24.58	4522.72	497
		09:00–10:00	37.00	6808.00	749
		10:00–11:00	38.12	7014.08	772
		11:00–12:00	39.13	7199.92	792
		12:00–13:00	54.59	10044.56	1105
		13:00–14:00	55.34	10182.56	1120
		14:00–15:00	55.81	10269.04	1130
		15:00–16:00	55.65	10239.60	1126
		16:00–17:00	40.20	7396.80	814
		Total operating cost of the chiller ($/year)=			8105
II	CAV and VAV	08:00–09:00	24.58	4522.72	497
		09:00–10:00	37.00	6808.00	749
		10:00–11:00	38.12	7014.08	772
		11:00–12:00	39.13	7199.92	792
		12:00–13:00	54.59	10044.56	1105
		13:00–14:00	55.34	10182.56	1120
		14:00–15:00	55.81	10269.04	1130
		15:00–16:00	55.65	10239.60	1126
		16:00–17:00	40.20	7396.80	814
		17:00–18:00	42.13	7751.92	853
		18:00–19:00	42.73	7862.32	865
		19:00–20:00	43.32	7970.88	877
		20:00–21:00	43.91	8079.44	889
		21:00–22:00	44.51	8189.84	901
		22:00–23:00	30.62	5634.08	620
		23:00–24:00	31.01	5705.84	628
		Total operating cost of the chiller ($/year)=			13736

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.

VAV and the CAV systems. The system lives of the VAV and the CAV system are expected to be the same, and it was taken as 15 years [5,7]. Therefore in the analysis, the present-worth cost technique was used [3,5–7] for evaluating the systems. The present-worth cost technique was used to examine total (initial and operating) costs of the two alternative systems (CAV and VAV) and the two operating scenarios (scenarios 1 and 2) over the analysis period.

Results of the LCC analysis are directly affected by the economic measures. Therefore, two different sets of interest and inflation rates were considered. In the first set (ecoset 1), annual interest and annual inflation rate were taken, respectively, as 6% and 0%, i.e. for a developed economy. In the second case (ecoset 2), an annual interest rate of 22% and an annual inflation rate of 12%, which can be typical to a developing country such as Turkey, were studied.

Table 7
Summary of the results obtained from the operating-cost analysis

Building	Scenario[a]	System		Operating cost ($/year)		
				Chiller	Fans	Total
School building	I		CAV	8105	4736	12,841
			VAV		2089	10,194
		Saving	$/years	0	2647	2647
			%		56	21
	II		CAV	13,736	8420	22,156
			VAV		2856	16,592
		Saving	$/year	0	5564	5564
			%		66	25
Office center	I		CAV	6824	4736	11,560
			VAV		1998	8821
		Saving	$/year	0	2738	2738
			%		58	24
	II		CAV	10,603	8420	19,023
			VAV		2650	13,253
		Saving	$/year	0	5770	5770
			%		69	30

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.

5.1. Results for ecoset 1

For the school building, it was found that by paying an extra investment of $19938 (Table 4) for the VAV system, it is possible to save $2647 for scenario 1 and $5564 for scenario 2 each year from the operating cost (Table 7).

Fig. 9 shows the variation with operating years of overall present worth costs of both air-conditioning systems for the school building. From the figure, it is seen that the cost of the VAV system is higher than that of the CAV system in the first years of the operation. However, after a certain period of time, the VAV system becomes economically attractive. At the end of the lifetime (15 years) the present worth cost of the VAV system is 3% lower than that of the CAV system for scenario 1. In the case of scenario 2, the advantage of the VAV system is pronounced. The present worth cost of the VAV system at the end of the lifetime is 11% lower than that of the CAV system.

From Fig. 9, it is also possible to determine the payback period of the VAV system with respect to the CAV system by comparing the curves. At the end of approximately 10.32 years for scenario 1 and 4.15 years for scenario 2, the extra investment for the VAV system has paid for itself, and thereafter it yields profits each year.

For the office center, the extra investment required for the VAV system is $19768 (Table 4) and annual operating cost saving is $2738 and $5770 for scenarios 1 and 2, respectively (Table 7).

The results of the LCC analysis for the office building are close to those of the school building (Fig. 10). The present-worth cost of the VAV system is again higher than that for the CAV system in the first operation years, and after a certain period of time it becomes smaller. The present worth cost of the VAV system at the end of

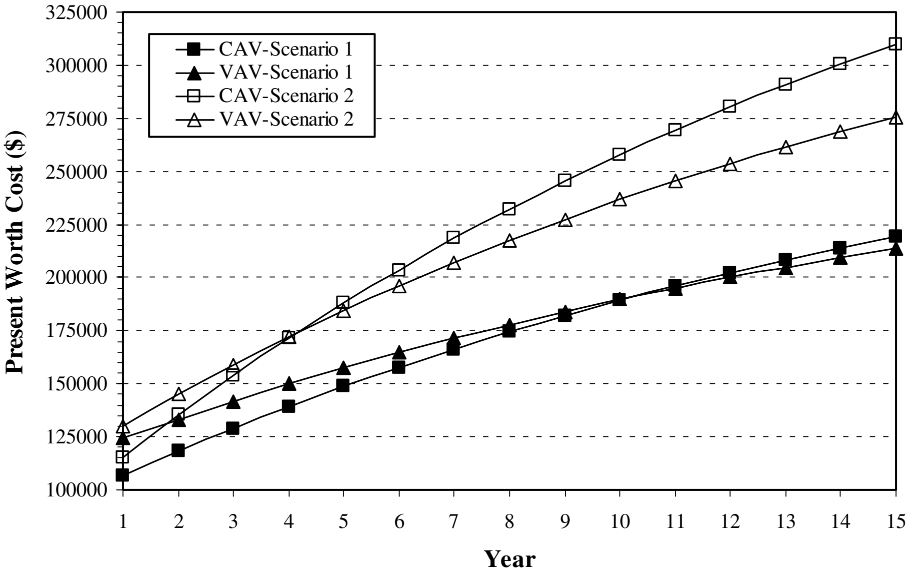

Fig. 9. Variation with operating years of present-worth cost for the school building for ecoset 1 (6% annual interest rate and 0% annual inflation rate).

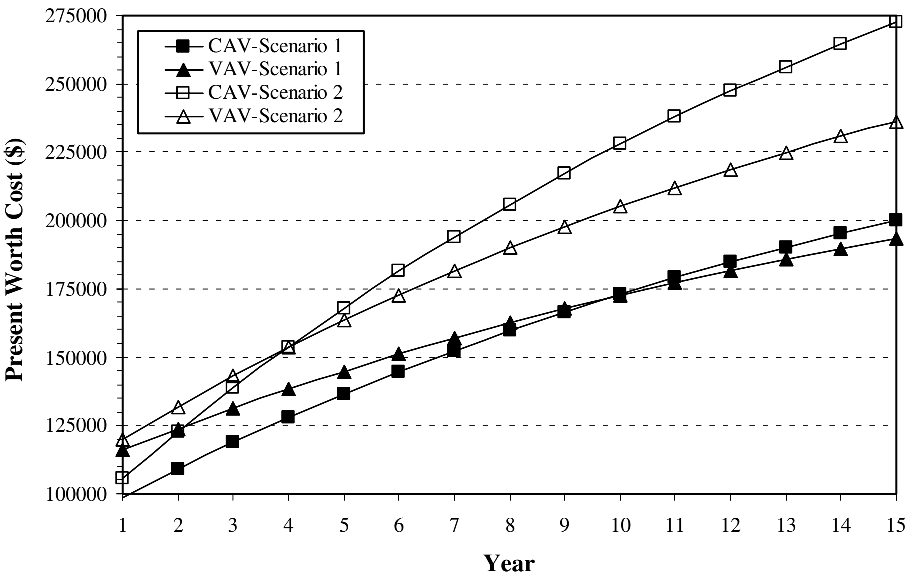

Fig. 10. Variation with operating years of present-worth cost of for the office center for ecoset 1 (6% annual interest rate and 0% annual inflation rate).

the lifetime is 3% and 13% lower than that of the CAV system for scenarios 1 and 2, respectively. When the payback period of the VAV system with respect to the CAV system is considered, it is found that payback period is 9.74 years for scenario 1, and 3.95 years for scenario 2.

5.2. Results for ecoset 2

To be able to find the best economic air-conditioning system for the sample building located in Adana, Turkey, the LCC analysis was also carried out for ecoset 2. Figs. 11 and 12 show the variations with operating years of the present-worth costs for the school building and the office center, respectively. Although the trends are similar to that for the ecoset 1, due to higher inflation and interest rates, the payback period for the VAV system with respect to the CAV system is longer (Table 8). For the school building, it is 13.06 and 4.51 years for scenarios 1 and 2, respectively. In the case of the office center, the payback time is slightly shorter (12.10 years for scenario 1 and 4.27 years for scenario 2).

Although a shorter payback time is better for an investment, it is difficult to quantify the feasible maximum payback-time. An investment is considered roughly to be "excellent" if the payback time is less than one-third of the lifetime of the investment. It is "good" if the payback time is less than one-half of the lifetime [1].

If one follows this rule of thumb, a VAV based air-conditioning system for both buildings (school and office) is "excellent" for scenario 2 for both developed (ecoset 1) and developing economies (ecoset 2). For scenario 2, which covers longer

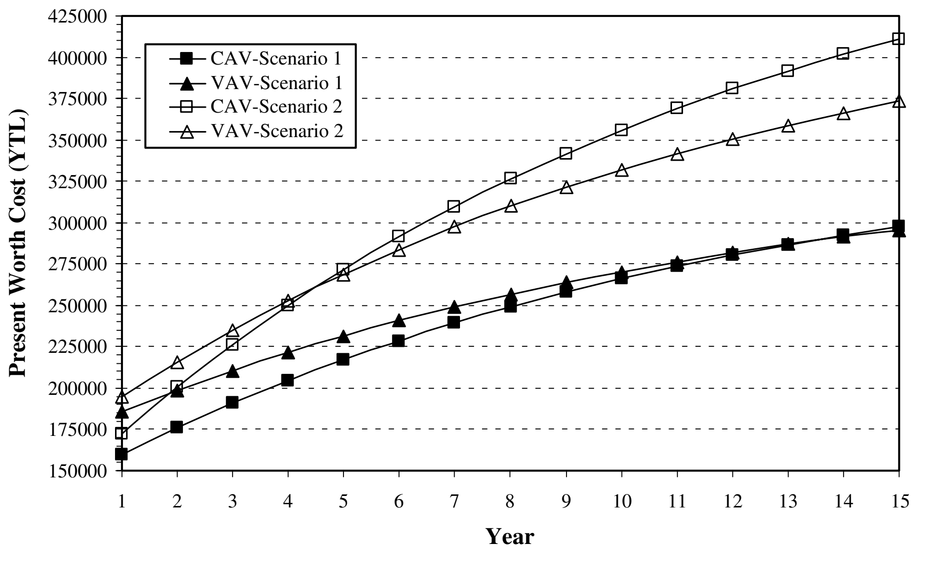

Fig. 11. Variation with operating years of present-worth cost for the school building for ecoset 2 (22% annual interest rate and 12% annual inflation rate).

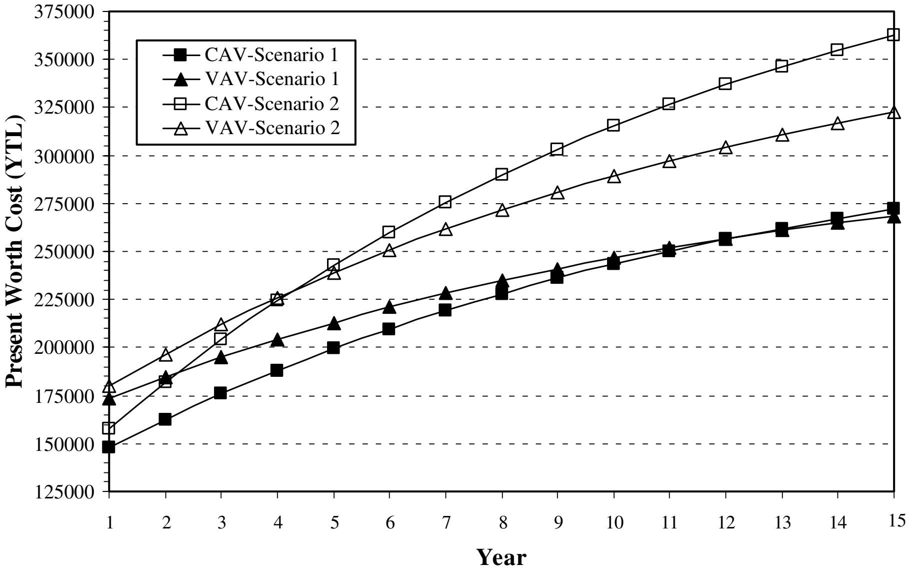

Fig. 12. Variation with operating years of present-worth cost for the office center for ecoset 2 (22% annual interest rate and 12% annual inflation rate).

Table 8
Life-cycle analysis results for ecosets 1 and 2

Building	Scenario[a]	Ecoset[b]	System	PWC at the end of lifetime	Payback period of VAV (years)
School building	I	I	VAV	$213576	10.32
			CAV	$219347	
		II	VAV	295612 YTL	13.06
			CAV	297841 YTL	
	II	I	VAV	$275718	4.15
			CAV	$309817	
		II	VAV	373305 YTL	4.51
			CAV	410949 YTL	
Office center	I	I	VAV	$193292	9.74
			CAV	$200120	
		II	VAV	268577 YTL	12.10
			CAV	272123 YTL	
	II	I	VAV	$236330	3.95
			CAV	$272602	
		II	VAV	322328 YTL	4.27
			CAV	362731 YTL	

[a] Operating time of the air-conditioning system is between 8:00 and 17:00 for scenario 1 and between 8:00 and 24:00 for scenario 2.
[b] Annual interest and annual inflation rates are, respectively, 6% and 0% for ecoset 1, and 22% and 12% for ecoset 2.

operating hours, the payback period of the VAV system with respect to the CAV system is less than 5 years in any case, and this makes the VAV system very attractive. Independent of building use (school or office) and economic measures (ecosets 1 and 2), the VAV system is not an economic alternative for scenario 1. For scenario 1, which covers shorter operating hours, the payback period of VAV system is longer than 10 years.

6. Conclusion

In this study, constant-air-volume and variable-air-volume air-conditioning systems were compared calculating initial and operating costs for a sample building located in Adana, Turkey. For comparison, life-cycle cost analysis was used with the present-worth cost method and a comparison was made for eight different cases. It was found that the present-worth cost of the VAV system is always lower than that of the CAV system at the end of the lifetime for all the cases considered. If the number of operating hours of the building is longer (scenario 2), the extra investment of the VAV system with respect to the CAV system pays itself back after approximately 4 years in all the cases considered and the VAV system is a very attractive choice for air-conditioning. However, the VAV system is not an economic alternative with shorter operating hours (scenario 1). In this case, the payback period of the VAV system with respect to the CAV system is always higher than 10 years.

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