Development of HVAC System Performance Criteria Using Factorial Design and DOE-2 Simulation[1]

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ABSTRACT

A new approach is described for the development of Heating, Ventilating, and Air-Conditioning (HVAC) System Performance Criteria for the Texas Building Energy Design Standard. This approach integrates a design of experimental methodology and DOE-2 simulation to identify the effects of control parameters on HVAC system energy performance. Three new criteria—transport, plant, and system performance factors—are used as measures of system performance. The procedure has been applied to the development of criteria for a variable-air-volume (VAV) and a constant-air-volume (CAV) system in three Texas climates. The results show that the air distribution system pressure loss, cooling coil exit temperature set-point, operation of an economizer, and use of dead band controls have significant effects on air transport energy use and total system performance. The selection of control strategies and set-points have a clear impact on energy use. There is also a great energy-saving potential of converting from a CAV to a VAV system.

1.0 INTRODUCTION

The objective of this paper is to describe the development of new HVAC system performance criteria for the Texas Building Energy Design Standard. This work is a part of a broader program to develop more efficient, and more flexible, state building standards. The long-term goal of the overall project is to facilitate the design and construction of cost effective, energy efficient state buildings in Texas.

There are two approaches to building standards: setting prescriptive criteria or setting performance criteria, each of which has its advantages and disadvantages. Prescriptive criteria seem to have reached a stage where further changes will be primarily the "tightening" of existing criteria. The real needs and opportunities for future standards are in establishing the more flexible performance criteria. The development of effective performance standards tools could have a real impact on the design of new buildings (4).

There are, in turn, two types of performance criteria. The first focuses on the performance of building components or subsystems: the envelope, the lighting, and the HVAC systems. In component performance criteria there is an opportunity for innovation and trade-offs, but only among the energy performance of the elements of the subsystem. The second approach looks at the performance of a building as a whole, allowing trade-offs among all of the building's energy-using systems. Several whole-building procedures have been developed and are part of state and national standards. However, they are not often used, as they require considerable analytical sophistication and cooperation across design disciplines. Component performance paths for the envelope and lighting systems are more frequently used.

The present Texas Standard includes component performance paths for envelope and lightning (3). It does not, however, include integrated HVAC system performance criteria. Neither do other state building energy standards—such as of California, Florida, and New York—nor does ASHRAE's Standard 90.1 (1). The present research has been undertaken to rectify this omission through the development of HVAC system performance criteria.

2.0 METHODOLOGIES AND TOOLS FOR ESTABLISHING HVAC SYSTEMS CRITERIA

2.1 General Approach

HVAC system performance is determined by a number of parameters, such as building schedule and type, HVAC system type and control variables (which include cooling/heating coil discharge temperature, thermostat set-point offset, thermostat dead-band, etc.), and fan system design. A direct

[1] Work funded by the State Energy Conservation Office, Texas General Services Commission, Austin, Texas, from Oil Overcharge funds.

approach that investigated the variation of parameters over their operating range would result in hundreds of specific HVAC design and operation combination simulations. This approach would be time consuming and labor intensive. Therefore, an effective and economical methodology has been adopted for modeling and analysis to identify the parameters that play the most important roles in HVAC system performance. The "design of experiments" methodology commonly applied in manufacturing and agricultural experimentation has proven to be very useful for this purpose, especially the two-level factorial design strategies. A brief introduction to the construction and analysis of factorial designs is given below.

The often-used building energy simulation program, DOE-2.1D has been used, rather than physical experiments, to explore the impact of the various system control and design parameters (2). Although this is a compromise, the time and cost requirements of physical experimentation on the scale required to accomplish the objectives of this project, and to verify the proposed procedure, would be prohibitive.

2.2 Design of Experiments

Consider an experiment conducted to determine three factors (A, B, and C), each set at two different levels. An experiment might be laid out as follows:

Table 1. Traditional Experiment Design

	Level of Factors			
Trial	A	B	C	Response
1	–	–	–	y_1
2	+	–	–	y_2
3	–	+	–	y_3
4	–	–	+	y_4

where – and + represent the lower and upper levels at which each factor is to be set. Results for these tests would provide some information about the main effects but would not indicate the interactions that might exist among the three factors, that is, if the level of A influences the extent to which the level B affects the response y_i. In the present instance, there is reason to expect there will be interaction among the factors of interest. The design-of-experiments approach outlined statistical procedures used to capture, in the fewest number of tests, both the main effects and the influence of interactions among variables. These procedures are referred to as *factorial design.*

In executing factorial design, an investigator selects both the variables of interest and a fixed number of "levels" (the specific values taken on by the variables) for each of the variables (factors). From this the number of possible combinations of levels and factors is determined. If there are L_1 levels for the first variable, L_2 for the second, . . ., and L_k for the kth, the complete arrangement requires $L_1 \times L_2 \times \ldots \times L_k$ experimental runs. For example, for three factors with levels of 2, 3, and 4 requires $2 \times 3 \times 4 = 24$ runs. If only two levels are needed for each of the three factors, only 8 runs ($2^3 = 8$) would be required. For two levels and five factors the number of runs would increase to $2^5 = 32$. Because the number of experiments increases rapidly as either the number of levels or the number of factors increases, statistical procedures have been developed to extract the maximum amount of information from as few as 8 experiments. Several texts on the design of experiments outline the details of full and fractional factorial designs. Two-level designs with three, four, and five factors have been used in this research.

2.3 Procedures for Two-Level Factorial Design

Designs in which each variable occurs at only two levels, i.e., the maximum and minimum values over a practical range of consideration, are most often used. These designs are useful for several reasons (6):

1. They require relatively few runs per factor studied; and although they are unable to explore fully a wide region in the factor space, they can indicate major trends and so determine a promising direction for further experimentation.

2. When more thorough local exploration is needed, they can be suitably augmented to form composite designs.

3. They form the basis for two-level fractional factorial designs. These fractional designs are often of great value at an early stage of investigation, when it is frequently good practice to use a preliminary experimental effort to examine a large number of factors superficially rather than a small number (which may or may not include the important ones) thoroughly.

4. The interpretation of the observations produced by the designs can proceed largely by using common sense and elementary arithmetic.

2.3.1. Calculation of Main Effects. If we have three variables A, B, C, taking each variable at two levels (highest and lowest denoted as + and -), the pattern for a full factorial design is:

Table 2. Two-Level Three-Factor Design

	Level of Factors			
Trial	A	B	C	Response
1	–	–	–	y_1
2	–	–	+	y_2
3	–	+	–	y_3
4	–	+	+	y_4
5	+	–	–	y_5
6	+	–	+	y_6
7	+	+	–	y_7
8	+	+	+	y_8

This test set-up is balanced (orthogonal). The benefit of an orthogonal test set-up is that it allows one to estimate the effect of each factor and identify any interactions among factors. For example, the effect of factor A on the response variable y can be estimated as follows. Determine the average value of the response variable y at the high (+) level from the data:

Find the average of y at the + level of A,

$$\overline{A}_+ = \left\{\frac{(y_5 + y_6 + y_7 + y_8)}{4}\right\}$$

Find the average of y at the - level of A,

$$\overline{A}_- = \left\{\frac{(y_1 + y_2 + y_3 + y_4)}{4}\right\}$$

The effect of factor A can then be represented by:

$$\text{Effect of A} = \left\{\overline{A}_+ - \overline{A}_-\right\}$$

The same procedure is applied to estimate the effects of factors B and C. One means of simplifying this process is to use what is referred to as a response table (Table 3) (6). If the experiment is replicated, which is usual in the case of physical experiments where it is necessary to account for uncontrollable variables, the y_i values in the response column are themselves the average of the corresponding response values in each of the repeated tests.

Yates' algorithm (2) provides a similar approach to identifying the variable effects. It has also been applied in the present work.

Table 3. Response Table: Two Levels, Three Factors

Trial	Resp	A_+	A_-	B_+	B_-	C_+	C_-
1	y_1		y_1		y_1		y_1
2	y_2		y_2		y_2	y_2	
3	y_3		y_3	y_3			y_3
4	y_4		y_4	y_4		y_4	
5	y_5	y_5			y_5		y_5
6	y_6	y_6			y_6	y_6	
7	y_7	y_7		y_7			y_7
8	y_8	y_8		y_8		y_8	
Sum	Σy_i	ΣA_+	ΣA_-	ΣB_+	ΣB_-	ΣC_+	ΣC_-
No.	8	4	4	4	4	4	4
Avg.		$\overline{A}_+$	$\overline{A}_-$	$\overline{B}_+$	$\overline{B}_-$	$\overline{C}_+$	$\overline{C}_-$
Effect		$\overline{A}_+ - \overline{A}_-$		$\overline{B}_+ - \overline{B}_-$		$\overline{C}_+ - \overline{C}_-$	

2.3.2. Parameter Interactions. To this point, variables have been treated as if they behave additively. This may not be the case; they may "interact." The effects of such interactions can be defined by using an algorithm presented by G. P. E. Box and J. S. Hunter (2). Starting with the factor table, we add three additional columns: AB, AC, and BC. Then the appropriate sign for the response variable for the interaction, either + or –, is determined by multiplying the signs of the values in the interaction columns for that trial. For example, for the AB interaction and trial response y_1 the sign would be (– x –) = +. For trial three (– x +) = –, and so on. The result is:

Table 4. Two-Level Three-Factor Design with Interactions

	Level of Factors			Interactions			
Trial	A	B	C	AB	AC	BC	Response
1	–	–	–	+	+	+	y_1
2	–	–	+	+	–	–	y_2
3	–	+	–	–	+	–	y_3
4	–	+	+	–	–	+	y_4
5	+	–	–	–	–	+	y_5
6	+	–	+	–	+	–	y_6
7	+	+	–	+	–	–	y_7
8	+	+	+	+	+	+	y_8

Table 5. Response Table: Two Levels, Three Factors with Interactions

Trial	Resp.	A_+	A_-	B_+	B_-	C_+	C_-	AB_+	AB_-	AC_+	AC_-	BC_+	BC_-
1	y1		y1		y1		y1	y1		y1		y1	
2	y2		y2		y2	y2		y2			y2		y2
3	y3		y3	y3			y3		y3	y3			y3
4	y4		y4	y4		y4			y4		y4	y4	
5	y5	y5			y5		y5		y5		y5	y5	
6	y6	y6			y6	y6			y6	y6			y6
7	y7	y7		y7			y7	y7			y7		y7
8	y8	y8		y8		y8		y8		y8		y8	
Sum	Σy_i	ΣA_+	ΣA_-	ΣB_+	ΣB_-	ΣC_+	ΣC_-	ΣAB_+	ΣAB_-	ΣAC_+	ΣAC_-	ΣBC_+	ΣBC_-
No.	8	4	4	4	4	4	4	4	4	4	4	4	4
Avg.		$\overline{A}_+$	$\overline{A}_-$	$\overline{B}_+$	$\overline{B}_-$	$\overline{C}_+$	$\overline{C}_-$	AB_+	AB_-	AC_+	AC_-	BC_+	BC_-
Effect		$\overline{A}_+ - \overline{A}_-$		$\overline{B}_+ - \overline{B}_-$		$\overline{C}_+ - \overline{C}_-$		$AB_{+}-AB_{-}$		$AC_{+}-AC_{-}$		$BC_{+}-BC_{-}$	

Although the procedure for this assignment of the + and – signs is easy to follow, the statistical basis for it is not obvious, nor is it easily explained here. The interested reader is directed to Box and Hunter (2).

The response table can now be modified to estimate these interactive effects. The resulting response table (Table 5) follows the same pattern as Table 3 with the sum and averaging procedure being carried out on the basis of the signs assigned in Table 4.

Decreasing the number of variables to two would reduce the number of trial runs to 4. Adding a fourth variable would double the number of trial runs to 16, adding a fifth variable to 32, and so on. However, the basic format of the design is very similar; in fact variables can be added and additional tests run in a modular fashion.

2.4. Application of DOE-2.1D to Generate Energy Use Data

The simulation tool for HVAC systems analysis in this research is the DOE-2.1D program developed by the US Department of Energy. DOE-2.1D is a building energy analysis computer program designed to explore the energy behavior of proposed and existing buildings, and their associated heating, ventilating, and air-conditioning systems. The program can simulate hour-by-hour performance of a building for each of the 8,760 hours in a year. The characteristics of this program have been well documented in a number of sources (5).

In this project, the sequence of steps using DOE-2.1D was as follows:

1. Collect input-related information about the design of the test building, such as the building envelope, schedules, HVAC systems, equipment, and fuel costs.
2. Develop input files for the different combinations of parameters: climate, operating schedule, system type, duct pressure loss, and control variables.
3. Run the simulation under a shell program or batch process procedure.
4. Postprocess data to form a suitable data base for export.
5. Repeat the whole process from steps one to four as required.

2.5 Further Processing of Data to Define HVAC System Performance

A spreadsheet application was used to further process the DOE-2.1D output reports and apply statistical procedures. The steps in this process were:

1. Extract needed information from the various DOE-2.1D simulation reports.
2. Transfer these results to a preformatted spreadsheet for review, plotting and calculations, and development of the response tables.
3. Apply the spreadsheet algorithms to carry out the response table analysis and calculate the

performance factors resulting from each of the DOE-2.1D simulations.

The end result of this effort was a set of data that could be used to define HVAC System Performance for the Texas Building Energy Design Standard.

3.0 DEFINING A BASIS FOR THE HVAC CRITERIA

A building is intended to provide a safe, healthy, and comfortable environment for human habitation and for productive work. HVAC systems play an important role in achieving these objectives through the regulation of the thermal environment and assuring air quality for comfortable conditions within the occupied space. Ventilation is required to assure indoor air quality while heating and cooling temper the thermal conditions. This regulation may include four or five sequential processes: 1) air distribution, 2) water, or other fluid, distribution, 3) heating or refrigeration, and in the case of cooling, 4) heat rejection (8). These processes are accomplished through one or more subsystems. These functions may be integrated so that they serve more than one function or they may be independent. The research reported here has focused on the performance of the air distribution and refrigeration subsystems, which certainly have significant impact on both the quality of the indoor environment and the economics of the building.

The performance characteristics of the refrigeration system (plant) are controlled primarily by the manufacturer and are best handled by establishing industrywide standards for rating equipment performance such as COP and SEER. The HVAC designer's role is primarily one of correctly calculating heating and cooling loads and then selecting appropriately sized, quality components. Current standards address load calculations by specifying the nature of load calculating procedures, limiting oversizing, and setting minimum peak and part-load performance as a function of equipment type and size.

Alternatively, responsibility for design of the thermal distribution system and control component selection is much more diffuse and open ended. It is usually a direct responsibility of the designer on the individual project. For these reasons, the present effort has developed performance criteria for the thermal distribution system in terms of three separate factors: 1) transport energy use, which reflects the energy effectiveness of air and fluid distribution and ventilation; 2) plant energy use, which reflects the energy effectiveness of refrigeration and heat rejection systems; and 3) overall or combined system energy use for evaluating the impact of transport and plant energy use on overall performance of the HVAC system. To develop these criteria, we have selected a building that can be used as a prototype, system types, system features, control parameters, and climates for consideration, as described below.

3.1 Building Description

The William B. Travis State Office Building, part of the Capitol Complex in Austin, was selected as a prototype for the first test of the criteria development process. The Travis building is representative of many of the buildings occupied by medium-sized State agencies. The physical and operating characteristics of the building were modified to be in compliance with the most recent revision of the Texas Building Energy Design Standard. The Travis Building is a 13-floor high-rise office building, with a total area of 400,300 ft^2. The first floor consists of an entrance lobby, hearing and meeting rooms, and office spaces. The rest of the building is modeled as office space, although the actual building includes a snack bar on the ground floor. The office floors are divided into a core and four perimeter zones oriented in the cardinal directions.

3.2 Climate

The Travis building was evaluated in two locations, Houston and Amarillo, to determine the extent to which climate influences the results.

3.3 HVAC System Description

A detailed description of the heating and cooling plant, operation schedules, system types, and control options and parameters must be defined before a DOE-2.1D analysis can be meaningfully considered. The building and system parameters considered to date are described below.

3.3.1 Heating and Cooling Plant. The building is modeled with a central plant, using gas-fired hot water boilers with an 80% efficiency and hermetic centrifugal chillers with a COP of 5.2. The effects of varying plant equipment efficiencies will be tested at a later date.

3.3.2 HVAC System. Normal space thermostat set-points were assumed to be 73°F for heating and 75°F for cooling with temperature offsets to 68°F and 80°F, respectively, during off-hours. The system was set up with off-hours cycle operation such that the fans will operate when zone temperatures are outside these setback or set-up temperature limits.

System Type: Two HVAC system types have been examined:

- VAVS (Variable-Air-Volume System with terminal reheat)

- CAV-DDS (Constant-Air-Volume, Dual-Duct System)

In the model, the building is served by either a single variable-air-volume (VAV) terminal reheat HVAC system, with each zone having separate air volume and temperature control, or a constant-air-volume, dual duct (CAV, DDS) HVAC system.

The variable-air-volume system, in its most basic configuration, consists of air-handling units with filter, dampers, cooling coils, variable speed draw-through fans and zone terminal reheating (hot water) coils and return fans. The duct system distributes supply air to variable-air-volume (VAV) terminal units located in the zones being served.

The CAV, dual-duct system provides constant flow, forced-air heating and cooling to multiple, individually controlled zones from an air-handling unit containing a filter, a blow-through type supply fan, a heating and a cooling coil. The hot and cold air are provided to individual mixing boxes located at each zone being served, where the two air streams are mixed in proper proportion to satisfy the space load in response to the command of the space thermostat.

System Operating Schedules: Two building operating schedules were considered to capture the effect of operating hours on energy use:

- A "regular office hours schedule" assumed to be operating from 7 am to 6 pm with some occupancy and lights until 9 pm.

- An "extended office hours schedule," that assumed reduced occupancy during evenings and weekends. This increased the number of weekend and evening operating hours and increased the annual internal load by approximately 5%.

The HVAC system was available to offset any drift from the specified set-back/set-up temperature control set-points during off-hours. Thus, there was some system energy use during off-hours. The model did not bring in ventilation air during off-hours operation.

System Options. Three system options were considered:

1. With or without an economizer [When used, the economizer brings in outside air if the outdoor dry bulb temperature is below 62°F.]

2. High- or low-pressure air distribution systems with air transport power levels at 1 W/cfm of air delivery or 0.5 W/cfm of air delivery.

3. With or without a heating thermostat set-point reset [When the heating reset is included, it reduces the heating set-point from 73°F to 68°F.]

4.0 HVAC CRITERIA

As noted above, the primary concerns in the design of HVAC systems can be grouped in three areas: fluid transport, primary plant efficiency (compressors or chillers and other refrigeration system components), and overall system performance. For this reason, three load-normalized factors are being proposed: the transport factor (TF), the plant factor (PF), and the overall system performance factor (SPF). This type of procedure was originally proposed by William Tao (7, 8, 9) and has been extended during the present project.

The transport factor is the ratio of coil loads to transport energy use, the energy used for transporting air and liquid. The plant factor is the ratio of coil loads to total plant energy use. The system performance factor is the ratio of coil loads to the sum of the transport energy and the plant energy. The systems performance factor is the final indicator of the HVAC system's energy efficiency. The transport, plant, and system performance factors are presently expressed as ratios of energy use rather than ratios of power.

The hope is that the revised definitions will be concise enough to ease the identification of system- and subsystem-level performance, which is of major interest to HVAC designers. It is also hoped that a means can be found to derive them from peak loads and daily load profiles. In computing these ratios, all the site electrical energy use and cooling loads are converted to source energy by assuming a power plant heat rate factor of 11,600 Btu/kWh, which is a typical value for gas/electrical conversion, transmission, and distribution in Texas. This conversion accounts for the relatively high quality and/or price of electric energy relative to natural gas. It is also an attempt to move the TF, PF, and SPF ratios closer to the factors that would be obtained based on Second Law of Thermodynamics analysis. Input for the TF, PF, and SPF were obtained from the DOE-2.1D simulation results.

Transport Factor (TF). The transport factor is defined as:

TF = Qt/(Ef + Ep) (1)

in which

Qt = Qheating+ Qcooling loads on the heating and cooling coils in the reference case. Data are from the DOE-2.1D SS-A report. *Qt* is the sum of energy extracted by the HVAC system during the operating hours of the system and is passed as a load to the plant program. It is the total load on cooling and heating coils.

Ef = fan energy used during all heating, cooling, heating/cooling, and floating operations. Data are from the SS-M report of DOE-2.1D.

Ep = pump energy used for chilling and hot water circulation. Data are from the PS-C report of DOE-2.1D.

Plant Factor (PF). The plant factor is defined as:

PF = Qt/(space heat + space cool) (2)

Qt = Qheating + Qcooling loads on the heating and cooling coils in the reference case. Data are from the DOE-2.1D SS-A report, the same as were used in transport factor.

Space heat and *space cool* are the total utility energy inputs to the plant program. Data are taken from the DOE-2.1D BEPS report.

The plant factor here reflects the total energy effectiveness of heating, refrigeration, and heat rejection. Refrigeration is the heart of cooling systems; it represents the highest capital outlay and accounts for a major portion of the energy consumption of the cooling system.

System Performance Factor (SPF). The system performance factor considers both the performance of plant and transport subsystems.

SPF = Qt/(space heat + space cool + Ef + Ep)

= 1/(1/TF + 1/PF) (3)

5.0 RESULTS

The total number of DOE-2 runs used to cover all combinations of the above parameters was 32. Analyzing these results using the tools and procedures outlined above provided a reasonably clear direction for the definition of appropriate HVAC system criteria. However, before examining the proposed criteria let us consider some of the results.

5.1 Effects of Climate and Extended Operation

Two important system parameters are design constraints, things that the designer must simply accept as they are: 1) location (climate), and 2) occupancy schedule. The effects of these factors were tested by considering building locations in Houston and Amarillo with regular and extended operating hours. Obviously, additional locations and operating schedules could have been considered. However, in this experiment, it seemed reasonable to choose just two locations that would bracket climate variations for the bulk of the state's buildings. In retrospect, two more varied occupancy and operation schedules should have been selected. Each load value is the average of four DOE-2 simulations with various system (ACV and VA) and control (economizer and heating reset) combinations. Using a two-level/two-factor response table to display the results obtained yields:

Table 6a. Two-Level, Two-Factor Analysis of Energy Use (MBtu/yr)

		Location		Hours		Location /Hrs	
	Avg.	Houst.	Amar.	E	R	1	2
1	42938	42938		42938		42938	
2	36834	36834			36834		36834
3	36353		36353	36353			36353
4	32345		32345		32345	32345	
	148470	79772	68698	79291	69180	75283	73187
	4	2	2	2	2	2	2
	37118	39886	34349	39645	34590	37641	36594
		5537	18%	5055	16%	1048	3%

These results indicate that the effect of climate change on source energy use is only 18%. Houston requires more source energy than Amarillo. The 16% increase with the extended operating schedule reflects both a 5% increase in annual internal load and an increase in operating hours. The interaction term, location/hours, is smaller but still notable.

If these same data are considered in terms of the nondimensional system performance factor, several changes are notable. The effect of location is reduced to 9% but is not eliminated, and the higher, or better, SPFs occur in Houston rather than in Amarillo. The effect of hours of operation is reduced even more, down to 4%, but again is not completely eliminated. Because one of the reasons for introducing the non-dimensional factors is to minimize the impact of variables beyond the designer's control, these results indicate that further work may be required in these areas.

Table 6b. Effects of Location and Hours of Operation on SPF

	Avg	Location: Houston	Location: Amarillo	Hours: E	Hours: R	Loc./Hr: 1	Loc./Hr: 2
1	2.50	2.50		2.50		2.50	
2	2.53	2.53			2.53		2.53
3	2.20		2.20	2.20			2.20
4	2.38		2.38		2.38	2.38	
	9.62	5.04	4.58	4.71	4.91	4.88	4.74
	4	2	2	2	2	2	2
	2.41	2.52	2.29	2.35	2.46	2.44	2.37
		0.23	9%	–0.10	–4%	0.07	3%

5.2 Effects of System Selection and Control Interactions

The next set of investigations considered the effects of system and control interactions. In this instance, the source energy was averaged over location and hours. The two-level/four-parameter response table that results from this analysis is summarized in Table 7. Those interactions with an effect of 1% or less are not shown.

Table 7 clearly illustrates the importance of system selection, showing an average 37% difference between a constant-air-volume and a variable-air-volume system. These results also demonstrate the importance of managing the air distribution system pressure loss, as reflected in the fan power change from 1 W/cfm to 0.5 W/cfm, which shows the potential of an 18% drop in overall energy use. There is also a significant interaction between the system choice and fan power requirements (8%), indicating that a change in the fan power required is more important in a CAV system than in a VAV system. However, these results indicate that a VAV system with a peak 1 W/cfm fan energy requirement will use, on average, less energy than a CAV system at 0.5 W/cfm. This finding indicates that a VAV system, from an energy point of view, would be a consistently better choice in Texas. The interaction in the system/economizer column indicates that the VAV system energy use is reduced somewhat more through the use of an economizer than is that of a CAV system. Dropping the heating set-point from 73°F to 68°F provides an average energy saving of 8%.

These results clearly indicate that the factors examined here—system choice, air distribution

Table 7. System Selection and Control Option Response Table

Source MBtu/yr	System: CAV	System: VAV	Fan Pwr W/cfm: 1.0	Fan Pwr W/cfm: 0.5	Heating Set-point: 72°F	Heating Set-point: 68°F	Economizer: OFF	Economizer: ON	System/ Fan Pwr: 1	System/ Fan Pwr: 2	System/ Econo: 1	System/ Econo: 2
45572	45572		45572		45572		45572			45572		45572
45915	45915		45915		45915			45915		45915	45915	
44427	44427		44427			44427	44427			44427		44427
42951	42951		42951			42951		42951		42951	42951	
37085	37085			37085	37085		37085		37085			37085
37572	37572			37572	37572			37572	37572		37572	
34684	34684			34684		34684	34684		34684			34684
34501	34501			34501		34501		34501	34501		34501	
32001		32001	32001		32001		32001		32001		32001	
29331		29331	29331		29331			29331	29331			29331
29619		29619	29619			29619	29619		29619		29619	
27124		27124	27124			27124		27124	27124			27124
28279		28279		28279	28279		28279			28279	28279	
25734		25734		25734	25734			25734		25734		25734
26012		26012		26012		26012	26012			26012	26012	
23617		23617		23617		23617		23617		23617		23617
544425	322707	221718	296941	247485	281490	262936	277680	266745	261918	282507	276850	267575
16	8	8	8	8	8	8	8	8	8	8	8	8
34027	40338	27715	37118	30936	35186	32867	34710	33343	32740	35313	34606	33447
	–12624	–37%	–6182	–18%	–2319	–7%	–1367	–4%	2574	8%	–1159	–3%

system pressure loss, heating set-point, and the application of the economizer cycle—each have a meaningful impact on the energy use in Texas buildings for heating, ventilating, and cooling. The procedure used also provides a means of gauging the extent of interaction among the various parameters. The conclusion drawn from these results is that the Texas Building Energy Design Standard HVAC system performance criteria must address each of these areas of concern.

5.3 Compliance Procedure for HVAC System Performance Criteria

The present Standard prescribes criteria for fan system performance, for constant- and variable-air-volume systems, in terms of a W/scfm limit for the total (supply, return, and exhaust) fan system. In addition, minimum design efficiencies are prescribed for plant equipment, boilers, and chillers. Thus, compliance with the HVAC system performance criteria requires that the designer show that the SPF for the proposed design, which is a function of the TF and PF for that design, does not exceed the SPF for the same type of system, determined by the prescriptive criteria described above.

A pass/fail determination is accomplished by running annual HVAC system simulations, using a tool such as DOE-2, to map system performance over the design variables (HVAC system type, control variables, fan system description, etc.) of interest for the design under consideration. During these runs, the building description, climate, and hours of operation are typically held fixed as parameters. However, because it is not practical for a designer to run these simulations to determine the HVAC system performance trade-offs, a spreadsheet program is being developed to calculate the TF, PF, and SPF from correlations of the appropriate DOE-2 outputs for standard sets of office building parameters for Texas state buildings. These correlations will capture the system performance mapping determined by the factorial design procedure described above. Thus, the designer will determine compliance by applying the spreadsheet program to determine proposed system parameter sets for which the SPF does not exceed that for the reference design, which is based on the prescriptive criteria.

6.0 CONCLUSIONS

The results of this project are promising, but not yet complete. The factorial analysis technique provides a clearer picture of the relative importance of the design decisions that influence building energy use and how those decisions interact. The insight gained through this analysis will provide a better basis for defining HVAC criteria, in terms of both selection and range, than has been available previously.

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