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A/C Energy Efficiency in UK Office Environments

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ABSTRACT

This paper presents preliminary findings of a two-year programme of field research and monitoring of the energy consumption of generic Air-Conditioning (A/C) systems in UK Office environments. The work is being undertaken to provide information on the actual energy consumption and operating efficiency of the systems as operated in these environments.

The preliminary findings presented in the paper include:

- The peak energy consumption per unit floor area by each generic A/C system type ranges from 20 W/m^2 for Chilled Ceiling systems, through to over 75 W/m^2 for Fancoil systems.
- A system performance ratio is defined based on estimated internal loads faced by the A/C system and the monitored consumption data, i.e. no correction for fabric and ventilation heat losses or gains. This ratio is used to allow a more direct comparison of the performance of the various A/C system as installed.
- An estimate that A/C loads in UK Offices could be comfortably reduced by over 50% if the lower energy systems could be replicated widely.

INTRODUCTION

Future projections of UK market trends suggest a large increase in the use of A/C resulting in increased energy demand and associated carbon emissions. *(BSRIA 2000)* This growth in the use of A/C threatens the UK government's commitment to reduce greenhouse gas emissions under the Kyoto protocol *(Hitchin 2000)* and has serious implications for the UK electricity supply infrastructure. *(National Grid Company 2001)*

Therefore the ability to select A/C systems that consume the least energy "in practice" is of importance if we are to minimize future carbon emissions. However, despite extensive testing and research into the performance of A/C and refrigeration equipment under laboratory conditions, comparatively little is known about how these 'efficiencies' translate into energy consumption in the real world. This research aims to provide some data to start filling this knowledge gap by monitoring the energy performance of A/C systems, "as found" in UK office accommodation with real occupants and operating practices.

The Welsh School of Architecture, Cardiff University in association with Toshiba-Carrier UK and the UK's Building Research Establishment, is undertaking the research. The work is also contributing data towards a concurrent research programme being undertaken by the UK National Grid Company and the UK Electricity Association, which aims to assess the effect of growth in the use of A/C on the UK's National Grid requirements.

The findings presented are derived from monitoring the energy consumption of 34 Office A/C systems at 15-minute intervals around the UK for between 12 and 18 months. Monitoring commenced in April 2000 and is expected to conclude in the summer of 2002. Internal and external environmental conditions are also being monitored concurrently at all sites in order to calculate the respective system loads over the same period.

RESEARCH OVERVIEW

The monitoring program is studying 34 installations of the following 5 generic A/C types:

- **Chilled Ceilings** (passive and active systems)
- **All-Air** (variable air volume (VAV) and constant volume (CV) systems)
- **Fancoils** (2-pipe and 4-pipe systems)
- **Split DX** (cooling only, 2-pipe inverter and reverse cycle systems)
- **3-pipe VRF/VRV** (direct expansion systems with the ability to simultaneously heat and cool)

The Office sites studied were selected to cover a number of examples of each of the generic types of A/C system (see table 1), and to mimic the UK national air-conditioned building stock regional distribution.

Table 1. Numbers of systems by system category

System type	All - air	Fancoils	Chilled Ceilings	DX - Splits	DX - VRF
Number of sites	9	7	5	9	4

The monitoring at each site covers the parameters shown in Table 2 at typically 15-minute intervals. For the purposes of this study it is recognised that the various system types often deliver differing levels of services but have limited ourselves to considering only the delivery of cooling to the occupied space. Loads associated with the provision of mechanical ventilation are therefore only included when the ventilation air is integral to the delivery of space cooling.

Table 2. Summary of monitored parameters at each site

Monitoring Parameters	**Measured units**	**Intervals**
Refrigeration, heat rejection & distribution loads associated with the cooling system	KWh & kVArh	10, 15,or 30 minutes
Internal temperature	°C	10, 15,or 30 minutes
Local external temperature	°C	10, 15,or 30 minutes
Local external relative humidity	%RH	10, 15,or 30 minutes

In addition to the monitoring shown, more detailed weather data has also been collected on a regional basis. We have also undertaken building surveys based on the CIBSE Energy Assessment and Reporting Methodology for Offices *(CIBSE 1999)* for each building.

The regional weather data includes; Temperature, Relative Humidity, Wind Speed & Direction, Solar Irradiance, and External Lux levels. Building surveys have been carried out on all the sample sites to determine the details of the building form & fabric, HVAC systems & controls, as well as their occupancy levels & patterns.

The currently planned outputs from the monitoring phase of the research include:

- Range of energy consumption of the generic system types
- Range of generic system performances based on space loads (An Internal Load Performance Ratio (ILPR) is produced for this measure, calculated as [internal load as calculated from survey (W/m^2)/ A/C system power consumption (W/m^2)])
- Range of power factors of A/C system components
- Range of proportion of energy consumption by A/C system components where possible
- Range of A/C consumption as a proportion of total building load
- Range of run-hours of A/C systems
- Refrigeration system Part-load profiles
- Range of occupied space temperatures provided by A/C systems

ENERGY CONSUMPTION PER UNIT AREA BY GENERIC SYSTEM TYPE

Figures 1 to 6 summarize the findings to date for the 'cooling only' energy consumption of the generic systems studied. This data is taken from the July 2001 monitored consumption for each system. The figures show the daily variation at 15-minute intervals in the weekday energy input to the A/C systems per m^2 of floor area served.

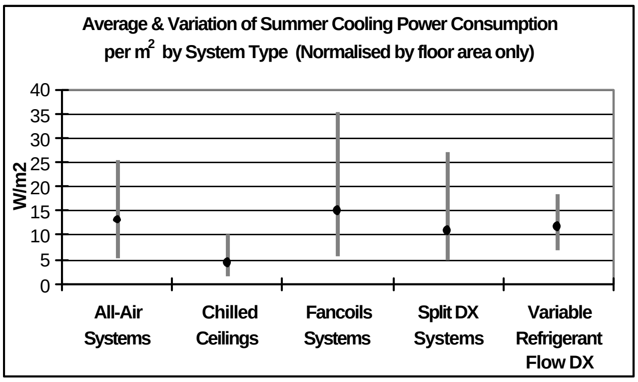


Figure 1.Cooling power consumption by system type.

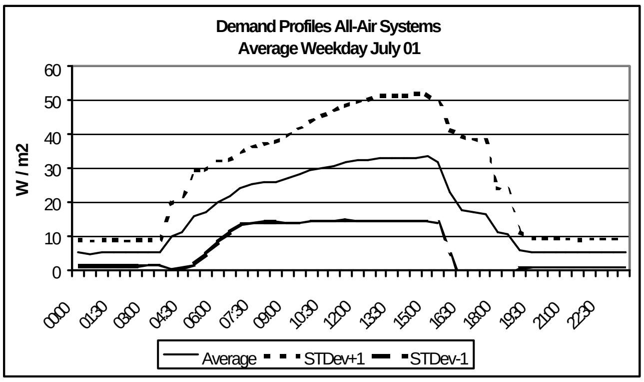


Figure 2. Average All-Air system energy profiles

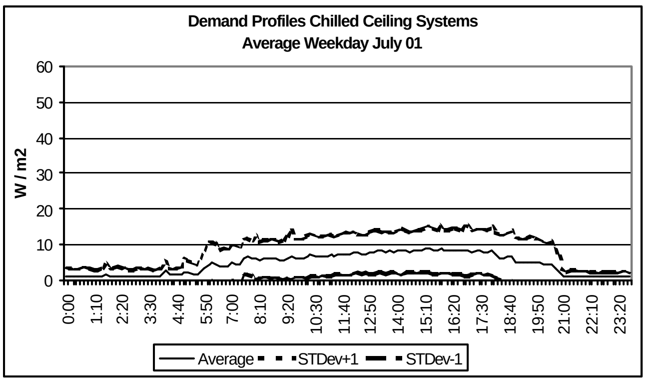


Figure 3. Average Chilled Ceiling energy profiles

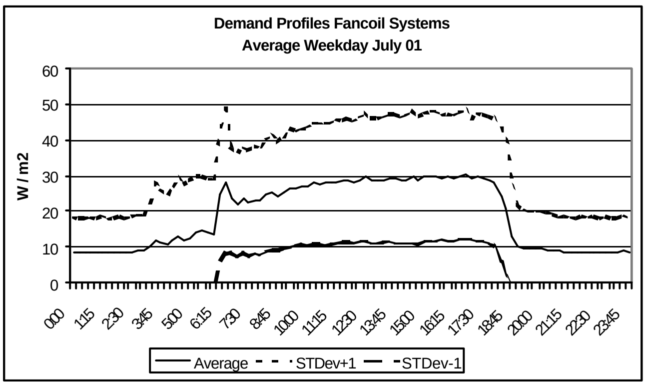
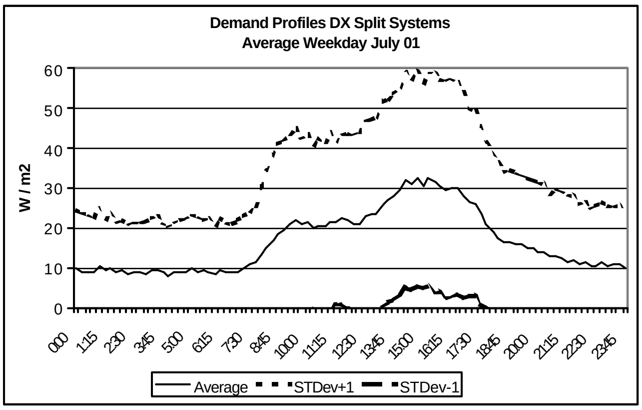


Figure 4. Average Fancoil system energy profiles



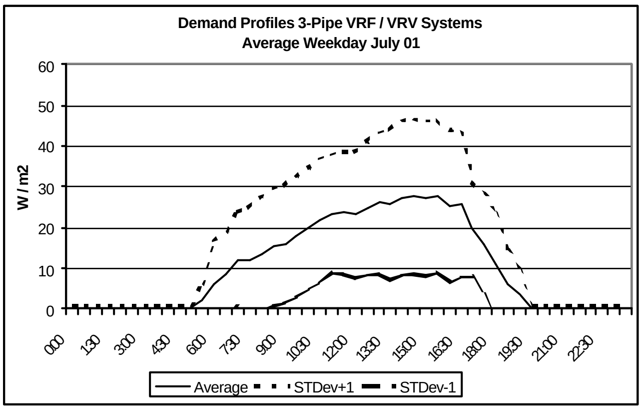


Figure 5. Average DX Split energy profiles

Figure 6. Average VRF/VRV energy profiles

Notable findings from figures 1 to 6 indicate:

- Peak power consumptions for the generic systems range from about 50 – 70 W/m^2 for All-air, DX, VRF and Fancoil, down to about 20 W/m^2 for Chilled Ceiling systems.
- Fancoil and all-air systems appear to consume the greatest amount of energy per unit area.
- Chilled ceiling systems consume the least energy per unit area.
- Chilled ceiling and VRF/VRV systems have the lowest ‘out-of-hours’ consumptions. The other system types have significant ‘out-of-hours’ energy demands.
- Most system consumptions rise during the working day, indicating reasonable control as the systems deal with the cumulative effect of solar gains and reduction of early morning cooling by the fabric.

ENERGY CONSUMPTION PER UNIT AREA BY GENERIC SYSTEM TYPE, NORMALIZED FOR INTERNAL LOADS

This section takes the data shown in figures 2 to 6 and normalizes it for the calculated internal load. The methodology for this calculation was as follows:

A survey of each site was undertaken to collect the required information on the buildings form, fabric, occupancy, and operation. The surveys were based upon the CIBSE Energy Assessment and Reporting Methodology *(CIBSE 1999)* and the internal loads have been calculated from the following information obtained during the surveys:

- Occupancy levels and patterns
- Type and quantity of heat producing appliances including equipment plate ratings.
- Type and quantity of lighting fixtures
- Method of lighting control

From the survey information the internal loads were calculated for each site using a CIBSE internal heat gain design calculation *(CIBSE 1999)*. Figure 7 shows the results of this calculation.

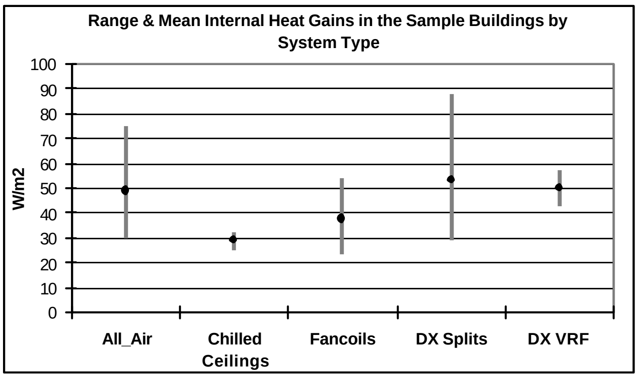


Figure 7. Calculated Internal Heat Gains

The calculated loads in our sample offices range from 24 W/m^2 to 88 W/m^2. These are broadly similar to current UK rules of thumb, which indicate internal heat gains in offices to be between 55 and 90 W/m^2 *(Hayward 1988)*. This may indicate that our calculated loads are higher than the actual loads within the buildings, as the rules of thumb are generally considered to be ‘safe’ design figures.

In order to graph this normalization it has been necessary to define a performance measure, which we have chosen to call the Internal Load Performance Ratio (ILPR). This is defined as:

$$ILPR = \frac{\text{calculated internal load (W/m2)}}{\text{power input to the AC system (W/m2)}}$$

The ILPR is therefore effectively a system Coefficient of Performance (COP) that does not include fabric or ventilation losses and gains, and uses a standard design methodology for calculating internal loads. From figure 7 it can be seen that the variation in internal loads imposed on the systems are quite large. It might also be noted that they are similar to the range of consumptions seen in figure 1.

Figures 8 to 13 show the results of normalizing the consumptions with these loads.

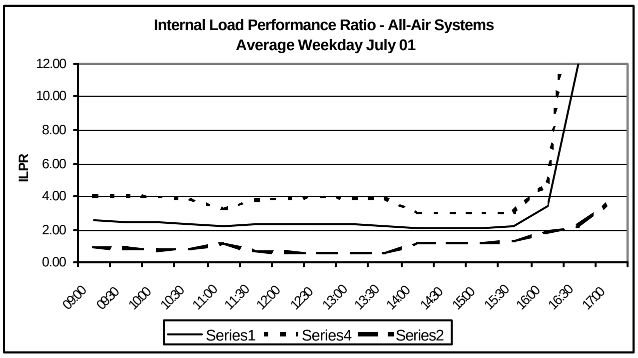


Figure 8. ILPR – All-Air Systems

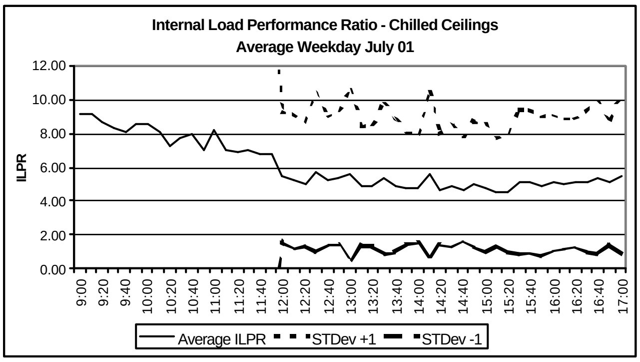


Figure 9. ILPR – Chilled Ceilings

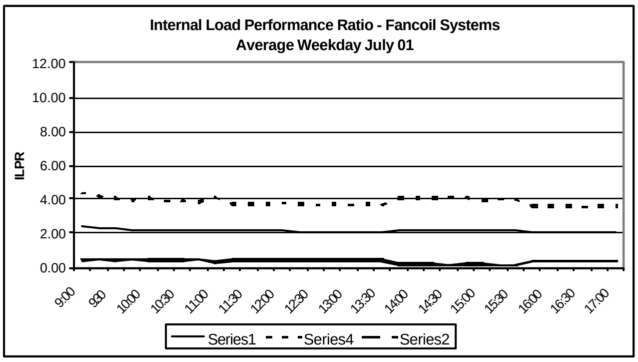


Figure 10. ILPR – Fancoils

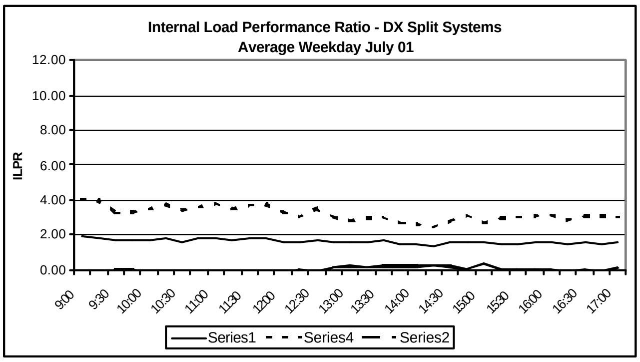


Figure 11. ILPR – DX Splits

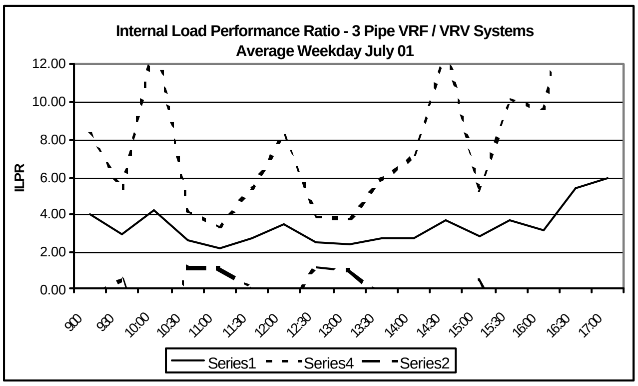


Figure 12. ILPR – 3-Pipe VRF/VRV

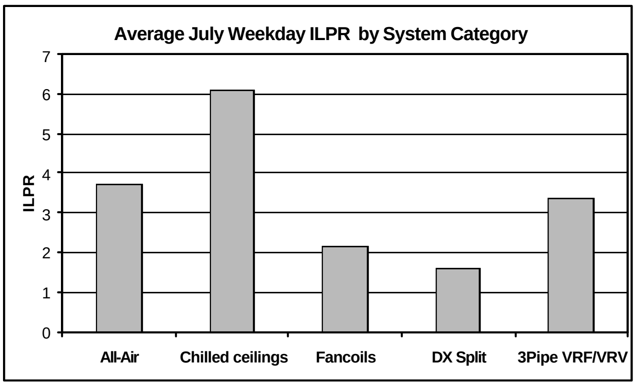


Figure 13. Comparison of Average ILPR By System Type

Notable findings from figures 8 to 13 indicate:

- Chilled ceilings still appear to be the most energy efficient systems
- VRF/VRV now emerge as the clear second best performer based on the ILPR definition of performance
- All-air systems, Fancoil systems and DX split systems appear to provide the lowest energy efficiencies in meeting the calculated loads. All air-systems appear to be as good as VRF/VRV systems from figure 13, but figure 8 shows this is simply the result of some of the sample systems turning off early during the working day. While we ought to just consider this as an example of good control, it is clear from the rest of the day that the all-air system performance is inherently no better than the Fancoil and DX systems.
- The ILPR's shown in figure 13 are perhaps higher than we might expect, given that they do not account for fabric or ventilation loads. This may be a consequence of the assumptions in the CIBSE Guide A design load calculation. Future analysis in this study will establish if this is the case.

GENERAL OBSERVATIONS

The preliminary findings presented in this section are based upon the period between March 2000 and December 2001. As a general point, the July 2001 period covered by the figures shown above was warmer than the 20-year average for the UK.

A key observation from the work, not shown in any of the figures or graphs here, is that the data suggests system control issues are a key factor affecting energy performance. A simple control issue on one system type increased the annual consumption by over 60%. Generally, localised systems and controls reduced cooling energy consumption, compared to similar systems under central control.

The **lowest** energy consumer of all the monitored systems utilised passive chilled beams served from a packaged air-cooled liquid chiller, with ventilation provided naturally through passive vents. Perimeter radiators served by gas boilers provide heating.

During July 2001 this system typically consumed only 5 W/m^2, with a peak of 15 W/m^2. It also operated for only 1891 hours per year (22%). Of interest is the fact that, even though this is a particularly low energy consuming system, the part-loading of the chiller was still quite poor - spending 90% of its time operating below 25% Capacity.

The **highest** energy consumer of the systems studied was a large office building served by a centralized 2-pipe fancoil system, with a large water-cooled screw compressor chiller and dry remote coolers. This system consumed an average of 37 W/m^2 during July 2001, reaching a peak of 75 W/m^2. The chiller ran 7683 hours per year (87%), spending 80% of that time below 25% of full-load. The main points of comparison for the two systems are summarized in Table 3.

Table 3. Comparison of lowest and highest energy consumer - selected data

Measure	Lowest	Highest
Typical summer energy input to entire A/C system (W/m^2)	5 (15 peak)	37 (75 peak)
Average Internal load served (W/m^2)	24.4	34.6
Average Internal Load Performance Ratio (ILPR)	7.7	0.68
Year of building construction	1989 (Refurbished 1995 with Chilled Ceilings)	1957 (Refurbished 2000)
Annual hours of use	1891 (22%)	7683 (87%)
Installed chiller capacity (W/m^2)	22.9 W/m^2	151.8 W/m^2
Glazing ratio:	40%	80%

From table 5 it is notable that the installed chiller capacities for the systems are roughly 1.5 to 2 times the peak demand recorded for the systems **including** their ancillary equipment.

CONCLUSIONS

There are significant differences between the uncorrected energy requirements per m^2 of treated floor area for the different air-conditioning system types. Peak fancoil system energy consumptions for the systems tested were around 75 W/m^2. In comparison, peak energy consumptions for the chilled ceiling systems were around 20 W/m^2. The remaining system types had peak consumptions of between 50 and 70 W/m^2.

Whilst these figures might be of interest in obtaining rules-of-thumb regarding the potential energy consumption for A/C systems based on any of the generic types, it is clear that the systems are having to deal with very different internal cooling loads.

To obtain a more accurate indication of the relative performance of the generic A/C system types we were able at this stage of the study to use a CIBSE design method calculation to normalize the monitored energy consumptions for the internal loads on the systems.

The results obtained after normalizing for these internal loads indicate that the energy consumption differences reduce for the majority of systems – though a clear efficiency ranking emerges, from DX splits as generally the most inefficient system type, through to the chilled ceiling systems which are markedly the most efficient.

These findings are still only provisional however, as the study has yet to model the heating and cooling loads imposed by the building fabric and ventilation for each building. Until this has been completed these apparent generic A/C system efficiency trends should be used cautiously. In particular, the study has suggested that some of the 'average' or 'poor' system types can deliver apparently outstanding efficiencies at individual sites, and these will need to be investigated in more detail.

However, assuming that the final conclusions do not alter dramatically, it would appear that the study will show that the provision of cooling in UK Office buildings can be undertaken far more efficiently than generally occurs at present.

The potential for reduction in current A/C energy use in the majority of UK Offices would appear to be comfortably over 50%, and possibly over 75% with holistic design techniques.

FUTURE WORK

The results and conclusions presented here have shown preliminary findings based on a standard methodology for calculating internal loads. The study still has to assess whether the building survey data and observations will produce similar internal loads to the CIBSE methodology.

It will also be necessary to assess the building fabric and ventilation thermal loads from our monitored data. It is anticipated that this information will be obtained via modeling, using ECOTECT software *(Marsh 2002)*.

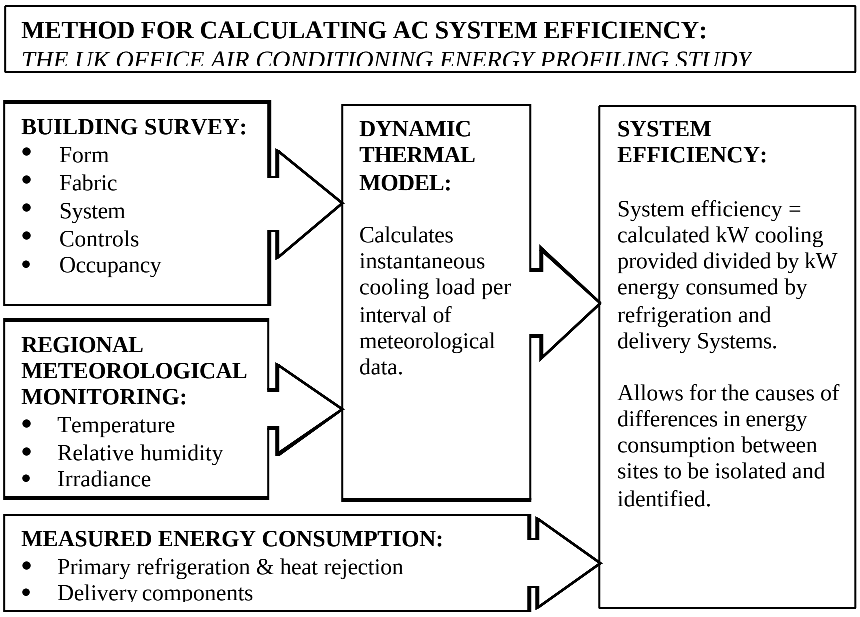


Figure 14. Method for calculating A/C system efficiency

Figure 14 shows how the study intends to produce the definitive system efficiency profiles for each building.

We expect some of the key outputs following the modeling work to be:

- Identification of the relative importance of load types, e.g. occupancy, fabric, solar, etc., for each office studied. From this will come information about the relative importance of building design versus A/C system design
- Predicted loads in offices studied, at 15-minute intervals
- Predicted A/C system efficiency profiles in the Offices studied, at 15 minute intervals
- Variation of cooling energy (W/m^2) required depending on system type, system control and method of cooling delivery
- More accurate 'rules-of-thumb' for rough sizing of various A/C system types
- An input to the next revision of the UK's Building Regulations Part L: Provisions for Energy Efficiency
- An Energy Efficiency Best Practice Programme publication updating the existing guidance in Good Practice Guide 74 on choosing A/C systems for energy efficiency
- Impact of plant sizing on cooling energy requirements for a given load for a given system

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