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Evaluations and Comparisons of the Achieved Energy and Environmental Performance of Two Library Buildings in England and Sweden

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ABSTRACT

Energy and occupant surveys have been carried out in two completed buildings at Visby in Sweden and Gloucester in England. The two buildings are similar in purpose, combining library and university departmental accommodation, but the Visby building is three times the size of the Gloucester building and also used by the general public. Both use a combination of passive measures (such as insulation, thermal capacitance, and daylighting), engineering systems, control measures, and renewable energy to help maximize their energy efficiency and minimize their use of delivered energy from public utilities and the associated carbon dioxide emissions. The measured annual energy performance of the two buildings—both overall and by individual end uses—is compared with UK benchmarks for office and university buildings and with other low-energy university library and departmental buildings investigated by the authors and associated organizations. The energy performance of the Visby library is already close to the best—and could become the very best of all the buildings studied by the authors if the recommended improvements to control and management are carried out and prove successful. Some of these are already in progress. Even before improvement, the building had done better than its design target, with very low energy consumption for heating more than compensating for a 30% increase in electricity consumption for other purposes. The Gloucester building offers more room for improvement.

INTRODUCTION

Energy and occupant surveys have been carried out at two completed buildings at Visby in Sweden and Gloucester in England. The two buildings are similar in purpose, combining library and university departmental accommodation, but the Visby building is three times the size of the Gloucester building and is also used by the general public. Both buildings were designed for minimum energy use and carbon dioxide emissions, using combinations of load avoidance, load reduction, engineering control and management measures, plus contributions from renewable energy supplies. Both use a combination of passive measures (such as insulation, thermal capacitance, and daylighting), engineering systems, control measures, and renewable energy to help maximize their energy efficiency and minimize their use of delivered energy from public utilities and the associated carbon dioxide emissions. Both have mechanical ventilation systems integrated into the building structure, with heat recovery using thermal wheels. The Visby building uses seawater heat pumps, while the Gloucester building has a more conventional heating system with condensing gas boilers. Both have photovoltaic (PV) panels, but the Gloucester installation is over ten times the size of Visby's installation.

The authors have undertaken assessments of the performance of the buildings in operation, in particular annual energy use and occupant satisfaction of the permanent staff. The methods used were derived from those successfully applied by the authors in the published series of Probe post-occupancy studies in the UK and elsewhere (*Building Research & Information* 2001). The performance assessment used robust methods developed by Probe to obtain sufficiently reliable information to draw meaningful conclusions and actionable findings without going to the expense of detailed monitoring.

This paper compares and contrasts the two buildings and their energy systems, reviews their energy performance and occupant satisfaction in comparison with each other and with

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other similar buildings previously studied by the authors, and concludes with some key messages that highlight the many successes of the buildings and also point out some of the shortcomings in the delivery of the design intent and what might yet be improved, all of which are relevant to the procurement and operation of buildings across Europe.

THE BUILDINGS AND THEIR ENERGY SYSTEMS

The Visby Building

Almedals Library in Visby, on the Swedish island of Gotland, was procured jointly by the Municipality and University of Gotland and completed in autumn 2001. In addition to the 4006 m^2 (net) of library accommodation, associated offices, and support areas shared between university and public use, the building contains 1408 m^2 of university teaching and research space and staff offices and 250 m^2 for the local authority. The gross area of the building is 7350 m^2. The treated floor area (TFA, used as the denominator in this report when expressing energy use or CO_2 emissions) is estimated to be 90% of the gross area, i.e., 6615 m^2.

Energy-Saving Strategy and Systems at Visby. The Visby building has an integrated approach to energy efficiency, with the following features:

- A highly insulated envelope with external walls that have a maximum U-factor of 0.15 $W/m^2{\cdot}K$, windows including rooflights of 1.2 $W/m^2{\cdot}K$, and roofing of 0.16 $W/m^2{\cdot}K$.
- Low air infiltration rates. An air leakage standard of 6 m^3/h per m^2 at 50 Pa was required by the 1988 Swedish Building Regulations (Limb 1994), but pressure testing has not been required for many years as it was shown some 20 years ago that Swedish designers and builders had learnt how to achieve such good airtightness routinely (Sherman and Chan 2004).
- Effective solar shading, with a limited south flank to an adjacent building, overhangs and trees on the east side, and shading by louvres with photovoltaic cells on the south side.
- Exposed internal concrete construction to retain heat.
- Low-velocity low-pressure mechanical ventilation with building-integrated low-resistance air paths and displacement ventilation in most areas. Some rooms, particularly the university teaching rooms on the fourth (top) floor, also have motorized openable windows.
- Heat wheels for heat recovery on the ventilation plant.
- An electric heat pump for heating via the air-handling plant and perimeter radiators, each with an electronic thermostatic controller responding to room temperature and BMS overrides.
- Seawater as the source of heat for the heat pump taken from 30 m depth in the Baltic, via a water-to-seawater heat exchanger in an underground pumping station at harborside.
- The ability to export surplus heat from the heat pump to adjacent buildings.
- In summer, using the cool water from the seawater heat exchanger directly for cooling the building, both via the ventilation plant and using chilled beams at ceiling level.
- Energy-efficient lighting, with good daylight in some areas, occupancy-sensing in meeting rooms, and automatic dimming in the triple-height entrance/meeting/cafe area at the north end where a fully glazed north wall faces onto a public park surrounded by historic buildings.
- Subject to obtaining planning consent as part of Visby's status as a World Heritage Site, there is a long-term plan to increase renewable energy supplies to the building by adding a wind turbine beside the harbor and more PV panels.

The Gloucester Building

The Learning Resource Centre (LRC) building at Gloucester was completed in autumn 2002 as part of a new university campus for the University of Gloucestershire, containing three main elements: the LRC; the Sports Science building, and student residences. At 2720 m^2 gross, the LRC is a little over one-third of the size of the Visby building, with a TFA estimated at 90% of the gross area, i.e., 2448 m^2. The LRC contains a library on the north side and a lecture theatre, teaching rooms, and staff offices on the south side.

Energy-Saving Strategy and Systems at Gloucester. The LRC also has an integrated approach to energy efficiency, with the following features:

- A highly insulated envelope for the UK, though not to the standard of the colder Visby. External walls have U-factors of 0.25 $W/m^2{\cdot}K$, windows and rooflights 1.9 $W/m^2{\cdot}K$, library with north-facing glazing 1.6 $W/m^2{\cdot}K$ and roofing 0.2 $W/m^2{\cdot}K$.
- Low air infiltration rates were aimed for, but this is something not achieved routinely in the UK (Potter et al. 1995; *Building Services* 2000). A pressure test undertaken upon completion revealed an air permeability at 50 Pa pressure of 10 m^3/h per m^2 of envelope area (including floor). This was incidentally just compliant with the building regulations requirement for non-domestic buildings in England and Wales introduced in 2002 but not in force for the LRC. The permeability is equivalent to an air leakage index of about 12 m^3/h per m^2 of envelope area (excluding floor) per hour, at least two times the air leakage index of the Visby building (which is also bulkier, with smaller surface-volume ratio).
- Effective solar shading, with a fully glazed north wall to the library with vertical fins and limited glazing on the other facades, with external horizontal louvres to the south and west.

- Integrated mechanical ventilation and cooling (with heat wheel heat recovery, as at Visby) with fabric heat storage using ventilated hollow core slabs with exposed concrete ceilings and ventilated raised floors in the library and offices.
- A separate concrete hollow-core slab system for the 200-seat lecture room, with variable-volume fans controlled by carbon dioxide sensors in the return air duct.
- Energy-efficient lighting.
- A large (64.4 kWp) photovoltaic array—over ten times the capacity of the installation at Visby—integrated with the sawtooth northlight roof of the adjacent sports science building.
- Heating at the LRC is relatively conventional, with condensing gas boilers in the adjacent Sports Science building supplying a constant-temperature circuit to heater batteries in the ventilation plant and a variable-temperature circuit to radiators under the windows and trench heating in the library on each of the three floors against the fully glazed north facade.

Electronic Control Systems

Both buildings include comprehensive HVAC controls through an electronic building management system (BMS), as described above. Lighting control was less comprehensive, with presence-sensing in a few areas in both buildings and automatic daylight-linked dimming in the entrance foyer and perimeter areas of the library at Visby, the latter still not working properly, and in the main spaces at Gloucester. At Gloucester, the designers proposed occupancy-sensing in the library (which occupies half the net floor area of the building), but this was rejected by the client and the project managers on the grounds of capital cost and poor operational experience on previous schemes.

Metering

Both buildings are located in a campus environment and are attached to other buildings. This means that the standard meters used by the utility suppliers are insufficient to measure the energy consumed by the building. A European Commission research project, Eubart (Islenet 2004), has meant (and facilitated) the installation of a lot more metering than is normally present in such buildings, which allows both the buildings' overall energy use to be measured precisely and an energy audit to be based on measured rather than calculated values. However, several problems have arisen with the metering, with the consequence that some of the objectives for it have not been fully met:

- A lack of clear and accurate information as to where exactly submeters sit on the electrical distribution network; this manifested itself in poor reconciliation at Visby between the main ventilation submeter and four fan sub-submeters and at Gloucester between the three plant submeters and bottom-up calculations.
- Poor documentation of the current transformer factors for the Visby submeters.
- Although the submeters were automatically read by the BMS (which often they are not), there was no strategy for processing the meter readings into a digestible energy report. In both buildings it proved necessary for the authors to spend a lot of time analyzing the readings to turn them into a plausible story for how energy was being used. In the future, particularly with the introduction of energy certificates based on measured consumption (see below), it is to be hoped that the metering strategy will include a scheme for processed outputs.
- Difficulties accounting for renewable sources of energy, energy exports, and centralized plant. Both buildings presented issues for energy measurement and certification that will not be common but that nevertheless will need to be dealt with. At Visby, some of the electricity assigned to the building by the utility was used to provide heat to adjacent buildings and had to be deducted. At Gloucester, heat came from a centralized plant whose efficiency was not being monitored. In both buildings, the contribution of PV had to be taken into account—we have reported the buildings' energy performance with and without the PV.

Perhaps because of the above, a scheme for energy monitoring and targeting (M&T) is not in place at either building. However, this study has laid the foundations for an M&T system to be introduced and the authors hope that the necessary resources will be made available to implement it.

An EU Directive (on the energy performance of buildings) required both buildings to display an energy certificate from January 2006. Although not yet published, it seems likely that this certificate will be based on metered energy consumption over a year, which suggests a need to meter such buildings individually, even when they are on a campus as is the case for these two buildings. As described above, neither building has an easy way to identify the building energy use precisely, even with the range of submeters available. At Gloucester in particular, there is a need to apportion the site's gas consumption to the three main buildings. This would require, in addition to what is already installed, a submeter on the gas used in the Sports Science plant room, a sub-submeter on the gas used by the water heaters, and heat meters on the space heating boilers' output to the Sports Science building.

Procurement and Management in Use

There are some interesting contrasts between the procurement procedures used by each building. The Municipality of Gotland employed in-house procurement staff who adopted a partner-like approach where all parties/contractors seemed to enjoy a shared interest in delivering a quality product at a fair price. The University of Gloucestershire employed an external project management team with a priority to contain the budget (and program). This lack of resources hindered the subcontractors and design consultants from fully resolving some of the issues that inevitably arose as a result of employing several innovative concepts and technologies.

The energy performance of any building is also strongly influenced by its operation and management. Three key factors shared by both buildings stand out in this regard:

1. Both the buildings are part of estates that contain many buildings spread out over a wide area and managed by the building owners' centralized Estates Departments rather than on-site building or facilities managers. Both buildings are also undoubtedly among the better performing of their estates, and one inevitable consequence is that they receive less attention.
2. A further common problem in the authors' experience, which also is apparent in both cases here, is that the Estates personnel are hardly, if at all, involved in the design or procurement of the building and so have little buy-in to the aspirations of the design team to achieve an outstanding performance in use. They are also often unaware of subtleties in the design intent and may not even witness the commissioning of the building's systems, let alone being able to sign off that the systems are working satisfactorily before they are given the responsibility for their operation. This means that problems in either the operation of the plant or its control in relation to the design intent are either not appreciated, not picked up, and/or certainly not owned by the people operating the building, and, as a result, are generally not resolved. Essentially they fall into the hole between the procurement team and the maintenance team when the building is handed over. Trying to resolve these problems has proved surprisingly difficult—more for organizational reasons than technical ones, as it involves a change of existing cultures.
3. In both organizations, the opportunities for fine-tuning were further complicated by changes in personnel; it seemed that as soon as we had spent enough time with an individual for them really to appreciate what needed to be done, they either left or were assigned to other duties and were no longer involved with the building.

REVIEW OF ENERGY PERFORMANCE

Table 1 shows the energy performance of the two buildings (expressed in kWh of heat, gas, or electricity, as appropriate, per m TFA per year) and relates it to various UK benchmarks and to figures for comparable university library and departmental buildings. The Gloucester building is shown twice, the first time with the gas consumed for heating climate corrected by the ratio of the regional degree-days (at a 15.5°C base) for the year of measurement (1,867) to the 20-year average for the region (1882 degree-days), the second time with correction to the 20-year average for the UK (2462 degree-days)—a much higher figure, as Gloucester is in a warmer than average region. The heating energy for the other buildings (including the Visby one) and the benchmarks in the table are all corrected to the UK average degree-days. The potential improved performance of the Visby building is also shown. In the lower part of the table, this energy use is converted into CO_2 emissions using current published UK factors (0.19 kg CO_2 per kWh of gas and 0.46 kg CO_2 per kWh of electricity). Figure 1 expresses the CO_2 figures from Table 1 graphically and forms the background to the discussion in this section of the paper, with reference back to the delivered energy figures in Table 1 as necessary.

Graphic Comparison of CO_2 Emissions

Figure 1 shows histograms of CO_2 emissions at UK factors broken down into the same end-use classification as in Energy Consumption Guide 19 (Carbon Trust 2003) from

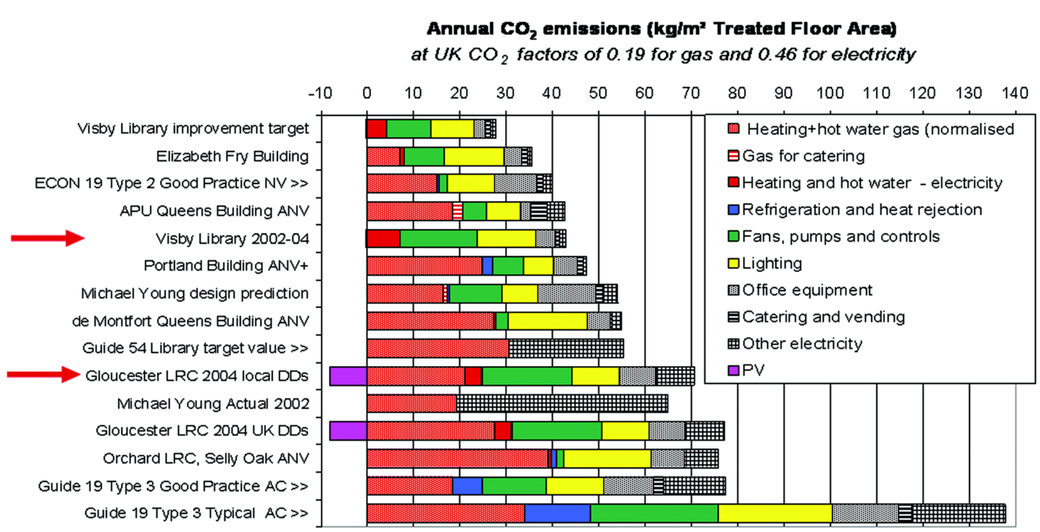

Figure 1 *Carbon dioxide emissions for the study buildings (noted with arrows) compared with benchmarks, etc.*

Table 1. Annual Heating and Electricity use in the Two Buildings per m^2 Treated Floor Area Expressed in kWh of the Relevant Fuel and as kg CO_2 at UK Standard Factors Compared with Other UK University Buildings and with Various UK Benchmarks, designated with ">>"

	Visby Library Improvement Target	Elizabeth Fry Building	ECON 19 Type 2 Good Practice NV >>	APU Queens Building ANV	Visby Library 2002–2004	Portland Building ANV+	Michael Young Design Prediction	de Montfort Queens Building ANV	Guide 54 Library Target Value >>	Gloucester LRC 2004 Local DDs	Michael Young Actual 2002	Gloucester LRC 2004 UK DDs	Orchard LRC, Selly Oak ANV	Guide 19 Type 3 Good Practice AC >>	Guide 19 Type 3 Typical AC >>
Figures in kWh/m^2 TFA															
Heating + hot water gas (normalized)	—	37.0	79.0	97.0	—	130.0	86.4	143.0	—	110.9	—	145.1	205.0	97.0	178.0
Gas for catering	—	—	—	11.0	—	—	4.4	—	—	—	—	—	—	—	—
Heating and hot water—electric	9.2	1.9	—	—	15.5	0.2	—	1.0	—	7.4	—	7.4	1.8	—	—
Refrigeration and heat rejection	—	0.0	1.0	—		5.0	1.1	—	—	0.6	—	0.6	2.1	14.0	31.0
Fans, pumps, and controls	20.8	19.0	4.0	11.0	35.8	14.5	24.3	6.0	—	42.0	—	42.0	3.6	30.0	60.0
Lighting	19.9	28.0	22.0	16.0	28.0	14.0	17.3	37.0	—	22.4	—	22.4	41.0	27.0	54.0
Office equipment	5.7	8.0	20.0	5.0	9.0	11.0	26.8	11.0	—	17.0	—	17.0	15.6	23.0	31.0
Catering and vending	2.0	3.0	3.0	8.0	2.0	3.0	3.5	1.0	—	0.3	—	0.3	—	5.0	6.0
Other	2.8	1.9	4.0	8.0	2.8	1.5	7.0	4.0	—	17.9	—	17.9	16.0	29.0	44.0
PV	–0.6	—	—	—	–0.6	—	—	—	—	–17.6	—	–17.6	—	—	—
Total gas (normalized)	—	**37.0**	**79.0**	**108.0**	—	**130.0**	**90.8**	**143.0**	**161.3**	**110.9**	**101.2**	**145.1**	**205.0**	**97.0**	**178.0**
Total electricity ex PV	**59.8**	**61.8**	**54.0**	**48.0**	**92.5**	**49.2**	**80.0**	**60.0**	**53.8**	**107.6**	**99.4**	**107.6**	**80.1**	**128.0**	**226.0**
Gloucester electricity nett of PV contribution >>										**90.0**		**90.0**			
Figures in kg CO_2/m^2 TFA															
Heating + hot water gas (normalized)	—	7.0	15.0	18.4	—	24.7	16.4	27.2	30.6	21.1	19.2	27.6	39.0	18.4	33.8
Gas for catering	—	—	—	2.1	—	—	0.8	—	—	—	—	—	—	—	—
Heating and hot water—electricity	4.2	0.9	—	—	7.1	0.1	—	0.5	—	3.4	—	3.4	0.8	—	—
Refrigeration and heat rejection	—	—	0.5	—	—	2.3	0.5	—	—	0.3	—	0.3	1.0	6.4	14.3
Fans, pumps, and controls	9.6	8.7	1.8	5.1	16.5	6.7	11.2	2.8	—	19.3	—	19.3	1.7	13.8	27.6
Lighting	9.2	12.9	10.1	7.4	12.9	6.4	8.0	17.0	—	10.3	—	10.3	18.9	12.4	24.8
Office equipment	2.6	3.7	9.2	2.3	4.1	5.1	12.3	5.1	—	7.8	—	7.8	7.2	10.6	14.3
Catering and vending	0.9	1.4	1.4	3.7	0.9	1.4	1.6	0.5	—	0.1	—	0.1	—	2.3	2.8
Other electricity	1.3	0.9	1.8	3.7	1.3	0.7	3.2	1.8	24.7	8.2	45.7	8.2	7.4	13.3	20.2
PV	–0.3	—	—	—	–0.3	—	—	—	—	–8.1	—	–8.1	—	—	—
Total gas (normalized)	**0.0**	**7.0**	**15.0**	**20.5**	**0.0**	**24.7**	**17.3**	**27.2**	**30.6**	**21.1**	**19.2**	**27.6**	**39.0**	**18.4**	**33.8**
Total electricity ex PV	**27.8**	**28.4**	**24.8**	**22.1**	**42.8**	**22.6**	**36.8**	**27.6**	**24.7**	**49.5**	**45.7**	**49.5**	**36.8**	**58.9**	**104.0**
Total CO_2	**27.8**	**35.5**	**39.9**	**42.6**	**42.8**	**47.3**	**54.1**	**54.8**	**55.4**	**70.6**	**65.0**	**77.1**	**75.8**	**77.3**	**137.8**
Gloucester CO_2 nett of PV contribution >>										**62.5**		**69.0**			

which three UK benchmarks are also included: for typical and good practice "Type 3" air-conditioned offices and for a good practice "Type 2" naturally ventilated office with a predominantly open plan layout. Also included are

- four UK benchmarks (see below),
- data from five well-known low-energy university departmental and library buildings in the UK previously known to the authors and published in the Probe series, and
- design and in-use figures for the Michael Young Business School building at the Open University, which also has a concrete hollow-core ceiling slab ventilation system and was completed in 2001.

Photovoltaic Contribution. Both buildings have PV integrated into their built form: incorporated into motorized shading louvers at Visby and on the south-facing part of a waveform north-light daylighting scheme at Gloucester. Figure 1 shows CO_2 emissions caused by energy use in the building to the right of the zero and the effect of PV contributions to the left. Hence, the renewable energy contribution by the PV at Gloucester avoids the emission of some 8 kg CO_2/m^2 and reduces the CO_2 associated with the annual delivered gas and electricity from 76 to 68 kg/m^2. The contribution of the smaller PV installation on the much larger Visby building (0.6 kg/m^2) is barely visible.

The Benchmarks. The four UK benchmarks shown in Figure 1 are, from top to bottom,

1. The Guide 19 (Carbon Trust 2003) Good Practice (GP) benchmark for a largely open-plan, naturally ventilated office. Offices in the UK that achieve GP energy performance levels are rare (5–10% of the stock) but authenticated by case study examples of buildings in use employing readily available techniques, technologies, and management practices at normal cost levels.
2. The Guide 54 (Carbon Trust undated) target values for library accommodation in higher education buildings. These are also set at GP levels. Note that this standard was set for traditional library accommodations, not including many PCs for example and probably with stackrooms, etc., which have a lower energy intensity.
3. The Guide 19 GP level for a standard "Type 3" air-conditioned (AC) office.
4. The Guide 19 typical level for a standard "Type 3" AC office. The "Typical" benchmark is shown because the design ambition of the Gloucester LRC was related to it.

Simple Comparison of Overall CO_2 Emissions with the Benchmarks

In relation to the benchmarks, and at UK conversion factors, the annual CO_2 emissions per square meter TFA at Visby, for the 2003–04 period monitored by the authors, were much lower than the good practice UK benchmarks for university libraries and AC office buildings. Indeed, in spite of the building's mechanical ventilation and cooling system, they were only marginally above the UK GP level for a naturally ventilated office building. If the operational improvements recommended by the authors are implemented —and some of them already have been—then the Visby Library could be some 25% better than the naturally ventilated benchmark and significantly the lowest-energy example of the eight low-energy university library/departmental buildings shown.

At Gloucester, the energy consumption of the building is 10% better than the Guide 19 GP level for an AC office and 20% better once the renewable contribution of the large PV array is taken into account. While just within the cohort of low-energy university buildings shown, the outcome is just below half the Guide 19 "Typical" level for an AC office, not the one-third to which the designers aspired. The main discrepancy is for the heating—the annual electricity consumption from the mains is 39.8% of the "Typical" level after the PV contribution has been deducted.

The reasons for the differences between the buildings and the targets are many and varied, as discussed below. First, however, we review overall performance in relation to the other low-energy buildings studied.

The Six Comparable Low-Energy University Buildings

The comparable buildings include four Probe studies (Asbridge and Cohen 1996; Cohen et al. 1996; Bordass et al. 1999; *Building Services* 2000), which were predominantly NV (though with a few mechanically ventilated and cooled areas, for example, server rooms and some lecture theaters). These are shown as ANV ("Advanced Natural Ventilation") in Figure 1, as the ventilation systems were designed using CFD (computational fluid dynamics) and/or salt bath modeling and were at least partially controlled automatically. The other two buildings include mechanical ventilation systems and so are more directly comparable to the two buildings in this study:

- The Elizabeth Fry Building at the University of East Anglia (Standeven et al. 1998), a concrete hollow-core ceiling slab building like Gloucester's LRC but with smaller, triple-glazed windows and a much higher level of airtightness. The building also benefited from a major fine-tuning exercise, supported by detailed monitoring and a high level of involvement and investment by the university services engineer, not only in spending time, but also in completely replacing the control system for the heating and ventilation system. The Elizabeth Fry Building was not only the lowest-energy mechanically ventilated building in Probe, but it had the highest level of summertime comfort in the occupant survey, in spite of having no mechanical cooling apart from nighttime ventilation.
- The Michael Young Building (Cohen 2003), the business school of the Open University at Milton Keynes, a building with wings having concrete hollow-core ceiling

slabs that were reasonably airtight, plus a central building of more conventional construction and servicing, which also proved less airtight.

At first sight, it is perhaps surprising that the total CO_2 emissions for both the ANV buildings and those with mechanical ventilation are similar, even if the breakdowns into end-uses are not, with heating and fans in the mechanically ventilated buildings often being comparable with heating only in the naturally ventilated ones. One important reason for this similarity was excessive air infiltration in the ANV buildings, with the Portland Building having an air leakage index of 15.6 m^3/h per m^2 at 50 Pa and Orchard LRC 31.9 m^3/h per m^2. In our experience, buildings that are insufficiently airtight not only require additional heat to warm the extra air during occupied periods but have raised temperature setpoints to overcome local problems of coldness, In addition, their heating systems are run for more hours per day and days per year, for example, with extended preheat periods. This all causes a rapid escalation in heating energy requirement.

Comparisons with the Other Six Case Study Buildings

The 2003–04 data for Visby Library compare well with all the other buildings apart from Elizabeth Fry. Even for these two, the energy profiles are very similar apart from the green area for fans, pumps, and controls, which takes 36 kWh/m^2 of electricity in Visby and 19 kWh/m^2 at Elizabeth Fry. The main differences between the two are:

- The fans in the Visby building take 28 kWh/m^2 versus 18 kWh/m^2 at Elizabeth Fry. The main reason is that for the first two years of operation, Visby's fans were operated at full speed 24 hours a day in order to remove any pollutants introduced with the building materials, finishes, furniture, and equipment. Visby is now experimenting with reduced volumes and time schedules, and fan energy use may fall substantially.
- The Elizabeth Fry Building has very small boilers with domestic-sized circulating pumps that operate for 700 hours a year or less. Visby extracts its heat and obtains its cooling from seawater, with the pumps using just over 7 kWh/m^2 (of which only about 10% is for cooling).

Tree diagrams, such as those illustrated in Figure 2, are a useful way to break down the annual energy use by fans and identify the scope for reductions. The key parameters are the efficiency of the ventilation system represented by the specific fan power (which takes account of the fan efficiency and the resistance of the complete air path, i.e., ducts, filters, heat exchangers, etc.), the ventilation rates, and the annual hours of use. The trees in Figure 2 show whole building average values but can equally be given for individual fans and zones. These diagrams show that due to higher ventilation rates and a worse (higher) specific fan power, the fan energy use is 30% higher

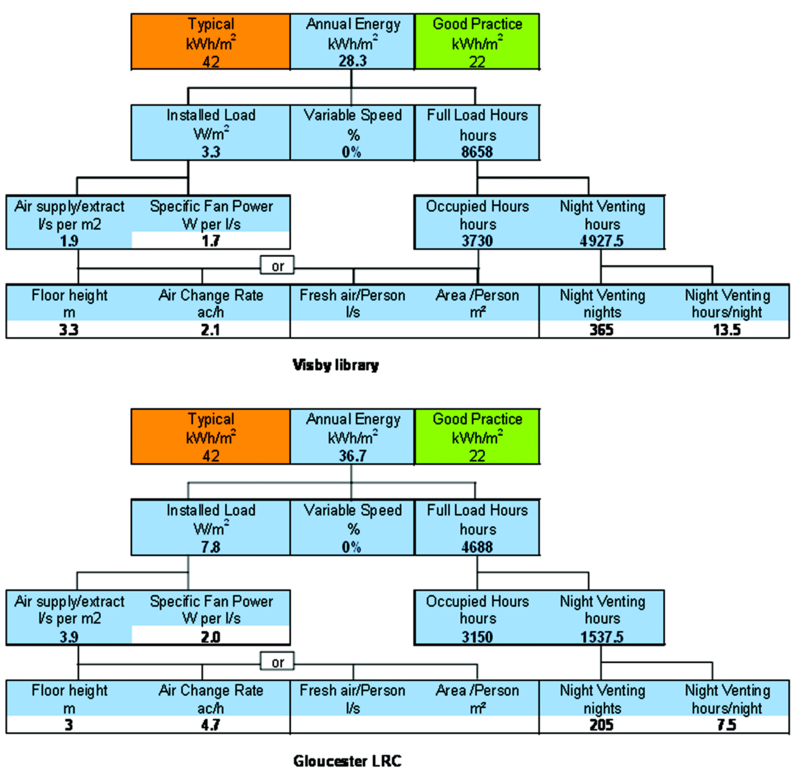

Figure 2 *Fan energy tree diagrams.*

for the higher pressure drop system at Gloucester, even though the fan operating hours are much higher at Visby. Nevertheless, in both buildings, the fan energy used by their ventilation systems lies between the benchmarks for "Typical" and "Good Practice" energy performance in a standard air-conditioned office building in the UK.

The Benefits of Controlled Ventilation

Given the substantial added electricity use by the fans, it is commendable that the CO_2 emissions from both Visby and Elizabeth Fry are comparable with the best of the naturally ventilated university buildings. The two buildings demonstrate the energy-saving contribution of controlled ventilation with thermal mass, heat recovery, and, if necessary, overnight cooling in an airtight building. However, as a building becomes less airtight, as at Gloucester, no longer are the CO_2 emissions caused by running the fans underwritten by the ventilation heat loss saved, and the ventilation plant also has to work harder to make up the deficit. Nevertheless, to reduce emissions further, it will be important to aim to minimize the use of electricity for fans, subject to attaining sufficient levels of heat transfer and air quality.

Energy Use for Heating

Energy use for heating and hot water in units of CO_2 is shown in Figure 3.

Although the heat pump at Visby uses expensive (and at UK factors, high CO_2) electricity and in spite of the colder Swedish climate, at 7 kg CO_2/m^2, Visby's heating requirement is very similar to that at Elizabeth Fry (normalized to the UK benchmark standard of 2462 heating degree-days at a 15.5°C base). However, once the extra consumption by the heating-related pumps (including the seawater pump) is included, Visby's requirement rises by 3 kg CO_2/m^2, or over 40%. The heat provided by the heat pump to the Visby building was 51.5 kWh/m^2 TFA as against the 99 kWh/m^2 provided at Gloucester (see Figure 4).

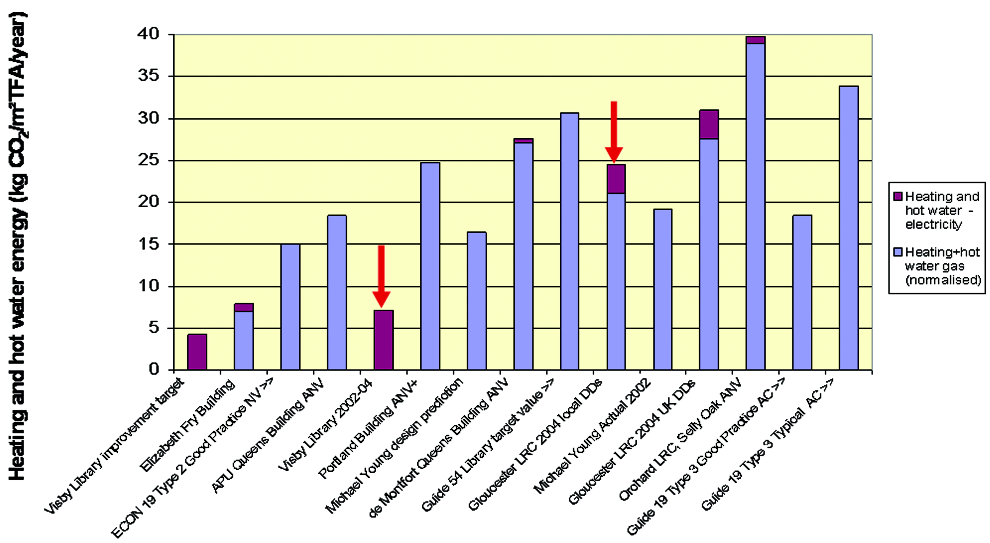

Figure 3 *Energy use for heating and hot water in the study buildings and benchmarks in units of CO_2.*

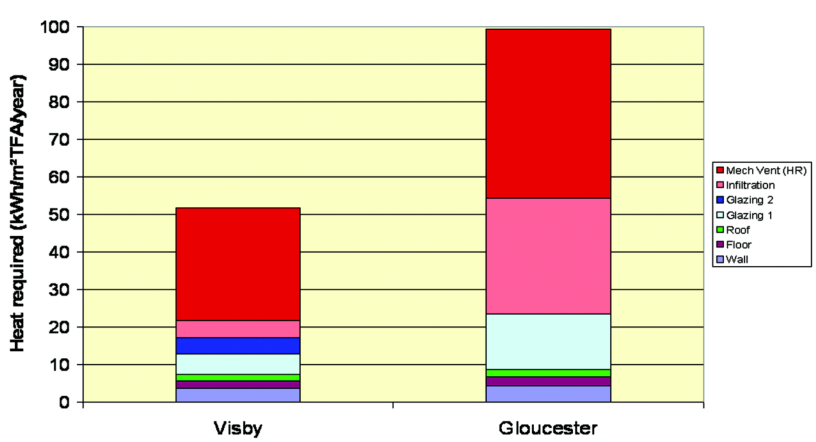

Figure 4 *Heat balance for the two buildings.*

The heat balance shown in Figure 4 confirms the major energy requirement of ventilation compared with fabric losses in both buildings but also the serious impact of infiltration, which generates fresh air changes but without any heat recovery. The impact of the large glazed north façades in both buildings is also apparent, but most particularly at Gloucester. Perversely, it is not unusual to find the heating energy requirement is lower in a colder climate; essentially, the colder it is, the more effort is placed on conserving heat.

Electricity Use for Cooling

This category includes energy used for mechanical refrigeration and heat rejection, excluding energy used for cooling equipment rooms such as file server rooms that are classed as "Other." At Visby the cooling is by the seawater loop and heat exchanger used to supply heat to the heat pump in winter. Although the pumps continue to operate in summer, the electricity consumption by all pumps (including seawater pumps) when used for cooling is commendably low at just 0.8 kWh/m^2. While Gloucester does use packaged direct expansion cooling units—one serving cooling coils in the air-handling unit for the lecture theater and the other for the rest of the building—they are of conventional design and intended for very hot weather only. In 2004 only the lecture theater unit was used, consuming 0.6 kWh/m^2 of electricity.

In both buildings, therefore, the design measures have been successful in largely avoiding the need for energy expenditure on supplementary cooling. Of course, some of the fan energy consumption will have been dedicated to extracting unwanted heat in summer, but the level of monitoring carried out does not allow this to be quantified.

Electricity Use for Lighting

Lighting energy use is lower at Gloucester (22 kWh/m^2) than at Visby (28 kWh/m^2), while the quality of light at Gloucester is better (see "The Occupant Survey Reports" on the following page). Energy tree diagrams for the two buildings are shown in Figure 5. At about 10 W/m^2, the average installed load density is higher at Gloucester, though at Visby it is higher in the office and public spaces and lower in the corridors, etc. Hours of operation of the public areas are longer at Visby owing to more extended opening and darker nights in winter.

Lighting control is somewhat disappointing in both buildings, as described above; and although consumption, particularly at Gloucester, is reasonable in relation to the benchmarks and to most other case study buildings, there is little advance on the "Good Practice" benchmark for an air-conditioned office (27 kWh/m^2). Although efficient lighting fittings and daylight dimming have done their bit, particularly at Gloucester (many of the fittings at Visby are more decorative, less efficient, and do not light some parts of some of the spaces adequately, particularly the corridors and the vertical surfaces of bookshelves in the library), it is really important to strive for better control, which can be installed and commissioned properly at a tiny fraction of the cost of the equivalent contribution from a PV system.

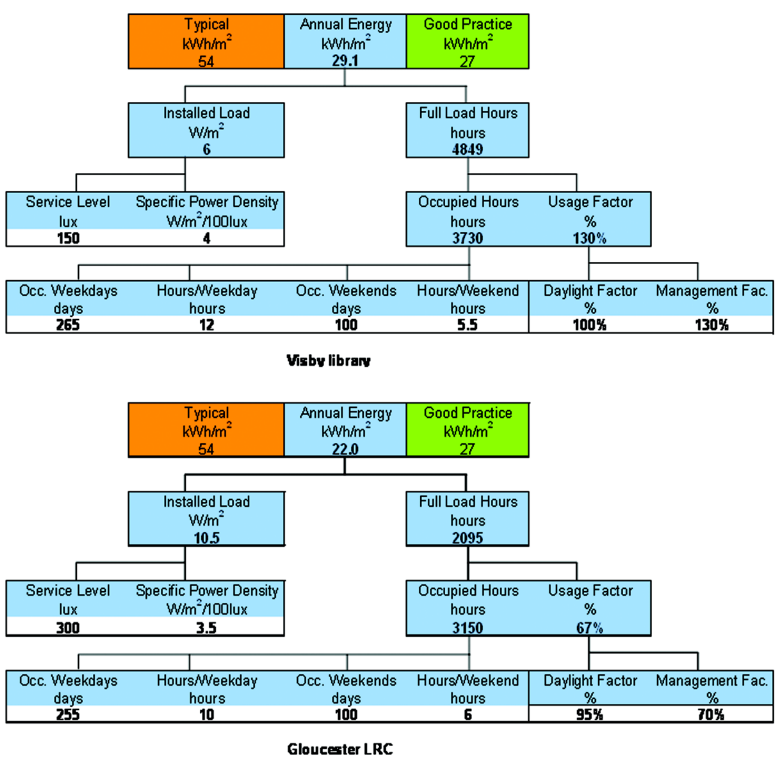

Figure 5 *Lighting energy tree diagrams.*

Electricity Use for Office Equipment

At 17 kWh/m^2, nearly twice the Visby level, electricity use by office equipment is relatively high in Gloucester because there are many more PCs there, about 200 compared to 110 in the much larger Visby building. The PCs at Gloucester are more energy-efficient (nearly all with flat screens as against 30% flat screens in Visby) and managed more efficiently as well (only switched on when people need them and routinely switched off at the end of the day, while a night survey at Visby revealed that about 20% of computers and 10% of screens remained on). The higher consumption at Gloucester is, therefore, entirely justifiable, but there is always room for improvement in the selection of equipment and management of computer use in both buildings.

Electricity use for Catering and Vending

Visby has a small kitchen in the public area serving drinks and snacks and a somewhat larger, but little-used, kitchen in the university space on the top floor. Total annual electricity consumption is small, at about 2 kWh/m^2.

At Gloucester, the only catering facility in the LRC is a small kitchenette for staff use. There is a cafe and vending machines in an adjacent building, which does not form part of this survey.

The low catering energy use in both buildings reflects the modest scale and use of these facilities.

Electricity Use for Other Purposes

Electricity used for other purposes includes lifts, external lighting (of which there is only a small amount in both buildings), security systems (in particular for library security), and audiovisual equipment, in particular communications/file server rooms and their air conditioning. The total at Gloucester is 15 kWh/m^2, with just over half from the server room. The figure for other uses at Visby is modest (at 3 kWh/m^2) because a similar amount of ancillary equipment is spread over a much larger building, and there is no server room.

REVIEW OF OCCUPANT SATISFACTION

A Probe-style occupant survey was issued to all permanent staff in both buildings (at Visby in a Swedish translation). The survey contains 65 questions on various aspects of the individual, the building, its services, its management, the internal environment, health, and productivity that have been progressively refined (and mostly simplified) over a period of 25 years.

- At Visby 34 people responded, 75% of the staff at the time, of which 25 were library staff and 9 were university staff with offices in the library. Fifteen percent were part-time in the building.
- At Gloucester there was a 100% response rate, but this amounted to only 16 staff; and 65% of these spent only part of their time in the building.
- At Gloucester, a survey of students was also undertaken, using a shorter questionnaire. Survey forms were issued to 45 students, with a 100% response.

The Occupant Survey Reports

Separate reports are available on both of the buildings, each with a summary report and three appendices—Appendix A, data tables; Appendix B, classified comments made on the survey forms; Appendix C, statistical graphics showing the distribution of responses to each question—plus an Appendix D for the Gloucester student survey. The results of the occupant surveys should be interpreted with some caution owing to the relatively small sample sizes. Nevertheless, owing to the high response rates, the results are meaningful, and differences from benchmarks are only quoted when they are statistically significant at the 95% confidence level. It should also be noted that buildings tend to be better liked by occupants who do not work in them all the time (e.g., the students and 65% of the staff at Gloucester).

Summary of Results

To summarize performance, ten key indicators are used. Staff survey results were as follows:

- *Image*—good in both buildings.
- *Overall comfort*—good in Visby, fair in Gloucester.
- *Design*—good in Visby, fair in Gloucester.
- *Needs*—fair in both buildings.
- *Health*—good in Visby, fair in Gloucester.
- *Perceived productivity*—good in Visby, fair in Gloucester.
- *Temperature in summer*—good in Visby, fair in Gloucester.
- *Temperature in winter*—fair in Visby, poor in Gloucester; both buildings tended to be cold.
- *Lighting*—good in Gloucester, the highest in the dataset, but poor in Visby where the electric lighting in the library tended to be gloomy and patchy.
- *Noise*—good in Gloucester, poor in Visby where problems have arisen from the joint use of the public/university library, with small children, the general public, students, and researchers all occupying the same space. Staff in the Visby library also complained there were no barriers to noise from the entrance area, where there is a cafe and meeting and exhibition space.

On an overall summary index incorporating average scores on all ten variables, both buildings were above average in a dataset of the 100 most recently surveyed buildings, with Visby having a score of 75 (out of 100 points) and Gloucester having 58. However, on other summary indices for occupant satisfaction and comfort, staff rated Visby in the upper quartile (top 25%) and Gloucester in the third quartile.

The students at Gloucester, however, reported very positive results. This has been a common finding of surveys of recent award-winning UK university buildings—they often have an image that students and visitors like, but less account has been taken of the needs and comfort of the staff that run them, an unfortunate but widespread oversight.

More Details

Responses of particular interest not forming part of the summary indexes, or providing more detail, include the following.

- Indoor air quality—good in both buildings. This and the relative coolness also tend to be associated with good perceptions of health.
- Furniture—occupants like it in both buildings.
- Low glare—also liked in both buildings.
- Noise—in spite of the widely differing overall scores on noise, people in both buildings scored well for noise from colleagues but were unhappy about noise from other people.

Specific Written Comments

In the written comments on the questionnaire surveys (Appendix B of the detailed reports), the following topics occurred several times.

- At Visby, specific complaints about insufficient light and too much noise in the library and public areas (the offices were fine) and that the building was cold in winter.
- Staff at Gloucester thought that the building was very attractive visually and liked the daylight on the north side. However, low winter temperatures and drafts were a problem, particularly in the region of the reception and issue desks. The long, unheated, glazed corridor between the LRC and the Sports Science building also drew adverse comment. There were also complaints of overheating in summer, particularly on the top floor.
- The perception of noise overall was relatively good. Certain aspects of noise led to specific comments, particularly about noise from other staff in the working area at Gloucester and the lack of acoustic separation of staff and student areas.
- At Gloucester major problems were related to staff needs: a cramped work area, insufficient space for book processing, very little storage (not even for coats), no staff room or meal area, no small meeting rooms, and no rooms for silent study or group work. It appears that the briefing process had not worked very well in relation to the needs of the support staff—perhaps because this was a new campus and they had not been appointed at the briefing stage.

CONCLUSIONS

The authors would highlight the following key design messages and lessons learned.

Successes

Use of mechanical refrigeration for cooling in summer of two deep-plan buildings with relatively intensive use has been avoided. At Visby this is achieved using seawater drawn from a depth of 30 m. To underline the success, the occupant rating of summer comfort in the Visby library was the best in the authors' experience. At Gloucester, the main mechanism is a high thermal mass building whose structure is cooled by night ventilation, although this is supported by careful exclusion of solar gain and use of low-energy light fittings and low-power PC screens.

The energy consumed for heating the Visby library, 15 kWh/m of electricity, is outstandingly low, although once it is converted by the heat pump into 52 kWh/m of heat, it may not be unusual for new commercial buildings in Sweden, although we have not seen any hard evidence (verified measurements) for this.

The occupant survey found that the image of both buildings was very high. This is a major success for the procurement teams who, in order to attract "customers," both had strong requirements to deliver more than just a functional facility.

The occupants' perception of the health aspects of the buildings was also very good, which was an explicit aim in Visby (health seems to feature more strongly as an important element of sustainability in Sweden than in some other countries) and must be a positive attribute for the body-conscious students of Gloucester's School of Sports Science. The Visby health result was reinforced by exceptional scores for summer and winter indoor air quality.

The occupants' rating of the lighting at Gloucester was the highest in the dataset and has come about partly due to an outstanding absence of glare.

Areas for Improvement

The relatively poor airtightness of the Gloucester building has had a marked impact on its performance and comfort. This outcome is particularly disappointing given that this issue was well known to the design/procurement team and was a condition for acceptance of the concrete hollow-core ceiling slab installation. We concur with the architects' view that the problem has been endemic to the UK construction industry and that we can anticipate step-change improvements as statutory requirements drive this issue up the project manager's priority list. Although a pressure test shows that it met the requirements of the UK regulations (which were introduced after it was designed), the limited airtightness of the building envelope (exacerbated by drafts through the reception inquiry window to an unheated space and by the all-glass facade on the north side) limits the ability of the concrete hollow-core structural ventilation/heat storage system to manage the heat flows and greatly increases the call on supplementary heat.

The concrete hollow-core ceiling slab system has proved its value in delivering summertime comfort largely without refrigeration, but this installation does not repeat the outstanding energy and occupant satisfaction success of the pioneering Elizabeth Fry building in Norwich. Certainly the task here might be considered more challenging (6 m per workstation in an open plan library, for example), but with seven years separating the two buildings, we expected a building that improved on the Elizabeth Fry building, not one considerably behind. The key message is that a concrete hollow-core ceiling slab ventilation system is not a panacea that obviates the need for care in design, installation, commissioning, and sea-trials. Indeed, given it is still not common, and, therefore, is relatively unknown to the contractors and consultants who specify and build it and supply and implement the controls and commission them, it actually seems to require more attention to detail than a more conventional approach.

A problem in both of the buildings is the relatively high use of electricity by the ventilation fans. Although Visby's system is the more efficient, during the monitoring period its annual energy use was high owing to 24-hour operation to help purge the buildings of chemicals released from the new building materials and finishes. In mid-2004, the management started to reduce the speeds of the fans and their operation outside normal hours, which should lead to significant economies. Nevertheless, the electricity consumed by the fans in both buildings is higher than might be hoped for. The key points here are, first, to reduce the specific fan powers by attention to detail in duct design and layout, filters, and heat exchangers. Then it is a question of controlling how many hours (and, if variable speed, at what rate) the fans must run to satisfy occupants' genuine needs.

Lighting control is another area where both buildings could have done better, particularly by avoiding lights being on in either well-daylit or unoccupied spaces. At Gloucester the designers' proposals for occupant-sensing control of the lighting in the library were not accepted by the client and the project manager owing to difficulties with previous projects, while at Visby electronic daylight dimming controls were fitted in the library areas but have yet to work properly. The problems at Visby may be thought to vindicate Gloucester's decision, but in the authors' experience, it is perfectly possible for lighting controls to work well and effectively. However, to achieve good lighting control requires an adequate budget and careful attention to detail by the client, the specifier, the installer, and finally the building manager. Sadly, this seldom happens, but it needs to if we are to achieve our objectives of minimizing the CO_2 footprints of our buildings.

Both buildings have experienced difficulties in getting some of their building service systems to work as intended. This can partly be ascribed to their pioneering nature and in any case is probably only apparent because of the limelight in which they have been placed by the Eubart project. However, it is also due to the haste with which buildings are usually handed over from the procurement teams, under pressure from the users, to the operators (in this case, the Estates Divisions). For these buildings, this situation was exacerbated by these two parties being completely different entities; the problems might have been greatly reduced had the Estates personnel been directly involved in the commissioning and handover procedures. At Gloucester, it appears that this process has yet to be accomplished entirely satisfactorily. At Visby this process was eventually achieved after considerable efforts by the controls contractor; however, personnel changes mean that the municipality will need to be proactive in encouraging the current building manager to look for further improvements in performance.

The buildings have proved to be extremely valuable test beds for advanced energy metering, monitoring, and targeting methods. However, despite much effort, the end results are only partly satisfactory. In particular, a scheme for energy M&T is not in place at either building. However, this study has laid the foundations for an M&T system to be introduced, and the authors hope that the necessary resources will be made available to implement it and be used by their respective Estates Divisions to ensure further improvement in each building's energy performance, even if the Eubart team is no longer prodding them.

Finally, the poor results for the lighting installation and noise disturbance found from the Visby occupant survey have to be mentioned as they are among the worst in the dataset. The noise problem seems to be a symptom of success, an almost inevitable consequence of combining university and public library functions and then encouraging the public to use the library. The lighting installation may have been a case of an aesthetic triumphing over a more functional approach, and it is hoped that improvements can be made that do not compromise the energy performance.

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