10396

Proc. CIBSE A: Building Serv. Eng. Res. Technol. 18(2) 109–114 (1997) Printed in Great Britain B424

Summary A new method is proposed to appraise the relative energy efficiency of designs for new or refurbished buildings. Based on the development of an energy efficiency index, it is simple to use and understand, and requires no particular expertise. The method offers a straightforward determination of likely energy performance. It addresses the total power rating of plant installed to achieve specified indoor environmental conditions, and the monitoring and control equipment which manages that capacity. Potential applications include appraising performance against established or proposed standards of good practice, testing compliance with energy performance specifications and ranking alternative design choices, either overall or at various stages of design. Inverted, the method offers targets for plant sizing. The strategy offers services designers a more authoritative argument for plant room space early in the design. Despite its simplicity the method promises good field performance. Limited data from six fully air-conditioned buildings reveal a perhaps surprisingly good correlation between the energy efficiency index and observed performance. Once performance data for a wider range of buildings are available, the method can be developed fully for widespread practical application.

Energy efficiency of buildings: Simple appraisal method

A B Birtles BEng PhD CEng FCIBSE and **P Grigg** MInstR
Building Research Establishment, Garston, Watford WD2 7JR, UK

Received 14 October 1996, in final form 16 December 1996

1 Introduction

The building performance concept has great attractions in building codes and regulations and in building labelling and rating schemes. In the former, it allows requirements to be defined in terms of performance goals rather than as a prescription of methods and measures which limit design freedoms and inhibit innovation. In the latter, it allows specifiers to define performance requirements in terms which best suit their needs, and procurers to assess and compare building performance systematically. In either case, however, to be practicable, methods of defining performance must be easy to understand and cheap. Calculations must be straightforward for lay persons as well as experts, so as readily to test compliance with regulations, contract requirements, or other performance claims.

An important dimension of building performance is energy efficiency. Successful labelling and targeting which are simple, easy to understand and cheap have only been achieved for dwellings[1]. No equivalent methods are widely used or known for the service sector (i.e. non-domestic buildings), though a great deal of international effort has been expended in developing suitable tools[2–5]. These projects are described in Reference 6.

It is perhaps obvious that the first requirement of an energy efficient building is that it be fully capable of providing an internal environment complying with health and safety legislation. In most cases there will also be good commercial and contractual reasons for meeting the client's even higher standards of environmental performance The most energy-efficient building is therefore defined here as the one which provides the specified indoor environment for the least use of energy. Depending upon requirements, this could just as easily be defined as the least use of fossil fuels, primary energy or least energy cost etc.

This paper proposes a new and very simple method, an energy efficiency index to appraise the relative energy efficiency of designs for new or refurbished buildings. In principle these may be of any type. The method can therefore be used to compare or rank the energy efficiency of buildings.The method could *not* be used to predict the energy consumption of a building, except perhaps under a standard set of average or typical conditions. It therefore does not address climatic effects or different management practices. However it does take specific account of the provision of plant and systems which facilitate good management and control. Despite its simplicity, the method promises good field performance. Limited data from six fully air-conditioned buildings show a good correlation between the energy efficiency index and achieved performance in use.

2 Method

The new method asserts that the likely energy performance may be determined straightforwardly by the total power rating of plant and equipment installed to achieve specified indoor environmental conditions, and by the equipment provided to monitor, control and thus manage that capacity.

The sizes (power ratings) of chillers, boilers, fans, pumps, etc. required to achieve specified internal climate conditions are ultimately determined by the net effects of building characteristics such as thermal mass, plan form, orientation, glazing ratio, shading, insulation, system type (VAV, fan-coil, etc.), the size of the lighting system and a whole spectrum of energy conservation measures which may have been incorporated. The energy consumed to condition the building then also depends on the operational efficiencies of plant and its equivalent full-load hours run, and on nothing else. All else being equal, one would expect a more energy-efficient building to use plant of a lower installed rating than would a less efficient one. Furthermore, using plant size (among other things) as an indicator of energy efficiency has the important benefit of deterring over-specification of plant for otherwise well designed buildings. This avoids (or reduces) the consequent inefficiencies of perennial part-load operation.

This analysis may seem obvious. However, if valid it offers a very neat way of avoiding consideration of an enormous amount of complicated design detail in assessing the likely energy efficiency of a building. The method is very flexible, particularly as applied to air-conditioned buildings.

Simple formulae may be postulated to relate plant ratings, efficiencies and hours run to an index of energy efficiency. This sounds simplistic, but preliminary calculations with field data show that the method works reasonably well in practice and has enormous potential.

In attempting to develop a new method, the UK Building Research Establishment (BRE) recognised that widespread acceptance and take-up by practitioners, specifiers, etc. would depend on the degree of consensus among these groups about how well it addresses their needs and concerns, both individually and collectively. Therefore beginning acknowledged representatives of all of these groups participated from the start through a progressive series of 12 development workshops. These were supported by background studies at BRE. This approach proved extremely productive.

The formulae below have been endorsed by the development workshops. These included representatives of building owners and operators, property developers, government, professional institutions, contractor bodies, manufacturer bodies, fuel suppliers and researchers.

3 Formulae

A notional figure for (primary) energy E consumed each year per square metre of floor area (kWh m^{-2}y^{-1}) to service a building can be calculated from:

$$E = \Sigma P_i H_i F_i \qquad (1)$$

in which the subscript i is taken across chillers (c), boilers(b), lamps(l), fans(f) and pumps(p). P_c is the power rating of chiller plant per square metre of floor area, H_c the annual equivalent full-load hours run by the chiller plant, and F_c a plant (chiller in this case) management factor which moderates plant efficiency and hours run through appropriate control actions. The other terms in equation 1 correspond to the energy consumed by boilers, lights and circulating fans and pumps respectively in kWh. To aid conceptual consistency here, note that any variations in operational efficiencies of plant items are ultimately manifest in corresponding changes in hours of plant operation required to satisfy operational loads.

In the above H is interpreted as the basic expectation of hours run, i.e. before any special management action is taken. This would be based on historical empirical expectations. Thus, for example, lights in offices are typically switched on at first arrival and not turned off until evening departure, or by the cleaning staff. BRE experience suggests H_l = 2300 h y^{-1} in offices. Similarly, BRE investigations have shown that typically in air-conditioning systems in offices, fans and pumps run for approximately 3700 h y^{-1} and refrigeration plant for about1000 h y^{-1}[7].

In practice, for virtually all air-conditioning systems, the energy consumed by circulating pumps is only a few per cent of that for fans. In most cases the terms for fans and pumps can be simplified to a composite term identified by the subscript fp.

The equation for E is then simplified. The equation is inverted to produce an intuitively better energy efficiency index which increases as energy efficiency rises.The overall index is then expressed in the form

$$I = A/E \qquad (2)$$

The calibration factor A is set to give a target index of 100 at an appropriate level of energy efficiency.

If such an index were to be used in building codes, the philosophy for setting a target for compliance might well be a desire to stretch designers, but not unreasonably, by raising minimum acceptable performance standards. Energy efficiency targets set by individual specifiers, however, are more likely to be more rigorous, possibly reflecting best rather than minimum acceptable practice. Calibration factors can in principle be set so as to allow different types of building (i.e. offices, shops, hotels, etc.) to produce comparable ratings (100 say). These would be proposed targets for equivalent standards of good practice in each case.

4 Management factors

The values assigned to the management factors depend on monitoring and control strategies. They are decided pragmatically by a combination of empirical experience and the collective judgements distilled from the workshops. Plant management systems may be used to monitor and control the internal environment, the energy used by system components, their operational efficiencies, their hours run, etc. All significant automatic control and monitoring measures increase the probability that essential conditions are maintained, hours run are minimised, plant and system efficiencies are maintained, and energy use is reduced. The monitoring strategy is important because a monitoring system may be of a type that can draw attention to 'out of range' operation and therefore increase the likelihood that corrective action will be taken. Such a system considerably reduces the likelihood of energy waste and ought to have better values for F_c, F_b, F_l and F_{fp} than one with no alarm functions. Examples of F_c and F_{fp} are given in Tables 1 and 2. Values for F_b and F_l are currently being developed.

In each table, where more than one measure is specified, the combined management factor is calculated by multiplying together the individual factors. For example, a system in column A which includes free cooling and full ice storage, with maximum provision for monitoring and reporting, would give a value for F_c of $0.9 \times 0.9 = 0.81$. In the tables, the management factors listed in column A, B or C will apply to a particular system depending upon the extent to which monitoring and reporting is provided for in the specification, as follows:

A: Provision as at B below, plus ability to draw attention to 'out of range' values.

B: Provision of energy metering of plant and/or metering of plant hours run, and/or monitoring of internal temperatures in zones.

C: No monitoring provided

5 Calibration data

Most of the building performance data held by BRE and others apply to building designs of the mid 1960s to late 1980s. It is reasonable to expect improvements in standards of practice over time, so current designs ought to be better and future designs ought to be better still. In relation to the performance of the building stock, the question is where to draw the line on standards of good and best practice, and indeed for minimum acceptable standards. Figure 1 shows the notional distribution of energy use among the population of UK office

Table 1 Cooling plant management factors

Footnote	Management operation	Factor A	Factor B	Factor C
1(a)	Free cooling from cooling tower	0.9	0.93	0.95
1(b) 1(c)	Variation of fresh air using economy cycle or mixed mode operation	0.85	0.9	0.95
2	Controls to restrict hours of operation	0.85	0.9	0.95
3	Controls to prevent simultaneous heating and cooling in same zone	0.9	0.93	0.95
4	Efficient control of plant capacity including modular plant	0.9	0.93	0.95
5(a)	Partial ice thermal storage	1.8	1.86	1.9
5(b)	Full ice thermal storage	0.9	0.93	0.95
	Total (i.e. column product) F_c			

Table 2 Distribution system management factors

Footnote	Management operation	Factor A	Factor B	Factor C
1(c)	Free cooling from mixed-mode operation	0.85	0.9	0.95
2	Controls to restrict hours of operation	0.9	0.93	0.95
6	Efficient means of controlling air flow rate	0.75	0.85	0.95
	Total (i.e. column product) F_{fp}			

Footnotes to Tables 1 and 2

1(a) Systems which permit cooling without operation of refrigeration equipment (e.g. strainer cycle, thermosyphon)

1(b) Economy cycle in which the fresh air and recirculated air mix is controlled by dampers

1(c) Mixed mode operation via sufficient openable windows to provide required internal environment from natural ventilation when outdoor conditions permit. This may only apply where perimeter zone exceeds 80% of treated floor area. Credit can only be claimed if interlocks inhibit air conditioning supply in zones with opened windows

2 Control to limit plant operation to occupancy hours; for control of condensation, optimum start/stop, or 'night purge' cooling

3 Controls including an interlock or dead band which precludes simultaneous heating and cooling in the same zone

4 Refrigeration plant capacity controlled on-line by means which reduce input power in proportion to cooling demand and maintain good part load efficiencies (e.g. modular plant with sequence controls; variable speed compressor; etc.)

5(a) Partial ice storage: Chiller may operate continuously, charging store overnight and supplementing during occupancy.

5(b) Full ice storage. Chiller operates only to recharge thermal store overnight/outside occupancy hours.

6 Air flow rate controlled by: Variable motor speed control which efficiently reduces input power at reduced output; Variable pitch fan blades; Variable inlet guide vanes.

buildings. No buildings consume less energy per square metre of floor area than E_{min}, though an upper tail represents a significant population of poor performers with high energy figures.

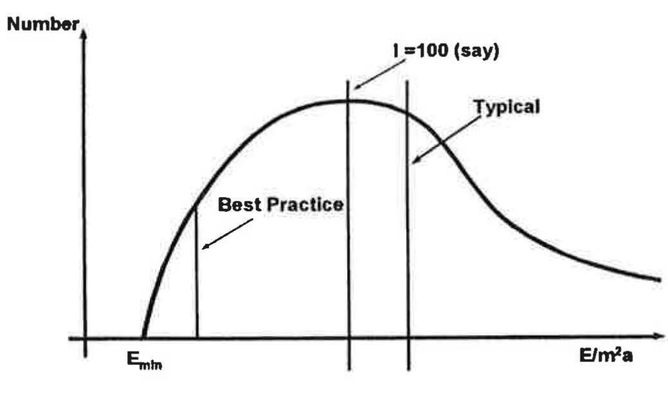

Figure 1 Distribution of energy use in UK offices

Similar data from field studies were used as a basis from *ECON-19, an Energy Consumption Guide for Office Buildings*[8]. Following this publication, it is possible to define two very useful standards using Figure 1. Thus we could define typical performance as the median of this distribution, and 'best practice' as energy consumption below the lower decile.

An advantage of the proposed rating method is that, in future years as knowledge and expertise within the industry evolve, the calibration factor A in equation 2 (and hence the performance required to reach the target 100 for example) can be adjusted very quickly without changing the methodology. The statistics for energy performance within the population of buildings will clearly differ for different countries with their ranges of climates and standards of practice. This means that different calibration factors would be needed to yield a suitable value of $I = 100$ in each case.

6 Practical results

The new methodology has been tested using data on existing designs. Several clear messages have emerged. The new method used as a target will lead designers, even at sketch stage, to think about how much energy the building is going to use. It could well give services designers a more authoritative rationale for and thus an easier route to sizing plant and building management provision. Thus plant room space could be addressed appropriately early in design. By reversing the formula, designers can start at the proposed target and work back to target plant sizings. This would encourage architects and clients to involve services engineers at an earlier stage. The results of these initial investigations are likely to demonstrate options to the architect as to whether changes to the structure are desirable or necessary. Thus improved inter-professional communication is a more subtle benefit flowing from this approach.

Data were available for six fully air-conditioned buildings, but on a limited basis. Only installed capacity for refrigeration equipment and for air and water distribution systems were covered. Data were also available for these buildings on management and control systems. These limited data were obtained from field surveys of the buildings and have been used to assess the performance of the proposed new method in practice. A hypothetical example to illustrate the calculation procedure is given in the Appendix.

Figure 2 plots the results based on these data. The figure shows the relationship between the observed total energy consumption E_T of each building and its energy index I_a calculated from equation 3 below:

$$I_a = B/(P_c F_c + P_{fp} F_{fp} R_{fp}) \qquad (3)$$

This equation is derived from equation 2 by removing the terms for boilers and lights, and dividing through by H_c to produce the ratio of hours run R_{fp} and a new calibration constant B which is equal to A/H_c.

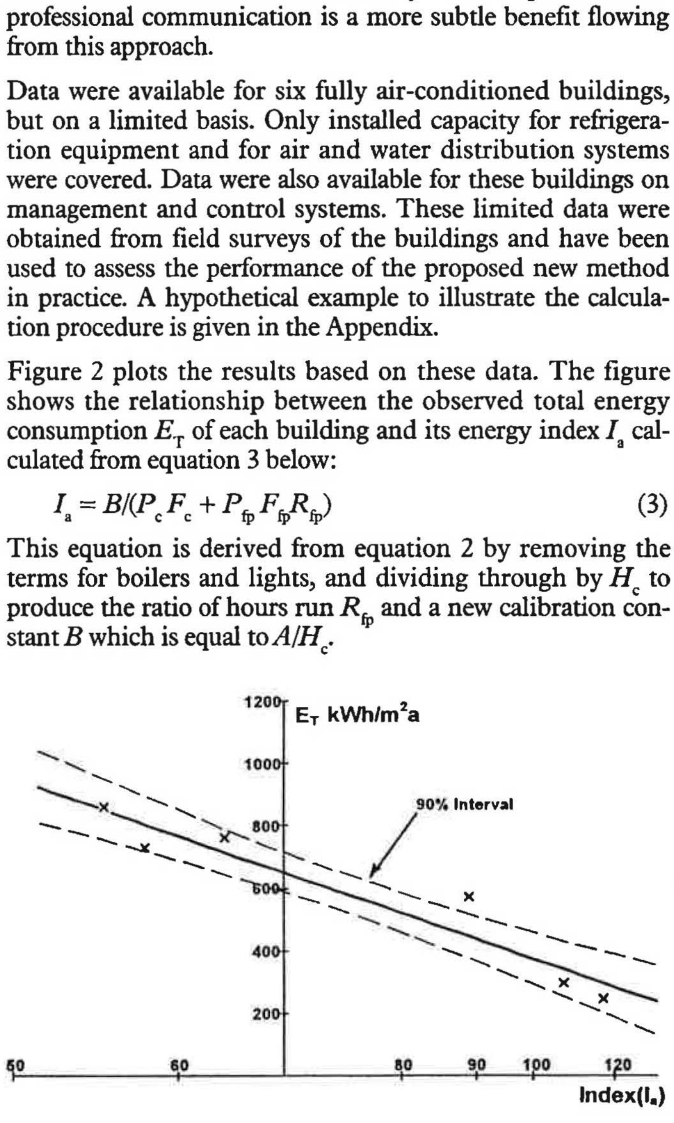

Figure 2 Energy use data for six air-conditioned offices

The figure also plots a simple linear regression of the index on energy consumption and the associated 90% confidence interval. The equation for this regression line is in principle given by:

$$E_T = A/I_a + C \qquad (4)$$

in which the 'constant' term C accounts essentially for the energy consumed by heating and lighting systems (and in principle all other energy usages not accounted for in equation 3).

The index scale used to plot Figure 2 can be seen to be non-linear, reflecting the inversion performed in equations 2, 3 and 4. Although it is based on such a limited data set, the degree of correlation obtained is clearly good. Treating the terms for lighting and heating systems etc. in equation 4 as a constant is of course a less than ideal assumption, but unavoidable given the lack of specific data. The main effect of this assumption is to increase the unexplained spread of data about the regression line.

Two important observations can be made on Figure 2 (or the complementary regression).

(*a*) It is possible to estimate the risk of making a wrong decision when assessing the likelihood of compliance with the requirements of a building code or performance specification. For example, around a nominal compliance index of 100, above a value of 89 there would be a less than 10% risk of rejecting an index of 100 or greater, and below a value of 121 a less than 10% risk of accepting an index lower than 100.

(*b*) Even with its present limitations, the index may be used as a preliminary predictor of energy consumption. Around typical performance levels the data show that this provides estimates within about 11%. This increases to 22% at 25% better energy performance, largely because of the distribution of the sample.

Most of the uncertainty within the computed 90% confidence limits is likely to be due to the small sample size and to the fact that the data are limited to only six buildings and chiller plant, fans and pumps. Clearly the potential performance of the method will improve when data are available from more buildings and include information on heating and lighting loads.

7 Sensitivity

In equation 3, the ratio R_{fp} of hours run turns out to be about 3.7 for office and retail buildings and about 7 for hotels. But as indicated below, the precise value of this ratio is not important. As illustrated by Figure 3, sensitivity testing showed that a 75% change in the ratio (i.e. from 2.7 to 4.7) made just a 5% difference to the energy efficiency index calculated across a wide range of values, once the value of B had been recalculated to maintain the target index at the same implied level of energy efficiency. The 5% variability is evident from the scatter of points about the straight line. This is a very important observation because it means that a precise value of the ratio is unimportant, and by implication, that the same will apply to equivalent terms in equation 2.

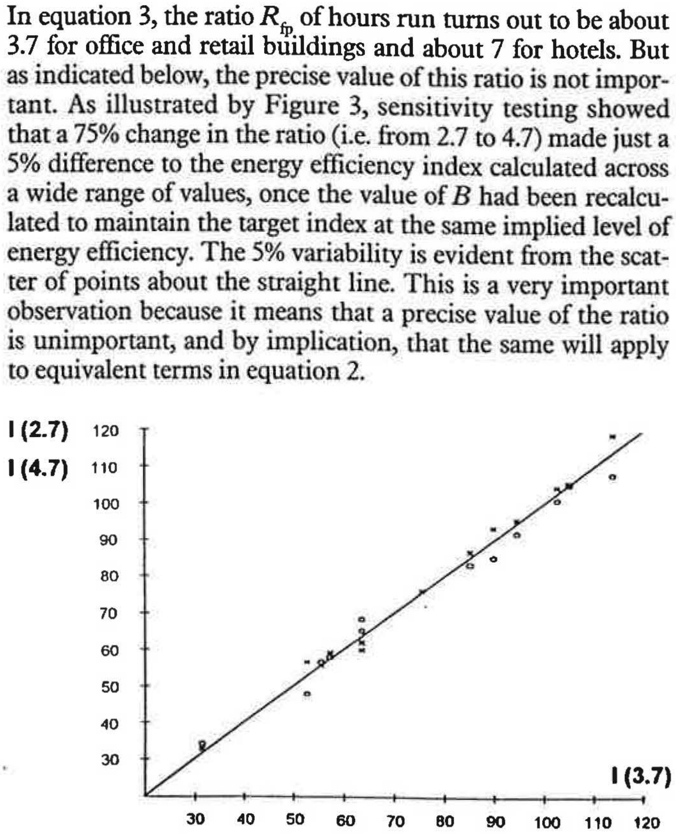

Figure 3 Sensitivity of index I to ratio of plant hours run (offices)

Refurbished buildings can be subject to significant constraints, such as local town planning constraints on a façade or limited floor-to-ceiling heights that cannot be altered. It is therefore important to recognise that there is a legitimate argument to set less stringent energy efficiency index targets for refurbishment.

The variable sensitivity of the index to changes in energy consumption can be exploited in this context. Figure 4 plots the energy efficiency index I_a as a function of the ratio of total energy consumption E_T to that of a building which achieves an index of 100 based on the regression line in Figure 2. The reciprocal relationship dictates the non-linear shape of this graph. On this basis, designers might instead be asked, for example, to improve the index by at least 10 or 20 points (say) unless before refurbishment it is already 90 or above. In that case the new index must (for example) be at least as good as the old. Figure 4 shows that the worse the building is to begin with, the greater is the improvement in energy performance required for a 10 or 20 point increase in the index.

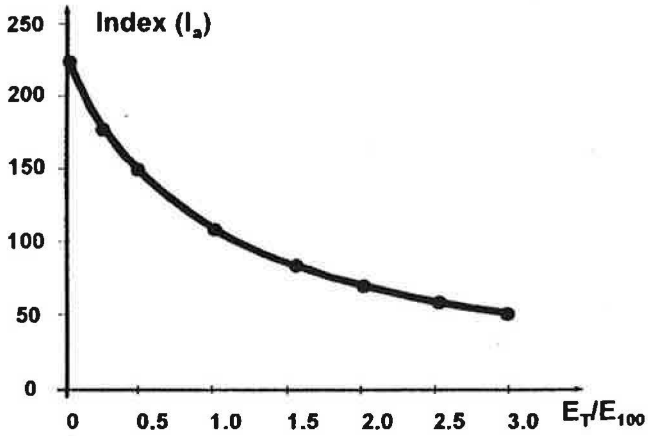

Figure 4 Energy performance index versus relative energy use

8 Conclusions

(*a*) A new method has been proposed which may be used to appraise the relative energy performance of designs for new or refurbished buildings, or to provide a rating for existing buildings.

(*b*) The method may be employed in practice as a design target or equally as a performance label, thus potentially providing the basis of an alternative route to defining regulatory requirements or performance specifications.

(*c*) As it is goal-based and non-prescriptive the method would permit design flexibility, and facilitates market freedom to optimise design solutions.

(*d*) The simplicity of the method would permit early estimates of plantroom size and associated space requirements.

(*e*) In design, the method would require integrated consideration of building services, fabric and envelope from the outset, thus ensuring that optimal solutions are not inhibited by more linear consideration of individual aspects of the building.

(*f*) As a consequence, it would also stimulate and encourage better inter-professional communication within design teams.

(*g*) The method is intrinsically simple to understand by clients and building control officials as well as by design professionals; thus facilitating high applicability and the likelihood of widespread take-up in practice.

(*h*) Despite its simplicity, early results based on limited practical data indicate that the method promises to work well in the field. Confidence in the method will grow as further field data are assembled.

References

1 *The Government's Standard Assessment Procedure for energy rating of dwellings* (SAP) (London: UK Department of the Environment) (1993)

2 *Energy design of new buildings except low-rise residential buildings* ASHRAE Standard 90.1 (Atlanta, GA: American Society of Heating, Refrigeration and Airconditioning Engineers) (1989)

3 *Energy performance of non-residential buildings – Determination method* Dutch Standard NEN 2916 (Delft, The Netherlands: NNI) (October 1994)

4 *Heat requirement in new buildings calculation of heat requirement* Nordic Committee on Building Regulations (NKB) Committee and Works Reports 1993:02 E (Helsinki: NKB) (1993)

5 *Wärmeschutzverordnung Bundesgesetzblatt* 2105(55) 2121–2132 (1994)

6 Moss S A Energy rating of non-domestic buildings *Proc. CIBSE/ASHRAE Joint National Conference, Harrogate, UK* Vol. 1 pp182–6 (Sept 1996)

7 Milbank N O, Dowdall J P and Slater A Investigation of maintenance and energy costs for services in office buildings *J. Inst. Heating Ventil. Eng.* 39 145–154 (Oct 1971)

8 *Energy Efficiency in Offices* Energy Consumption Guide 19 (London: Energy Efficiency Office, UK Department of the Environment) (Oct 1991)

Acknowledgements

This work was carried out as part of the Building Research Establishment's programme of research for the UK Department of the Environment. It is necessary to acknowledge that the development of the method is a result of inputs from a wide range of people, including: Air Conditioning and Refrigeration Industry Board, EA Technology, British Property Federation, British Broadcasting Corportation, British Council for Offices, BCSC, British Gas, Chartered Institution of Building Services Engineers, Construction Industry Council, HEVAC Association, Heating and Ventilating Contractors Association and the UK Department of the Environment. The authors would like to thank them for their invaluable contributions via participation in a series of 12 developmental workshops held at the Building Research Establishment during 1996.

Appendix: Example calculation for air-conditioned office

Specifications	
Floor area of treated office space	3000 m^2
Refrigeration plant type	Electric vapour compression
Refrigeration plant capacity rated electrical input	150 kW
Rated electrical power demand per unit area	50.0 W m^{-2}

Taking, for example, a value of 2.6 for the conversion factor from delivered electrical to primary energy units, the rated primary power demand per unit area is given by

$$P_c = 50.0 \times 2.6 = 130.0 \text{ W m}^{-2}$$

A1 Refrigeration monitoring and management

In this example mixed-mode operation is provided for, so it is possible to switch to natural ventilation when circumstances permit. Modular plant is scheduled to match capacity as nearly as possible to demand. The plant is controlled by a time clock for intermittent occupancy. The energy consumption of the refrigeration plant is to be metered, but there will be no automatic provision to report excess use. Column B of Table 1 is therefore used to determine the refrigeration plant management factor F_c appropriate to the management measures incorporated in the design as follows:

	B
Mixed mode operation	0.9
Hours of use controlled by time-clock	0.9
Modular plant (closely matches output to demand)	0.93

Hence the refrigeration plant management factor is given by

$$F_c = 0.9 \times 0.9 \times 0.93 = 0.75$$

A2 Distribution systems

Specifications

Rated electrical input to air and water distribution fans and pumps	35 kW
Electrical power rating per unit area	11.7 W m^{-2}
Primary power rating per unit area P_{fp}	30.3 W m^{-2}

A3 Distribution system monitoring and management

The energy consumption of the major distribution plant is to be metered, but there will be no automatic provision to report excess use. Column B of Table 2 is therefore used to determine the distribution system management factor F_{fp} appropriate to the management measures incorporated in the design as follows:

	B
Mixed-mode operation	0.9
Hours of use controlled by time-clock	0.93

Hence the distribution management factor is given by

$$F_{fp} = 0.9 \times 0.93 = 0.84$$

A4 Index calculation

The Index is then calculated from equation 3. If a value for A_C of 21 000 is suggested, for example, to represent the notional minimum standard indicated by Figure 1, this gives:

$$I = 21\,000/(130 \times 0.75 + 30.3 \times 0.84 \times 3.7)$$

giving a value of the index for this design of approximately 110.