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# Model-based benchmarking with application to laboratory buildings

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## Abstract

The most common method of benchmarking energy use in buildings is to compare the energy use of the building under consideration with the energy use of a population of like buildings. Usually there is some empirical compensation for features and factors that affect energy use such as the size of the building and the weather conditions. Two fundamental limitations of this approach are: (1) only similar kinds of buildings can be compared; and (2) the entire population may be inefficient, which would cause many inefficient buildings to be rated as efficient. The first limitation is important when benchmarking laboratory buildings because there is no public database of energy use and building features that can be used to construct empirical benchmarks for laboratories. The second limitation is also important because there is evidence that energy-consuming processes in laboratory buildings, especially HVAC systems, are inefficient because of highly conservative design practices. This paper describes a benchmarking method that is fundamentally different than the method described above. The principle of the new method is to construct a benchmark that represents the minimum amount of energy required to meet a set of basic functional requirements of the building. These requirements include code-compliant environmental controls, adequate lighting, etc. The benchmark is computed based on idealized models of equipment and system performance. Using idealized models produces a benchmark that is independent of design and easy to compute. Once the benchmark has been computed for a single building, an effectiveness metric is computed by dividing the model-based benchmark by the actual consumption. This metric, or its inverse, can be compared with the metrics of other buildings. Since functional requirements have been incorporated into the benchmark, it is possible to compare the performance of dissimilar buildings, or buildings that have rare or unique functional requirements. The performance of the model-based benchmarking method was compared with two alternative methods based on the ability to predict actual energy use. Using building energy data from the UC Berkeley campus, it was shown that the model-based benchmarking method was more accurate when a combination of laboratory and non-laboratory buildings was analyzed.

*Keywords:* Model-based; Benchmarking; Laboratory buildings

## 1. Introduction

Benchmarking is one of the first activities in the process of deciding whether or not to invest in energy-conservation measures in buildings. Consequently, improvements in benchmarking methods could have a large impact on energy use and the profitability of companies that use energy or provide energy services.

Most energy service companies (ESCOs) and other organizations responsible for energy-efficiency of buildings use the mean or median value of the energy use intensity (EUI) for the kind of building being investigated as a benchmark for determining whether or not the building is a good candidate for energy-conservation measures. The EUI is the average power normalized by gross plan area of the building. In the US, it is typically expressed in kW h/ft$^2$ per year or MBTU/ft$^2$ per year.

The EUI accounts for only one building feature that affects energy consumption: plan area. To account for the effect of other features that affect energy consumption, benchmarks have been constructed by using statistical methods to correlate other features with energy use [1,2]. Sharp's method is based on an analysis of the 1992 commercial buildings energy consumption survey (CBECS) database [3]. Linear regression models were used to correlate building characteristics with energy consumption. Seven of the 75 characteristics investigated were found to be statistically significant indicators of energy consumption.

Sharp's method has been modified slightly and used as the basis of the Energy Star® benchmark [4]. Rather than using census location as a proxy for weather, the Energy Star® benchmark explicitly compensates for weather. The Energy Star® benchmark is the 25th percentile of the EUI distribution, because this level is expected to be the level required for compliance with energy codes.

An energy analysis activity that is related to benchmarking is baselining. The key difference between benchmarking

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## Nomenclature

| | |
|---|---|
| $a$ | standard temperature lapse rate (0.0065 K/m) |
| $A_l$ | gross plan area (e.g. square footage) of the lab |
| $A_{Lab}$ | calculated laboratory space area |
| $A'_{Lab}$ | reported laboratory space area |
| $A_o$ | gross plan area of the non-lab space |
| $c$ | ceiling height (3.05 m) |
| $C_1$ | saturated vapor pressure constant (−5674.5359) |
| $C_2$ | saturated vapor pressure constant (6.3925247) |
| $C_3$ | saturated vapor pressure constant (−0.009677843) |
| $C_4$ | saturated vapor pressure constant (0.000000622115701) |
| $C_5$ | saturated vapor pressure constant (0.0000000020747825) |
| $C_6$ | saturated vapor pressure constant (−0.0000000000009484024) |
| $C_7$ | saturated vapor pressure constant (4.1635019) |
| $C_8$ | saturated vapor pressure constant (−5800.2206) |
| $C_9$ | saturated vapor pressure constant (1.3914993) |
| $C_{10}$ | saturated vapor pressure constant (−0.048640239) |
| $C_{11}$ | saturated vapor pressure constant (0.000041764768) |
| $C_{12}$ | saturated vapor pressure constant (−0.000000014452093) |
| $C_{13}$ | saturated vapor pressure constant (6.5459673) |
| COP | coefficient of performance of chiller used for benchmark calculations (default = 5) |
| $d$ | height of the opening below the sash of a closed fume hood (0.076 m) |
| ET | equation of time (min) |
| $f_p$ | specific pump flow rate (default = $2.9 \times 10^{-8}$ (m$^3$/s)/W) |
| $F_{al}$ | flow from the outdoors to the lab |
| $F_{ao}$ | flow from the outdoors to the office |
| $\underline{F}_{ao}$ | maximum flow from the outdoors to the office |
| $\overline{F}_{ao}$ | minimum flow from the outdoors to the office |
| $F_{la,e}$ | flow from the lab to the outdoors through the general space exhaust |
| $F_{la,h}$ | flow from the lab to the outdoors through the fume hoods |
| $F_{oa}$ | flow from the office to the outdoors |
| $g$ | gravitational constant (9.80665 m/s$^2$) |
| $h_a$ | specific enthalpy of air |
| $h_c$ | specific enthalpy of conditioned air |
| $h_o$ | specific enthalpy of transfer air from office to lab |
| $h_{occ}$ | heat generation per person (100 W per person) |
| $h_{o,u}$ | specific enthalpy of non-air-conditioned office air |
| $H_{c,o}$ | cooling load of office space |
| $H_{o,c}$ | load (heating or cooling) of air-conditioned office space |
| $H_{occ,l}$ | heat generated by occupants in the lab area |
| $H_{occ,o}$ | heat generated by occupants in the non-lab (office) area |
| $H_{sunrise}$ | sunrise hour |
| $H_{sunset}$ | sunset hour |
| $L$ | linear quantity of fume hoods |
| LAT | local latitude (degree of arc) |
| LON | local longitude (degree of arc) |
| LSM | local standard time meridian (degree of arc) |
| $m_a$ | molecular weight of dry air (28.9645 kg/mol) |
| $m_w$ | molecular weight of water (18.01528 kg/mol) |
| $M$ | total mass of laboratory air |
| $N_l$ | number of laboratory occupants |
| $N_o$ | number of office occupants |
| $p_w$ | vapor pressure of water in air |
| $p_{w,c}$ | vapor pressure of water in conditioned air |
| $p_{ws}$ | saturated vapor pressure of water in air |
| $p_{ws,c}$ | saturated vapor pressure of water in conditioned air |
| $P$ | atmospheric pressure |
| $P_0$ | standard atmospheric pressure at sea level (101.3 kPa) |
| $P_{l,l}$ | lighting power in the lab space |
| $P_{l,o}$ | lighting power in the non-lab (office) space |
| $P_{pp,l}$ | plug and process power in the lab space |
| $P_{pp,o}$ | plug and process power in the non-lab (office) space |
| $\underline{q}_{ao}$ | minimum outdoor air volume flow per person for the office |
| $\overline{q}_{ao}$ | maximum outdoor air volume flow per unit of plan area for the office |
| $r_l$ | fraction of lab space that is air-conditioned |
| $r_o$ | fraction of office space that is air-conditioned |
| $R$ | gas constant of air |
| $R_a$ | gas constant of dry air (287.055 J/(kg K)) |
| $R_c$ | gas constant of conditioned air |
| $R_w$ | gas constant of water vapor (461.520 J/(kg K)) |
| $T_0$ | standard absolute temperature at sea level (288 K) |
| $T_c$ | conditioned space temperature (default = 22.2°C) |
| $V$ | fume hood face velocity (0.5 m/s) |
| $W$ | humidity mass ratio |
| $W_c$ | humidity mass ratio of conditioned air |

*Greek letters*

| | |
|---|---|
| $\delta$ | solar declination (degree of arc) |
| $\varepsilon_e$ | electrical consumption effectiveness |
| $\varepsilon_f$ | fuel consumption effectiveness |
| $\phi$ | relative humidity |
| $\phi_c$ | relative humidity of conditioned air |
| $\lambda$ | specific lighting power (default = 0.04 W/m$^2$) |
| $\pi_f$ | specific fan power (default = 1700 W/(m$^3$/s)) |

| | |
|---|---|
| $\pi_p$ | specific pump power (default = 99,868 W/(m$^3$/s)) |
| $\pi_{pp,l}$ | specific plug and process power for lab (default = 0.11 W/m$^2$) |
| $\pi_{pp,o}$ | specific equipment power for office (default = 140 W per person) |
| $\rho$ | density of air |
| $\rho_a$ | density of outdoor (ambient) air |
| $\rho_c$ | density of conditioned air |
| $\Omega$ | air-change rate |

and baselining is that benchmarking generally involves a comparison of energy performance with other buildings, while baselining generally involves a comparison of past energy performance of a single building with current energy performance. The most common methods of baselining are similar to the methods described above for benchmarking. Statistical methods are typically used to correlate weather data and other important variables of a single building with measured energy use. Examples of this kind of baselining are described in [5,6].

Laboratory buildings consume considerably more energy per square foot than other kinds of commercial buildings, and they are becoming increasingly energy intensive. In [7] it is estimated that energy use intensities in laboratory buildings are four to five times higher than those found in non-laboratory buildings, such as offices, and that energy consumption in laboratory buildings in California is growing exponentially at a rate of 3.9% per year. In [8] it was shown that the energy intensity of laboratory buildings on the UC Berkeley campus is three times greater than that of non-laboratory buildings. For laboratory buildings constructed after 1980 it is six times that of non-laboratory buildings.

One of the reasons that the energy intensity of laboratories is so high is because of the HVAC requirements that are specific to laboratories. Due to the nature of work in laboratories, the air-change rate must be higher than in other kinds of commercial buildings, and they are usually supplied with 100% outside air. Large quantities of air are exhausted from the laboratory either through the exhaust from the occupied space or from fume hoods or other local exhaust devices. The movement of large quantities of air causes the fan power used by laboratory buildings to be high. Conditioning large quantities of air causes the chiller power to be high.

Concerns for occupant safety and reliable process operation combined with considerable uncertainty about the magnitude and variation of heating and cooling loads often leads to decisions which result in the inefficient operation of laboratory buildings. This problem is amplified by the fact that the energy intensity of laboratory buildings is high and the energy consumption is growing exponentially. Consequently, there is a need for tools that will allow operations staff to determine how well laboratory buildings are operating so that design and operational problems can be addressed.

One problem with existing benchmarking methods is that they do not sufficiently account for differing functional requirements of buildings. This problem is particularly acute in laboratory buildings, where the functional requirements are unique and vary considerably from one laboratory to another. It also makes it difficult to apply existing benchmarking methods to dissimilar buildings. For example, it is not possible using existing benchmarking methods to compare the performance of laboratory buildings with office buildings. The ability to do so is important because nearly all laboratory buildings contain non-laboratory space. Although Sharp's method does account for some functional requirements, many of the functional requirements that have a significant impact on energy use are not included. For example, temperature control, humidity control, ventilation rate, filtration efficiency, and plug and process loads are not explicitly treated as functional requirements.

Another problem with existing benchmarking methods is that all current benchmarks are based on the performance of other buildings. They do not reflect the extent to which the energy-efficiency could be improved because the entire population could be making ineffective use of energy. Therefore, existing benchmarking methods cannot be used by an energy engineer to determine the energy-saving potential that exists even in buildings that are considered to be energy-efficient.

## 2. Method

There are numerous performance metrics in existence for engineered systems. Two important kinds are efficiency metrics and effectiveness metrics. Efficiency metrics are used to compare output with input. Metrics of this type include the thermodynamic efficiency of a heat engine, which is shaft power divided by fuel power, and the mechanical efficiency of a fan, which is aerodynamic power divided by shaft power. Efficiency metrics are not applicable to the development of a whole-building energy consumption benchmark, because it is difficult to define the output of a building and because it is difficult to quantify the output even if it can be defined. The output is not the energy consumption. It might be the comfort provided to the occupants, or it might be the work output of the occupants.

Effectiveness metrics involve a comparison with a benchmark, and are therefore relevant to the development of a whole-building energy consumption benchmark. An example of an effectiveness metric is heat exchanger effectiveness, which is defined as the actual heat transfer divided by the maximum possible heat transfer [9]. Engineering effectiveness metrics do not always use the theoretically best performance as a benchmark. For example, ventilation effectiveness is often defined as the measured age accumulation of air in a building divided by the age accumulation for a perfect-mixing system, which has twice the age accumulation of the most effective system (a plug-flow system) [10]. The key difference between efficiency and effectiveness is that efficiency is a comparison of input and output while effectiveness is a comparison of a key system variable (not necessarily the output) with a well-defined, calculable, and often theoretically ideal benchmark.

The most common performance metric for whole-building energy consumption is EUI. This metric is not particularly useful by itself because many other factors besides plan area affect energy consumption. This fact is evident from the range of values in the first table of [8]. In this set of buildings, which are all laboratory buildings located on the UC Berkeley campus (and therefore exposed to the same weather), S.D. is 70% of the mean. This illustrates that EUI is not a discriminating metric. Part of the reason that there is a large variation in this metric for this set of buildings is because some of the buildings are not air-conditioned, because lighting efficiency varies, because plug and process loads vary, and because the design of the air distribution systems vary.

In this section, a benchmark that compensates for weather differences, design differences, and usage differences is described. The objective is for the benchmark to be the energy consumption of an "ideal" building that consumes the minimum amount of energy required to achieve the same indoor temperature, humidity, lighting, and ventilation conditions as the actual building. The energy consumption benchmark derived from the "ideal" building is determined using mathematical models, so the method is called model-based benchmarking. Complications that arise from defining and computing the theoretical minimum are addressed by using simplifying assumptions. The result is a benchmark that represents a highly effective use of energy.

Model-based benchmarking has two parts. First, the benchmark is computed and the actual energy consumption is compared with the benchmark. The ratio of the benchmark to the actual consumption is an effectiveness metric analogous with other engineering effectiveness metrics such as heat exchanger effectiveness. The second part of model-based benchmarking involves a comparison of the effectiveness of a particular building with that of a set of buildings, and with the past performance of that same building. This part of model-based benchmarking involves statistical comparisons. Since the benchmarking calculations compensate for functional requirements, it is possible to use model-based benchmarking to compare the performance of buildings with dissimilar features and functional requirements.

### *2.1. Defining the benchmark*

The performance of the ideal building is more difficult to quantify than the performance of the ideal heat exchanger. Therefore, the ideal building is selected with features that make the calculation of the minimum energy consumption a tractable problem with some simplifying assumptions.

The following is a list of the important features and assumptions.

#### *2.1.1. No energy storage*

This definition also implies that the structure of the building is not used for thermal storage. Defining the benchmark building as having no energy storage significantly simplifies the calculations. Most laboratory facilities have little or no energy storage. Since the benchmark is defined as having no storage, laboratory buildings with energy storage may, in theory, use less energy than the benchmark.

#### *2.1.2. No conduction or transmission*

The benchmark building has perfect insulation and allows no transmission of solar energy into the building. This assumption also significantly reduces the complexity of computing the benchmark. Laboratory energy consumption is dominated by ventilation rather than by heat transfer through the shell, so there would be little benefit to including conduction and transmission in the calculations. If this benchmark were used to analyze the energy consumption of non-laboratory buildings, the results would indicate that the non-laboratory buildings were less effective at using energy because heat transfer through the shell is a larger component of the load in non-laboratory buildings.

#### *2.1.3. Maximum use of daylight*

The lighting power benchmark is zero between sunrise and sunset. When the building is in use between sunset and sunrise, the benchmark is the average specific lighting power reported in [8], which is 0.04 $W/m^2$.

#### *2.1.4. Empirical benchmark for plug and process loads*

For the laboratory space, the default specific plug and process power is the average value reported in [8], which is 0.11 $W/m^2$. For the non-laboratory space, the default specific plug and process power is 140 W per person, which is derived from power requirements of office computers.

#### *2.1.5. Fan power*

In theory, the minimum fan power required to move air is zero because it could be moved at an arbitrarily low static pressure (i.e. with arbitrarily low resistance). This is not a reasonable benchmark because ducts must have a finite size. Therefore, the specific fan power specified by the California energy code (title 24), for constant volume systems (1700 $W/(m^3/s)$) is used as the benchmark for fan power.

#### *2.1.6. Transportation systems*

Efficient elevator systems use counterweights and energy recovery so that they do not contribute substantially to the total energy consumption of a building. Consequently, the benchmark for transportation systems is zero power. This benchmark will penalize buildings with hydraulic elevators more than buildings with counterweighted elevators.

#### *2.1.7. Efficient air distribution*

VAV laboratories will use considerably less energy than constant volume laboratories as long as the design air-change

Table 1
Inputs for the benchmark

| No. | Required inputs | Inputs with defaults |
|---|---|---|
| 1 | Plan area of lab space | Lab air-change rate (6 $h^{-1}$) |
| 2 | Plan area of non-lab space | Specific ventilation rate for non-lab space (0.0094 ($m^3$/s) per person) |
| 3 | Linear feet of fume hoods | Space temperature (22.2°C) |
| 4 | Fraction of lab space that is air-conditioned | Space relative humidity (50%) |
| 5 | Fraction of non-lab space that is air-conditioned | Schedule of operation (24/7 for lab; 7 a.m.–9 p.m., 7 days for non-lab) |
| 6 | Location | Number of lab occupants (1/(71 $m^2$)) |
| 7 | Electrical consumption | Number of non-lab occupants (1/(71 $m^2$)) |
| 8 | Fuel consumption | Specific fan power (1700 W/($m^3$/s)) |
| 9 | Time duration | Specific pump flow rate ($2.9 \times 10^{-8}$ ($m^3$/s)/W) |
| 10 | | Specific pump power (99,868 W/($m^3$/s)) |
| 11 | | Plug and process load for lab space (0.11 W/$m^2$) |
| 12 | | Plug and process load for non-lab space (140 W per person) |

rate is sufficiently low and as long as fume hoods are closed when not in use. According to Black [11], sashes of fume hoods on the UC Berkeley campus are generally found to be in the closed position. This indicates that the need for occupants to be working at the hoods is intermittent, and that selecting the benchmark as constantly closed would only penalize facilities where fume hoods were left open unnecessarily and persistently. With sashes in the closed position, the ventilation rate will usually be dependent on the air-change requirement and not on the fume hood exhaust flow rate.

### 2.1.8. Control of waste heat

It is assumed that the ideal building can use waste heat when heat is needed, and that it can reject waste heat when it is not needed. For the laboratory space, the benchmark is based on controlling heat from lighting and plug and process loads. For the non-laboratory space, the benchmark is based on controlling heat from lighting. For equipment, this could be achieved by locating the equipment in a ventilated cabinet, which was exhausted when heat was not needed, but which was recycled when heating was required.

## 2.2. Computing the benchmark

It is possible to compute the energy consumption of the benchmark from first principles with relatively little information about the building.

### 2.2.1. Inputs

The inputs for the benchmarking calculations are shown in Table 1. The required inputs have no defaults; the user must provide these. There are 12 other inputs with defaults that may be changed by the user. The defaults are shown in parentheses.

The default for the design air-change rate is derived from [12]. The default for the schedule is derived from the operation of labs on the UC Berkeley campus. The defaults for specific pump flow rate, specific pump power, and average plug and process load power for the lab is derived from measurements made by Huizenga et al., [8]. The default for the number of occupants is derived from the CBECS database [3]. The default for the plug and process power for non-lab space is based on one computer per person. According to Brown [13], the power consumption of a computer, monitor, and laser printer operating in idle mode are 56, 60, and 24 W, respectively.

### 2.2.2. Calculations

Table 2 shows the initial calculations and hourly variables that are calculated. Details regarding these calculations are included in Appendix A.

### 2.2.3. Outputs

After the hourly power calculations are completed, the results are accumulated for the time periods of interest. Two performance metrics are computed. They are the electrical

Table 2
Calculated constants and variables

| No. | Initial calculations | Properties calculated hourly | Load-related calculations |
|---|---|---|---|
| 1 | Indoor pressure | Outdoor humidity ratio | Minimum outdoor air flow rate |
| 2 | Indoor vapor pressure | Outdoor specific enthalpy | Maximum outdoor air flow rate |
| 3 | Indoor humidity ratio | Outdoor air density | Cooling loads (lab and non-lab) |
| 4 | Indoor enthalpy | System status (on or off) | Fan power (lab and non-lab) |
| 5 | Indoor density | | Pump power (lab and non-lab) |
| 6 | Fume hood flow rate | | Heating load (lab and non-lab) |
| 7 | Exhaust flow rate of lab | | |
| 8 | Occupant loads | | |

consumption effectiveness and the fuel consumption effectiveness. The electrical consumption effectiveness, denoted as $\varepsilon_e$, is defined as the electrical consumption of the benchmark divided by the actual electrical consumption for the same time period. Similarly, the fuel consumption effectiveness, denoted as $\varepsilon_f$, is defined as the fuel consumption of the benchmark divided by the actual fuel consumption for the same time period. Consequently, higher values are better than lower values, and the values should range between 0 and 1.

### 2.3. Statistical comparison

After the electrical energy and fuel consumption effectiveness metrics have been computed for a particular building they are compared with the metrics for a set of buildings. The mean and variance of each metric in the comparison set is computed so that the user can determine if the performance of the test building is above or below the norm, and by how much. If the performance is significantly poorer than average, then the protocols described in [8] could be used to investigate the cause.

### 2.4. Benchmarking tool and database

#### 2.4.1. Description

In order to compare the energy consumption of one or more laboratory buildings with that of others, a database has been created. The database contains tables for the building statistics provided by the users as well as tables for weather data. Forms for entering data, initiating calculations, and displaying the results have been created so that the database is easy to use.

The building statistics include the data necessary for calculating the benchmarks as well as data that will be useful for filtering. These additional inputs include performance metrics that may have been determined from a more detailed audit of the building using the protocols described in [8], as well as design information that is relevant to energy consumption analysis (e.g. VAV or constant volume air distribution). A detailed description of the benchmarking tool and database can be found in [14].

#### 2.4.2. Features

The tool has been designed to handle time intervals of arbitrary duration. The start date for all intervals but the first is the end date for the previous interval. The tool has also been designed to handle multiple meters so that data from electrical bills can be entered directly into the database.

Results are displayed with a set of graphs. Two of the graphs are used to show how the electrical and fuel consumption effectiveness values of a single building compare with a population of buildings. The computed effectiveness is shown as a vertical line on a smooth distribution that is derived from the statistics of the population. A third graph shows the scatter plot of the electrical and fuel consumption effectiveness of the targeted building and the population of buildings with which it is being compared. The fourth graph is a time series of the electrical consumption effectiveness of the target building for the set of time intervals that the effectiveness was computed. This time series can be used to establish a baseline for the building, and can also be used to detect unusual performance.

The benchmarking calculations are also transformed into metrics that are familiar to energy engineers for each of the subsystems in the building. For example, the energy calculations for the lighting power are transformed into a metric such as average watts per unit of plan area. The benchmark is also transformed into a whole-building average power density (e.g. average total watts per unit of plan area). This metric, combined with a target for the effectiveness could be used as a design-intent target.

## 3. Results of application of model-based benchmarking

### 3.1. Statistical analysis methods

We used a set of parametric and non-parametric statistical methods to analyze the performance of the model-based benchmarking method and compare it with existing benchmarking methods. All of the non-parametric statistics used here are described in Siegel and Castellan [15]. The parametric statistics used here are described in all introductory statistics texts.

We used the Pearson product-moment correlation coefficient and the Spearman rank-order correlation coefficient to test for association between actual and predicted energy consumption. If the differences between the actual consumption and the consumption predicted by the models were normally distributed, then the square of the Pearson coefficient is the percentage of the variance explained by the model. As noted by Sharp [1] and others, the residuals for building energy-use data are frequently not normally distributed. The Spearman coefficient is a non-parametric measure of association that has a similar interpretation as the Pearson coefficient. It can be used to measure association when the underlying distribution is not known.

We used the robust rank-order test to compare the effectiveness of buildings with and without mechanical cooling. The robust rank-order test is a non-parametric equivalent to the two-sample *t*-test, which is the standard parametric test for a difference between means.

### 3.2. Effect of cooling equipment on effectiveness

Due to strict energy requirements for state buildings in California, some of the laboratory buildings on the UC Berkeley campus are not mechanically cooled. This fact allows us to compare the effect of air-conditioning on energy consumption effectiveness.

Of the 19 laboratory buildings studied, one had no mechanical cooling, eight had negligible cooling capacity,

Table 3
Effectiveness of cooled and uncooled buildings

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | *U*-test | *P* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Little cooling | 0.16 | 0.26 | 0.54 | 0.61 | 0.71 | 0.73 | 0.75 | 0.78 | 0.82 | 2.46 | 2.8% |
| 100% cooling | 0.20 | 0.24 | 0.27 | 0.38 | 0.39 | – | – | – | – | | |

and five were completely cooled by vapor compression. The effectiveness of these 14 buildings is shown in Table 3. The mean and median of the electrical consumption effectiveness for the uncooled buildings were 0.60 and 0.71, respectively. The mean and median of the electrical consumption effectiveness for the cooled buildings were 0.29 and 0.27, respectively. Since the benchmark compensates for the functional requirement of cooling, the effectiveness of the cooled buildings should be equal to the effectiveness of the uncooled buildings if the cooling system were as efficient as the other systems in the building. The robust rank-order test [15] was used to determine whether or not the difference between the median values of the two sets is significant. The probability of observing a difference this large or larger with this sign by chance is 2.8%. Therefore the difference is statistically significant. This does not mean that mechanical cooling caused the difference, but it does provide evidence for a causal relationship.

### 3.3. Performance comparison

Comparing one benchmarking method with another is complicated by the fact that the "true" energy-use effectiveness cannot be measured. However, we can measure how well different benchmarking methods compensate for features or functional requirements that affect energy use. This can be accomplished by comparing the degree of association (correlation) between the "model" associated with each method and the actual energy consumption.

In this section, the model-based benchmarking method described in this report is compared with benchmarking based on the EUI metric and Sharp's method using buildings located on the UC Berkeley campus. All of these buildings nominally have the same occupant density, computer density, and schedule, and all of them are owner-occupied. None of the laboratories have economizers; all are 100% outside air systems. Therefore, Sharp's method differs from the EUI method only by compensating for whether or not the building has a chiller.

For each method, two different correlation coefficients were computed. They were the Pearson product-moment correlation coefficient and the Spearman rank-order correlation coefficient.

Table 4 shows the square of the two coefficients for each of the three methods when applied to 19 laboratory buildings on the UC Berkeley campus. The Siegel–Tukey test was used to test whether or not the size of the residuals was significantly different from one method to another. This test indicates that the difference between Sharp's method and the model-based method is not statistically significant.

Inspection of the residuals shows that one of the 19 buildings is an outlier. This laboratory contains a class 100 cleanroom, so the filtration requirements are significantly different. The benchmarking calculations used here are designed for typical filtration requirements, so the cleanroom uses significantly more energy than the benchmark. This problem could be eliminated if filtration requirements were included as an input to the benchmarking calculations. When this building is eliminated from the data set, then the correlation coefficients are as shown in Table 5. Again, the Siegel–Tukey test indicates that the differences are not significant.

Table 6 shows the two coefficients for each of the three methods when applied to 19 laboratory buildings and 9 non-laboratory buildings on the UC Berkeley campus. This table illustrates that model-based benchmarking is better at comparing the performance of dissimilar building types than are empirical methods of benchmarking. In this case the difference between the model-based method and Sharp's

Table 4
Comparison of methods

| | Pearson coefficient, $R^2$ (%) | Spearman coefficient, $R_s^2$ (%) |
|---|---|---|
| Model-based method | 41 | 55 |
| Sharp's method | 46 | 63 |
| EUI method | 40 | 52 |

Table 5
Comparison with outlier removed

| | Pearson coefficient, $R^2$ (%) | Spearman coefficient, $R_s^2$ (%) |
|---|---|---|
| Model-based method | 73 | 53 |
| Sharp's method | 54 | 58 |
| EUI method | 51 | 45 |

Table 6
Comparison with dissimilar building types

| | Pearson coefficient, $R^2$ (%) | Spearman coefficient, $R_s^2$ (%) |
|---|---|---|
| Model-based method | 43 | 41 |
| Sharp's method | 16 | 19 |
| EUI method | 22 | 18 |

method is statistically significant. The single-sided probability of observing a larger difference by chance is just 3.2%. However, the difference between the model-based method and the EUI method is still not statistically significant at the 95% level of confidence. The single-sided probability of observing a larger difference by chance is 6.4%.

## 4. Discussion and conclusions

The benchmarking method described in this paper will penalize buildings that use inefficient systems for energy-consuming functional requirements. For example, buildings with the following design subsystems or features will be penalized:

1. oversized systems if part-load efficiencies are poor;
2. constant volume systems;
3. any systems that use reheat;
4. hydraulic elevators;
5. inefficient lighting systems;
6. inefficient fans and air distribution systems.

   Additionally, the following operational factors will be penalized:
7. fume hoods left open;
8. poor controller tuning, if it induces sequential heating and cooling;
9. faulty control logic, if it induces simultaneous heating and cooling.

The benchmarking method will also penalize buildings in which fume hoods must be used (i.e. opened) continually. Based on the experience of UC Berkeley facilities staff and the fact that open fume hoods are a safety hazard, it is expected that this will be a rare requirement. The benchmarking method will also penalize buildings that do not have laboratory space or that have very little laboratory space because conduction and transmission heat transfer is a larger fraction of the heating and cooling load in those buildings. This will only be a problem for the case where a small laboratory is connected to a large non-laboratory building. The magnitude of these ‘‘unfair’’ penalties is difficult to quantify and it will be different for each case.

The analysis described in the Section 3 indicates that air-conditioned buildings may use energy less effectively than non-air-conditioned buildings even after the functional requirement of cooling has been considered. This result may indicate that typical mechanical cooling designs are inefficient relative to the efficiency of other systems such as lighting systems, or that the benchmarking method unfairly penalizes mechanical cooling. It is possible that simplifying assumptions used to compute the benchmark, which include the use of component efficiencies, may unfairly penalize mechanical cooling and ventilation relative to lighting or plug and process power. More research is needed to determine the cause of the finding, but it is consistent with the perception that HVAC systems in modern laboratories are significantly oversized, which causes inefficiency.

When applying the model-based benchmarking method to non-lab buildings in addition to lab buildings, the model-based approach was clearly better than the two alternatives. This fact demonstrates one of the advantages of model-based benchmarking over empirical methods. A single model can be used to benchmark and compare a wide variety of buildings. It should be noted, however, that although the correlation between energy use and predicted energy use was much higher using the model-based method than either of the two empirical methods, it was much lower than when applied to just laboratory buildings. This could be due to a large variation in efficiency when considering a larger, more diverse population of buildings, or it could be that the models are less accurate when applied to non-lab buildings. Future research is needed to determine the efficacy of using the existing model-based benchmarking method for analyzing the energy performance of non-lab buildings.

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## Appendix A. Energy consumption calculations

This appendix contains a list of the calculation procedures for computing the benchmarks. Unit conversions are not shown here.

Fig. 1 shows the flow rates used in the calculations. The first letter of the subscripts refers to the space that the air is coming from. The second letter refers to the space that the air is going to.

### *A.1. Precalculations*

#### *A.1.1. Lab area*

$$A_{\mathrm{Lab}} = \frac{1}{2}(A'_{\mathrm{Lab}} + 1489 + 50L) \qquad \text{(A.1)}$$

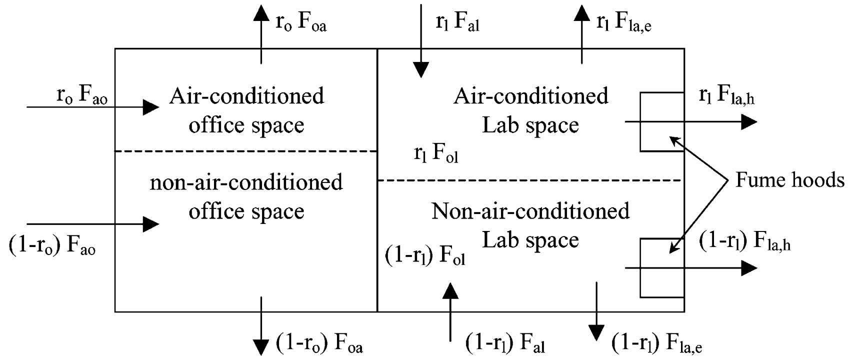

Fig. 1. Schematic diagram of the laboratory building.

*A.1.2. Space pressure*

Space pressure is computed based on the NACA standard atmosphere. Below an altitude of 10,769 m (35,332 ft) above sea level, the pressure of the standard atmosphere is given by the following equation [16]:

$$P = P_0\left(1 - \frac{a}{T_0}Z\right)^{g/aR_a} \tag{A.2}$$

Minimum outdoor air volume flow rate for office

$$\underline{Q}_{ao} = \underline{q}_{ao}N_o \tag{A.3}$$

Maximum outdoor air volume office

$$\overline{Q}_{ao} = \overline{q}_{ao}A_o \tag{A.4}$$

*A.1.3. Saturated vapor pressure of conditioned air*

According to ASHRAE [17], the saturated vapor pressure is given by the following empirical relation when the air temperature is less than 0°C:

$$p_{ws,c} = \exp\left(\frac{C_1}{T_c} + C_2 + C_3T_c + C_4T_c^2 + C_5T_c^3 + C_6T_c^4 + C_7\ln(T_c)\right) \tag{A.5}$$

When the temperature is greater than 0°C, the saturated vapor pressure is given by the following empirical relation:

$$p_{ws,c} = \exp\left(\frac{C_8}{T_c} + C_9 + C_{10}T_c + C_{11}T_c^2 + C_{12}T_c^3 + C_{13}\ln(T_c)\right) \tag{A.6}$$

The values for the constants are given in nomenclature. Using the constants in the nomenclature requires that the temperature in Eqs. (A.5) and (A.6) is in K, and results in Pascal pressure units.

*A.1.4. Vapor pressure of conditioned air*

The vapor pressure is equal to the product of the relative humidity and the saturated vapor pressure.

$$p_{w,c} = p_{ws,c}\phi_c \tag{A.7}$$

*A.1.5. Humidity mass ratio of conditioned air*

The humidity mass ratio is the ratio of the mass of water vapor in the air to the mass of dry air in the air. It is computed based on the molecular masses of dry air and water, the pressure, and the vapor pressure as follows:

$$W_c = \frac{m_w}{m_a}\frac{p_{w,c}}{P - p_{w,c}} \tag{A.8}$$

*A.1.6. Gas constant of conditioned air*

The gas constant of the air is the mass-weighted average of the gas constants of dry air and water vapor. It is computed as follows:

$$R_c = \frac{R_a + R_wW_c}{1 + W_c} \tag{A.9}$$

*A.1.7. Specific enthalpy of conditioned air*

The specific enthalpy of air is computed as follows:

$$h_c = \frac{T_c + W_c(2501 + 1.805T_c)}{1 + W_c} \tag{A.10}$$

Note that Eq. (A.10) is different than that published in [17], because Eq. (A.10) is the energy per unit mass of moist air rather than per unit mass of dry air.

*A.1.8. Density of conditioned air*

The density is calculated as follows:

$$\rho_c = \frac{P}{R_cT_c} \tag{A.11}$$

*A.1.9. Fume hood mass flow rate*

The total mass flow rate through the fume hoods is computed as follows:

$$F_{la,h} = \rho_cLVd \tag{A.12}$$

*A.1.10. Total laboratory exhaust air mass flow rate*

The total mass flow rate of air exhausted from the laboratory through fume hoods and space exhaust is computed as follows:

$$M = \rho_c A_l c \quad (A.13)$$

$$F_{la} = \max(F_{la,h}, M\Omega) \quad (A.14)$$

Eq. (A.13) indicates that the total exhaust flow rate may either be determined by the design air-change rate or by the number of fume hoods.

### A.1.11. Laboratory supply air mass flow rate

The supply air mass flow rate to the laboratory is computed as follows:

$$F_{al} = F_{la} \quad (A.15)$$

### A.1.12. Laboratory occupant load

The laboratory occupant load is computed as follows:

$$H_{occ,l} = h_{occ} N_l \quad (A.16)$$

### A.1.13. Office occupant load

The office occupant load is computed by substituting the number of office occupants for the number of laboratory occupants in Eq. (A.15).

### A.1.14. Lab lighting load

The lab lighting load is computed as follows:

$$P_{l,l} = \lambda A_l \quad (A.17)$$

### A.1.15. Office lighting load

The office lighting load is computed by substituting the gross plan area of the office for the gross plan area of the lab in Eq. (A.16).

## A.2. Hourly calculations

### A.2.1. Saturated vapor pressure of outdoor air

The saturated vapor pressure of outdoor air is computed using Eq. (A.5) or (A.6) with the outdoor air temperature substituted for the conditioned air temperature.

### A.2.2. Vapor pressure of outdoor air

The vapor pressure of outdoor air is computed using Eq. (A.7) with the outdoor air temperature substituted for the conditioned air temperature, and the relative humidity of the outdoor air substituted for the relative humidity of the conditioned air.

### A.2.3. Humidity mass ratio of outdoor air

The humidity mass ratio of outdoor air is computed using Eq. (A.8) with the outdoor air vapor pressure substituted for the conditioned air vapor pressure.

### A.2.4. Gas constant of outdoor air

The gas constant of outdoor air is computed using Eq. (A.9) with the outdoor air humidity mass ratio substituted for the conditioned air humidity mass ratio.

### A.2.5. Specific enthalpy of outdoor air

The specific enthalpy of outdoor air is computed using Eq. (A.10) with the outdoor air temperature substituted for the conditioned air temperature, and the humidity mass ratio of the outdoor air substituted for the humidity mass ratio of the conditioned air.

### A.2.6. Density of outdoor air

The density of outdoor air is computed using Eq. (A.11) with the outdoor air temperature substituted for the conditioned air temperature, and the gas constant of the outdoor air substituted for the gas constant of the conditioned air.

### A.2.7. Is system on?

If the schedule indicates that the system is on, then $O = 1$, otherwise $O = 0$.

### A.2.8. Minimum outdoor air mass flow rate for the office

The minimum outdoor air mass flow rate for the office is the maximum of the flow rate required for ventilation and the makeup airflow rate for the lab.

$$\underline{F}_{ao} = \rho_a \underline{Q}_{ao} \quad (A.18)$$

### A.2.9. Maximum outdoor air mass flow rate for the office

The maximum outdoor air mass flow rate for the office is computed as follows:

$$\overline{F}_{ao} = \rho_a \overline{Q}_{ao} \quad (A.19)$$

### A.2.10. Lighting energy use

Following equations could calculate sunrise and sunset hour for each month. Since we assume that there is no difference between sunset or sunrise times among the days in 1 month, we only calculate 12 sunset and 12 sunrise times in 1 year (Table 7).

$$\begin{aligned} H_{sunrise} = {} & \tfrac{1}{60}[720 - 4 \times \arccos(-\tan \mathrm{LAT} \times \tan \delta) \\ & - \mathrm{ET} - 4(\mathrm{LSM} - \mathrm{LON})] \end{aligned} \quad (A.20)$$

$$\begin{aligned} H_{sunset} = {} & \tfrac{1}{60}[720 + 4 \times \arccos(-\tan \mathrm{LAT} \times \tan \delta) \\ & - \mathrm{ET} - 4(\mathrm{LSM} - \mathrm{LON})] \end{aligned} \quad (A.21)$$

### A.2.11. Compute the thermal load on the office space

The following calculations are made assuming that the entire office space is air-conditioned. Compensation for partially air-conditioned office spaces is made later.

The office load calculation is based on the assumption that fan power does not contribute to the load. The logic for computing the load when there is an economizer and control of waste heat from lights is as follows. If $h_c - h_a \leq 0$, then

$$F_{ao} = \underline{F}_{ao} \quad (A.22)$$

$$H_o = F_{ao}(h_c - h_a) - H_{occ,o} - P_{pp,o} \quad (A.23)$$

Table 7
Monthly coefficients for sunrise and sunset calculations

| | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | January | February | March | April | May | June | July | August | September | October | November | December |
| ET (min) | −11.2 | −13.9 | −7.5 | 1.1 | 3.3 | −1.4 | −6.2 | −2.4 | 7.5 | 15.4 | 13.8 | 1.6 |
| $\delta$ (degree of arc) | −20.0 | −10.8 | 0.0 | 11.6 | 20.0 | 23.45 | 20.6 | 12.3 | 0.0 | −10.5 | −19.8 | −23.45 |

Otherwise, compute the load with the maximum flow rate and no lighting load as follows:

$$H_{o,1} = \overline{F}_{ao}(h_c - h_a) - H_{occ,o} - P_{pp,o} \tag{A.24}$$

If $H_{o,1} \leq 0$, then

$$F_{ao} = \overline{F}_{ao} \tag{A.25}$$

$$H_o = H_{o,1} \tag{A.26}$$

Otherwise, compute the load with the minimum outdoor airflow rate and the maximum lighting load as follows:

$$H_{o,2} = \underline{F}_{ao}(h_c - h_a) - H_{occ,o} - P_{pp,o} - P_{l,o} \tag{A.27}$$

If $H_{o,2} \leq 0$, then $H_o = 0$. The outdoor airflow rate under this condition is computed as follows. Compute the load assuming a minimum flow rate and no lighting load as follows:

$$H_{o,3} = \underline{F}_{ao}(h_c - h_a) - H_{occ,o} - P_{pp,o} \tag{A.28}$$

If $H_{o,3} \geq 0$, then

$$F_{ao} = \underline{F}_{ao} \tag{A.29}$$

Otherwise

$$F_{ao} = \frac{H_{occ,o} + P_{pp,o}}{h_c - h_a} \tag{A.30}$$

If $H_{o,2} > 0$, then $F_{ao} = \underline{F}_{ao}$ and $H_o = H_{o,2}$. If the system is off, then the office load is 0.

### A.2.12. Compute office cooling load

If the office load is negative, then the cooling load equals the magnitude of the office load. Otherwise it equals 0. This is computed as follows:

$$H_{c,o} = |\min(0, r_o H_o)| \tag{A.31}$$

### A.2.13. Compute the office heating load

The office heating load is computed as follows:

$$H_{h,o} = \max(0, H_o) \tag{A.32}$$

### A.2.14. Compute office fan power

The office fan power is computed as follows:

$$P_{f,o} = \frac{F_{ao}\pi_f}{\rho_a} \tag{A.33}$$

### A.2.15. Compute office pump power

The office pump power is computed as follows:

$$P_{p,o} = \max(H_{c,o}, H_{h,o}) f_p \pi_p \tag{A.34}$$

### A.2.16. Compute office electrical power

The electrical power is computed as follows:

$$P_o = \frac{H_{c,o}}{\mathrm{COP}} + P_{pp,o} + P_{l,o} + P_{f,o} + P_{p,o} \tag{A.35}$$

### A.2.17. Compute thermal load of the lab space

The following calculations are made assuming that the entire lab space is air-conditioned. Compensation for partially air-conditioned lab spaces is made later.

The lab load calculation is based on the assumptions that fan power does not contribute to the load, and that waste heat from lights, and plug and process loads is used for heating but rejected when cooling. The thermal load with waste heat from lights and plug and process power is as follows:

$$H_{l,h} = F_{la}(h_c - h_a) - H_{occ,l} - P_{l,l} - P_{pp,l} \tag{A.36}$$

The logic for computing the lab load to effectively use waste heat is as follows. First, compute the load according to Eq. (A.38). Then compute the load assuming that the heat from lights and equipment is exhausted.

$$H_{l,e} = F_{la}(h_c - h_a) - H_{occ,l} \tag{A.37}$$

The lab load with effective use of waste heat is the following. If the sign of $H_{l,h}$ is not the same as the sign of $H_{l,e}$ then the load is 0. Otherwise, the load is equal to the value of $H_{l,h}$ or $H_{l,e}$ with the smallest magnitude.

### A.2.18. Compute the lab cooling load

This calculation is similar to the cooling load calculation for the office.

$$H_{c,l} = |\min(0, r_l H_l)| \tag{A.38}$$

### A.2.19. Compute the heating load for the lab

This calculation is similar to the heating load calculation for the office.

$$H_{h,l} = \max(0, H_l) \tag{A.39}$$

### A.2.20. Compute the lab fan power

This calculation is similar to the fan power calculation for the office.

$$P_{f,l} = \frac{F_{la}\pi_f}{\rho_a} \tag{A.40}$$

### *A.2.21. Compute the lab pump power*

This calculation is similar to the pump power calculation for the office.

$$P_{\mathrm{p,l}} = \max(H_{\mathrm{c,l}}, H_{\mathrm{h,l}}) f_{\mathrm{p}} \pi_{\mathrm{p}} \qquad \text{(A.41)}$$

### *A.2.22. Compute the total electrical power for the lab*

This calculation is similar to the electrical load calculation for the office.

$$P_{\mathrm{l}} = \frac{H_{\mathrm{c,l}}}{\mathrm{COP}} + P_{\mathrm{pp,l}} + P_{\mathrm{l,l}} + P_{\mathrm{f,l}} + P_{\mathrm{p,l}} \qquad \text{(A.42)}$$

### *A.2.23. Compute the electrical consumption benchmark*

The electrical consumption benchmark is the sum of the electrical loads times the time interval corresponding to each load (1 h).

### *A.2.24. Compute the fuel consumption benchmark*

The fuel consumption is the sum of the heating loads times the time interval corresponding to each load (1 h).

### *A.2.25. Compute the electrical consumption effectiveness*

The electrical consumption effectiveness is the electrical consumption benchmark divided by the actual electrical consumption.

### *A.2.26. Compute the fuel consumption effectiveness*

The fuel consumption effectiveness is the fuel consumption benchmark divided by the actual fuel consumption.

## References

[1] T. Sharp, Energy benchmarking in commercial office buildings, Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency in Buildings 4 (1996) 321–329.

[2] A.B. Birtles, Energy efficiency of buildings: simple appraisal method, Building Services Engineering Research and Technology 18 (2) (1997) 109–114.

[3] US Department of Energy, Commercial Building Characteristics 1995, Washington, DC, 1995.

[4] T.W. Hicks, D.W. Clough, The Energy Star® building label: building performance through benchmarking and recognition, Proceedings of the ACEEE 1996 Summer Study on Energy Efficiency in Buildings 4 (1998) 205–210.

[5] T.A. Reddy, N.F. Saman, D.E. Claridge, J.S. Haberl, W.D. Turner, A.T. Chalifoux, Baselining methodology for facility-level monthly energy use. 1. Theoretical aspects, ASHRAE Transactions 103 (2) (1997) 336–347.

[6] R. Sonderegger, Baseline model for utility bill analysis using both weather and non-weather-related variables, ASHRAE Transactions 104 (2) (1998) 859–870.

[7] E. Mills, G. Bell, D. Sartor, A. Chen, D. Avery, M. Siminovitch, S. Greenberg, G. Marton, A. de Almeida, L.E. Lock, Energy efficiency in California laboratory-type facilities, LBNL Report No. LBNL-39061, 1996.

[8] C. Huizenga, W. Van Liere, F. Bauman, Development of low-cost monitoring protocols for evaluating energy use in Laboratory Buildings Center for Environmental Design Research, UC Berkeley, Report No. CEDR-02-98, 1998.

[9] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, 4th Edition, Wiley, New York, 1996, pp. 599–600.

[10] C.C. Federspiel, Air-change effectiveness: theory and calculation methods, Indoor Air 9 (1999) 47–56.

[11] P. Black, Personal communication, Department of Facilities Management, University of California, Berkeley, 1998.

[12] G.C. Bell, D. Sartor, E. Mills, A design guide for energy-efficient research laboratories, CIEE, LBNL Report No. 777, 1998.

[13] W.K. Brown, Laboratory design loads — what we know, do not know, and need to know, ASHRAE Transactions 102 (1) (1996) 711–722.

[14] C.C. Federspiel, Q. Zhang, E. Arens, Laboratory Field Studies/ Performance Feedback, CEDR-05-99, 1999.

[15] S. Siegel, N.J. Castellan, Nonparametric Statistics for the Behavioral Sciences, McGraw-Hill, New York, 1988.

[16] R.L. List, Smithsonian meteorological tables, Smithsonian Institution, Washington, DC, 1971, pp. 265–266.

[17] ASHRAE, Chapter 6: Psychrometrics, ASHRAE Fundamentals Handbook, ASHRAE, Atlanta, 1997.