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Daily energy consumption signatures and control charts for air-conditioned buildings

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ABSTRACT

Energy signatures for air conditioning systems can have characteristics which are not seen with heating systems. This paper explains and illustrates some of the characteristics that are specific to air conditioning systems and describes how energy signatures that take account of them can be applied to produce benchmarks, control charts and diagnostic information. It focusses on the use of energy signatures derived from measured daily system energy consumption.

Daily energy signatures can generate more robust energy consumption benchmarks and provide additional insight into unusual energy demand patterns compared to monthly or weekly signatures, albeit requiring slightly more data. In particular, they distinguish between weekday and weekend consumptions. They can be used to generate benchmarks based on standardised annual consumption or standardised annual load factor. In addition they can be used to generate control charts to identify days of unusual consumption for individual systems. More sets of daily energy consumption data are needed to evaluate their diagnostic power.

1. Introduction

The use of energy signatures to characterise heating energy consumption is an established procedure but their application to air conditioning is relatively unfamiliar. One complication is that energy signatures for air conditioning systems can have characteristics which are not seen with heating systems, and the assumptions which hold for heating do not necessarily apply to air conditioning.

This paper explains and illustrates some of these characteristics and describes how these energy signatures can be applied to produce benchmarks, control charts and diagnostic information for air conditioning systems. It focusses on the use of energy signatures derived from measured daily energy consumption of the whole system that is providing cooling into a space. The paper describes procedures and provides an illustrative Case Study to illustrate their application: further work is necessary in the areas of data collection to enable benchmarks to be defined, and practical application to build confidence – or reveal limitations – in the value of the procedures.

Part 1 of the paper refers to previous work, introduces the different forms of energy signatures that may be encountered and illustrates the component elements of a typical air conditioning energy signature using data from a UK office building.

Part 2 addresses the applications of empirical energy signatures: consumption benchmarks, annual load factor benchmarks, control charts and energy efficiency diagnosis.

Part 3 discusses how daily cooling energy signatures may be used to diagnose which aspects of system design or operation would repay further investigation. In general, identification of specific causes of energy wastage will require on-site investigation or the analysis of more detailed consumption data—for example, by remote automatic analysis. (The term "energy wastage" is used to denote energy consumed in excess of a "reasonable minimum" level that is necessary to provide the required service. Clearly what can be considered a "reasonable minimum" depends on the context—replacing equipment may, for example, be considered unreasonable in the short run, but reasonable at some point in the future.)

2. Part 1: Fundamentals

2.1. Energy signatures for air conditioning

2.1.1. Energy signatures

A building energy signature is a plot of the energy consumption of a building versus the mean ambient air temperature, usually on

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a daily basis [1]. It has been widely used as a means of characterising the heating energy consumption of buildings but less commonly for cooling energy consumptions [2–6]. Energy signatures are commonly based on the total energy supplied to a building, usually broken down by fuel type, but they may also be based on submetered data for particular end-uses. Energy signatures may be, in principle, based on different time periods: in this paper we focus on signatures based on daily consumptions and daily mean outdoor temperatures. This level of detail provides useful information in a readily assimilated form and requires a limited amount of data and analysis. Much more information, including the identification of specific faults can be extracted from the automated analysis of sub-hourly data [7].

This paper considers the energy consumption of air-conditioning systems used to provide comfort cooling in buildings. While it focusses on the energy used for cooling, the approach is also applicable to measured consumptions of complete air conditioning systems, including energy used by fans and (reverse-cycle) heating. Sub-metering of components at the required level is relatively straightforward in principle, and may be an element of a building energy management system or be carried out remotely.

2.1.2. Forms of energy signatures for air conditioning

Heating energy signatures conventionally take the form of a fixed base consumption plus – above a threshold or base temperature – a linear relationship between consumption and temperature. In practice, there are also day to day variations that are not correlated with outdoor temperature. These may be caused, for example, by variations of solar gain, wind velocity or direction, or of heat gains associated with differing occupancy patterns.

The relatively few published examples of energy signatures for air conditioning identified in Section 2.1.1 show a similar linear trend, notwithstanding that they might be expected to display some curvature due to variations of efficiency or dehumidification load with outside temperature. However, as discussed below, some types of air conditioning systems can be expected to have energy signatures that display discontinuities.

Energy signatures may be applied to the energy consumption of a complete air conditioning system, including mechanical ventilation, or separately to the cooling and air handling subsystems. In the former case there may be consumption by fans or pumps at times when there is no heating or cooling load.

The next part of the paper considers the energy signatures of some of the more common types of air conditioning system. The importance of the different features discussed varies according to climate and building design and use.

2.1.2.1. Reverse-cycle systems. Some air conditioning systems are capable of operating as heat pumps, operating in reverse cycle mode. These systems include packaged systems with and without a ventilation element. In this case the energy signature contains both the cooling (right hand side) and heating (left hand side) aspects of the basic energy signature as shown in Fig. 1. The slopes of the two

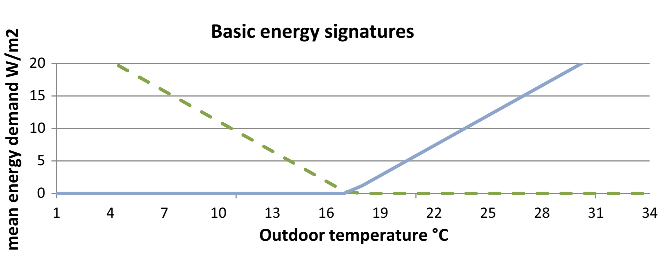

Fig. 1. Principles: Basic energy signatures.

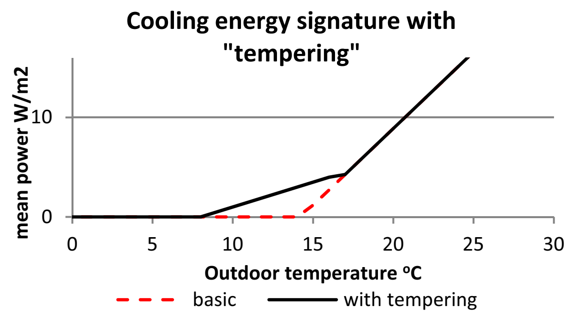

Fig. 2. Principles: Cooling energy signature with tempering.

gradients will be numerically different, corresponding to differences between the cooling energy efficiency ratio and the heating coefficient of performance.

2.1.2.2. "Tempering" of supply air. Larger air conditioning systems commonly provide a mechanical ventilation service via an air handling subsystem which also provides an element of initial cooling and heating. This supply of cooled air is insufficient to meet the cooling demands under all circumstances and a separate – usually water-based – subsystem provides more localised additional cooling and heating when required.

In order to avoid localised cooler areas and discomfort from cold draughts, the temperature difference between the supply and room air temperatures is usually limited: typically to a temperature difference of between 5 and 8 degrees C see, for example [8]. As a result, there are times when the supply air has to be warmed or "tempered" to meet this supply air temperature comfort requirement. This means that there will be times when the cooling demand in the building could be met in principle by the outdoor air supply but the use of tempered supply air results in a demand on the cooling sub-system. The energy implications of this feature are most significant for combinations of climate and building in which a cooling demand often coincides with cool outdoor temperatures.

Tempering removes the contribution of mechanical ventilation to the temperature sensitivity of heating and cooling demand, which results in the form of cooling energy signature shown in Fig. 2. This form of cooling energy signature has two segments, a base temperature corresponding to the fabric heat gains only and a change of gradient at the upper supply temperature limit for tempering[1]. The air system still provides a degree of cooling—the supply temperature is below the room temperature, but the majority of the cooling is provided by the water (or refrigerant) subsystem.

2.1.2.3. Pre-cooling. In hot climates where the outdoor air temperature is frequently above the desired indoor temperature, air conditioning systems may use heat exchangers to pre-cool the incoming outdoor air by transferring heat to the cooler exhaust air. This will reduce the temperature sensitivity of the cooling consumption at times when the outdoor temperature exceeds the indoor temperature.

2.1.2.4. Free cooling. All-air systems meet peak cooling demands entirely through the supply of cooled air and therefore have relatively large air supply volumes. When the outdoor air temperature is below the indoor temperature and there is a cooling demand, the proportion of outdoor air in the air supply can be increased above that needed purely for ventilation, providing "free cooling" without

[1] There is a corresponding change of gradient in the heating energy signature at the same outdoor temperature, reflecting the additional heating that is required.

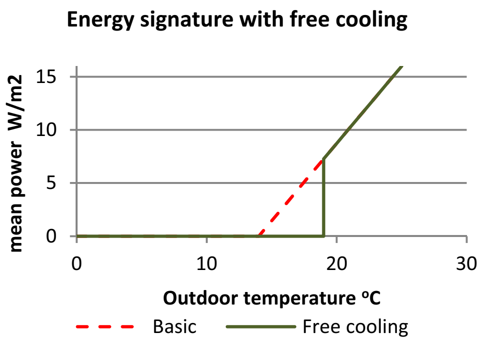

Fig. 3. Principles: Energy signature with free cooling.

the operation of the cooling generator. At lower cooling loads, air that is in excess of that needed to provide an adequate supply of outdoor air is recirculated.

The energy signature with free cooling has the form shown in Fig. 3. Below a threshold outdoor temperature at which cooling demand can just be met by free cooling; there is no demand on the cooling generator. Above that temperature the usual relationship holds.

2.1.3. Components of energy signatures: An example

2.1.3.1. Background. This section is illustrated with a set of measured data of chiller consumption. The data are from an office building of 7668 square metres floor area, of which 5936 square metres is air-conditioned by a 4-pipe fan coil system with tempered mechanical ventilation. The nominal installed cooling capacity is 300 kW. The building has a total glazed area of 726 square metres predominantly facing East and West and is located in southwest England.

As can be seen, the range of daily mean outdoor temperatures over the year is between about 1 °C and 27 °C. Reported occupancy is weekday-only between 0700 and 2100, with cleaners in the building from 0500. However, the energy signatures suggest that the system is live at weekends.

Fig. 4 shows the daily chiller energy consumption plotted against mean outdoor temperature for a complete year (more information on the building and data is available at [9]). There is a clear difference between trends for weekdays and weekend days, though a few of the weekday consumptions seem to fit the weekend trend. It is likely these are holidays or atypical weekdays.

Converting the information on the scatter plot into an energy signature can be done in two ways. Splitting the data into

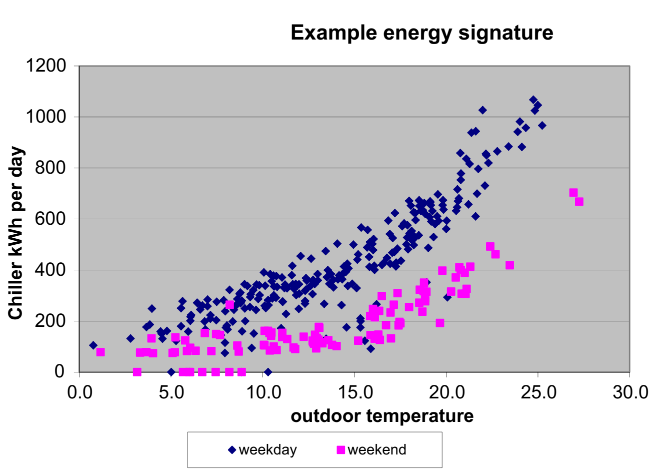

Fig. 4. Example Scatter Plot.

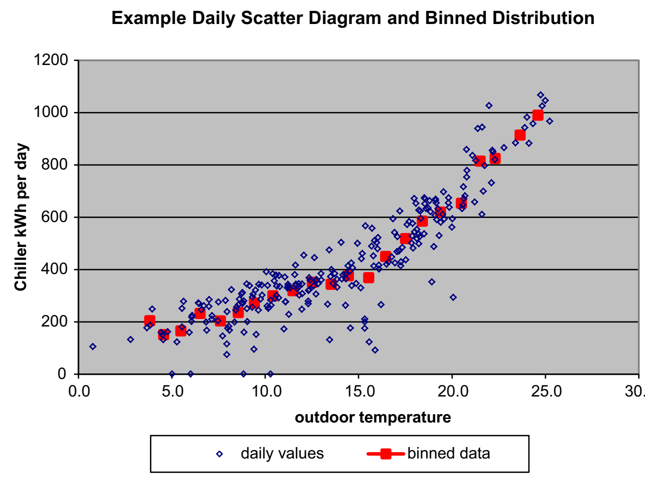

Fig. 5. Binned and daily values of Weekday only data.

temperature bins and identifying the median values in each bin has the advantage of making no prior assumptions about the shape of signature. However, it requires sufficient data over a sufficiently wide range of temperatures to be reliable. This is likely to be problematic, especially with less than, say, nine months data, and for high outdoor temperatures which may be rarely experienced. The simpler approach of fitting linear segments to the data avoids these issues at the expense of restricting the possible shape of the signature. This is the approach illustrated in this paper.

2.1.4. Basic parameters: Weekend data

The *base temperature* for the weekend data is, by inspection, about 16 °C see Fig. 5. (A more robust way to determine this is to iteratively search for the value that gives the best fit to a two-segment linear model [1].)

Below this temperature (and ignoring several zero energy days early in the monitoring period) daily consumption falls within a fairly narrow band. The mean daily consumption (or "*base consumption*" on these days is 137.9 kW h per day (0.97 W/m^2 mean). The best estimate for the *temperature sensitivity* at these temperatures is 3.39 kW h per day/°C (0.024 W/m^2 °C) i.e. essentially there is zero sensitivity to external temperature.

A linear regression on the consumption values for days with temperatures above 16 °C produces an estimate of the *temperature sensitivity*: 41.48 kW h per day/°C (0.291 W/m^2 °C).

2.1.5. Basic parameters for weekday data

From the energy signature, there seems no reason to assume that the "*base consumption*" differs from weekend days, though this is more difficult to assess. The *base temperature* appears to be below 10 °C but is not very clearly defined.

The best-fit *temperature sensitivity* over *all* weekdays is 36.61 kW h per day per °C (0.257 W/m^2 °C), which is about 10% less than the figure for weekends. On the warmest days the distribution of daily consumptions has a somewhat steeper gradient. For temperatures above 15 °C, the temperature sensitivity is much higher at 66.74 kWh per day per °C (0.468 W/m^2 °C). A best fit estimate for the temperature at which the sensitivity changes is about 17.9, say 18 °C. The energy signature therefore has the general characteristics for a system with "tempering" as described in Section 2.1.

The temperature sensitivity at the lower temperatures is 18.2 kW h per day per °C (0.127 W/m^2 °C). This is physically implausible for a mechanically ventilated building: assuming typical occupancy levels and outdoor air supply rates, the minimum recommended outdoor supply rates alone would result in a higher value of the temperature sensitivity. This supports the interpretation that this change is due to tempering.

There are day to day variations of daily consumption beyond those related to mean outdoor temperature or weekday/weekend differences. These are presumably caused by variations in solar gain, equipment and lighting use, occupancy and perhaps other factors. The "base temperature" and other parameters of the energy signature plot reflect their average values. We can extract the values as the difference between each day's consumption and the "best fit" energy signature—the residual values. The magnitude and relative frequency of the residual values provides additional insight into the structure of daily consumption.

2.1.6. Day to day variability

The residuals are taken to represent variations of heat gain to the conditioned space and, in physical terms, we can consider these heat gains to have two components: a base level that is present on every (week- or weekend) day plus a range of day to day gains. The scale of the variable component can be gauged from the range of values of the residuals—for example by the difference between the highest and lowest deciles[2].

The interval between, say, the 10%ile and 90%ile values is an indication of the range of the residuals. In this building, this range at weekends 141 kW h per day (0.98 W/m^2 mean) and is not materially different at temperatures above and below the base temperature. The range on weekdays is higher than on weekends, at 222 kW h per day (1.56 W/m^2 mean).

We can estimate the impact of the average level of heat of gains for this example, as we have measured internal temperatures for this building. The difference between the observed base temperature and the indoor temperature, multiplied by the observed temperature sensitivity shows the "base level" of internal heat gains to be equivalent to a cooling consumption of 370 kW h per weekday day. (The physical gains will be higher since the consumption reflects the efficiency of the chiller). The mean value can be compared to the range of the variable element, which is 222 kW h per weekday. Thus, in this building the day to day variability is comparable in magnitude to the average level of heat gains. For weekend days the comparable figures are 110 kW h per day and 141 kW h per day.

2.1.7. Standardised peak day demand

Using the information about day to day variability, the energy signature can be used to estimate not only the expected daily consumptions for any given external temperature, but also a standardised peak day demand. This can be used for benchmarking system operation, as is explained in Part 2.

The basic procedure is straightforward:

- First, select the outdoor daily mean temperature of interest and determine the mean daily consumption associated with it.
- Second, select an "exceedance limit" for the day to day variability – for example the value that is only exceeded for 5% of days – and determine the associated consumption above the mean.
- Third, add the two values together[3].

For example, in the example system, if the chosen outdoor mean temperature is 25 °C the mean daily chiller consumption is 1046 kW h/m^2. By analysis of the residuals from the regression lines, the 5% exceedance value is 25 kW h/m^2, so the standardised peak daily demand is 1071 kW h/m^2.

If more detailed monitoring data are available, the same procedure can be used to calculate a standardised peak hourly (or half-hourly) demand, which can be compared to the expected peak consumption for the design cooling capacity[4].

3. Part 2: Benchmarking applications

3.1. Consumption benchmarks

3.1.1. Standardised annual consumption per unit floor area

Comparison of measured monthly and annual cooling consumptions between years and between buildings in different locations is complicated by the fact that it is weather-dependent. Energy signatures enable the effects of differences in outdoor temperature to be compensated for (at least for daily mean temperatures). Once the energy signature has been established, a standardised annual or monthly consumption is readily calculated by applying a standard distribution of outdoor temperatures. It is, of course, important to first characterise the shape and parameter values of the signature correctly. In many cases floor area will be a suitable normalising parameter to allow inter-building comparisons, and this is a commonly used metric at present.

The choice of the 'standard year' temperatures is important since the impact of factors such as free cooling and supply air temperature tempering will depend on the climate. Different 'standard years' will be needed for different climate zones. In particular, the impact of "tempering" effects will be more important in climates for which the combination of cool outdoor air with a need for cooling in a building frequently occurs.

3.1.2. Annual load factor

The annual load factor for cooling is conventionally described in terms of "equivalent full-load hours" or EFLH (see, for example [10]): the annual consumption divided by the design peak demand (or the maximum possible power input of the installed plant, which may be different). Similar metrics can be applied to other components such as fans.

We consider two variations on this benchmark to be possible and practical:

- If measured consumptions are available at, say, hourly intervals or shorter, the connected power may be replaced by an empirical standardised peak hourly (or sub-hourly) power derived from the energy signature in manner similar to that described for peak days in Section 2.1.7.
- Since this level of detail will not always be available, a more useful definition uses the standardised peak daily consumption described in Section 2.1.7. The ratio between standardised annual consumption and standardised peak day consumption is a load factor which may is characterised in terms of "equivalent peak days".

In the example system, the maximum observed (15 min) input power was 98 kW or 16.5 W/m^2. On this basis the annual Equivalent full-load hour (EFLH) figure is 1308 h[5]. This is slightly higher than

[2] Other criteria are obviously possible.

[3] This procedure generates an easily calculated useful metric, but a statistically more robust approach would also take into account the probability of different external temperatures.

[4] The connected power of the installed cooling equipment will clearly be larger than the standardised peak day consumption because it has to meet short-term loads, because there may be a need for margin to satisfy possible future load increases and in order to provide redundancy to cover equipment failures or maintenance periods.

[5] Based on the peak consumption day (1070 kW h, or a 24-h mean of 44.6 kW) the load factor can be expressed as 120 peak consumption days. (And the peak consumption day is equivalent to 10.9 h of maximum power).

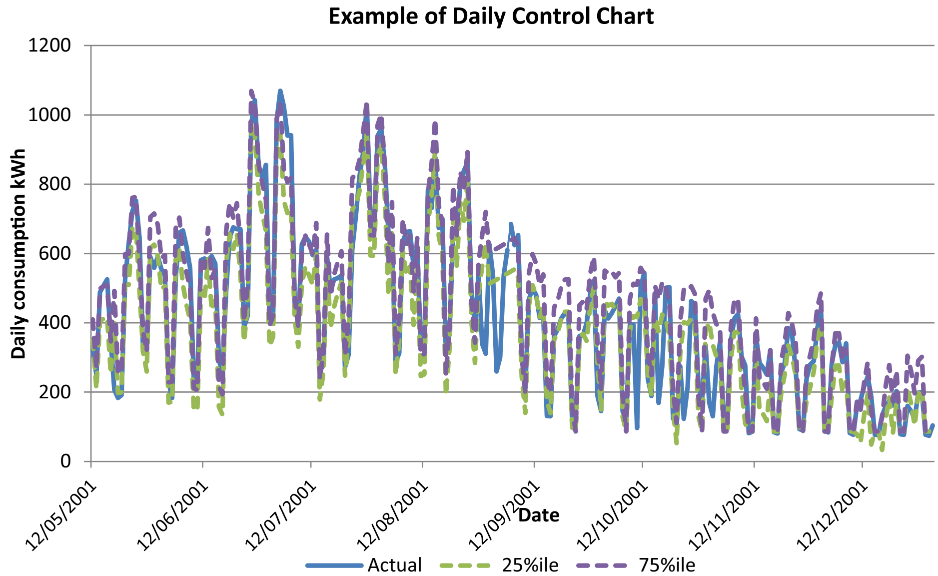

Fig. 6. Example control chart.

typical UK "rule-of-thumb" estimates but it is appreciably higher than typical simulation-based estimates.

Equivalent full-load hours or equivalent full-load day benchmarks have the advantage that they do not require knowledge of the size of the conditioned space. They are also less sensitive to differences in equipment efficiency (except to the extent that these vary between the peak day and other days).

3.1.3. Daily control charts

The energy signature can be combined with the information about the distribution of residual values to produce a daily control chart that identifies when abnormal daily consumptions occur—in effect, a form of short-term benchmarking of the system against itself. Daily control charts provide warnings but do not provide significant diagnostic information about specific faults. This type of information can be provided by a sub-hourly energy signature and by sub-hourly interval residual values, providing exception reports at the time they are needed for control actions to be taken.

For control charts it is necessary to first identify whether there are significant differences between the signatures of, for example, weekdays and weekend days (or any other days of the week). The range of expected consumptions for any combination of day type and outdoor temperature can then be easily derived and plotted.

Fig. 6 shows a daily control chart applied to the example building referred to earlier. The days on which the 25%ile limit (broken line) is low are weekend days. Fig. 6 shows that there are also some days of low consumption (solid line) which are not at weekends, such as public holidays. Here the range limits are set to the upper and lower quartiles, so excursions outside the indicative range are relatively frequent. "Out of range" excursions may, of course, have simple explanations such as occasional holidays or intentional longer working hours, but they serve to alert building managers to possible malfunctions in the normal operation of the plant.

In the example chart, it is noticeable that

- The average outdoor temperature and the distinction between weekdays and weekend days produces a good general predictor of daily consumption.
- Occasions of lower than predicted consumption are weekdays on which the consumption seems more characteristic of weekends.
- The most noticeable occasions of higher than predicted consumption are weekdays other than Mondays, though there is no other obvious pattern.

4. Part 3: Diagnosis of energy wastage for cooling systems

4.1. General principles

4.1.1. Background

Benchmarking of air conditioning consumption and control charts can provide initial steps in the identification of unusually high (or low) levels of energy consumption, but provide little in the way of diagnosis of the causes of energy wastage. In fact, low consumption is not necessarily associated with high energy efficiency if it is accompanied by a poor quality of service.

In principle, the parameters of (and derived from) an energy signature can provide additional diagnostic information. The diagnostic power of the individual parameter values can only be properly tested once there is sufficient measured data from a large enough sample of buildings and systems to empirically characterise individual values as being unusually high or low. At present this is not the case.

The expected form of a daily energy signature can be derived straightforwardly from a simple model of the heat balance of a building and its HVAC system. However, the inverse procedure—reliably deriving a building's or system's thermal energy characteristics from an observed energy signature is more difficult. There are two reasons for this:

The same signature may result from different combinations of parameters. Typically, there is more than one set of assumptions about a building and its HVAC systems that can result in a given energy signature. For example, heat losses may result from poor insulation or poor building air-tightness.

A simple thermal model of a building or system ignores or simplifies effects that can significantly influence the energy signature. For example, solar heat gains are seasonal in nature and heat gains from lighting vary with day length, so these effects are therefore somewhat correlated with outdoor temperature. In addition, the efficiency (energy efficiency ratio) of air-cooled chillers varies with load and ambient temperature-dependency.

In consequence, energy efficiency inferences drawn from energy signatures should generally be seen as indicators of possible energy wastage needing more detailed examination by either physical inspection or more detailed monitoring (see, for example [7]).

Notwithstanding this caveat, we need a conceptual model in order to extract diagnostic information, but it must be one that recognises the possibility of at least the major ambiguities of interpretation.

4.1.2. A simple model

The basic premise is that for the space(s) served by the system, over a 24-h period there can be considered to be a balance between heat gains and heat losses. This is obviously an approximation, but one that the existence of a consistent energy signature seems to justify. The model is illustrated by an example below.

4.1.2.1. Description.

- For brevity, the example model uses daily average kWh values per square metre of treated floor space[6]. In practice there is also day to day variability due to differences in heat gains or wind-speed but, in order to clarify the principles, are omitted here. indoor to outdoor non-ventilation conductance (fabric plus infiltration) as U (kW h per day per deg C) (taken as constant)
- indoor to outdoor ventilation conductance as V (kW h per day per deg C) (taken as constant for days when ventilation is provided, but may differ between weekdays and weekend days)[7]
- heat gains (solar plus equipment and occupants) as G (kW h per day) (varies from day to day)
- cooling consumption as C (kW h_e per day) (varies from day to day)
- cooling demand as D (kW h per day) (varies from day to day)

and: energy efficiency ratio as $EER = D/C$ (taken as constant but in practice varying with demand level and outdoor temperature)

denote: daily average air temperatures as:

- outdoor temperature as t_o (°C), (varies from day to day)
- indoor temperature as t_i (°C), (taken as constant, but may differ between weekdays and weekend days).

4.1.2.2. Model derivation. For systems with a supply air temperature limit, we have, as shown in Fig. 2, three operating regions (which may differ between weekdays and weekend days)[8].

Region 1. At outdoor temperatures below some base temperature, t_b, demand is taken to be a constant, a_0 (kW h per day) (and may be zero)

$$D = a_0 \quad (1)$$

Region 2. At outdoor temperatures between the base temperature, t_b (°C), and a second index temperature, t_s (°C), demand varies linearly with temperature with slope b_1 (kW h per day per deg C) and intercept a_1 (kW h per day)

$$D = a_1 + b_1 \times t_o \quad (2)$$

Region 3. When t_o (°C), is above t_s (°C), demand varies linearly with temperature but with different parameter values: with slope b_2 (kW h per day per deg C) and intercept a_2 (kW h per day)

$$D = a_2 + b_2 \times t_o \quad (3)$$

[6] The exact definition of treated floor space may vary: for benchmarking purposes it is important to have an agreed definition.

[7] In practice, this is dependent on system operating time.

[8] The model can be extend to systems with (air side) free cooling, which have an additional region: systems without a supply air temperature limit do not have the second index temperature.

Assume that the temperature at which ventilation air is supplied to the treated space is not allowed to fall below some threshold value in order to avoid thermal discomfort from cool downdraughts, and that this corresponds to the transition temperature, t_s, between operating Regions 2 and 3.

In region 2:

$$D = G - (t_i - t_o) \times U - (t_i - t_s) \times V \quad (4)$$

So

$$a_1 = G - t_i \times U - (t_i - t_s) \times V \quad \text{and} \quad b_1 = U \quad (5)$$

In region 3:

$$D = G - (t_i - t_o) \times (U + V) \quad (6)$$

So

$$a_2 = G - t_i \times (U + V) \quad \text{and} \quad b_2 = (U + V) \quad (7)$$

And

$$\frac{V}{U} = \left(\left(\frac{b2}{b1}\right) - 1\right) \quad (8)$$

(note that this is independent of D and therefore of EER. It is also independent of G)

At the base temperature, t_b, we have:

$$D = a_0 = G - (t_i - t_b) \times U - (t_i - t_s) \times V \quad (9)$$

So

$$t_b = t_i - (t_i - t_s) \times \frac{V}{U} - \frac{(G - a_o)}{U} \quad (10)$$

We can also determine a second "hidden" base temperature t_{bb} where the trend line of Region 3 intercepts the base demand:

$$D = a_0 = G - (t_i - t_o) \times (U + V) \quad (11)$$

$$t_{bb} = t_i - \left(\frac{(G - a_o)}{(V + U)}\right) \quad (12)$$

If $t_s < t_b$, then t_{bb} corresponds to the change of slope of the energy signature (it is the traditional definition of "base temperature")

By re-arranging we can see that

$$t_{bb} - t_b = (t_s - t_{bb}) \times \frac{V}{U} \quad (13)$$

This is a restatement of the relationship between b_2 and b_1 noted above and is independent of both EER and G

4.1.2.3. Model Interpretation. The parameters a, b, t_b, t_s, t_{bb} can be determined from the energy signature. Three of them, and the derived parameter V/U, are independent of EER, the energy efficiency ratio of the system (to the extent that EER is constant): t_{bb}, t_b, t_s, V/U. The parameters a, b and G are dependent on EER as they are based on energy consumption rather than cooling demand[9].

Having adjusted for the effect of outdoor temperature, we assume that the residuals from the trend line reflect differences in heat gains G. As noted in 1.6 above, we expect the heat gains to be positive but the residuals are centred about a zero value. We therefore need to estimate a true zero value. In principle we could set this to the largest negative residual but this may be determined by some other factor (such as the apparent operation in weekend mode on weekdays). A range indicator derived from the residuals is therefore a more robust indicator.

[9] If the output of the cooling generator is known, energy signatures based on supplied cooling may be used.

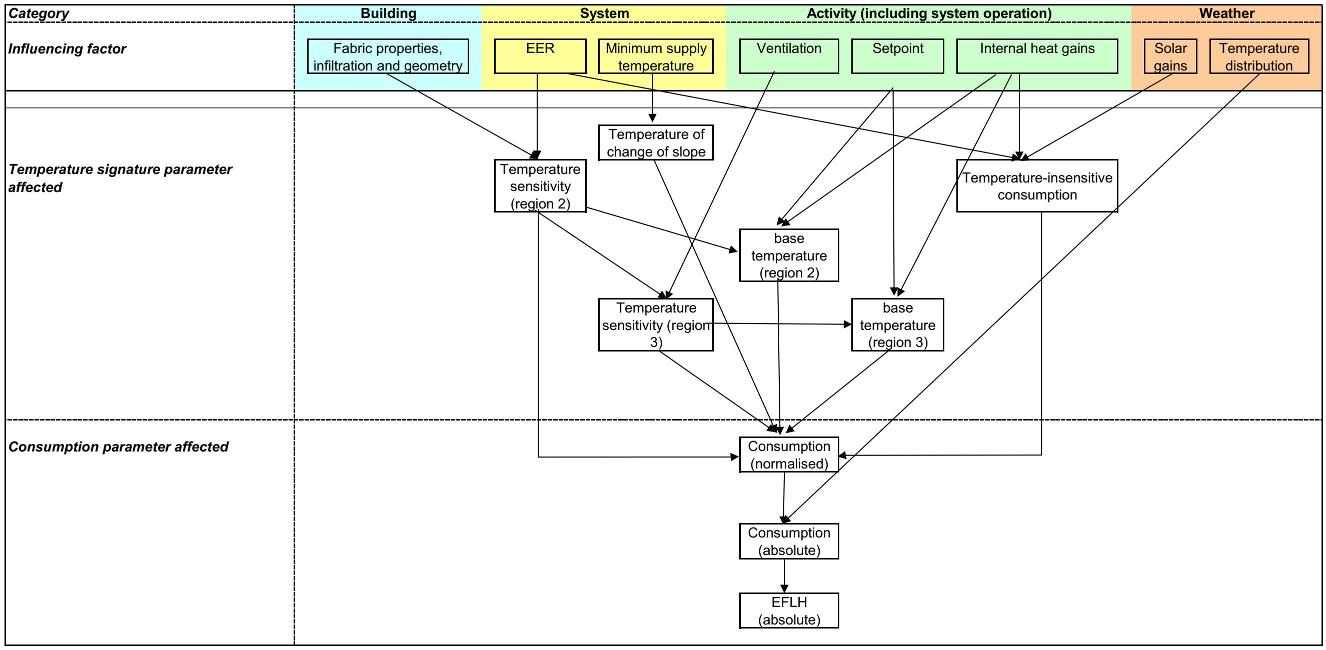

Fig. 7. Interactions between parameters.

4.1.3. *Interactions and diagnostics*

The values of the parameters depend on features of the building, occupancy, HVAC system and their operation, and their relationship with the annual consumption and annual load factor is not entirely simple. The interactions are shown schematically in Fig. 7

It is possible to map the expected impact of building and system features onto parameter values. The reverse process is more difficult, especially where more than one feature (or its opposite counterpart) may be present.

Table 1 maps the interactions for a simple energy signature. Some of these impacts are climate-dependent: in climates where the outdoor temperature is usually below the indoor set-point, increased ventilation or lower insulation levels will normally result in lower annual cooling demands[10]; the converse is true if the outdoor temperature is commonly above the indoor set-point.

Because of the way they interact, individual parameter values have limited diagnostic value. As can be seen in Table 1 combinations of parameter values can have more diagnostic power. For example, a high value for temperature sensitivity could indicate either a low SEER or large heat losses through the fabric or by ventilation (and each would be associated with a high peak day demand). However, the latter would be accompanied by a higher base temperature and a lower standardised annual cooling consumption.

Even so, there are ambiguities. For example, without knowing the indoor temperatures, it is not possible to distinguish between the effects due to large average heat gains and a low internal temperature. In addition, more than one effect may be present: diagnoses from energy signatures will usually only offer possibilities that need further exploration.

The symbols in Table 1 may be formalised as representing high (+), intermediate (=), or low (−) values. For example the boundaries of "high" and "low" could be defined as being the upper and lower quartiles of a range of observed values from different buildings.

This leads to four possible states for each parameter value:

- High (=high).
- Not low (=high or intermediate).
- Not high (=intermediate or low).
- Low (=low).

(Or "any" = high or intermediate or low).

We can be used to express combinations of parameter values as logical diagnostic statements, such as: if "A is high" AND "B is not high" then. . .. [11]. Some examples are given below:

Indicator for high internal gains

- low base temperature AND high non-temperature sensitive demand.

If there is no change of temperature sensitivity, it is difficult to separate poor building fabric from high ventilation.

Indicator for either of these:

- high base temperature AND high temperature sensitivity AND not-low non-temperature sensitive demand.

  When there is a change of temperature sensitivity, the following indicators can be used
- Indicator for poor building fabric (high infiltration or poor insulation).
- high Region 2 base temperature AND high Region 2 temperature sensitivity AND not-low non-temperature sensitive demand.

  Indicators for high ventilation rate
- high Region 3 temperature sensitivity AND not-high Region 2 temperature sensitivity

  Indicators for warm climate
- high annual consumption AND not-high standardised annual consumption,
- high EFLH AND not-high standardised EFLH.

[10] But correspondingly high heating demands.

[11] In principle, we could also use more finely-grained numerical values.

Table 1
Impact of building or system feature on parameter value.

	Impact of building or system feature on parameter value						
		Energy signature parameters			Derived (standardised) parameters		
	Observed annual consumption	Temperature sensitivity	Base temperature	Range of residuals	Annual consumption	Peak day consumption	Annual load factor
Feature							
Warm weather	+	=	=	=	=	=	=
High average heat gains	+	=	–	=	+	+	+
Large variability of gains (e.g. from large solar gains)	=	=	=	+	=	+ If based on range; = if based on average gains	=
Large heat losses through fabric or by ventilation	–	+	+	=	–	+	–
Low internal temperature set-point	+	=	–	=	+	+	+
Low SEER (and EER)	+	+	=	+	+	+	=
Low part-load EER	+	+	=	+	+	=	+

Key: + high, = intermediate, −low.

5. Part 4: Discussion and conclusions

5.1. Discussion

5.1.1. Related methods

The procedures described in the paper bring together elements of related existing methods, notably those relating to system diagrams [11] and degree-days [4,6].

System diagrams, typically based on hourly time intervals, have a long history as a means of illustrating the different modes of operation of HVAC systems. They have also been combined with bin analysis to predict energy consumption based on outdoor temperatures, ignoring the impact of building thermal capacity or load-dependent efficiency variation. Empirical daily energy signatures are, in effect, the inverse process of observing how consumption varies with temperature.

The concept of cooling degree-days demands the assumption of a linear relationship between consumption and outdoor temperature which is not always the case. The appropriate choice of base temperature for cooling degree-days has long been a subject of debate, perhaps because of a lack of appreciation that the relationship may not be linear (or at least not uniformly so). The use of daily consumptions and temperatures in energy signatures permits a more fine-grained analysis, not least because weekdays and weekend days can be separated.

5.1.2. Practical considerations

The comparative energy benchmarking of buildings is an important process but, because consumption is affected by so many factors, it is a rather blunt instrument. It can identify outliers in terms of energy consumption, but will not detect situations where the overall consumption appears reasonable but is still higher than could be achieved for the building and its systems.

This paper has suggested how the parameters of energy signatures can be used diagnostically, but realistically, this is limited to providing pointers to possible problem areas. More detailed diagnosis requires more frequent data and appropriate analysis tools—see for example [7].

In addition, many types of building contain spaces with different uses. The discrimination of energy benchmarks would be improved if the range of parameter values associated with different activities was known. A first step towards this would be to focus on buildings that only contain a single type of activity. This could be complemented by collecting and analysing data from a range of buildings and empirically identifying clusters of buildings that share similar characteristics—though this would not necessarily identify the causes of differences or similarities.

Occasionally it may be possible to extract values for particular activities by monitoring individual spaces separately but a more realistic approach would be to infer the contribution of each activity from observed consumptions of a sufficiently large and diverse sample of buildings. This would be a challenging task, though the possibility of constructing tailored consumption and power benchmarks for combinations of components, areas and activities has been demonstrated using sub-hourly data by the iSERVcmb project [7][12].

5.1.3. Possible future refinements

Several potential refinements to the procedures suggest themselves. These have not been systematically examined, but some have been tentatively explored for the system used as an illustrative example. The results may, of course, not apply generally.

5.1.3.1. Impact of the effective thermal capacity of the building. For daily heating consumption, it is known that the correlation of daily consumption and outdoor temperature is improved if a weighted rolling mean temperature is used (typically 0.5 × today's mean + 0.5 × yesterday's rolling mean: this is equivalent to assuming a building to have a time constant of some tens of hours). The use of this weighted outdoor temperature does reduce the scatter slightly: the size of the 25% to 75% range of residuals is reduced by about 5%. This suggests that a small part of the day to day variability results from the building's thermal inertia.

For this building, consumptions are available for 15 min intervals. Examination of the weekday residuals by (hourly) time of day shows that the median values show a consistent asymptotic increase in consumption throughout the occupied period. This would be consistent with a thermal inertia influence[13].

5.1.4. Impact of solar gains

Solar gains will typically be a significant component of the heat gains to a space in parts of the year and, in temperate climates, can be expected to contribute to the day to day variability of consumption. It would therefore be helpful to be able to identify them from the energy signature. If daily solar radiation data are available, correlations with the residuals may be sought, but the

[12] Simulation studies might provide a more accessible starting point.

[13] The effect of thermal inertia on the response to external temperature and to internal heat gains would be expected to differ.

radiation information is unlikely to be readily available[14]. Alternatively, the residuals for similar temperatures in different seasons may be compared—especially between Spring and Autumn, when similar outdoor temperatures are associated with different day-lengths and levels of solar gains.

This approach was explored for weekday data in the example building—with inconclusive results: the day to day variation was large compared to inter-seasonal differences. However, it was noted that the largest residual values tended to occur on the warmest days which (in the UK) are usually sunny.

5.1.4.1. Impact of latent loads. The relatively limited amount of empirical evidence suggests that latent cooling loads, which are rarely negligible, do not fundamentally affect the form of energy signatures—at least for comfort cooling applications in temperate climates. For example, the use of degree-days based on wet-bulb temperature has been suggested and occasionally implemented [4,6] and might have benefits. This is an issue that deserves further investigation.

5.2. Conclusions

Energy signatures of air conditioning systems can be of several different shapes: the linear assumption which underpins degree-day analysis is not always valid.

Daily energy signatures can generate more robust energy consumption benchmarks and provide extra insight into unusual energy demand patterns for cooling systems, compared to monthly or weekly energy signatures. They can be used to generate benchmarks based on standardised annual consumptions or standardised annual load factor. In addition they can be used to generate control charts to identify days of unusual consumption for individual systems.

The parameter values of energy signatures have limited diagnostic power when considered individually, but combinations of values can provide pointers to the causes of unusual consumption levels. Additional investigation is required to positively identify specific causes, however.

More sets of daily consumption data are needed in order to evaluate the apparent diagnostic power of daily energy signatures. The recent availability of large quantities of sub-hourly data and the demonstration of the practicability of using it to identify specific sources of energy wastage [7] provide a means of going well beyond what is possible with daily energy signatures. However, this approach has the not inconsiderable issue of having to deal with much greater volumes of data, and all the problems this brings.

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Annex. Sensitivity of annual consumption to energy signature characteristics: an example

It is instructive to explore the sensitivity of annual consumption to different features of the energy signature. In the illustrative example, removing "tempering" would reduce annual cooling consumption by 15%. (There would also be a corresponding decrease in heating energy requirement).

[14] At least onsite—measurements from nearby meteorological stations might be available and satellite data is also now available.

Table 2
Sensitivities.

Measure	Scale of change to obtain 15% chiller energy saving
System	
Preheating of supply air	Completely remove
EER	Improve by 15%
No-load consumption	Reduce by 38%
Ventilation rate	Reduce by 69%. (There is a trade-off between loads on days when the outdoor temperature is above the set-point and those when it is below. This is affected by the use of tempering, which reduces the scope for "free cooling")
Activity	
Heat gains	Reduce by 16% (Reducing the gains reduces the number of days when cooling is required in addition to reducing the load when it is)
Internal temperature	Increase by 1.6 °C
Climate	
External temperature	Decrease by 1.75 °C. (Retaining the same distribution pattern)
Building	
Fabric and infiltration losses	Decrease losses by 34% (As for ventilation there is a trade-off between the effect on days warmer than the setpoint and those below it)

It is also instructive to explore the scale of changes to other parameters that would be necessary to obtain the same savings. These are shown in Table 2. below. In this building, consumption is sensitive to set-point values and to outdoor temperatures, and rather insensitive to ventilation rates.

Making plausible assumptions about the likely characteristics of an all-air system, the savings of cooling energy consumption as a result of a free cooling system would be about 25%. There would be, of course, additional energy use by fans which might well exceed these savings.

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