A Study Into The Extent Of Oversizing In 50 HVAC Systems

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BSRIA are currently conducting a research project aimed at promoting identification and amelioration of plant oversizing, with particular emphasis on providing assessment of potential energy savings achievable through the application of remedial measures. The objective of the project is to update existing BSRIA guidance, which will provide building operators with information on how to identify excess HVAC plant capacity and how to enhance the performance of such plant. The publication will highlight the extent of oversizing found in 50 UK sites, whilst additional case studies will look at the savings achieved on sites where action has been taken to ameliorate the issues associated with oversized plant. 50 HVAC systems have been monitored and the extent of plant oversizing established through analysis. It was found that 80% of heating plant, 56% of ventilation plant, and 100% of chiller plant incorporated capacity in excess of that required to meet design conditions. This paper presents the findings of these 50 initial case studies and a description of the monitoring and analysis techniques that were used.

INTRODUCTION

It is generally accepted that oversizing of building services plant is common in the UK and it has been estimated that 10 - 15% of HVAC energy consumption in UK building stock is due to plant oversizing[1]. Apart from the implications on energy consumption, excessive plant capacity can also result in increased capital costs, space requirements, reduced system efficiency, control problems, increased maintenance requirements and reduced plant life.

BSRIA has already produced guidance [2,3,4] illustrating how building operators can identify plant that is oversized and suggests some measures that can be adopted to improve the performance of it. BSRIA is now establishing exactly how serious the oversizing issue is by identifying the typical extent of the phenomenon in the UK. In addition to this, it is intended that the current research study will also authenticate the typical energy savings achievable from adopting remedial measures through the study of a number of before and after case studies.

Oversizing

The oversizing of plant is usually a result of the principles inherent in design calculations, the use of design margins, limitations of manufacturers' stock sizing, or change in building use, and more often than not a combination of all of these.

Design margins can be defined as 'any percentage change to a design value, parameter or calculation result whether a deliberate and valid design decision, a contingency or safety factor or an inadvertent addition'[5]. The use of margins without adequate (and defined) justification can be summarised as poor design and certainly not recognised as 'good design practice'. Given the current interest in value engineering and the emphasis in the Latham report [6] on design responsibilities and best practice it is important that designers should minimise margins by closer evaluation of their validity.

Heating Plant Margins

There are certain cases where plant oversizing is required for satisfactory plant operation such as boiler margins for pre-heating intermittently heated buildings. Boilers sized for steady state heat losses can be operated intermittently for most of the time and increased margins may be justified by a decrease in energy consumption. The CIBSE Guide B[7] recommends that a balance is struck between the extra cost of oversizing the boiler, and the expected energy savings achieved through intermittent operation. Determining the optimum boiler capacity required for an intermittent heating strategy can be complicated. There are a number of factors to be considered such as type of heating system, the building's thermal time constant and the rate of heat loss. Plant oversizing in excess of 25% of steady design requirements are unlikely to be justified and operation at low loads may lead to corrosion and loss in efficiency.

Cooling Plant Margins

CIBSE Guide A[8] advises that the maximum coincident gain should be the basis of plant sizing. However, if accurate control of room temperature is required it is advised that some additional capacity may be needed.

Ventilation Plant Margins

Margins to allow for installation variations tend to vary between engineers. UK engineers typically add 10% to the calculated fan total pressure[9].

Oversizing Factors

This paper details oversizing for heating, cooling and ventilation systems in terms of oversizing factors (OF's). These factors were developed from previous research [2,3,4]. Plant with an OF of 1 can be defined as plant with the 'ideal' capacity sized for steady state design conditions. This does not allow for any margins or stand-by capacity. It should be remembered that plant sized for steady state design conditions will have excess capacity when the outside conditions are less severe than the design day and therefore margins will exist for the majority of the time. Any OF above 1 will indicate the degree of excess capacity there is in the system and vice versa for any factor below 1. An OF of 2 would imply that the plant has got twice the capacity that is actually needed whereas an OF of 0.5 would indicate that the plant has only got half the capacity needed to meet design conditions.

HEATING PLANT

Twenty five heating systems were monitored in accordance with published guidance[3]. Thermistor temperature probes and data loggers monitored the flow and return temperatures of boiler plant at one minute intervals. External and internal air temperatures were also monitored every 15 minutes using temperature loggers. The existence and extent of oversized heating plant was then established by plotting the action of each burner during the coldest hour at the end of an occupied week. Where analysis had been conducted for a period above the external design temperature then formulae provided in the guidance for such instances were applied to adjust the OF's appropriately (see Appendix A).

Figure 1 illustrates the typical cycling characteristics associated with oversized heating plant, the OF is calculated from the ratio of burner on-time to total cycle time.

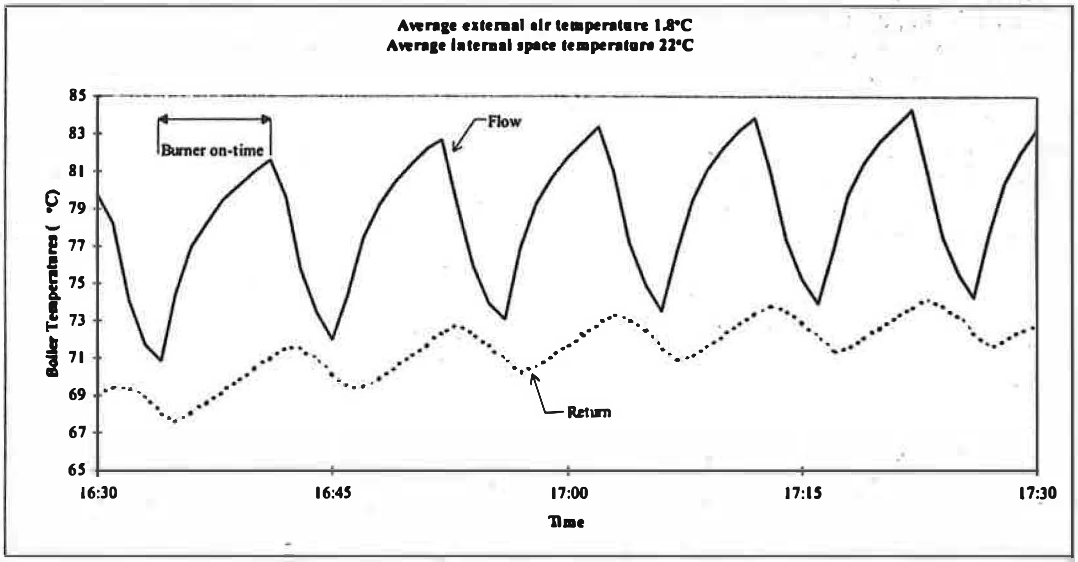

Figure 1: Boiler Temperature Profile Illustrating Burner On/Off Time

This process was repeated in 25 heating systems in an attempt to gauge a representative view of the actual extent of oversized heating plant in the UK (see Figure 2). The building applications they served varied from office buildings, schools, and leisure facilities, and related to both intermittent and continuously operated systems.

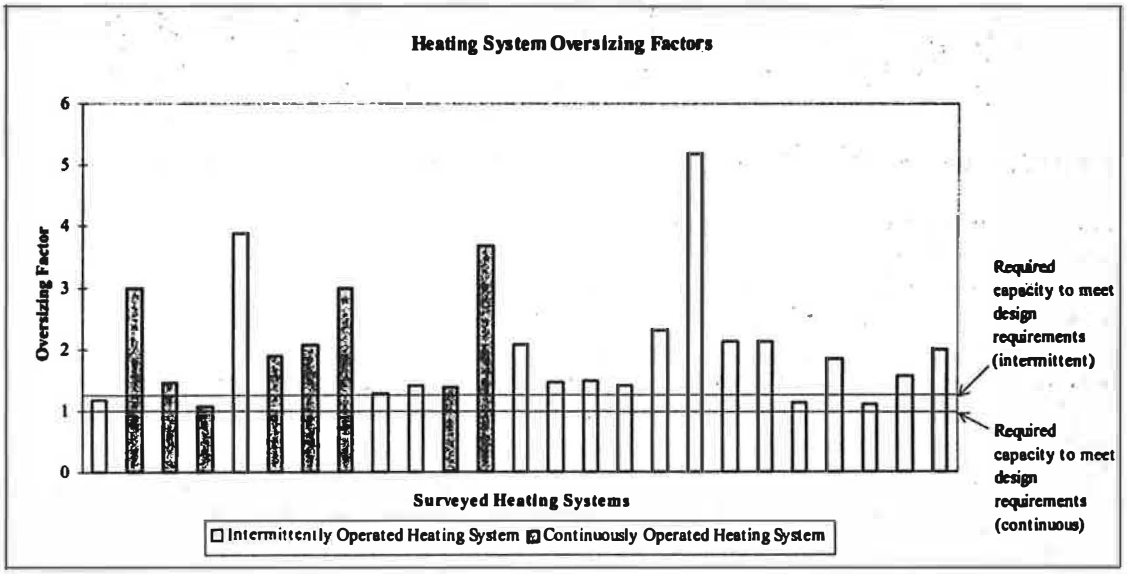

Figure 2: Heating System Oversizing Factors

From the surveys it was found that 88% of the continuously operated systems and 76% of the intermittent systems had more capacity than was required. If these percentages were applied throughout the UK building stock the implications for plant capital cost and potentially poor operational efficiency are significant. The required capacity line for intermittent systems used in figure 2, is based on a 25% margin. Actual preheating requirements will be as individual as the buildings and will depend on several factors including expected internal heat gains, building heat loss and thermal time constants.

VENTILATION PLANT

In accordance with published guidance[2] the monitoring of 16 constant air volume (CAV) systems was conducted. Air flow rates were measured by undertaking a velocity traverse in the supply and extract ducts. Measurements were taken using a pitot tube and micromanometer. Any oversizing of the fans was then calculated in terms of excess flow generated, which is the ratio of actual to specified air changes per hour (ac/hr) (see Appendix B). The ventilation system should provide the minimum recommended fresh air requirements. However, it is the supply air change rate which dictates the fan duty. It is therefore, the actual number of ac/hr being provided from the fan compared to the recommended air change rate which determines if and by how much a fan is oversized.

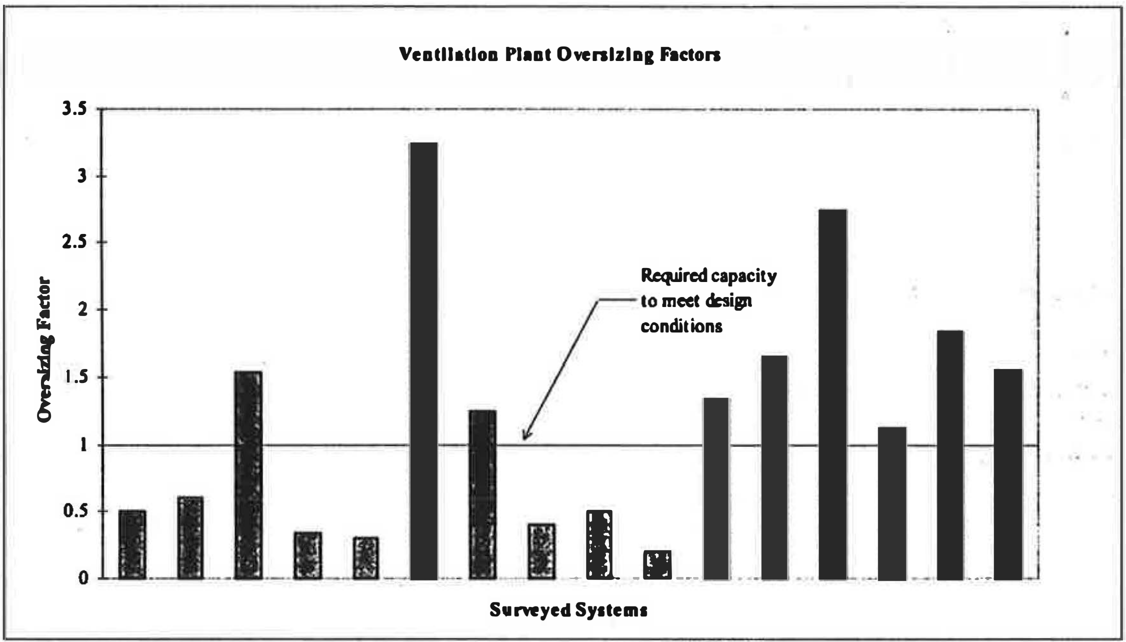

Figure 3: Ventilation Plant Oversizing Factors Based On CIBSE[7] Recommendations

From the surveys it was found that 56% of the ventilation plant had more capacity than was required (see Figure 3). There was some significant oversizing found with up to as much as 3 times the necessary fan size found in some instances. In contrast to the maximum OF's found, the results clearly show that there were a number of buildings in which the ventilation plant was not large enough to provide the current recommended air change requirements. In many instances actual original design data was not available. In such cases solely CIBSE recommendations on appropriate ac/hr were used as a basis for oversizing. Resulting OF's may therefore not be representative in terms of designers intentions but will be in terms of industry guidelines for airflow requirements for such building types. Another contributing factor to this could be that the air change rates recommended by CIBSE[7] are given in ranges for each building type. Using the limits of a recommended range gave significantly different results. For this reason the median values were always used.

COOLING PLANT

The monitoring of 9 cooling systems was conducted during the summer period. Following appropriate guidance[4], current transformer clamps were connected to each phase of each contactor serving the compressors of the cooling plant. Thermistor bead surface probes were attached to the chilled water flow and return pipes serving the chiller unit and the data was logged at one minute intervals. External and internal air temperatures were also monitored and logged every 15 minutes using temperature loggers. The existence and extent of oversized cooling plant was then established by plotting the control state of each compressor during the warmest hour of the week during occupancy. Cooling load is made up from loads associated with solar gain, internal gains, dehumidification requirements, and the heat transferred through the building fabric. Cooling systems should therefore be assessed when the influences peak but when the cooling demand is as stable as possible. This is usually taken to occur on a hot afternoon, assuming that the combined cooling loads will peak simultaneously with outside temperature. This assumption simplifies the monitoring and analysis required by omitting the need to monitor external and internal humidity. However, high wet bulb temperatures will require more work from the chiller to maintain suitable relative humidity in the building. It may complicate the process, but to accurately establish when peak loads occur, the outdoor wet bulb and internal relative humidity should be monitored in addition to the OAT. The OF is the ratio of the maximum number of available chiller plant stages to the average number of stages operating over peak load (see Appendix C). Where analysis has been conducted for a period with peak outside air temperature (OAT) below the external design temperature then formulae have been applied to adjust the OF's appropriately.

Figure 4 illustrates the typical cycling characteristics associated with oversized cooling plant. When monitoring water temperatures using surface probes, care must be taken to recognise that accuracy may be compromised through the thermal contact. For more accurate results immersion probes should be used where possible.

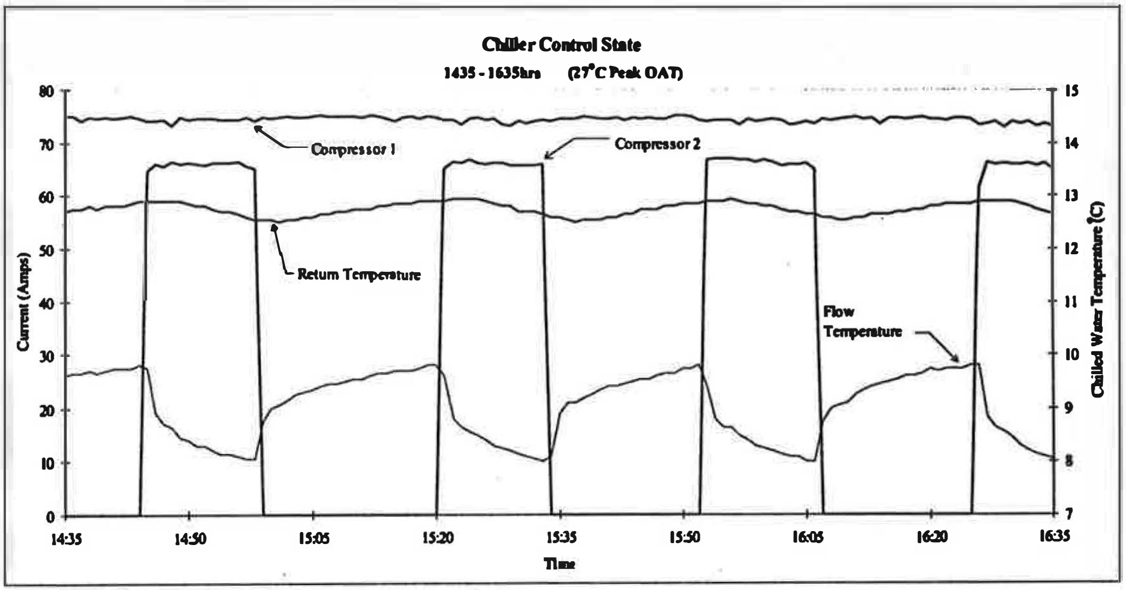

Figure 4: Typical Chiller Operation Profile

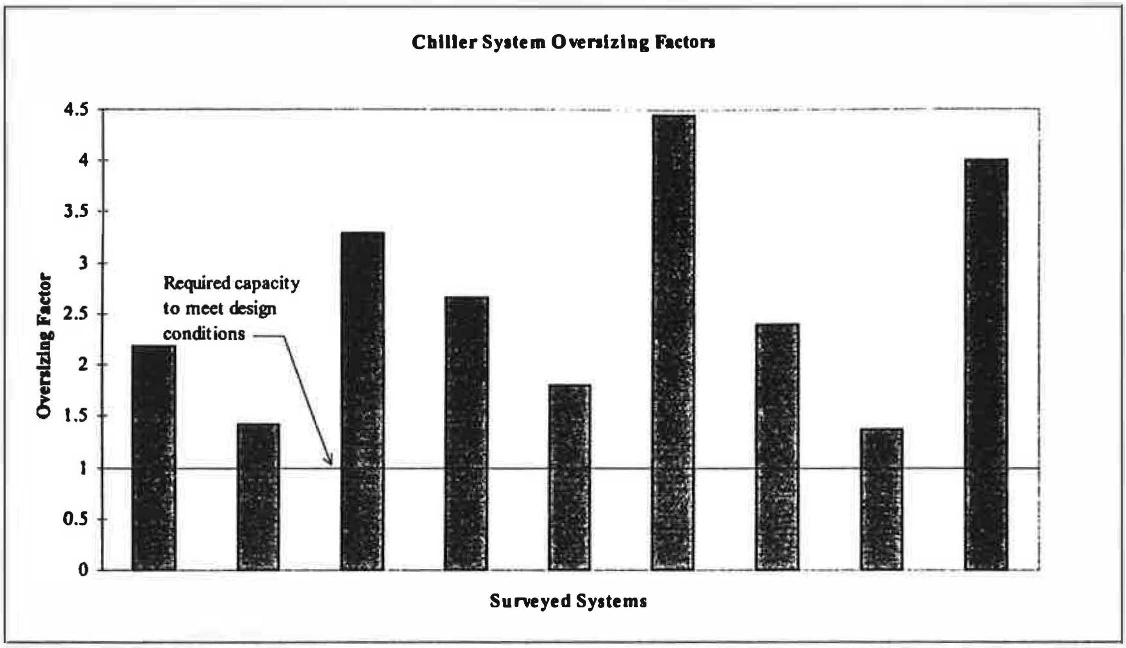

Figure 5: Cooling Plant Oversizing

From the surveys it was found that 100% of the cooling systems had more capacity than was required (see Figure 5).

DISCUSSION

The surveys conducted have highlighted the problem of oversized HVAC plant with the worst instances found to be in heating and cooling plant. These typically account for 23% and 17% of energy costs respectively in a large air conditioned office building[3,4]. Whilst the potential implications of inefficient oversized plant can be costly, the affect of modular plant and method of capacity control may offset some of the increased energy consumption. The results have also indicated that there is no such thing as 'typical' oversizing. This is confirmed in figure 6 which groups those buildings in which more than one system was surveyed.

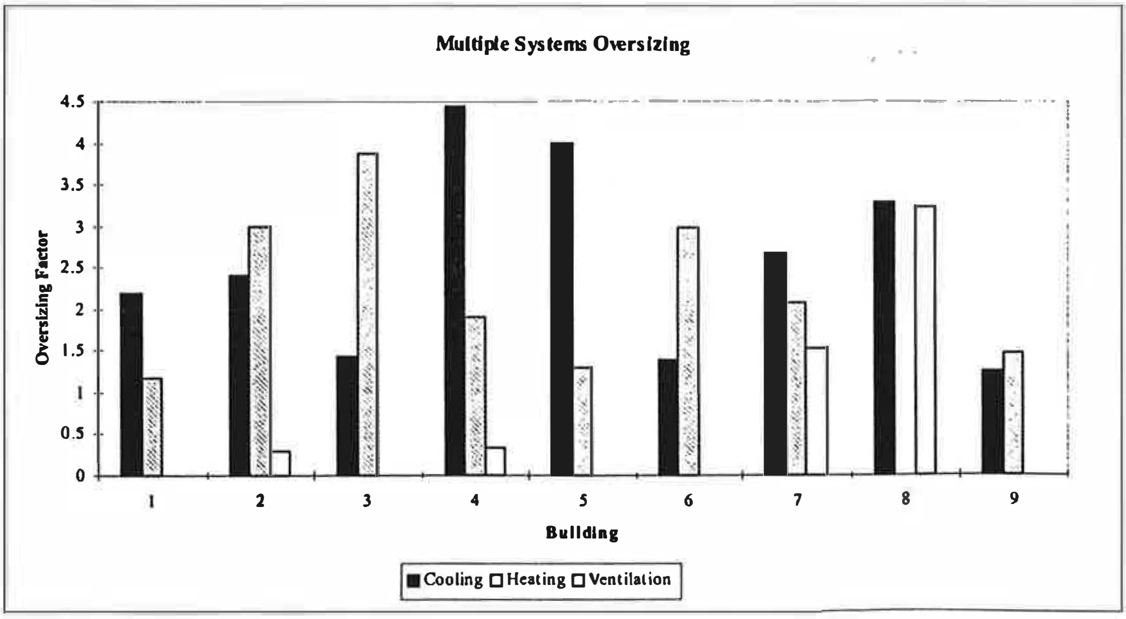

Figure 6: Multiple System Oversizing

Establishing Oversizing Patterns

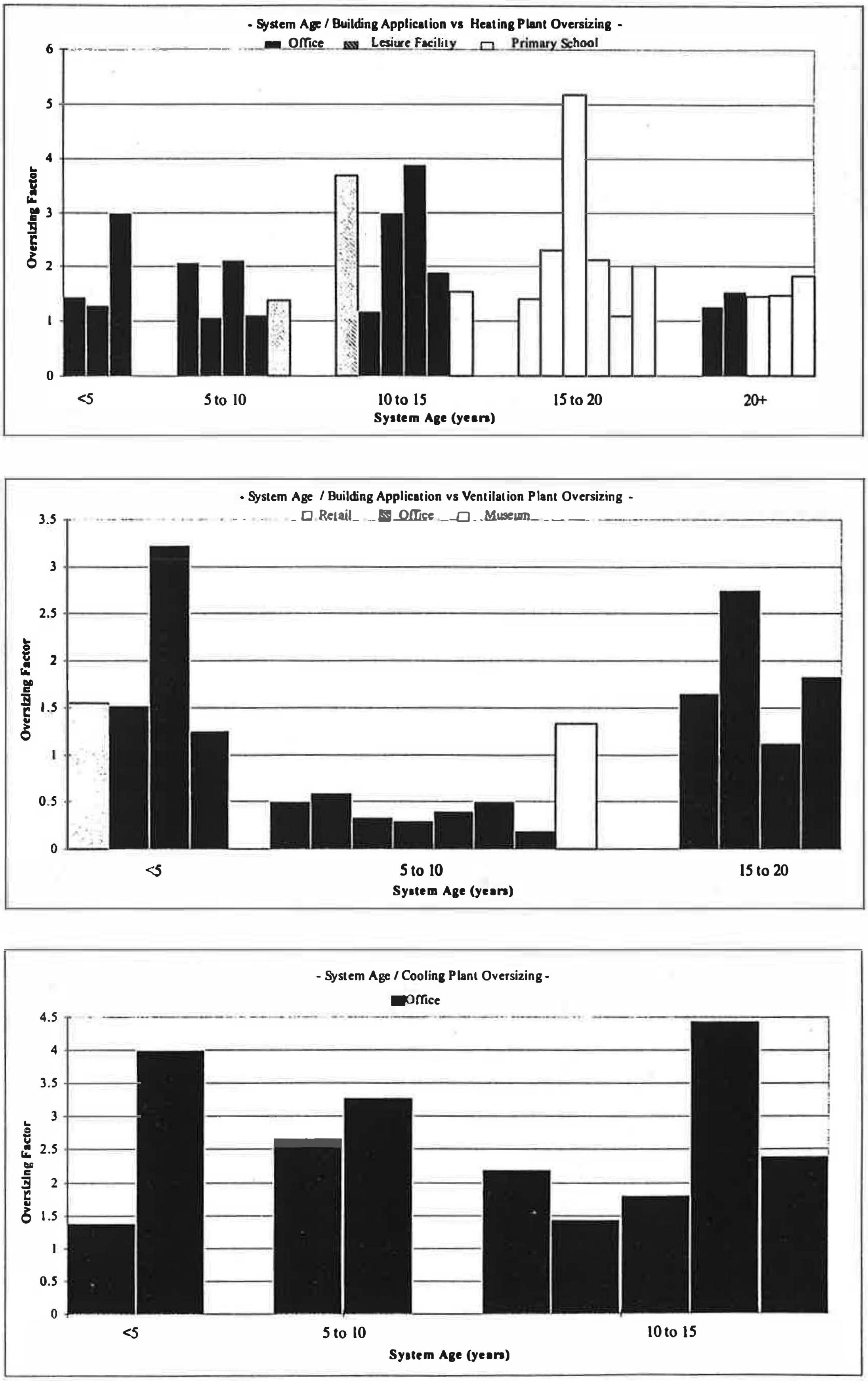

Figure 7: Oversizing in relation to system age and building application

Where possible, the oversizing results have been classified into different building types and system age. The results of this exercise are highlighted in figure 7.

There is little indication that either HVAC system age, nor the building application are of any great significance on the extent of oversizing. Better design and building practices over recent years combined with an ever increasing focus on energy efficiency should imply that newer buildings show a decrease in oversizing. However, this does not manifest itself in the monitoring results for any of the plant. The older buildings may have HVAC loads that have changed from that initially intended which in turn leads to a shift in plant requirements and may result in the plant becoming over or undersized.

From the surveys, there are no apparent improvements in the extent of oversizing in the newer systems. With the availability of improved capacity control techniques such as variable speed drives, modulating burners and sequencing control, reduction in OF's should be achievable. Trends in designing for flexibility, the increasing use of litigation, increasing internal gains with better insulated buildings, or the increasing use of software packages which tend to incorporate margins usually unknown to the user, may all contribute to the OF's remaining high.

The problem of oversizing at the design stage is further heightened in speculative office buildings. In such cases the actual internal gains are unknown at the design stage and will be very much dependant on the tenants' working practices. Good capacity control of HVAC plant is essential in all buildings.

Heating plants of 20 years or older did, however, prove to have the most consistent and lowest OF's. For the ventilation surveys systems 10 to 15 years old nearly all proved to be undersized. No relationships between system age and cooling plant emerged at all.

Incorrect assessment of internal heat gains may be a possible reason for such an extent of oversized cooling plant. Small power loads, particularly for office and other equipment is generally far less than design calculations predict[10,11,12].

CONCLUSION

What has clearly emerged from this study is that there is no trend when it comes to oversized plant which suggests that overengineering and poor system evaluation is still present in modern building services design practices. This is most surprising considering all the advances in HVAC plant technology and in building services design over the last 20 years. However, oversizing of plant is not such a problem if modular and/or good capacity control techniques are adopted. It is for this reason that the next stage in the BSRIA project is to identify and promote the typical savings that can be achieved when remedial action is taken on such items of oversized plant. This will be done through monitoring a number of case study buildings before and after such remedial measures have been applied. The ultimate goal of the project is to produce guidance which will aid building operators by initially illustrating how to identify if they have oversized plant and then to demonstrate the measures that can be taken to enhance the performance of such plant. The guidance will be of use to building operators attempting to achieve energy savings with existing plant. It will also be of use in those buildings in which plant refurbishment is intended by helping to determine the correct replacement size. In addition, the process may also detect defects in system operation that are affecting system performance.

The new publication will take the form of a guidance note incorporating:

- Summary of 50 oversizing case studies
- Implications of oversizing
- HVAC plant monitoring techniques
- Monitoring technique case studies
- Step by step calculations to establish installed excess plant capacity in terms of oversizing factors
- Performance enhancing techniques, including typical achievable savings
- Step by step energy saving calculations
- Energy saving case studies

The full results from the BSRIA study will be available early next year in the publication 'Enhancing the performance of oversized plant'.

ACKNOWLEDGEMENTS

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APPENDIX A: EXAMPLE OF BOILER OVERSIZING ASSESSMENT

System Description

Six gas fired boilers provide a heating capacity of 300 kW to 1858 m^2 of office space in the South East of England. The boilers are served with on/off burners and are operated continuously. The building and the plant are 10 years old.

Methodology

The methodology is as follows[3].

Step 1: Basic indicators

Basic heating plant capacity yardsticks[13] are used as an initial indicator of oversizing.

Building Type	Installed Capacity	Basic Yardstick[6]	Expected Oversizing Factor
Office	162 W/m^2	90 W/m^2	1.8

Step 2: Plant Monitoring

A more accurate assessment of boiler oversizing was conducted using plant monitoring. The plant monitoring was implemented during a cold winter week as described and the coldest outside air temperature (OAT) for a one hour period during building occupation was determined from the external temperature logger. The average OAT for the selected period was found be 0°C, with a corresponding average internal air temperature of 23.4°C.

Step 3: Assess observed boiler plant oversizing

The temperature profiles for the boilers were plotted for the selected one hour period which equated to a total cycle time for the six boilers of 360 minutes. The total burner on time was found to be 105 minutes. The OF for the boiler plant was determined by calculating:

$$\text{OF} = \frac{\text{Total cycle-time}}{\text{Burner cycle-time}} = \frac{360}{105} = \mathbf{3.43}$$

Step 4: Adapt for design steady-state

The external design temperature for the South East of England is -3°C[7] and therefore the OF must be adapted to cope with this more extreme condition.

$$\text{Design steady-state OF} = \text{OF} \times \frac{(T_b - T_m)}{(T_b - T_d)}$$

where:

T_b = base external temperature for which no space heating is required (assume 3.5°C less than the average space temperature during occupancy - from maximum 19°C[14] heating restriction and 15.5°C[15] degree day base temperature. Health care premises use a base temperature of 18.5°C)

T_m = monitored external air temperature (take the average external temperature used for calculating initial OF)

T_d = design external temperature

$$\text{Design steady-state OF} = 3.43 \times \frac{(19.9 - 0)}{(19.9 - (-3))} = \mathbf{2.98}$$

For an intermittently heated building additional heating system capacity may be required to heat up the building in the morning, particularly after a weekend. For such cases further analysis is required to assess these preheat requirements. It should also be noted that where burners are high/low or modulating, then the control signal to the burner must be monitored and the OF is the reciprocal of this average control signal during the hour of the peak afternoon (assuming 0-10V signal).

APPENDIX B: EXAMPLE OF VENTILATION PLANT OVERSIZING ASSESSMENT

System Description

An AHU in a 4th floor plantroom provides via fan coil units, a constant air volume (CAV) to 7333 m^3 of office space. The system comprises of two main supply ducts and two main extract ducts serving opposite ends of the building. Existing test points where located on each of these ducts.

Methodology

The methodology for CAV systems is as follows[2], different methodology is required when assessing variable air volume systems.

Step 1: Basic indicators

Basic fan capacity yardsticks derived from CIBSE recommended air change rates[7] are used as an initial indicator of oversizing.

Building Type	Recommended Air Changes[7]	Basic Fan Capacity Yardstick (air supply)
Office	5 Ach/hr	1.4 l/s/m^3

Step 2: Plant Monitoring

A series of air flow rates for both supply and extract fans were measured and logged for each of the 2 supply ducts and the 2 extract ducts.

Supply : Branch A

Duct Size : 1050 x 650 mm

	Measured Velocity (m/s)					
Position	1	2	3	4	5	6
1	4.0	4.2	5.1	5.7	5.8	5.6
2	7.6	7.7	9.8	10.0	10.8	10.3
3	12.0	13.2	13.5	13.9	14.0	13.4
4	14.3	14.8	14.5	14.5	14.5	14.2
5	12.8	15.1	14.7	14.7	13.2	9.0
Average	10.14	11.00	11.52	11.76	11.66	10.50
Overall Average	11.10					

Supply : Branch B

Duct Size : 1050 x 650 mm

	Measured Velocity (m/s)					
Position	1	2	3	4	5	6
1	8.9	10.0	10.8	11.3	11.0	10.4
2	10.6	11.4	11.8	11.8	12.0	11.6
3	11.0	11.5	12.0	12.1	12.2	12.0
4	12.1	12.6	12.8	12.7	12.7	12.0
5	13.1	13.0	12.9	13.1	13.3	13.0
Average	11.14	11.70	12.06	12.20	12.24	11.80
Overall Average	11.86					

Supply Volume : average supply velocity (m/s) x duct area (m^2)

Branch A: 11.1 x 0.68 = 7.55 m^3/s
Branch B: 6.3 x 0.748 = 4.71 m^3/s
Actual supply volume (Q): 7.55 + 4.71 = **15.61 m^3/s**

Measured air changes per hour :

$$\frac{Q \times 3600}{V} = \frac{15.6 \times 3600}{7333} = \mathbf{7.66}$$

where:
V = volume of space served (m^3)

Supply fan OF was then calculated using:

$$\frac{\text{Measured air changes per hour}}{\text{Recommended air changes per hour}} = \frac{7.66}{5} = \mathbf{1.53}$$

APPENDIX C: EXAMPLE OF COOLING PLANT OVERSIZING ASSESSMENT

System Description

Three, two step chillers provide a cooling capacity of 1200 kW to an office space with a total mechanically cooled floor area of 5200 m^2. The plant and building are 12 years old and are located in the South East of England.

Methodology

The methodology followed is per recommended guidance[4].

Step 1: Basic indicators

Basic cooling plant capacity yardsticks[13] are used as an initial indicator of oversizing.

Building Type	Installed Capacity	Basic Yardstick[13]	Expected Oversizing Factor
Office	231 W/m^2	140 W/m^2	1.65

Step 2: Plant Monitoring

A more accurate assessment of chiller plant oversizing was conducted using plant monitoring. The plant monitoring was implemented during a warm summer week as described and the hottest OAT for a one hour period during building occupation was determined from the external temperature logger. The average OAT for the selected period was found be 29°C.

Step 3: Assess observed chiller plant oversizing

The control states of each compressor of each chiller were plotted for the selected one hour period and the average number of stages operating assessed. The OF of the chiller plant was then found by calculating:

$$OF = \frac{\text{Maximum number of available chiller plant stages}}{\text{Average number of stages operating over hour of peak load}} = \frac{6}{4.2} = \mathbf{1.43}$$

Step 4: Adapt for design steady-state

If the outside conditions had been cooler than the recommended design conditions[7] then the OF would need to have been reduced to accommodate this. Since the OAT met the specified 29°C for the South East of England, there was no need to conduct further analysis and the OF stands at 1.43. The calculations required to adjust the OF can be found in the *Oversized cooling and pumping plant*, Guidance Note[4].