Proposed Tools and Capabilities for Proactive Multi-Building Load Management: Part 2—Aggregated Operation

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ABSTRACT

ASHRAE Research Project 1146, "Building Operation and Dynamics Within an Aggregated Load," was meant to (a) identify situations under which aggregating individual building loads is attractive for managing total, multi-building loads and (b) identify and evaluate operating and control strategies for use in individual buildings that will reduce energy operating costs at the aggregate level by taking advantage of the diversity in demand among buildings. Tasks undertaken in the first of two phases involved an extended background study on electric utility aggregation, a detailed description of three case-study sites where multi-building load aggregation and subsequent energy management strategies were performed, and a summary of the lessons learned from the case studies. The second phase of the work developed a list of 11 proposed tools that could be used by aggregators and their customers to control the aggregate load. This paper describes the functionality of proposed tools 5-11, which concern optimal operation of the aggregate of buildings and the management of load, electrical power, and financial data.

INTRODUCTION

ASHRAE Research Project 1146, "Building Operation and Dynamics Within an Aggregated Load," identified conditions under which aggregating individual loads for large commercial buildings is attractive for managing total, multi-building load and identified and evaluated operating strategies for use in individual buildings that will reduce energy operating costs at the aggregate level by taking advantage of the diversity in demand among buildings (Reddy and Norford 2002). Phase I of the work involved an extended background study and historical perspective on electric utility aggregation, a detailed description of three case-study sites where load aggregation and subsequent energy management strategies were performed, and a summary of the lessons learned from the case studies. Phase 2 formulated a list of 11 proposed tools that could be used by aggregators and their customers to alter the operation of buildings in order to control load and presented a DOE-2 (Winklemann et al. 1993) simulation case study, which consisted of aggregating three different building types (an office building, a hotel, and a retail store) to illustrate the benefits of multi-building load aggregation and control. The scope of the research was not to develop tools to the extent that load aggregators can use them. Rather, this research *described the functionality of proposed tools*, provided relevant review of prior work, and identified future work needed for each of these tools.

Reddy et al. (2003) described the Phase I results as well as the simulation case study. Reddy and Norford (2003) described utility deregulation, listed the types of issues faced by building owners and load aggregators, overviewed the 11 proposed tools, and specifically described the functionality of tools 1-4. This paper describes the remaining tools. Tools 5-8, the "proactive load control" set, determine how much load to curtail and specific end-use load-curtailment measures to implement in specific buildings. Tools 9-11, the "management of load, power, and financial data" set, concern the communication of price and load information, measurement of load-control action, and financial payments and penalties. Figure 1 depicts the 11 proposed tools.

PROPOSED TOOL 5: LOAD FORECASTING

Overview

The objectives of the proposed load-forecasting tool are threefold: to forecast for the next 12-24 hours the aggregated load of an individual building; to simultaneously forecast the

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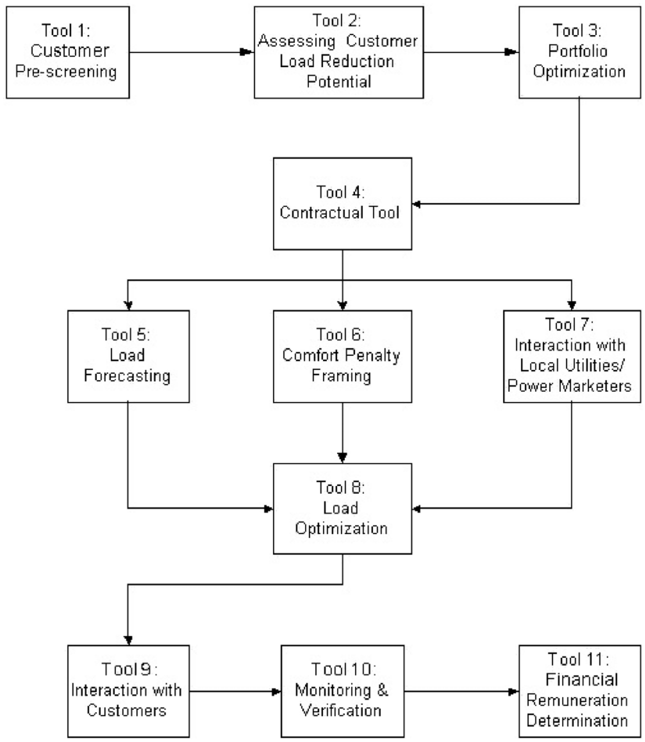

Figure 1 *Flowchart of tools needed by load aggregators offering proactive load management services.*

disaggregated controllable loads; and to estimate the impact of measures that have the potential to reduce the controllable loads. The term "building load" focuses on electrical loads in this study, but thermal loads directly impact electrical loads and influence thermal comfort, which constrains load reductions. A detailed literature review of building load models was compiled by Reddy et al. (1998a). Load-forecasting methods can be classified as follows:

1. *Semi-empirical.* The aggregator has an empirical estimate of demand increase, for example a kW/°C metric for each building and day type. Whether such rules of thumb allow end-use to be predicted with the required degree of accuracy is uncertain.
2. *Statistical/adaptive models from historic data.* If measured demand data are available for a year, which is usually not the case for end-use loads, one could develop statistical models for different types of days. Studies in the past (Fels 1986; Kissock et al. 1998; Katipamula et al. 1998) indicated that the outdoor dry-bulb temperature is the most important regressor variable, at monthly and even at daily time scales. Classical linear functions are not appropriate for describing energy use in many buildings because of the presence of functional discontinuities, called "change points." These change-points are caused by HVAC operating and control algorithms and schedules, including economizer cycles (Reddy et al. 1998b).
3. *Simulation-based.* The building simulation approach adopts an engineering simulation model and "tunes" the inputs of the program so that simulated output and measured values of building energy use match closely. A simulation program thus calibrated could then serve as a more reliable means of predicting the energy use of the building when operated under different climatic or different pre-specified operating conditions. One can distinguish between two different types of engineering simulation models: "detailed," general-purpose, fixed-schematic models such as DOE-2 (Norford et al. 1989; Bronson et al. 1992; Bou-Saada 1994), and BLAST (Manke et al. 1996) or "simplified," fixed-schematic HVAC system models based on the air-side models developed by ASHRAE TC 4.7 (Knebel 1983) and adopted in slightly different forms by many workers (Katipamula and Claridge 1993; Liu and Claridge 1995). Both the detailed and the simplified calibrated model approaches have yet to reach a stage of maturity in methodology development where they can be used routinely and with confidence by people other than skilled analysts.

Whole-Building Thermal and Electrical Load Models

Few papers describe on-line models for building thermal loads. MacArthur et al. (1989) presented results for a recursive time series model. Kawashima et al. (1995) evaluated autoregressive integrated moving average (ARIMA), exponentially weighted moving average (EWMA), ordinary regression, and artificial neural network (ANN) models and found ANN to be the most accurate. Henze et al. (1997) considered various mathematical forms to predict thermal loads and assess their impact on the performance of a controller for thermal storage systems. Their load models included an unbiased random walk, a bin predictor model, a harmonic predictor model, and an autoregressive network predictor model. Katipamula and Brambley (2003) switched from a neural net to a set of time series, binned by temperature, to predict whole-building load as part of a diagnostics tool. Daryanian et al. (1994) developed a two-step online procedure for forecasting the day-ahead hourly cooling load. First, the total load for the next day was estimated on the basis of the forecasted average outdoor temperature, the total load for the previous day, and the day type (weekday or weekend). Second, the total load was distributed among the 24 hours on the basis of historical load-distribution percentages. Regression analyses showed that outdoor temperature accounted for about 80% of the variation in load and that the use of three independent variables (temperature, previous load, and day type) produced a correlation coefficient (R^2) of 0.95. Forty days of data were used to establish the hourly load shapes.

Electric utilities monitor the whole building loads of most of their larger customers at 15-minute or 30-minute intervals. It would be advantageous for proactive load aggregators to make use of this rich source of information. Akbari (1995) showed that such data could be used to understand customer patterns as well as separate the effects of weather-dependent and weather-independent effects, both on an individual customer as well as customer-class basis. Forrester and Wepfer (1984) used multiple linear regression to develop a load prediction algorithm for the whole-building electricity use of a large commercial building. The algorithm allowed summer energy and peak use to be predicted up to four hours in advance with an accuracy of 2.5%. Seem and Braun (1991) reviewed deterministic (including polynomial, exponential, and sinusoidal functions) and stochastic (including autoregressive and autoregressive moving average) time-series models. They described a Cerebellar Model Articulation Controller (CMAC) to forecast electricity demand, relying on the EWMA method to update a lookup table to map system inputs and outputs. They noted that stochastic time series methods could be used to model the difference between a time series and a deterministic model for that time series. They then combined a deterministic and a stochastic model and adaptively determined the three autoregression parameters used in the stochastic model. Electricity data gathered from a grocery store and a restaurant were used to demonstrate the accuracy and robustness of the algorithm.

Efforts have been made to estimate end-use loads from whole-building measurements:

1. Econometric modeling (Usoro and Schick 1986). The objective was to develop and demonstrate new methods for estimating load shapes for residential end uses by disaggregating metered whole-house data. Hourly data for a year were obtained from 125 utility customers. At the first of two analysis levels, 60-70 parameters characterizing daily, weekly, seasonal, and weather-sensitive patterns of the load were extracted. At the second level, cross-sectional regressions measured the influence of household demographics and appliance ownership.
2. Algorithmic approaches such as the statistically adjusted engineering (SAE) method and the end-use disaggregation algorithm (EDA). EDA (Akbari 1995) used hourly whole-building data along with audit information about the building and certain physical constraints to produce hourly load profiles for air conditioning, lighting, fans and pumps, and miscellaneous loads. This approach was applied to two buildings (office and retail) with an average error of less than 5% during daytime operation.
3. The signal processing approach developed by MIT researchers (Norford and Leeb 1996; Luo et al. 2002) where rapid sensing of whole-building electrical use along with sophisticated processing techniques allow individual loads to be detected with reasonable accuracy.

Component Models

Measurement techniques and calculations are detailed in ASHRAE, AMCA, and ASME standards for air-handling-unit fans and in ASME and the Hydraulics Institute standards for pumps, as described by Phelan et al. (1997a). For constant-volume airflow systems, a one-time power measurement and a knowledge of the operating schedule are sufficient. For VAV systems, Phelan et al. studied the ability of linear and quadratic models to predict electricity use as a function of mass flow rate and concluded that although quadratic models are superior to linear models in predicting energy use, the linear model seemed to be the better overall predictor of both energy and demand (i.e., maximum monthly power consumed by the fan). For variable-flow water systems, achieved with either a throttling valve or a variable-speed drive, Phelan et al. concluded that quadratic models were superior to linear models in predicting electricity use as a function of mass flow rate.

Polynomial and thermodynamic models can describe in-situ chiller performance. Polynomial models correlate chiller (or evaporator) thermal cooling capacity or load and the electrical power consumed by the chiller (or compressor). For example, based on functional forms in the DOE-2 building simulation software (LBL 1980), electricity use can be modeled as a tri-quadratic polynomial model. This model has 11 parameters to identify. All of them are unlikely to be statistically significant and a step-wise regression with the sample data set yields the optimal set of parameters to retain. Braun (1992) used a bi-quadratic model with two regressor variables containing six empirical coefficients, namely, cooling load on the chiller and the difference between the ambient wet-bulb temperature and the fluid temperature leaving the evaporator (or the supply temperature to the building). Others (for example, Hydeman 1997) have proposed slightly different variants of such polynomial models.

Thermodynamic models, recommended by Phelan et al. (1997b), are preferred because they generally have fewer model parameters and those parameters, based on physical principles, tend to be more robust. The model proposed by Gordon and Ng (2000) correlates the chiller COP (the ratio of chiller thermal cooling capacity to the electrical power consumed by the compressor) with the easily measurable fluid inlet temperature to the condenser, the fluid temperature leaving the evaporator, and the thermal cooling capacity of the evaporator. The complete model has three parameters that are identified by multiple linear regression. This model and polynomial models have been studied in detail by Reddy and Andersen (2002) and Jiang and Reddy (2003).

Available Software

Private load consultants, load aggregators, and utilities have developed and have been using software tools that pertain to the load-forecasting tool. Although many of these tools are proprietary, a report by EPRI (Ried 1987) summarizes the capabilities of numerous tools by functionality. Software pertinent to Tool 5 can be divided into three groups: load data analysis software that allows processing and analyzing large amounts of monitored data from a particular facility or buildings; tools that evaluate numerous load management technologies along with their long-term financial implications for a specific customer; and probabilistic and scenario-based forecasting tools that assess and predict risks associated with forecasting uncertainties and decomposing sources of errors.

PROPOSED TOOL 6: COMFORT PENALTY FRAMING

The objective of this proposed tool is to provide a procedure to modify the indoor environment (specifically by allowing the indoor dry-bulb temperature to increase in a predetermined and controlled manner) so as to reduce electric demand at the expense of predefined overall occupant comfort. This differs from the approach described in numerous studies (for example, Braun et al. 2001; Braun and Chaturvedi 2002), which involves pre-cooling the building and making use of the building thermal heat capacity to shave demand peaks without compromising occupant comfort.

The basic issues involve: (1) formulating the strategy in terms of being able to mathematically quantify varying degrees of occupant discomfort associated with specific indoor environmental changes given the fuzziness surrounding human comfort modeling; (2) assessing whether the technical capability of present day HVAC systems and their associated controls permit such a strategy to be implemented practically; and (3) determining whether the building-specific data needed for this tool can be collected for specific circumstances. The procedure may seem drastic and unacceptable when electricity prices are moderately low but may be more attractive when demand charges are very high.

The semi-empirical model based on the Predicted Mean Vote (PMV) index proposed by Fanger (1972) and described in ASHRAE (2001) represents an average value of a large group of people. Dissatisfied occupants are likely to complain, and Fanger (1972) suggested another index called the PPD (Predicted Percentage of Dissatisfied occupants), which he related to PMV. In an office setting, air temperature and humidity are the two main variables for the physical comfort model. Gagge et al. (1986) proposed an extension of the PMV method that is more accurate under sweating conditions. Berglund (1989) found that temperature had an order of magnitude greater effect on human comfort than did humidity in determining human comfort. He also found that subjects indicated that equal changes in humidity are more perceptible at higher humidity levels than at lower humidities. Load management is likely to be implemented during hot summer days, when high humidity levels and their adverse impacts on human comfort will be a major issue. An excellent review and results of recent climate chamber test of subjects exposed to high humidity levels have been provided by Fountain et al. (1999).

Suggested Strategy and Data Requirements

The portfolio of the aggregator includes several buildings. Within each building, there are several control panels and circuit loops in each control panel. A sample chart is shown in Figure 2. The practical implementation of this tool involves first creating a knowledge table like that shown in Table 1.

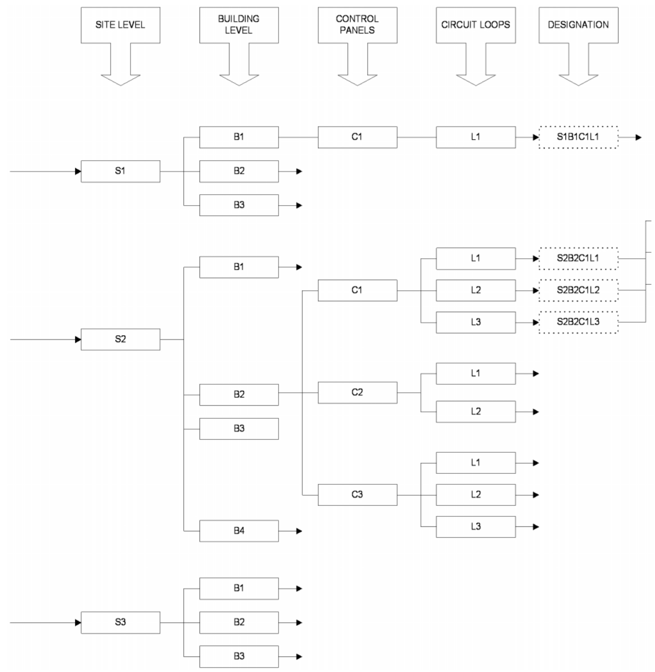

Figure 2 *Schematic illustrating the type of disaggregation needed for the Load Optimization Tool.*

Each circuit loop is designated by a code, an index number, and the type of load. The load-reduction potential (in kW) of each loop is determined by either measurement or best-guess estimates. Note that on/off (O/O) equipment has one number, while the ramped (R) loads associated with HVAC equipment and the dynamic (D) loads associated with thermal storage can take on numerical values from 0 to a maximum value. The next step is to fill the remaining columns in Table 1 with the fraction of uncomfortable occupants (FUO) at each loop, determined by the following equation:

$$FUO_i = \frac{PPD_i \cdot N_i}{\sum_{i=1}^{k} N_i} \tag{1}$$

where

k = total number of circuit loops

N_i = number of occupants in each loop i

The last column of Table1 simply indicates the availability of electric supply for the corresponding circuit loop. For example, an availability status = 0 may imply that electric supply cannot be curtailed because of other constraints (conference room or ongoing experiments). Once such knowledge tables are created, they can be used as a source of data input for Tool 8 where the actual load optimization is done (i.e., determining which loads to curtail such that the stipulated load reduction target is met while minimizing the total FUO).

Table 1. The Type of Data Needed for the Proposed Load Optimization Tool

Designation	No	Load type (O/O,R,D)	Load reduction (kW)	PPD (%)	Number of occupants	FUO	Avail. Status
S1B1C1L1	1	O/O	15	25	15	0.0019	0
S1B1C1L2	2	R	0-25	0-10	40	0-0.0020	1
.....	...						
S1B1C2L1	...	R	0-22	0-20	45	0-0.0045	1
...	....	D	0-50	0-35	60	0-0.0105	1
Total	k	-	1,000	-	2,000	-	-

Discussion

Goldman (1999) reviewed comfort modeling studies and stressed the need to include the thermal capacity of the body. He suggested that conditions where the demand *D* is between 20% and 40% of the body's capacity *C* for temperature regulation may cause some human discomfort but would likely lead to greater occupant productivity. However, ratios of $(D/C) > 40\%$ should be avoided because they are associated with decreased performance.

The recommendation that thermal comfort be bounded by PMV values between –0.5 and 0.5 can be debated. Goldman (1999) quoted a study by Macintyre that pointed out, based on experimental data, that the standard deviation for PMV is one full-scale unit between exposures (i.e., a PMV of 4 has a 95% confidence range from 2 to 6) and is about 0.8 scale units both within and between subjects for hourly readings throughout a single long exposure. From a practical point of view, one could argue that PMV values of 1 (which result in PPD = 26%, i.e., 52% of the occupants likely to be uncomfortable) are a more realistic range. The practical implication of such speculations is that the normally accepted comfort temperature bounds of 22.2-23.9°C (72-75°F) can be extended upward to 25.6-26.7°C (78-80°F) during load-control periods.

The PMV-PPD approach for modeling thermal comfort is applicable in steady state only. In practice, the willingness of occupants to put up with visually or thermally uncomfortable conditions depends strongly on their duration and incentives. Occupants might be willing to have office temperatures rise sharply, but for only one or two hours and for a limited number of days. During those short periods, workers could schedule meal breaks, seek to work in cooler parts of the building, go outside, or perform less demanding work.

Thermal sensation complaints are the most common kind of service requests, and the labor associated with HVAC maintenance can be reduced by 20% if the frequency of these complaints is reduced (Federspiel 1998). The main cause of thermal comfort complaints was unsatisfactory performance of HVAC systems and controls rather than individual differences in preferred temperature. Complaint-based strategies to control HVAC systems have been suggested. MacArthur (1986) proposed using PMV for controlling thermal conditions in buildings. Federspiel and Asada (1994) developed a control system based on a modified version of PMV. Federspiel (2000) developed a complaint model to simulate complaint behavior. Martin et al. (2002) evaluated different strategies to respond to thermal sensation complaints. Federspiel's model quantifies the cost in service calls associated with high- or low-temperature complaints; such costs would not be incurred in response to deliberate changes in temperature associated with a load-control program, but the metric may still be applicable for load control as a financial indicator of thermal discomfort that is an alternative to estimating a cost/PPD ratio.

Hamalainen et al. (2000) described how to model the consumption strategies of buyers of residential electric heating so that a certain amount of intentional discomfort was tolerated provided the financial gain was enough of an incentive. This study is the closest in the literature to the type of strategy proposed in this project. The model for human discomfort involved the deviation in actual indoor temperature from an ideal value, less complex than an approach involving PMV-PPD.

Introducing controlled discomfort to occupants in a building goes against the grain of current practice. As it is, facility personnel are hard pressed to maintain occupant comfort and minimize complaints, in part due to old or improper HVAC design, maintenance, control, and time. Because maintenance, operation, and control of HVAC systems are likely to improve with recent technological developments in networking and automated fault diagnosis, a strategy such as that outlined here may be both implementable and acceptable to the facility and occupants. Such an approach requires a good model that combines PPD with some measure of time or number of occurrences during which occupants will be subjected to uncomfortable indoor conditions. It could include a weighting factor that tends to increase the absolute value of PPD for longer periods of time or a simple multiplier that expresses willingness of occupants to endure uncomfortable conditions. The willingness would increase with financial incentive and decrease with duration.

Table 2. Predictable Factors Governing Electricity Prices Over Various Time Scales

Cost Component	Time Scale: 1-3 days	Seasonal	Multi-Year
Load	Short-term weather variations Existence of interruptible or price-sensitive demand	Business outlook Climate outlook (El Nino, etc.)	Demographic trends Market structure, pricing options
Supply Curve	Unit availability & maintenance schedule Market conditions Market power	Fuel Prices Maintenance schedules Hydropower availability and scheduling/ operations Long-term contracts Scheduled export/ import Market power	Fuel Prices New Entry and Retirement Market power
Congestion	Transmission line and generating unit outages Fluctuations in patterns of demand	Seasonal variations in line capacity, etc. Wheeling Hydropower delivery patterns Line maintenance schedules	Transmission expansion projects Siting of new units, retirements Demographic trends

PROPOSED TOOL 7: INTERACTION OF AGGREGATORS AND CUSTOMERS WITH POWER MARKETS AND INDEPENDENT SYSTEM OPERATORS

Power marketers are required to purchase power, making use of well-established mechanisms. A brief review is helpful in the context of proactive aggregators and their customers because it establishes the nature of the price forecasts and power purchases needed to facilitate cost-effective load control.

Price Forecasts

The price of electricity at any location at any point in time is a function of system load, the supply curve (quantity vs. price) of available energy, and transmission congestion. Each of these elements can be predicted over various time scales, based on the factors listed in Table 2. All of these time scales are of interest for load management. The multi-year time scale is important for decisions regarding investment in load reduction technology, the seasonal timescale is appropriate for process scheduling and planning for backup fuel supplies, and the one-to-three-day time scale is used for optimal implementation of load management strategies.

In some states, one-day to three-day price forecasts may be available from the Independent System Operator (ISO). Commercial subscription services also provide short-term price forecasts. One service offers on its website frequently updated, current-week price and volatility forecasts for some regions of the country; forecasts are made with neural net, regression, and time-series (ARIMA) models. Another service is based on a proprietary, short-term forecasting model that uses exogenous load, fuel cost, and unit-availability forecast data to predict locational market; the model accesses a detailed, proprietary database of generating unit operating data and transmission system characteristics.

Purchases in the Spot Market

A power exchange is a spot market for electricity. Organizations needing power can communicate that need and organizations with uncommitted power can specify a price at which they are willing to sell. Load-serving entities, with a contractual obligation to provide power to customers, use the spot market to meet their obligations or to sell purchased power in excess of their needs.

Today, aggregators and their customers typically do not interact with the spot market. Such interaction is a key part of a successful load-control effort. If the marketer's contract with the aggregator's customers provides incentives for load control, the power marketer will buy or sell power as usual, but will forecast to the aggregator or directly to the aggregated customer its need (for purchase) or opportunity (for sale) to do so. Customers will then need to obtain a price forecast from the ISO or an independent agency.

Purchases of Reserve Power as Required by the Independent System Operator

ISOs require power marketers to have available more power than their customers demand at any time. The ISO establishes the reserve requirement based on the possible loss of the largest generator or transmission line and a mix of other factors, including uncertainty surrounding load forecasts. Responsibility for reserves may be allocated to entities making use of the transmission system in proportion to the fraction of the system load required by each user. Users— power marketers and other load-serving entities—may have secured estimated reserves in the forward market. In general, users may have too little or too much at a given hour and could then settle among themselves in an *ex post* clearing market or purchase reserves from the ISO, which in turn had secured them from generating units. The benefits of load control, therefore, extend to include reserve power because the requirement for reserve power will decrease

Table 3. Comparison of the Best Objective Function Found by GA Search with the Minimum and Maximum Values Found Via the Exhaustive Search, for Different Weights

Runs	Demand weight	Energy consumption weight	Cumulative temperature weight	Maximum temperature weight	GA minimum objective function	Exhaustive search minimum objective function	Exhaustive search maximum objective function
1-4	1	1	0	0	84.6	84.6	88.5
5-8	10	1	0	0	141.8	141.7	156.0
9-12	1	1	1	0	85.0	85.0	98.7
13-16	10	1	1	0	142.1	142.1	166.2
17-20	1	1	1	0.1	87.5	87.5	102.3
21-24	10	1	1	0.1	144.7	144.6	169.8

as load drops. Settlement will be done after the fact and will need to be included in the financial remuneration calculations that this report labels as Tool 11.

PROPOSED TOOL 8: LOAD CONTROL VIA GENERATION OF ALTERNATIVE CONTROL STRATEGIES AND SEARCH FOR OPTIMUM

Load-control strategies under consideration are short-term measures that reduce operating costs and possibly thermal comfort. The DOE-2 simulation program used in this research to investigate changes in load shapes in three buildings (Reddy et al. 2003) incorporated sufficient detail about building materials and mechanical systems but would have been a cumbersome tool for generating a large number of alternative load control strategies in order to identify an optimal trade-off of cost savings and thermal-comfort penalties. While such simulations can be run in a batch mode, with automated variation in key parameters, this research instead automatically generated alternative control strategies with a dynamic model based on a popular general-purpose engineering mathematics program (Mathworks 2001). The model was a two-resistor two-capacitor (2R2C) nodal model of a single 100 m^2 room and was simulated over a single day at one-minute time steps. Outside temperature was a pure sinusoid and solar gains were a sinusoid limited to positive values. Solar and internal gains were split between the air-temperature node and the structural-mass node. Only sensible loads were simulated. In its initial configuration, the model included a fixed-COP chiller and a fixed-efficiency fan. The airside system was later extended to include a VAV system.

This simulation was much less detailed than publicly available building-energy simulation programs but offered two advantages. First, short-term load control measures were readily programmed. These measures focused on limiting the lighting power and the chiller power to a specified fraction of the maximum. Second, the simulation was run in a programming environment that could readily implement a freeware genetic-algorithm (GA) search engine. The GA search engine made it easy to define an objective function, which always included energy consumption and optionally included demand and temperature deviation from setpoint, and to search over a large number of possible control strategies for those strategies that minimized the objective function.

Optimization

The GA was used to find the optimal solution for a single building for different forms of the objective function. Members of the population were defined by the limit on air conditioning and the hour in which that limit would take place and a similar limit and hour for lighting. For purposes of the GA, the step size for limits on air conditioning and lighting was defined as 0.1, ranging from 0 (no service) to 1.0 (no reduction in service). The load-control period was four hours, noon to 4 p.m. The GA search was performed for the four possible combinations of population size, three and ten, and number of generations, two and ten. In each case, the GA was set up to remember all past simulations and not repeat a simulation in its search for the optimum. A population of ten and a run with ten generations required no more than 74 simulations, well below the theoretical maximum of 100. The GA results were compared with the optimal solution found by an exhaustive search. The exhaustive search was limited to control steps of 0.2, to speed up the calculations. With this step size and a four-hour load-control period, the number of possible load-control actions was 576 (six load-control steps over four hours for air conditioning and for lighting). For a given set of weights in the objective function, there was very little difference in the minimum value of the objective function, as determined by the GA, for different choices of population size and number of generations. The GA required only 5% of the number of simulations used by the exhaustive search (28/576, where 28 simulations were needed for a population of three and ten generations) to produce excellent results. Table 3 shows that the GA was consistently at or very near the minimum values found by the exhaustive search.

Lessons learned from the single-building optimization included the following:

- The peak air-conditioning load increased when air conditioning was curtailed, due to the pick-up load. Depending on the magnitude of demand and energy charges, curtailment of air conditioning may or may not reduce operating costs.
- While many combinations of lighting and air-conditioning curtailment produced similarly low values of the objective function (weighted cost of energy and loss of service), others were poor choices with objective functions that were 15% higher than the best choices. High objective function values found in this work were associated with reductions in air conditioning that saved little energy and greatly increased the thermal-comfort penalty.
- The GA was able to find relatively small differences in objective function. It did not consistently find the absolute minimum when the search space had a shallow contour, but the extent of suboptimality was trivially small.
- For a problem where there are a large number of near-optimal solutions, the GA search can be limited to small populations and a small number of generations.
- The same control strategy produced the best performance for all six sets of weights on demand, energy, and thermal performance: turning off the lights completely for one hour, which was not subject to a visual-comfort penalty, and limiting the air-conditioning output to 0.6 of maximum value for a single hour. A second strategy produced the worst performance: turning off the air conditioner for an hour and maintaining the lights at rated power throughout the load-control period. This suggests that some amount of off-line testing may establish heuristics that can usefully supplement or replace time-critical on-line simulations.

A two-building search took a different form due to the very large number of possible load-control strategies. Recall that there were 576 combinations for a single building, using control step sizes of 0.2. For two buildings, the number of combinations is 331,776. This was far too many to consider exhaustively (576 simulations required about nine hours on a 450 MHz PIII personal computer). For this project, two-building load-control was evaluated by combining limited sets of simulations for a single building. Two sets of single-building simulations were run, one consisting of three different load-control combinations and the other of ten. The number of two-building combinations was therefore nine for the first set and 100 for the second. Objective functions were then formed with different weights for the two-building hourly energy use and temperature deviations. Using ten simulations for a single building and 100 two-building combinations produced objective function values that were 0.1% to 4.5% lower than results for nine combinations. While the simulation environment was used to examine two identical buildings, in principle the approach should work for dissimilar buildings, including the case when the peak loads are unequal in magnitude and are shifted in time, as may be due to variations in exposure to afternoon solar radiation. Dissimilar buildings were not tested. Although appropriate for this problem, a GA was not used. Lessons from the two-building optimization included the following:

- For a given set of weights, the objective function for the worst-case two-building combination was 2.9-10.2% higher than the best-case combination. The higher range was associated with large demand charges. Under such charges, it is important to pay attention to two-building load-control combinations.
- When the objective function included only energy costs, there was essentially no difference among strategies that involved turning off the air conditioning in the two buildings during the same or during staggered hours. This was expected, given the lack of a demand charge. There is no need to use a GA to search for such a solution. Further, turning off air conditioning was little better than doing nothing—only a 3% reduction in the objective function, which in this case represents energy charges. This result was also expected, given the results for a single building. If building owners or operators are willing to curtail cooling for only a short period (one hour), the savings may be small and require no consideration of buildings in aggregate.
- Simultaneously turning off lights and air conditioners in both buildings was the worst option when a demand charge was imposed, due to the coincident pickup load following the load-control hour.

To summarize, a genetic algorithm was found to be an appropriate tool for evaluating load-control measures. It has been used successfully in a number of HVAC applications, as documented in Caldas and Norford (2003). However, the simplified building simulation was not an ideal platform because of its limited description of HVAC systems. Subsequent work not part of this project (Xing 2004) made use of a more complete energy-simulation program and evaluated several optimization strategies for multiple buildings, including GAs.

POST-CONTRACTUAL CAPABILITIES

The last set of three proposed tools concerns communication of price and load information, measurement of load-control action, and financial payments and penalties for load control or lack thereof.

Proposed Tool 9: Communication Between Aggregator and Customer

Tool 9 deals with ways by which load aggregators should set up communication channels to inform their customers about impending peak days, the price signal, the possible curtailment measures they could activate, and how much they would save if one or several of these measures were to be implemented. The customer then needs to respond to requests, not only with a message indicating compliance or noncompliance, but also to specify which of the measures he or she is willing to initiate. For this two-way communication to work satisfactorily, certain standards and procedures must be defined and adhered to; otherwise missed opportunities or oversights could be very costly to both aggregator and customers.

Electric utilities in the regulated market have initiated several load shedding programs in the past. In programs targeted at curtailing residential air conditioning via direct load control, utilities, with prior consent of the participating customers, cycle the air conditioners either by radio signal or power-line carrier (EPRI 1987). Utilities also have had experience with voluntary price-induced curtailment programs, such as peak-activated rates, real-time pricing, and time-of-day rates (Orange and Rockland 1987). Although some of these concepts and hardware are applicable, major improvements and enhanced capabilities will be needed.

One attractive option is to enhance the capability of the current generation of networked building automation systems. Although these systems are primarily meant to assist in proper facility management, which includes energy management, comfort monitoring, facility operation and service and space planning, it is likely that in the near future they would include such capabilities as fault detection and diagnosis and predictive maintenance scheduling, as well as the ability to allow supervisory control essential for load shedding to be implemented from a central location in the facility. A new field, "enterprise energy management," is evolving that involves different levels:

- Baselining and understanding current usage (includes sophisticated reporting systems that allow the operator to understand and evaluate energy use campus-wide);
- Managing enterprise utility usage after the utility contract and reporting process are in place. This involves real-time monitoring, deciding how best to control load depending on real-time pricing rates and negotiated rates, and the ability to react by load shedding;
- Utility enterprise resource planning, which encompasses managing, forecasting and reacting to dynamic enterprise utility rates.

Building automation systems of the future are likely to include the above capabilities, while also having the ability to gather weather forecasts and changing utility market rates. However, all these services are based on the ability to define the energy-related information services and analysis of data requirements. A recently completed ASHRAE research project (Kintner-Meyer and Burns 2001a, 2001b) focused on the issues of communication standardization for utility/customer information services and presented a comprehensive review of existing architectures and capabilities. The formulation and development of Tool 9 can benefit greatly from this project. Nine information services (revenue meter reading, quality of service monitoring, real-time price transmission, load management service, on-site generation supervisory control, energy efficient monitoring, weather reporting and forecasting services, indoor air quality monitoring, and dynamic demand bidding into a power exchange) were studied. Emphasis was placed on the application (data models) and scenario (time-sequence diagrams) interoperability needed to implement the services, building on existing communication interoperability. Some extensions to existing communication protocols (BACnet, for example, as documented in ASHRAE 1995) are needed to lay a foundation for tool development.

Proposed Tool 10: Monitoring and Verification

The objective of this proposed tool is to measure the amount of load curtailed by the customer relative to a previously agreed upon baseline, as a result of an aggregator-initiated request to curtail load. A second objective is to provide the necessary end-use monitored data for both the total-facility baseline load and the contribution of the important disaggregated end-use loads (needed for Tool 5), in order that annual adjustments can be made to both these types of uses due to inevitable changes in building operation, changes in installed loads, and electricity creep. The envisioned features and capabilities of Tool 10 are:

1. Measurement of demand reduction. Direct measurement can be used to determine the amount of load curtailed by the customer in response to an aggregator-initiated request, via the following tasks:

(a) Install and commission, or recalibrate existing, load meter(s) for the whole building or facility.

(b) Use measured data from (a) to establish a mutually agreeable baseline for demand during peak days.

(c) Inspect equipment periodically and calibrate as necessary.

(d) Process and store all collected data over time. Whenever load curtailment measures are implemented, corresponding data are used for analysis.

2. Baseline adjustments. Baseline energy use varies appreciably over time (Claridge 1998) due to removal or addition of equipment, addition of such systems as thermal storage that change peak load behavior, changes in the way the building is operated diurnally, and new construction. The proposed tool should include necessary analytical routines that would use monitored data to make the necessary changes.

3. Support for proposed Tool 5: load forecasting. Tool 5 requires that forecast models of the important end-uses be developed (or be available) so that the aggregator can first determine and then recommend to the customer the specific curtailment measures to implement. The instrumentation and monitoring capability should extend to end-use loads. Moreover, even these end-uses would have to be adjusted over time (as in (2) above), and so all the tasks listed under (1) above would also apply to each end use.

The formulation of this proposed tool can benefit greatly from measurement and verification (M&V) standards and guidelines developed during the last decade, notably IPMVP (2001) and GPC14P (ASHRAE 2002). Other pertinent M&V

programs/documents are U.S. Federal Performance Measurement and Verification Protocol (USDOE 1996), U.S. EPA Conservation Verification Protocols (USEPA 1995), the World Bank's monitoring and evaluation guidelines (World Bank 1994), the U.S. Initiative on Joint Implementation (USIJI 1996), California's Measurement and Evaluation Tools (CPUC 1998), LBNL's guideline (Vine and Sathaye 1999), and the North American Energy Measurement and Verification Protocol (NEMVP 1996). One useful reference for M&V issues is the special issue of the *ASME Journal of Solar Energy Engineering* (Claridge 1998), "Methods of Analysis of Measured Energy Data in Commercial Buildings."

The IPMVP and the ASHRAE GPC 14P documents merit a brief description. IPMVP (2001, an updated version of the 1997 document) is the result of a concerted effort between state and federal agencies as well as financial and energy efficiency experts. It is a consensus document that provides an overview of current best-practice techniques available for verifying results of energy-efficiency, water-efficiency, and renewable-energy projects. It establishes a general framework and terminology to assist buyers and sellers of M&V services. It is not intended to prescribe contractual terms between buyers and sellers of energy efficiency, although it provides guidance on some of these issues. Once the contractual issues are decided, this document can help in the selection of the M&V approach that is most appropriate for the project costs and anticipated savings, technology-specific requirements, and risk allocation between buyer and seller.

The IPMVP document proposes three M&V methods for determining energy savings from retrofits or operational and maintenance improvements in buildings. Option A deals with one-time measurements before and after the energy-conservation measure, Option B involves monitoring specific end-uses for a period of time (for example, weeks to months) before and after the retrofit, and Option C entails measuring whole-building consumption for a baseline period of at least several months before the retrofit and continuously following the retrofit. Although none of the options applies specifically to Tool 10, Options B or C can guide development of this tool.

ASHRAE (2002) GPC 14P is a more technical document that complements the IPMVP document. It provides three methods for measuring savings from energy conservation retrofits: component isolation, main-meter before-after measurements, and calibrated simulation. It encompasses all forms of energy (electricity, gas, oil, district heating/cooling, etc.) in residential, commercial, and industrial buildings. Sampling methodologies, metering standards, and major industrial process loads are excluded. Both documents contain annexes that discuss issues about sensors and data loggers, instrument accuracy, equipment selection criteria, cost implications, calibration, routine maintenance and inspection, and data accuracy needs.

Although there is an extensive literature on how to develop baseline models from statistical considerations (see for example, ASHRAE 2002 or Claridge 1998), it is unlikely that a statistical approach will apply to Tool 10 because the focus is on measuring demand savings over a period of a few hours only. The baseline demand profile for the building or facility is likely to be negotiated by both the energy manager and the load aggregator based on actual measured load profiles of, say, the last five peak days or some such criterion. Sophisticated statistical (or engineering-based modeling) techniques are unlikely to be resorted to in the beginning, though their future adoption as the tool matures is likely. When this does occur, issues such as the uncertainty in the demand savings (see, for example, Reddy et al. 1998b and Reddy and Claridge 2000) will acquire relevance.

Proposed Tool 11: Financial Remuneration Determination

Customers who shift load when requested should be rewarded in accordance with a contractually specified formula, the subject of Tool 11. There are a number of issues:

1. *Magnitude of cost savings for the aggregate of buildings.* The contract with the power marketer must specify how the cost savings are computed. There are several options. Most simply, the power marketer could offer a flat rate per kW of curtailed load. It would leave the power marketer with a certain amount of risk that spot prices would be much higher than anticipated and leave customers with the risk that spot prices would be lower. More accurately, the power marketer could compute its costs for spot-market prices relative to bilateral contracts.
2. *Baselines for each building.* Load reductions need to be computed relative to a load baseline established as an average over a small number of recent days during which there was no load-control activity. Free riders should be avoided if possible.
3. *Allocation of savings.* If savings are not specified on an *a priori*, fixed payment per kW basis, there is a need to allocate savings attributed to the group as a whole. Most simply, customers could benefit according to their average load or their operating costs. More accurately, customers would benefit according to shifted load, as measured during times of interest to the power marketer.

Savings must be calculated on an *ex post* basis to account for actual and not forecasted market prices and the cost that power marketers bear to provide the reserves required by the Independent System Operators.

In the past, financial calculations have been implemented at the scale of a local utility or an entire state. Rewards for load control have been offered on a fixed-price basis, either a one-time payment (as for utility reduction of residential air conditioning via radio control) or on a fixed price per kW of reduced load. Any lack of precision in the calculations has been absorbed by the utility or state. Those who effectively bear the burden of excessive payments to participants are affected at very low levels, by dint of the large number of nonparticipants.

In a small set of customers served in aggregate, such imprecisions are likely to make more of a difference. It is therefore necessary that remunerations be calculated equitably and accurately. Such calculations are a natural extension, on a smaller scale, of the type of calculations now in effect in power markets.

CONCLUDING REMARKS AND SUMMARY

Effective load control for aggregates of buildings depends on a suite of information-processing tools. This research has proposed a reasonable set of tools and identified their functionality. Many of the tools are required for single-building load control and many have been already developed to some extent. The proposed tools described in this paper can be summarized as follows:

- **Load forecasting.** Extensive work on the forecasting of building thermal and electrical loads obviates the need for additional effort solely for the purpose of multi-building load control. Notably, recent efforts aim to implement load predictions in on-line controllers, primarily for night cooling.
- **Thermal comfort.** This research proposed a method for estimating thermal comfort at the local level (an individual office or thermal zone—wherever zone temperature data are available) and then forming an occupancy-weighted estimate of thermal comfort within an entire building. Such a weighted average would permit an assessment of the thermal-comfort penalty associated with zone-specific load control measures, including increases in zone temperature. This type of control introduces a dynamic aspect to thermal comfort because occupants will be exposed to increased temperatures and humidities for relatively short periods (a few hours). While the body may physiologically respond rapidly, occupants who are informed of the reason for the load control and its anticipated duration may adapt psychologically and experience minimal discomfort.
- **Interaction of aggregators and customers with power markets and Independent System Operators.** Electricity price forecasts are available from some Independent System Operators and from commercial services.
- **Load Control.** This research explored the use of an optimization method based on genetic algorithms to select the best short-term load control measure for a single building. Energy simulation was done with a simple two-node thermal model and a simplified cooling plant; future work should make use of more complete, publicly available simulation packages. Limited multi-building optimization was based on an enumerative search of a small number of possible load reductions. Future work with multiple buildings should test the use of genetic algorithms, which are suited for large problems, and the use of numerical representations of load shapes pre-calculated from energy simulation, to avoid needing to run very large numbers of energy simulations in the course of an optimization calculation.
- **Communication between aggregator and customers.** This area has been and will continue to be developed for single-building energy management. Data structures have been proposed recently for implementation in BACnet.
- **Monitoring and verification.** These activities will take place in individual buildings and will be based on techniques developed for single-building use. Results will be used to support load forecasts and calculation of payments.
- **Financial remuneration.** Financial remuneration is already part of single-building load control. Needed for multi-building control are formulas for determining the share of the load reduction in aggregate that is due to the action of any one building.

Load control is not currently part of most load-aggregation programs, which are focused on buying power and obtaining the best price for electricity. There have been and are exceptions. Local utility companies have in the past sponsored so-called cooperative programs, in which participants are contractually obligated to shed a specified amount of load as a group in response to utility notification. California has recently rewarded businesses that have shed load when requested. Exceptions aside, it is worth asking why load control has not been more broadly built into load aggregation. One answer is that neither simulations nor field experiments have been brought to bear, to the extent that savings from load control are documented and assessed. Another answer is that the contractual, measurement, and bookkeeping tools are not in place. These tools, which in effect sandwich the technical tools (or, put another way, form the front and back ends of a load-control program), can be envisioned as junior versions of tools that have recently been developed for use in power markets. The scale is different—much smaller. Potential developers of these tools, which could be aggregators or their consultants, need some assurance that there is a market for load-control programs. To accelerate the implementation of effective multi-building load control, the following research and development is recommended:

- Research to measure changes in thermal comfort in response to short-term load control measures.
- Tests of short-term load-control measures in commercial buildings. Ease of implementation, load reduction, and increase in temperature at a zonal level should be measured. Pickup loads should also be recorded, for purposes of assessing how to stagger load-reduction across multiples of buildings.
- Load-reduction-potential tools should be developed to the point where aggregators can use them with confidence. This is now important in the California Power Authority's Demand Reserves Partnership program.
- Optimal-control tools should be further developed for

single- and multi-building short-term load-control measures. These tools should account for thermal- and visual-comfort penalties.

- A financial remuneration methodology should be established to account for the contribution of an individual building to the load reduction of the aggregate.

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