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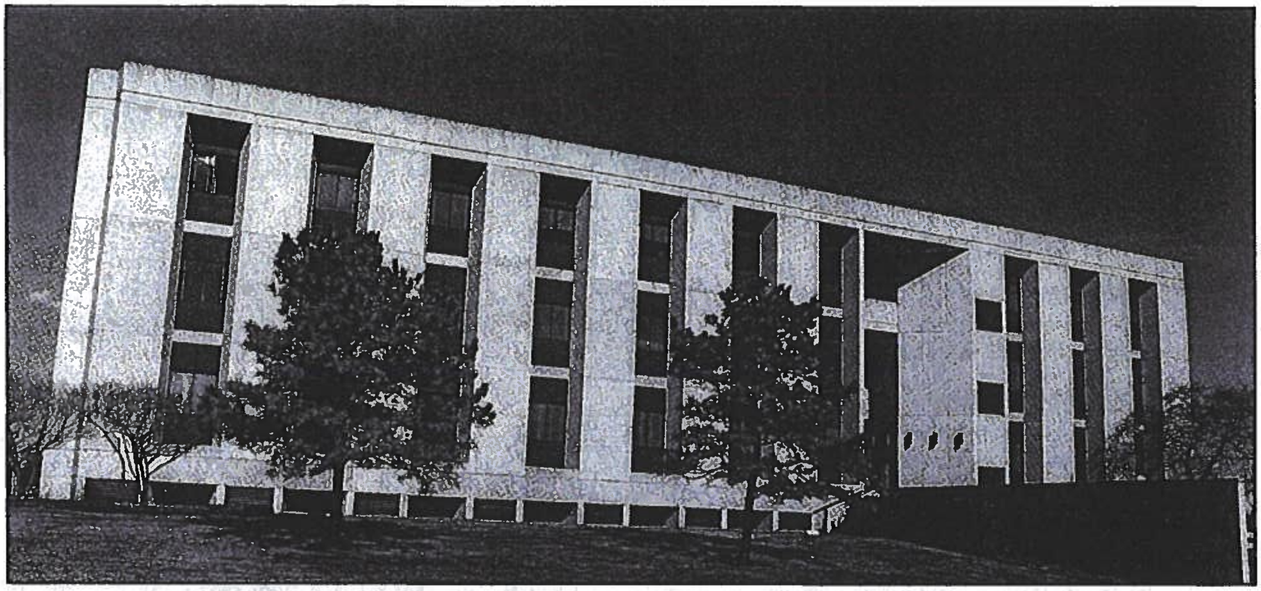

Figure 1: The Engineering Center (EC) is a four-story, multipurpose building at a university campus in central Texas.

The Great Energy Predictor Shootout II

Measuring Retrofit Savings

By *J. S. Haberl, Ph.D., P.E.*
Member ASHRAE

and

S. Thamilseran

A second energy predictor shootout contest, a follow-up to the successful first Predictor Shootout contest, has been conducted to evaluate the most effective empirical, or inverse regression models for modeling hourly whole-building energy baselines for purposes of measuring savings from energy conservation retrofits. This second contest used two sets of measured hourly pre-retrofit and post-retrofit data from buildings participating in a revolving loan program in Texas. The accuracy of the contestant's models was evaluated by determining their ability to predict data that were carefully removed from the training (or pre-retrofit) period. A comparison of the savings predicted by the models was also performed.

The results from the contest show that neural networks again provide the more accurate model of a building's energy use. However, in contrast to the first contest (Kreider and Haberl 1994a, 1994b), the second contest's results show that cleverly assembled statistical models also appear to be as accurate, and more accurate in some cases, than some of the neural network entries. When the models were used to forecast the baseline use into the post-retrofit period, large variations in the predicted savings occurred among the models, particularly for the cooling energy savings in one of the case study buildings. These variations appear to be due to the models' ability (or inability) to capture certain energy performance characteristics and the modeler's assumptions about the post-retrofit energy use.

A summary of the first contest can be found in the June 1994 *ASHRAE Journal* (Kreider and Haberl 1994a) as well as the accompanying *ASHRAE Transactions* papers (Kreider and Haberl 1994b; Feuston and Thurtell 1994; Iijima et al. 1994; Kawashima 1994; MacKay 1994; Ohlsson et al. 1994; and Stevenson 1994). ASHRAE has also published a technical data bulletin that contains all the papers and the hourly data set from the first contest (ASHRAE 1994). A second technical bulletin for this contest has also been proposed.

About the Authors

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Sabaratnan Thamilseran is a doctoral candidate in mechanical engineering and research assistant at the Energy Systems Laboratory.

To facilitate the second contest, data were collected from two buildings that received energy conserving retrofits from the Texas LoanSTAR program (Claridge et al. 1994). These buildings were carefully chosen from a group of buildings so that they could provide the contestants with two significantly different data sets. Both of the case study buildings are described in detail in the *ASHRAE Transactions* paper by Haberl and Thamilseran (1996). A brief description of the buildings follows.

Case Study Building

Case Study #1: The Engineering Center. The Engineering Center (EC), shown in *Figure 1*, is located in central Texas on a university campus, and contains 30,000 m^2 (324,000 ft^2) of classrooms, offices, a computer center and laboratory facilities comprising four stories and includes an unconditioned underground parking garage.

It was constructed in the early 1970s and is a heavy structure with 0.15 m (6 in.) concrete floors and insulated exterior walls made of precast concrete and porcelain-plated steel panels. About 12% of the exterior wall area is covered with single pane, bronze-tinted glazing. The building is occupied from 7:30 a.m. to 6:30 p.m. on weekdays, and has reduced occupancy from 7:30 a.m. to 5:30 p.m. on weekends. It also contains a computer facility that is operated 24 hours a day.

The building is primarily served by 12 dual-duct air-handling units located in the underground parking garage. Chilled and hot water for the cooling and heating coils are supplied to the building by the campus physical plant. The primary retrofit to the building was to replace the constant-air-volume (CAV) air distribution system with a variable speed drive, VAV system. *Figure 2* shows the data that were provided to the contestants for the Engineering Center for the pre-retrofit training period (Jan. 1, 1990 to Nov. 27, 1990) and post retrofit periods (Nov. 28, 1990 to Dec. 31, 1992).

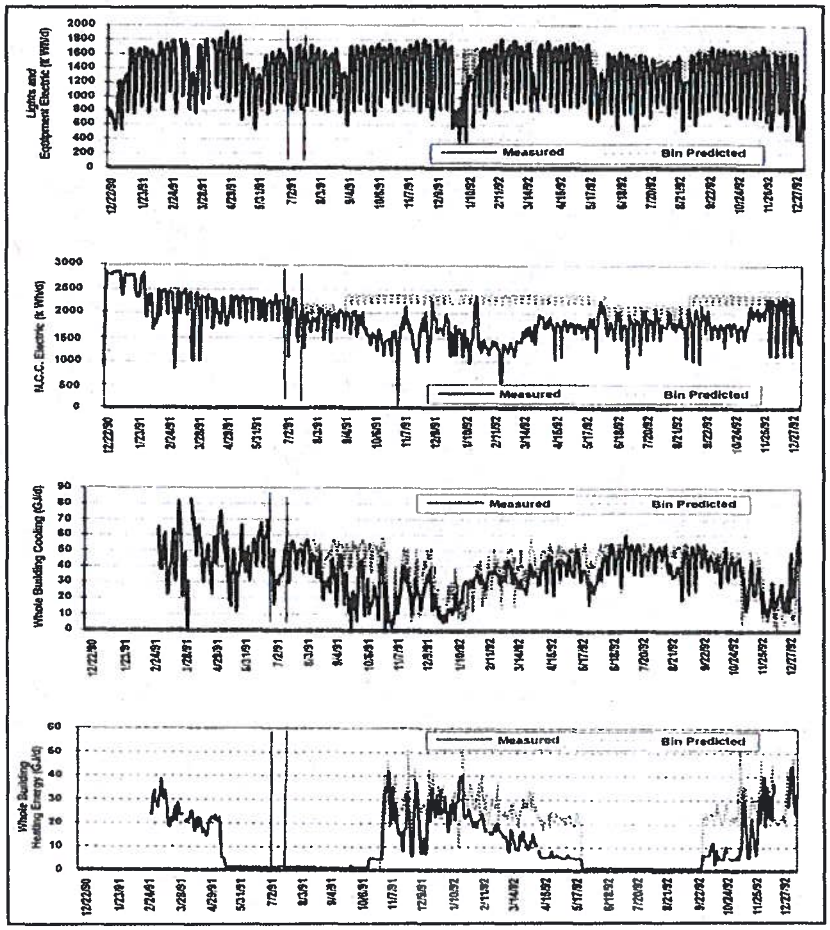

Figure 2:* Daily Time Series Plots for the Engineering Center. In the upper figure daily motor control center electricity use (MCC) is shown, followed by chilled water and hot water use in the middle and lower graphs. Daily summaries of the hourly data are shown for the training, construction and post-retrofit periods. Missing data occur for two months in 1990 for the MCC and lights and equipment channels, from April through November of 1991 for chilled water, and for hot water during April 1991, and June through December of 1991. In the post-retrofit period the daily energy use predicted by a bin model is also shown.

Cast Study #2: The Business Building. The Business Building (BUS) is located at a university in the Dallas-Ft. Worth area. It contains 13,926 m^2 (149,900 ft^2) of gross conditioned space and consists of six stories of classrooms, offices and lecture halls. It was constructed in 1970 and is face brick on block wall construction. About 10% of the exterior wall area is covered with single pane, tinted glazing. The building is occupied from 8 a.m. to 6 p.m. Monday through Friday for regular classes and occasionally after 6 p.m. for night classes and on weekends for special purposes.

The building is served by three large dual-duct air-handling units which were retrofitted to operate as VAV dual-duct systems in July of 1991. Chilled water and hot water (from steam) for cooling and heating coils are supplied to the building by the campus utility plant.

According to the audit report, during the pre-retrofit period the air-handling units (AHUs) were supposed to operate 24 hours per day, although there was a considerable variation in the measured daily electricity consumption. This variation was caused by the following: part-load operation of the AHUs during building's unoccupied period and irregular on/off combinations of pumps and fans. In the post-retrofit period a reduced number of the units were operated

* Full-page versions of Figure 2 and Figure 3 can be found in a longer version of this article in the *ASHRAE Transactions, Volume 102, Part 2*.

during occupied periods (i.e., 17 hours per day, seven days per week).

The primary retrofits were to replace the Constant Air Volume (CAV) air distribution systems with a variable speed drive, VAV air distribution system, and to improve the control of lighting using occupancy sensors in classrooms.

Figure 3 shows daily time series plots of the data from the Business Building. In the upper figure daily lights and receptacle electricity use is shown. In the second figure MCC electricity use is shown, and in the third graph from the top chilled water use is shown with heating energy use shown in the bottom graph. Data shown are for the pre-retrofit training period, construction and post-retrofit periods as indicated by the two vertical lines in the summer of 1991. In a similar fashion to the Engineering Center, lighting and receptacle electricity use is a derived channel that is obtained by subtracting motor control center electricity use from the whole-building electricity use.

The Second Competition and Data Sets

The competition began in June 1994 and ended Nov. 1, 1994. To enter the competition contestants needed to visit the anonymous ftp site on the internet, download the training and testing data sets, perform their analysis, and submit their answers in the agreed-upon format. In the second contest the actual post-retrofit data were supplied to the contestants since their model's accuracy was determined from data that was withheld from the training period (i.e., pre-retrofit period). Graphical daily summaries similar to those shown in *Figure 2* and *Figure 3* were also provided to give the contestants a general idea of what to expect from the different channels of data. Additional details concerning the data sets and competition rules can be found in Haberl and Thamilseran (1996).

At the close of the competition, the results were analyzed, the winners were announced and invited to write papers describing their modeling methods (Chonan et al. 1996; Jang et al. 1996; Katipamula 1996; Dodier and Henze 1996). Interest in the second contest was significant, although less than the first contest.

Fifty visitors downloaded the general "readme.txt" file that described the contest, eleven contestants tried their hand at the contest and downloaded the training and testing data sets. Four contestants completed the analysis in the agreed-upon format before the closing date of November 1, 1994. The results produced by the contestants are predictions of the dependent variables (i.e., building energy use) for the removal periods in the training data set and predictions which use the pre-retrofit parameters in the post-retrofit period.

These predictions were submitted to the organizers who compared the predictions of the removed data against the actual data using an hourly Coefficient of Variation [CV(RMSE)] and Mean Bias Error (MBE). The CV(RMSE) is the measure of the variability of the data or how much spread exists in the data cloud. The MBE is an evaluation of the off-centered bias in the comparative grouping of the data points.

Results

Evaluation of the Accuracy of the Models. The overall ranking was determined from the coefficient of variation of the root-

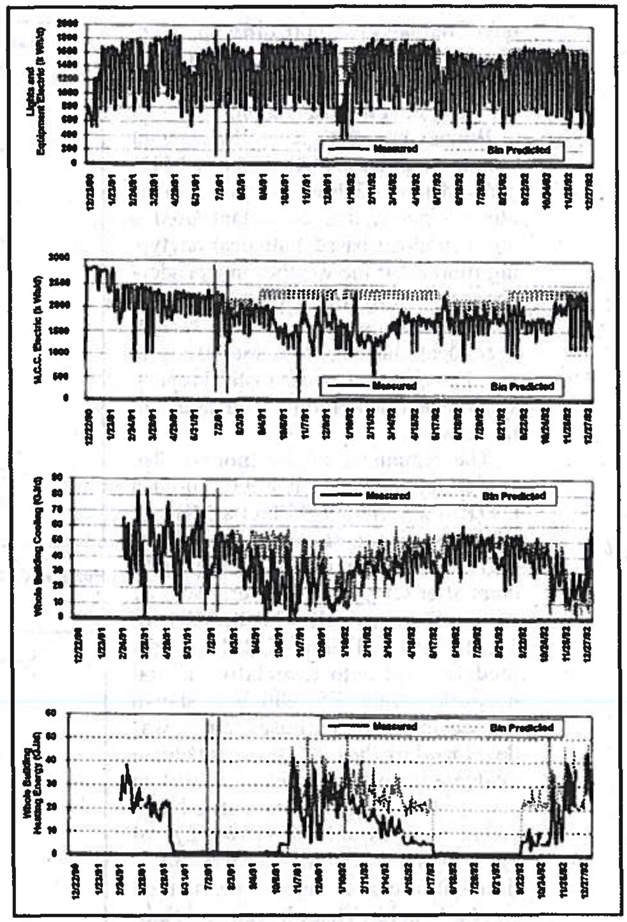

Figure 3: Daily time series plots of the Business Building (BUS). Beginning with the upper figure, daily lights and equipment electricity use is shown followed by motor control center electricity (MCC), chilled water and heating energy use. Data shown are for the pre-retrofit training period, construction and post-retrofit periods. Missing data occurred for three months in 1991 for chilled water and hot water, and for a few weeks in December 1992. In the post-retrofit period the daily energy use predicted by a bin model is also shown.

mean-square-error [CV(RMSE)]. The mean bias error (MBE) was to be used as a secondary parameter in the event of a tie. A detailed listing of the accuracy of the contestants models can be found in Haberl and Thamilseran 1996.

The overall winner of the second contest was E4 (see acknowledgements) who scored a global CV(RMSE) of 16.91% and a MBE of –2.43%. This contestant used a combination of 10 neural networks (i.e., one for each of the target variables) with two hidden layers of 25 units each. The accuracy of the model by Winner #1 was remarkable, varying from an average 6.87% for the Engineering Center to an average 26.95% for the Business Building. In both the Engineering Center and the Business Building, the dependent variables that were weather dependent were more of a challenge to predict than the electricity use. All the dependent channels in the Business Building were more difficult to predict than the Engineering Center because of the Business Building's on/off mode of HVAC operation.

Winner #2 was right on the heels of winner #1 with a CV(RMSE) of 18.51% and a MBE of –3.46%. In contrast to the other winners, this contestant used a non-neural-net-based statistical daytyping routine for the weather independent channels and weekday-weekend, hourly multiple regressions for the weather dependent channels. It is interesting to note that a finely tuned statistical regression model can perform as well as a neural network.

The remainder of the models also performed well. Winner #3 scored a CV(RMSE) of 19.71% and a MBE of –1.38% using a Bayesian non-linear regression with multiple hyper-parameters after removal of outliers. Winner #4 had an overall CV(RMSE) of 30.21% and a MBE of –2.83% using a feed forward auto associative neural network. Model E5, which is shown for comparative purposes only, was developed by the contest organizers to evaluate the other models and uses an inverse bin method. This method produced an overall CV(RMSE) of 18.59% and a MBE of –2.89%. Additional information about the method can be found in Thamilseran and Haberl (1995).

The accuracy of all the models is remarkable considering there is a built-in inaccuracy in the method used to evaluate the models. This test inaccuracy is due to the fact that the days that were removed from the training period for testing purposes did not exactly represent the average of the days in the training period. For the Engineering Center, the average difference between the removed data and the training data varied from a CV(RMSE) of 0.11% for the motor control center to 6.65% for the heating data, and averaged 2.66%. In the Business Building, the difference varied from 1.96% for the whole-building electricity to 21.45% for the cooling energy data, and averaged 9.59%.

There are several additional features about the data sets that are worth pointing out. First, in the Engineering Center, almost all systems were run 24 hours per day in the pre-retrofit and post-retrofit periods. This is in contrast to the Business Building where systems are turned on during the daytime and turned off in the evenings. *Figure 2* also reveals that there were significant missing data in the post retrofit period for the Engineering Center due to malfunctioning flow sensors. This required the development and use of both pre-retrofit and post-retrofit models to calculate and compare the savings for the entire 12 month post retrofit period.

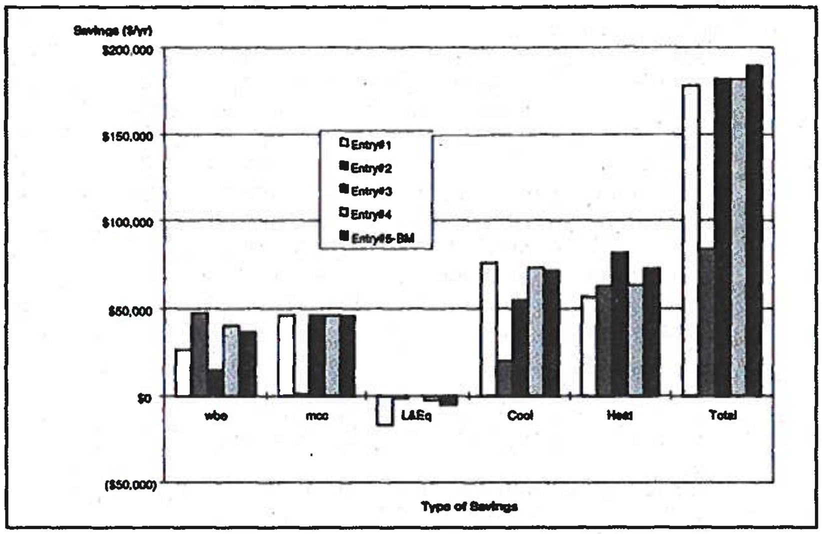

Figure 4: Annual savings comparisons for the Engineering Center for 1992.

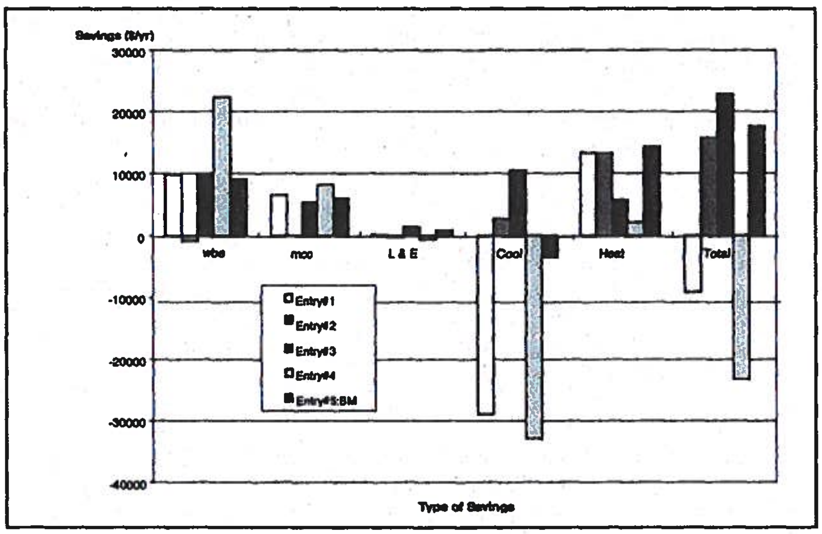

Figure 5: Annual savings comparisons for the Business Building for 1992.

Evaluation of the savings predicted by the models. In general, the evaluation of the accuracy of the four models showed that their ability to predict the removed data was remarkably similar, with the top three models having an overall hourly CV(RMSE) of less than 20%. Unfortunately, the comparison of the savings calculations by the four models for both buildings was mixed. *Tables 1* and *Table 2* provide the cost savings predicted by the four models. *Figure 4* and *Figure 5* provide a graphical comparison of the data presented in *Table 1* and *Table 2*.

For the Engineering Center, the channels affected by the retrofit included the MCC, cooling, and heating channels. Therefore, the savings for the Engineering Center considered only the MCC,

Entry#	Engineering Center Savings (C.TST)			
	mcc	Cool	Heat	Total
E1	$45,928	$75,808	$56,487	$178,224
E2	$1,043	$19,922	$62,434	$83,399
E3	$45,933	$54,574	$81,562	$182,069
E4	$45,879	$73,034	$63,028	$181,941
E5-BM	$45,836	$71,330	$72,490	$189,655
AVG	$36,924	$58,934	$67,200	$163,058
Total 1993	$237,044 (15.6%) NOTE 1	$162,409 (36.3%)	$18,519 (36.2%)	$419,972 (38.8%) NOTE 2

Table 1: Annual savings calculated by the four contestants for the Engineering Center for 1992.
In the Engineering Center savings were calculated using the following costs: $0.0278/kWh electricity consumption, $4.67/MBtu Cooling energy use, and $4.75/MBtu heating energy use. The last row in the table shows the 1993 annual energy use as reported in the LoanSTAR Annual Energy Consumption Report (AECR), and ratio of the average savings to the 1993 annual utility expenditure by end-use.

NOTES:
1) 1993 total use shown is for the actual measured whole-buildng use. Percentages shown represent the average mcc, cooling, heating and total savings divided by the respective 1993 post-retrofit energy use.
2) 1993 total use includes whole-building electricity, chilled water and hot water as published in the 1993 LoanSTAR Annual Energy Consumption Report (AECR).

Entry #	Business Building Savings (D.TST)				
	mcc	L & E	Cool	Heat	Total
E1	$6,478	$111	($28,927)	$13,264	($9,074)
E2	$20	($218)	$2,655	$13,217	$15,673
E3	$5,332	$1,345	$10,464	$5,682	$22,822
E4	$8,120	($494)	($32,920)	$2,071	($23,223)
E5-BM	$5,968	$767	($3,423)	$14,294	$17,606
AVG	$5,184	$302	($10,430)	$9,706	$4,761
Total 1993	$70,034 (7.4%) NOTE 1	N/A (0.43%)	$59,371 (17.5%)	$18,338 (52.9%)	$147,743 (3.2%) NOTE 2

Table 2: Annual savings calculated by the four contestants for the Business Building for 1992.
In the Business Building the savings were calculated using the following costs: $0.02931/kWh electricity consumption, $4.417/MBtu Cooling energy use, and $3.64/MBtu heating energy use. Electric demand savings were not calculated for either building since they are located on university campuses and receive their services from a central plant.

NOTES:
1) 1993 total use shown is for the measured whole-buildng use. Percentages shown represent the average mcc, L&E, cooling, heating and total savings divided by the respective 1993 post-retrofit energy use.
2) 1993 total use includes whole-building electricity, chilled water and hot water as published in the 1993 LoanSTAR Annual Energy Consumption Report (AECR).

cooling, and heating channels. *Table 1* and *Figure 4* display the savings for the MCC, cooling and heating channels as calculated by the five methods. Savings for the whole-building electricity and lights and equipment are shown in *Figure 4*, but are not included in the savings calculations shown in *Table 1*.

Several features are worth pointing out in *Table 1* and *Figure 4*. First, the total savings predicted by all five methods was remarkably similar with an average savings of $163,058, this represented 38.8% of the post-retrofit energy use which is substantially above the model's prediction accuracy or CV(RMSE). The highest savings, calculated by E5, were $189,655, which is only 16.3% above the average of all five methods. The lowest savings, calculated by E2, were $83,399, which is 48.9% below the average.

Like the Engineering Center, the savings at the Business Building were calculated by comparing the projection of the pre-retrofit or baseline models into the post-retrofit period against the actual measured post-retrofit period energy use from these channels. For the Business Building, the channels affected by the retrofit included the Lights and Equipment (LEQ) channel, the MCC channel, and the cooling and heating channels.

In a similar fashion to the Engineering Center, all differences in the Business Building's whole-building electricity (WBE) channels could not be attributed to the retrofit. Therefore, the savings for the Business Building considered only the LEQ, MCC, cooling, and heating channels. *Table 2* and *Figure 5* display the savings for the LEQ, MCC, cooling and heating channels as calculated by the five methods for the Business Building. Savings for the whole-building electricity and Lights and Equipment are shown in *Figure 5* but are not included in the totals indicated in *Table 2*.

The prediction of savings for the Business Buildings were not as consistent as the Engineering Center in several ways. First, with the exception of the heating energy savings, none of the predicted savings at the business building rose above the inherent noise in the models (i.e., the noise predicted by the average CV(RMSE) = 30.8%). Second, only three of the models predicted positive savings from the retrofits to the Business Building. None of these three models was the most accurate model in predicting the training period data. Specifically, the model with the closest fit in the training period (Winner #1, contestant E4) was one of the two models that predicted negative total savings for the Business Building. Models E2 (Winner #4), E3 (Winner #2) and E5 (the bin method) predicted positive savings of $15,673, $22,822, and $17,605, respectively.

The variable that seemed to cause the major difference in the predictions was the cooling energy use savings. Both Models E1 and E4 under-predicted the cooling energy savings when compared to the other models. One reason for this under prediction may be the strong on/off (occupied/unoccupied) operation of systems in the building during this period. Such on/off operation makes the savings more difficult to predict since the systems were not being run during evenings and weekends.

This would seem to indicate that factors other than the accuracy of the model can play an important role in the model's ability to predict energy use into the future. In the Engineering Center and the Business Building one of the major influencing factors was the assumption that was made about semester and non-semester schedules. In practice, the analyst would know these schedules. Also, in contrast to the Engineering Center, the predicted savings in the Business Building represented a much smaller portion (only 3.2%) of the total annual utility cost.

Summary and Discussion

The results from the second contest reconfirm certain results from the first contest, and have also provided some exciting new insights about the use of such baseline models for calculating the savings from energy conservation retrofits. First, the second contest's results show that neural networks again provide the most accurate model of a building's energy use. However, the accuracy of the neural network entries varied according to the assumptions that the contestants made about the training data sets and how skilled the contestants were in choosing and assembling their networks. One of the suprises of the second contest was the fact that cleverly assembled statistical models appear to be as accurate, or in some cases, more accurate than some of the neural network entries.

Another surprise was that when these models were used to forecast the baseline use into the post-retrofit period, large variations in the savings can occur in certain buildings, particularly for the cooling energy savings in the Business Building. These variations appear to be due to the model's ability (or inability) to predict savings in buildings with significant on-off schedule and characteristics and assumptions that the contestants made about the post-retrofit energy use, specifically, the periods for semester, non-semester schedules which influence the on-off operation.

In general, all four models and the bin method predicted similar savings for Engineering Center building. However, in the Business Building the savings predictions represented a smaller fraction of the annual energy costs and were smaller than the noise of the models (i.e. the models are too noisy to accurately predict the savings). It would appear that only contestants E2, E3 and the bin method made similar predictions of savings for the Business Building. The differences in the savings predictions at the Business Building also seem to indicate the importance of assessing the noise in the models and paying close attention to assumptions about schedules, etc.

One of the other findings that can be inferred from the second contest regards the accuracy of the models and their ability to predict savings. If one assumes that the model's prediction ability is indicated by the CV(RMSE) then only those savings for the Engineering Center and Business Building that rise out of this range can be deemed as being larger than the inherent noise in the model and therefore, the model is appropriate for calculating savings.

In the case of the Engineering Center, it appears as though all the models adequately predicted the savings. However, in the Business Building the ratio of the estimated savings to the post-retrofit utility costs were considerably smaller than the models' CV(RMSE) which should indicate that the savings at the

Business Building are more difficult to predict at the whole building level. This uncertainty in the models' predictions should raise a flag of caution for those who invest in energy conservation without regard for how the savings are evaluated. Furthermore, it would seem to indicate that additional studies are needed to determine when it is necessary to use additional end-use metering and highly accurate models or when a simplified analysis will suffice.

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Also, the fifty persons who visited the anonymous ftp site where the Predictor Shootout II contest instructions and data were posted, especially the four entrants who successfully completed their predictions. These four entrants are listed below according to their model's goodness-of-fit:

Winner #1, Entry E4: R. Dodier, G. Henze, Joint Center for Energy management, Dept. of Civil Engineering, University of Colorado at Boulder, Boulder, CO 80309, Tel: 303-492-3915, email: dodier@bechtel.colorado.edu, henze@bechtel.colorado.edu.

Winner #2, Entry E3: S. Katipamula, Battelle Northwest National Laboratory, P.O.Box 999, Richland, Washington U.S.A. 99352, Tel: 509-372-4592, email: s_katipamula@pnl.gov.

Winner #3, Entry E1: Y. Chonan, K. Nishida and T. Matsumoto, Department of Electrical Engineering, Waseda University, 3-4-1 Ohkubo Shinjuku-ku, Tokyo 169 Japan, Tel/Fax:01-3-3702-4735, email:chonan@matsumoto.elec.waseda.ac.jp.

Winner #4, Entry E2: K. Jang, E. Bartlett, and R. Nelson, Dept. of Mechanical Engineering, H.M. Black Engineering Bldg., Iowa State University, Ames, Iowa, 50011, Tel: 515-294-6886 or Fax: 515-294-3261, email: ronn@iastate.edu.

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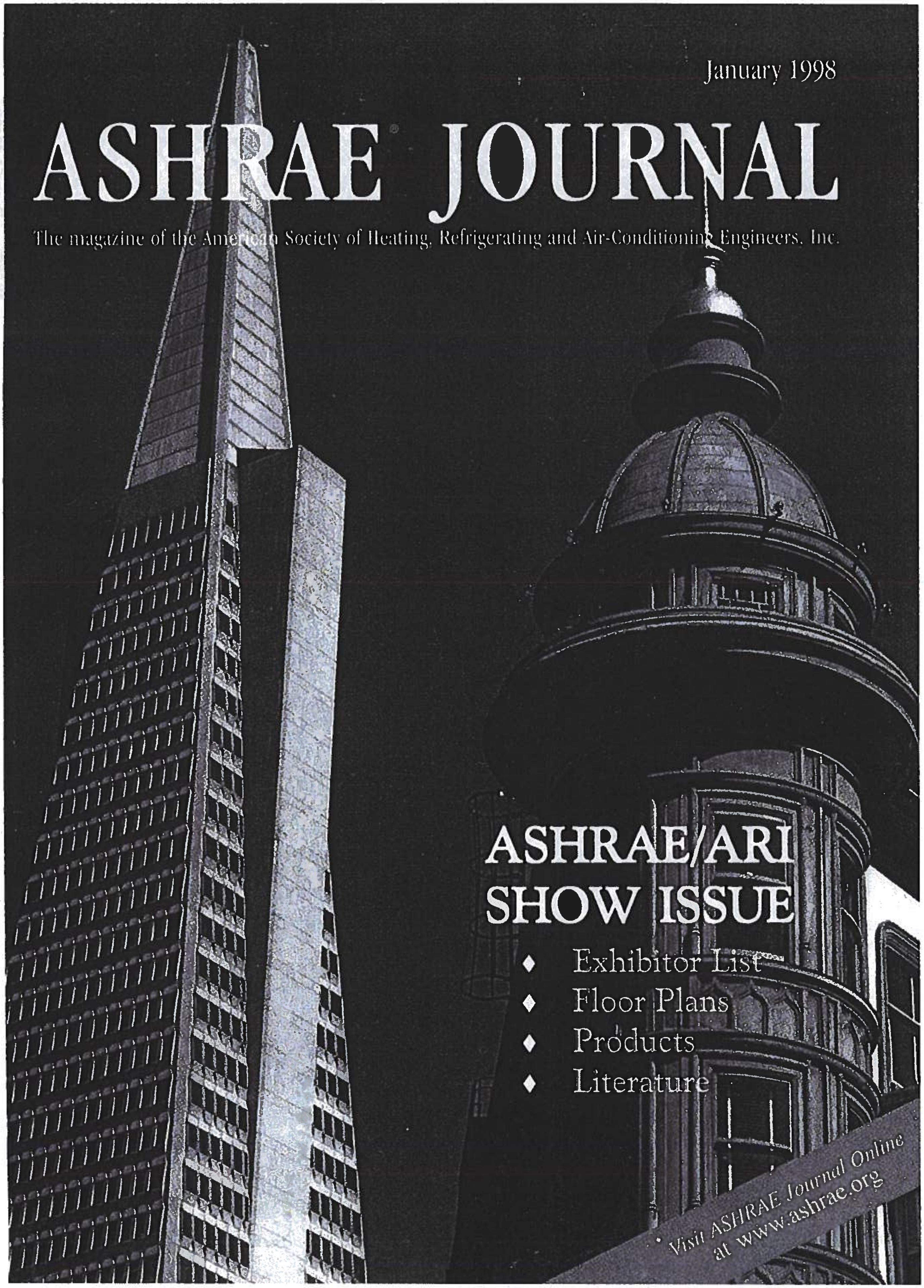

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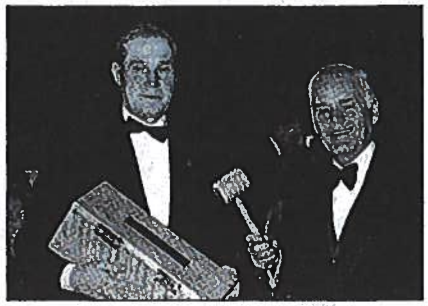

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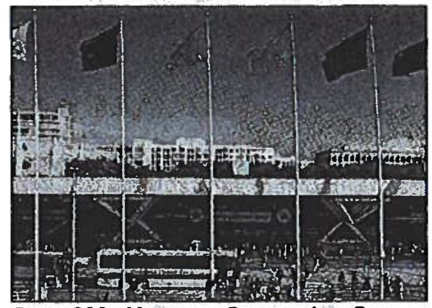

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