MIXED MODE VENTILATION AND COOLING SYSTEMS IN BUILDINGS
Draft report of a scoping study for BRE by Bill Bordass

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1 SUMMARY AND CONCLUSIONS

1.1 Background

1.1.1 WHAT IS MIXED MODE?
Mixed Mode (MM) is a term for hybrid buildings and systems which combine natural and mechanical ventilation and cooling. Strategically, this can be done in three different ways:
- **Contingency**: with openable windows and planned for easy addition (or removal) of mechanical systems.
- **Zoned**: with different services in different parts of the building.
- **Complementary**: with natural and mechanical systems present together.

1.1.2 WHAT DOES MIXED MODE OFFER?
The study has identified three main groups of objectives:
1. “Tunable” buildings with longer life, greater adaptability of space and services, less waste, lower cost, and fewer burdens for management.
2. Better occupant satisfaction, by combining the perceived advantages of openable windows with mechanical servicing for suitable levels of health, safety and comfort.
3. Reductions in energy use and the associated greenhouse gas and pollutant emissions.

1.1.3 WHERE DOES IT FIT IN?
Until recently, MM was regarded as on the fringe of good practice, a somewhat shaky middle ground between natural ventilation (NV) and full air-conditioning (AC). An alternative opinion is that mixing natural and mechanical systems should be a perfectly normal way of doing things - just as with natural and artificial lighting. While we endorse this opinion in principle (and in appropriate circumstances, MM can be superior to both natural ventilation and air-conditioning) it is also true that some parts of the ground are still shaky.

1.1.4 COMBINING NATURAL AND MECHANICAL SYSTEMS
Where systems are complementary, a wide range of combinations and operating modes is possible. The operating strategies - which can change with time - normally fall into one of three main groups:
1. **Concurrent**: Where natural and mechanical systems operate together.
2. **Changeover**: At certain points, the operating mode of the system changes: for example with natural ventilation in the day and mechanical removal of excess heat overnight; or with mechanical systems operating only in cold and hot weather.
3. **Alternate**: Once the choice of natural or mechanical has been made, it stands for typically many years, for example with close-control air-conditioning in a naturally-ventilated shell in which the windows have been locked shut.

1.1.5 SCOPE OF THIS REPORT
This report is of a scoping study carried out in the first half of 1996 to:
- review the state of the art knowledge of MM systems;
- clarify the scope and methodology of any further case study, thermal modelling or market research work required to support the production of a proposed CIBSE Applications Manual;
- as an initial input to raise the profile of MM amongst the architectural and engineering professions; and
- to provide immediate guidance on the major pitfalls in the design of these systems and how they might be avoided.

The study has been restricted predominantly to office buildings in the UK. Overseas examples need more study.
1.2 State of the art: mixed mode design

1.2.1 STATE OF THE ART GENERALLY
The scoping study indicates that MM concepts could have an important role to play in the provision of cost-effective, adaptable, lower-energy, comfortable, future-proof buildings. It has found over sixty examples which have been built over the past twenty years, or are now under construction. Having initially been restricted to owner-occupiers and the public sector, a few examples are now emerging in the speculative market, where their adaptability should potentially be a strong selling point for both occupier and investor. A market study is recommended, which asks owners and occupiers whether they would go MM again.

1.2.2 STATE OF THE ART: CONTINGENCY DESIGNS
Contingency designs are relatively few, or perhaps relatively difficult to identify because most buildings are capable of modification as a last resort! We consider that the art of contingency design - where mechanical services can be added to a naturally-ventilated building (or vice-versa) - needs further development. For example, for the Body Shop to have the largely naturally-ventilated head office they wanted while meeting institutional demands, the building had to have ceiling void, rising duct and plant space to allow full VAV air-conditioning to be added. However, given the effectiveness of the passive systems, if this building were ever to be mechanically cooled or air-conditioned it is unlikely that VAV would now be chosen! Ideally it would be possible for services to be added quickly and easily in a variety of ways: by room, by floor, by wing, and so on. However, there is also the risk of the MM “scam”, where the developer leaves out essential features and the unwitting tenant picks up the tab. We recommend an imaginative study of the architectural, structural and services engineering options for contingency designs, including methods for policing the more obvious scams.

1.2.3 STATE OF THE ART: ZONED DESIGNS
Zoning occurs in many buildings anyway. However, the term is useful is raising awareness that a building does not need to be completely sealed and air-conditioned just because certain parts have to. It could be useful to illustrate the opportunities for zoning with some case studies and worked examples.

1.2.4 STATE OF THE ART: COMPLEMENTARY DESIGNS
The most common systems, and those of most interest to services engineers, have both natural and mechanical systems present and complementing each other. A good thing about this approach is that it can converge with a highly efficient design of an air-conditioned building and provide a transitional route between energy-dependent and more passive solutions. Earlier studies indicated that such systems could perform reasonably as far as the occupants were concerned, but sometimes their technical and energy performance was disappointing. The current study indicates that although there are some areas of progress (for instance in one or two “trickle-charged” buildings with continuously-ventilated hollow core slabs), in others shortcomings in technical and particularly in energy performance persist. This requires urgent attention, both through further investigation and in the development of good practice guidance on how to include the extra mechanical services without losing the value of the low-energy building design.
1.3 State of the art: mixed mode in use

1.3.1 Contingency designs in use

Contingency designs are relatively few. Some are successful as naturally-ventilated, and have required few if any additional services, vindicating this risk management approach. Going the other way, a few shallow-plan air-conditioned offices of the early 1970s (particularly those for local authorities) have reverted (or are considering reversion) to natural ventilation or MM. On the other hand, some have quickly had mechanical systems added which probably should have been there in the first place. We have also been warned by BREEM surveyors that it is not unknown for developers of some buildings cynically to omit the necessary ventilation and cooling systems, to collect the natural ventilation and refrigerant avoidance credits, to promote the building spuriously as low-energy, and to pass on the costs of what are really essential systems to the tenant. Of course, there may be tax advantages to this.

We are beginning to hear of poor comfort votes in some recently completed buildings with advanced natural ventilation: particularly in the deeper plans and where there are non-traditional relationships between occupants and windows. Here we think that narrowing thresholds of discomfort - that well-known effect that requires environmental conditions in sealed buildings to be kept in a narrower range than in “free-running” ones - may be partly responsible. In these situations, MM strategies might have been more robust. When these buildings are appraised, the origin of the problems and the potential for MM should be explored.

1.3.2 Zoned designs in use

Zoning is most successfully done where the zoned parts are functionally different from the others. In spaces of similar appearance and use, local differences in servicing can lead to misunderstandings (where different behaviour is required depending upon exactly what is provided in the area) and jealousies (e.g. in hot weather if an area in which cooling is provided - perhaps to counter higher solar or internal gains - is noticeably more comfortable). This can lead to creeping, and perhaps inefficient, AC. Caution needs to be raised about designs in which the servicing of ostensibly-similar spaces differs from place to place. In addition, it could be worth exploring how different systems could be integrated more seamlessly.

1.3.3 Complementary designs in use

Complementary designs are the most common and reveal the widest range of successes and difficulties. Earlier BRECSU and EnREI studies showed that they could work very well, but that design and control problems could easily occur, leading to lower performance and higher energy use than anticipated, particularly the latter because in buildings with openable windows people are more tolerant of the former. At present largely anecdotal information from more recently-completed buildings suggests that, with a few notable exceptions, these problems are (if anything) becoming more widespread. There are several reasons why this might be:

i. As low-energy design becomes more mainstream, it is attracting a wider range of people who may over-reach themselves or repeat old mistakes. Others may regard it as a technical fix and not re-think their approaches sufficiently.

ii. The earlier designs tended to be in fairly heavyweight shells. Some newer ones in are in lighter, more thermally responsive, less robust (and often less airtight) curtain-walled construction derived from their AC predecessors. They are designed less in response to the environment and so lean more heavily upon their mechanical systems.

iii. The earlier buildings were seen through from beginning-to-end by one designer. Responsibilities are now more split, e.g. with design-and-build and shell-and-core.

iv. Client requirements are more exacting and buildings are often more intensively used.

v. Management is more often outsourced, and may not take (or be contracted to take) ownership of unusual systems.

vi. New technology, including computer modelling, permits designers to envisage increasingly elaborate operating strategies which may not be realised in practice.

vii. Intense competition and fast-tracking makes it difficult to pay attention to critical detail.

viii. Occupant and management needs, habits and expectations are not well understood.

There is a great need for more research and for design guidance in this area, and the surveys suggest that there may be scope for slimming-down the mechanical ventilation component.
1.4 What are the main issues?

1.4.1 In the following sections, the problems will be related to the key objectives outlined in 1.1.2: Adaptable, manageable and cost-effective; more comfortable; and lower in energy use.

1.4.2 ADAPTABLE?
Few MM buildings have yet had to prove their adaptability. Partly this can be attributed to their robustness: where windows can be opened, occupants complain less about shortfalls in mechanical systems; and vice-versa, so the tolerance margins are widened-out. As with the contingency designs, we also think that there is scope for improvements in adaptability.

1.4.3 MANAGEABLE?
For the more sophisticated systems, the equipment is not dissimilar to that in an air-conditioned building, though generally somewhat smaller and simpler, and sometimes without - or without much - refrigeration. Maintenance and fine-tuning requirements tend not to be as exacting owing to the simpler systems and wider tolerance margins, and some systems are very simple - for example with constant-volume, constant-temperature background ventilation. Operationally, however, some changeover systems can be quite complex, and have a tendency to default to concurrent operation (see 1.4.5). Maintenance and cleaning associated with the openable windows also has to be taken into account.

1.4.4 COST-EFFECTIVE?
MM buildings tend to cost up to 15% less per square metre than air-conditioned alternatives of a similar perceived quality standard, with a typical quoted level of 5% for buildings with extensive mechanical ventilation. Sometimes the planning or the need for access to windows may also reduce the usable area that can be fitted on the site, or the ratio of usable to nett internal area. Since the capital cost margin can be quite small (except for naturally-ventilated contingency designs), the payoff really needs to come in occupant satisfaction, lower energy consumption and environmental impact, higher rental values, or lower costs in use - including environmental costs. More study of these is required.

1.4.5 MORE COMFORTABLE?
The earlier studies indicated that MM buildings were usually perceived as more comfortable than similar ones with natural ventilation alone. In particular, air movement and peak temperatures in summer were better. In addition, the occupants were more forgiving, i.e: their general impression of comfort was higher than one would have anticipated by averaging their votes on individual aspects. This time round, the anecdotal message is more mixed, at least for the offices which did not have mechanical refrigeration: this may be partially a consequence of the hot 1995 summer. Other problems may however arise from lighter-weight envelopes and insufficiently well-controlled heat gains. There are also indications that in deeper-plan spaces and where individuals do not have good perceived control, people are less tolerant of elevated summertime temperatures than current assumptions suggest. However, a short, relatively hot period is also no reason to condemn a design: recent studies for BRECSU at the Open University suggest that on a year-round basis people may prefer a passive solution, even if summertime temperatures are occasionally high (but a passive solution with optional comfort cooling might be even better!). We recommend more occupant surveys of perceived comfort, accompanied by physical measurements where appropriate. Comfort criteria may also need to be reviewed in relation to degree of control and proximity to windows.

Centrally-activated system changeover can be problematic. For example, if a mechanical system springs into life, while on average people may be more comfortable, some may be inconvenienced by the change in local conditions and complain. After a while, management may then choose to select concurrent operation instead, as a simpler and more reliable strategy. People may also find it difficult to relate to a system which has seemingly no consistent logic. Designers must be made aware that changeover systems often default to concurrent operation and take care when planning changeover strategies, which recently have tended to become increasingly elaborate. However, there is scope for more use of demand-activated and interlocked changeover systems, for example using interval timers and window switches.
1.4.6 LOWER IN ENERGY USE?

In relation to natural ventilation, energy cost and CO₂ savings by controlled mechanical ventilation have often been claimed but seldom proved, particularly in the UK fuel economy with heating by gas - and this also applied to MM buildings. In relation to air-conditioning, MM buildings potentially offer reductions in energy consumption for fans, pumps and cooling. While the last two can often be proven, for fan consumption the picture is less clear. For many recent systems air volumes, specific fan power, and often hours of operation are relatively high, particularly if systems designed for occasional changeover use (eg: mechanical night ventilation) are operated concurrently, and particularly at high speed. Great care is required to design mechanical ventilation systems for MM buildings which are both genuinely intrinsically low-energy and which can be operated to minimise avoidable waste. Guidance on this would be useful. Careful attention is also required to comfort, control and manageability of systems which have a variety of possible operating states, and for minimising the downside risk of wasteful operation. Energy audits of recent MM buildings are recommended, perhaps using the Office Assessment Method which was developed as part of an EnREI project and which is being used successfully in the current PROBE studies in Building Services - the CIBSE Journal.

1.5 Scope of proposed guidance

1.5.1 MM has great potential in principle. However, it is not yet well-described or its features, strengths and limitations properly explored or understood by either the demand-side or the supply-side of the market. Now an increasing number of buildings are being constructed along these principles, we fear that it could easily get a bad name through gratuitous or well-meaning but misinformed responses, and by not living up to its aspirations. For example:

- Contingency design could be used as an excuse for a cheap cop-out in which the passive design measures are not throughly done and to which the mechanical systems, added quickly, were more expensive, less effective, less long-lasting and less-efficient than if they had been built-in to start with.
- Complementary designs may not deliver (and some are not delivering) their promises for comfort and particularly energy-efficiency.

1.5.2 There is a clear need for the proposed CIBSE Applications Manual, which would probably concentrate on complementary systems. Some work necessary to support this has already been outlined in the italic sections above. We recommend that an early draft is written quickly based upon current knowledge. This can then be fleshed-out with studies as necessary under the following headings:

- A survey of the attitudes of existing owners and occupiers to MM systems.
- Occupant questionnaire surveys on comfort, control and usability.
- Energy surveys, with lessons for future design and management.
- More detailed environment and comfort surveys, if deemed appropriate.
- An options study for adaptable designs, including contingency designs.
- Possibly some simple models of cost, energy and risk.

1.5.3 In addition, we recommend another well-illustrated document which aims to develop the concepts and improve everyone’s awareness of them. It should not over-sell the mixed mode route but instead help those who are already trying to do a better job and to identify common pitfalls. It should be readable by all the parties involved: from clients, through property, building and facilities management professionals, to the end-user. It could:

- explain the MM route, its varieties, and their likely opportunities and pitfalls;
- develop the agenda for adaptable contingency designs;
- set down and develop the attributes of complementary design, and
- identify the areas requiring careful attention to strategy and to detail to help to enhance the good features of effectiveness, efficiency and usability and adaptability and to minimise the risk of failure.

In a sentence, the key message would seem to be to aim for excellence in robust integration, with features that add functionality, not complication.
2 INTRODUCTION

2.1 CLASSIFICATION OF BUILDINGS BY VENTILATION TYPE
Buildings are frequently classified by their predominant means of ventilation and cooling: naturally-ventilated (NV), mechanically-ventilated (MV), or air-conditioned (AC). But buildings often contain a variety of HVAC services; with some MV in NV buildings, if only in toilets; mechanical and natural ventilation combined in supply-only or extract-only systems. Most AC buildings also have some NV and MV areas. Many “AC” buildings are not AC in the strict sense of the term, but merely comfort-cooled - though this can be perfectly appropriate.

2.2 MIXED-MODE DESIGNS
This report reviews mixed-mode (MM) designs, which deliberately set out to combine natural and mechanical systems in the same space, though not necessarily at the same time. MM is a conceptual approach, not just an engineering solution. It can help to meet owners’ and occupiers’ requirements for adaptability in an uncertain world, and avoid wasting money and energy on buying or running inappropriate and unnecessary environmental services. From the environmental point of view, MM offers a prospect of more robust, adaptable, manageable, long-lived, and cost-effective buildings; with fewer in-use emissions of greenhouse gases and pollutants, and improved occupant satisfaction. While there is a rapidly-increasing interest in MM, at present it is still seen as somewhat unusual. However, just as we routinely mix natural and artificial lighting without a second thought, perhaps MM should be seen as the normal way of doing things?

MM principles can apply to all building types. However, the prime emphasis here is on offices: in which there is already considerable interest and experience and the greatest immediate opportunities. Commercial and public sector offices account for some 12% of the UK’s non-domestic floorspace, 17% of commercial and public sector CO₂ emissions, and 5% of all buildings-related CO₂ emissions [16]. MM principles are also relevant to a similar (but probably less energy-intensive) amount of office-like space in sectors including industry, education, transport, laboratories, retailing and public services. In all sectors, this office-like space is also increasing as more activities are undertaken on desk-top computers, while some traditional office blocks and other building types are becoming redundant.

2.3 THE OFFICE MARKET
Opportunities for mechanical ventilation alone in UK offices have been limited (though they are now increasing with modern techniques of heat storage etc.); and this has contributed to a sharp division of this predominantly speculative market into NV and AC buildings. Indeed, patterns of institutional investment can be seen as having fostered the development of an increasingly limited range of building types [22]. Since the early 1980s, air-conditioning has been the institutional norm for the larger and more prestigious office buildings in the UK (at least in the better locations where rental values can stand it) and in spite of some setbacks such as building-related sickness. The very familiarity of the now standard office block provides a comfortable sense of security for investors and occupiers alike [23].

2.4 EXEMPLARS AND OPPORTUNITIES
Over the past twenty years, some owner-occupiers have been more adventurous and prepared to build MM offices. However, in today’s rapidly-changing world, former owner-occupiers are now more likely to rent, or to procure their own buildings in joint ventures with developers, and to sell them to institutional investors as “pre-lets” and lease them back. To improve marketability, the buildings must then conform with market standards- although pre-lets have more scope for variation than in the purely speculative product. While there is now wider interest in MM designs, the market is still understandably cautious about what many regard as somewhat nebulous products with an uncertain value and which may not sell; may not work (or not without making unreasonable demands on occupants and management); may lack flexibility; and may not even meet their environmental aspirations. Nevertheless, we see great opportunities for looser-fit, more generic, less specialised buildings which can readily be adapted to the needs of different occupants, activities, and even sometimes sectors.
2.5 FUTURE ENVIRONMENTAL TRENDS
The environmental imperative and trends in public attitudes make serious professional consideration of passive, low-energy solutions essential. For example, the draft CIBSE Design and Applications Manual on Natural Ventilation in Non-domestic Buildings [1, page 1.11] recommends natural ventilation as the default design strategy, followed by mixed-mode, with sealed buildings with full air-conditioning as the last resort. The Air Infiltration and Ventilation Centre [103] states that all buildings which are likely to need active cooling should adopt MM design guidelines.

2.6 FUTURE BUSINESS TRENDS
At first perhaps surprisingly, the business imperative also points in a similar direction: to cost-effective flexibility; a greater emphasis on user needs and environmental impact; and lowering costs while adding value and behaving more responsibly. For instance, preliminary outputs [7] from the BRE/DEGW study of New Environments for Working (NEW) indicate that medium-depth buildings are best suited to many aspects for tomorrow’s changing workplace. The suggested 15 metres glass-to-glass distance is near the upper limit for natural ventilation (particularly if ceiling heights are constrained and there is a need for cellular offices) but fertile territory for MM options. In the context of high uncertainty, high variability, and occupant preferences, the NEW study also sees MM ventilation and cooling systems as often being the most appropriate in principle, although sometimes requiring technical innovation.

2.7 PURPOSE OF THIS REPORT
The report is intended to put some flesh on the bones of MM strategies, and to set the scene for a possible CIBSE Applications Manual on mixed-mode design which will complement the new one on Natural Ventilation [1]. But not only engineers need information and advice. This report should also pave the way for related publications which can help to improve professional and market awareness of the strengths (and weaknesses) of MM approaches; to identify any proven techniques and technologies; and to discuss possible avenues for conceptual and technical innovations of a relatively straightforward nature.
3 STRUCTURE OF THIS REPORT

This report is in four main parts, together with conclusions, references and appendices.

3.1 PART A MIXED MODE IN THEORY
Chapter A1 outlines the reasons for wishing to take this approach, and the potential strengths and weaknesses of MM in relation to the NV and AC alternatives. Chapter A2 discusses definitions of MM, both generally, in classifying its different aspects and varieties, and in relation to the features adopted in completed MM buildings. More details can be found in Appendix X. Chapter A3 discusses strategies and their selection, and includes strategic briefing, an outline of the purposes and methods of ventilation and cooling, and a selection chart.

3.2 PART B MIXED MODE IN PRACTICE
After an introduction, Chapter B2 reviews the features of some existing MM buildings, and identifies some common characteristics and features of particular interest. Some aspects of the buildings are explored further in Chapter B3 and their engineering systems in B4. Chapter B5 outlines some problems which commonly seem to occur and that new designs should seek to guard against. The concluding Chapter B6 sets down some major themes which are thought to require dissemination or guidance.

3.3 PART C PRINCIPLES OF DESIGN AND MANAGEMENT
This explores issues thought to be critical to any design guidance. The introduction is followed by an outline of good practice design principles which aim to combine good environmental performance with adaptability and occupant satisfaction. Chapters C3, C4 and C5 then consider the critical technical issues of window design, mechanical services integration, and their control in relation to occupant comfort. The concluding Chapter C6 discusses operation, management and maintenance: all critical to the success of these buildings and systems, which must be designed to suit management and occupant needs and to avoid unmanageable complexity.

3.4 PART D NON-DESIGN ISSUES
Many reasons for choosing (or avoiding!) MM solutions are not related to their design potential but to possible opportunities for (and obstacles to) their uptake. These include marketability, cost-effectiveness, energy and environmental benefits, and health issues. Following an introduction, the four main chapters discuss each of these in turn.

3.5 PART E NEXT STEPS
This summarises the various arguments, and suggests future work necessary to obtain more information, to provide incentives and guidance, and to develop a CIBSE Applications Manual on MM design, or some aspects of it.
A1 STRATEGIC OPPORTUNITIES, STRENGTHS AND WEAKNESSES

A1.1 ORIGINS OF MIXED-MODE
The term mixed-mode (MM) was coined to classify buildings reviewed in BRECSU office case studies which were neither predominantly naturally-ventilated nor fully air-conditioned. It was first used in public in 1989 [4], though the buildings themselves pre-date a term which had to be coined to describe them! Some of these hybrids had quality features normally associated with prestige AC offices, but were cheaper (or certainly no more expensive) to buy and to run, used less energy with fewer emissions, and gave similar or better occupant satisfaction. Some NV buildings had also evolved into MM of a kind, adding comfort cooling and other systems while keeping their openable windows. The initial definition [2] was *a building with complementary systems of ventilation and cooling available, frequently background mechanical ventilation at low volume (typically one or two air-changes per hour, sometimes with chilling), together with openable windows.* A more detailed categorisation, developed by Max Fordham and Partners (MFP) [3], is discussed in Chapter A2 and Appendix X.

A1.2 BEYOND A SINGLE CHOICE
At a very early stage, irreversible decisions are often made to seal and air-condition an office building because NV is (or is seen to be) unable to meet all the design requirements or contingencies, or because AC will be (or is predicted to be) a better investment for the site regardless of technical need. MM strategies can potentially offer a wide range of benefits by creating a “bridge” between NV and AC, avoiding such all-or-nothing choices and offering other advantages. Indeed, one might reasonably expect a blend of natural and mechanical systems to be more appropriate to many requirements than options at the far ends of the scale.

A1.3 AN UNKNOWN QUANTITY
In spite of this, MM is still a somewhat unknown quantity. Until design standards and strategic, technical and managerial solutions are better defined, it could be a mixed blessing. For example nobody may quite know what is what; facilities staff may need more engineering competence than is reasonable; adaptation - although straightforward in principle - could prove expensive and its results uncertain; and alternative systems could clash, wasting energy and not necessarily improving comfort. All these will also tend to lower a building’s market value.

A1.4 COMPARISON OF POTENTIAL STRENGTHS AND WEAKNESSES
This report attempts to present a balanced view and to identify ways of enhancing good points whilst taking account of and attempting to minimise potential problems and failure paths. Table A1 reviews some general features, with their strengths, weaknesses, and other comments, for the seven potential beneficiaries outlined below. Other attributes will be assessed after MM principles and technologies have been explored in more detail.

1 *For the developer.* A cost-effective (though not normally lowest-cost) approach with potential to appeal to a wide range of customers. In particular it could give the “flexibility” that is often an important selling point of full AC, at lower cost and with less energy consumption and energy-dependency. AC’s promise of flexibility is not always delivered in practice: tenants often have to do more re-engineering than expected, and then spend more time and money on maintenance and management than they feel is reasonable or often wish to provide [6]. However, the complexity, and not specifically the AC may be the problem: designers of MM schemes must always be acutely aware of this pitfall.

2 *For the investor.* By being more readily adaptable to a range of occupant requirements and future scenarios, MM could potentially be a better short- and long-term investment.
For the designer. MM could make it easier to provide buildings for users with unknown needs - and not only for speculative buildings: many organisations and the uses they make of buildings are changing fast. Technically MM may also be able to stop a building which can’t quite work with natural ventilation - for example with too deep a plan, needing some additional cooling or heat removal, or having a noisy road too near one facade, becoming fully air-conditioned by default. By combining natural ventilation with mechanical systems MM could offer the best of both worlds......or perhaps the worst!

For the occupier. MM could potentially meet the requirements of some, if not most, occupiers more effectively, more straightforwardly, and at lower cost than sealed, air-conditioned buildings. It may also fit business strategic thinking in an increasingly uncertain world, by hedging bets and demonstrating concern for occupants, the environment and “no-frills” waste avoidance.

For the building manager. MM buildings may be potentially more robust, more adaptable, and have fewer costs, maintenance and management burdens. However, there are new skills to be learned.

For the individual occupant. In surveys [e.g: 89], occupants often say that they like to have openable windows. Where they have them (and provided the windows open onto a reasonable environment) occupants also seem to be more accepting of numerous aspects of the internal environment, including summertime temperatures, noise and air quality. However, recent studies [26, 27] indicate that the benefits of natural ventilation are often perceived primarily by those sitting next to the windows. Mixed-mode designs promise some of the benefits of openable windows in an internal environment which can be objectively better than would be possible with natural ventilation alone.

For the environment. Potentially longer-lived buildings with less energy consumption, less risk of premature obsolescence, and sometimes possibly including modular plant which could be sold and re-used if it was no longer required. A smooth transition to more sustainable buildings, but with less of a risk of non-performance in today’s harsh business environment.

A1.5 MAJOR THEMES

Strong themes which come through in Table A1 include a need for:
• Clear strategic approaches.
• Systems which complement each other rather than clash.
• Manageable systems which seek to avoid unnecessary complication.
• Avoiding wasteful energy performance, for example by taking care that systems are not too powerful, inefficient, on too much, or fight each other.
• Improving controls: for occupants, for management, and for effective energy-efficient operation.
• Clearer standards and generic exemplars.
• For some types of MM building, trying to reduce the plant which is a permanent (or semi-permanent) part of the building and adding components when and where necessary in a modular form which can be readily adapted and exchanged.

For all varieties of MM, simple and ingenious methods of providing the required adaptability could provide inspiration for designers and their clients. Some theoretical options are outlined in reference [11], but we think that the concepts need to be developed, clarified and illustrated.
### TABLE A1.1  MIXED-MODE SYSTEMS: SOME POTENTIAL STRENGTHS AND WEAKNESSES

<table>
<thead>
<tr>
<th>ITEM</th>
<th>POTENTIAL STRENGTHS</th>
<th>WEAKNESSES</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> For the developer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Widen the potential market by providing more adaptable, generic buildings.</td>
<td>Building lettable (faster?) to a broader range of tenants.</td>
<td>Some tenants may have to do more to get into the building.</td>
</tr>
<tr>
<td>1.2</td>
<td>Costs less than an air-conditioned building (but more than a naturally-ventilated one), this needs good value engineering.</td>
<td>More money can be spent on passive fabric with long term value, less on obsolescent services.</td>
<td>May get less lettable area on a site. Openable windows may be extra cost if air-conditioning is needed.</td>
</tr>
<tr>
<td>1.3</td>
<td>Extension of “shell and core” concept. Adaptable to meet changing needs.</td>
<td>You get (and pay for) only what you need.</td>
<td>Late enhancements may be more necessary or more expensive.</td>
</tr>
<tr>
<td><strong>2</strong> For the investor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Better long-term investment value. A. Helps to avoid obsolescence.</td>
<td>Sound decisions have to be made.</td>
<td>No clear examplars yet.</td>
</tr>
<tr>
<td></td>
<td>C. Re-fits can be done faster.</td>
<td>More tinkering may be required.</td>
<td>More standardisation could be helpful.</td>
</tr>
<tr>
<td><strong>3</strong> For the designer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Helps to deal with uncertainties in briefs for unknown clients or changing needs.</td>
<td>More detailed requirements and decisions can be left to the occupier.</td>
<td>Clear strategic thinking is necessary to get the fundamentals right. Who will pay for the extra design time?</td>
</tr>
<tr>
<td>3.2</td>
<td>Extends the limits of natural ventilation.</td>
<td>Permits deeper and more complex plans with greater “flexibility”.</td>
<td>Occupants distant from windows feel less comfortable than those nearby.</td>
</tr>
<tr>
<td>3.3</td>
<td>Permits the use of openable windows in mechanically-serviced buildings.</td>
<td>Solutions can be more appropriate to the context. May reduce costs.</td>
<td>Potential confusion, antagonistic operation, and complication.</td>
</tr>
<tr>
<td>3.4</td>
<td>Can avoid unnecessary use of mechanical systems, in space and in time.</td>
<td>Less to go wrong. Potential cost, energy and maintenance savings.</td>
<td>Energy may not be saved if systems are inefficient or poorly-managed.</td>
</tr>
<tr>
<td>3.5</td>
<td>Air quality can be controlled mechanically with low-volume background ventilation. A. Low power mechanical systems possible if windows are openable.</td>
<td>Too much window opening may undermine the mechanical system.</td>
<td>Systems may run too much.</td>
</tr>
<tr>
<td></td>
<td>B. Can help avoid winter draughts.</td>
<td>Energy consumption and emissions may increase-though they need not.</td>
<td>Systems may run too much.</td>
</tr>
<tr>
<td></td>
<td>C. Can remove local</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4</strong> For the occupying organisation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Doesn't pay for what it doesn’t need.</td>
<td>Suits current “lean and fit”, no-frills business cultures.</td>
<td>Exploiting adaptability potential may require more (or different) skills.</td>
</tr>
<tr>
<td>4.2</td>
<td>Services are innately adaptable.</td>
<td>Potential to tailor to needs at lower capital and energy cost.</td>
<td>Adaptation may be more expensive for some than upfront investment.</td>
</tr>
<tr>
<td>4.3</td>
<td>May be fiscal advantages.</td>
<td>Supplementary relocatable services may be tax-deductible business plant rather than building elements.</td>
<td>Danger that this might discourage capital investment and bias to short-life, low-efficiency solutions.</td>
</tr>
<tr>
<td>4.4</td>
<td>Easier to dispose of or to sublet.</td>
<td>Attracts a wider range of new tenants.</td>
<td>May require investment in services modifications.</td>
</tr>
<tr>
<td>ITEM</td>
<td>POTENTIAL STRENGTHS</td>
<td>WEAKNESSES</td>
<td>COMMENTS</td>
</tr>
<tr>
<td>------</td>
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</tr>
<tr>
<td><strong>5</strong></td>
<td>For the building manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>No need to look after systems which are not essential to the building's function.</td>
<td>Less time spent on routine, more to focus on genuine needs.</td>
<td>If systems are less standard, they may require more knowledge and insight to look after.</td>
</tr>
<tr>
<td>5.2</td>
<td>Habitability of the building is less tightly-coupled to minute-to-minute mechanical services performance.</td>
<td>If windows are openable, occasional shortcomings are less likely to grow into urgent management problems.</td>
<td>A. The potential variety of equipment and operating modes may be complicated and confusing.</td>
</tr>
<tr>
<td>5.3</td>
<td>More robust, less fragile. Potential to cope more easily with breakdowns and the unexpected.</td>
<td>A. More likely to fail &quot;soft&quot;, giving more time to put things right, for both short- and longer-term issues.</td>
<td>May have less power in immediate reserve. Management must be sympathetic to making changes.</td>
</tr>
<tr>
<td><strong>6</strong></td>
<td>For the individual and group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Most occupants prefer openable windows, even if they don't use them much.</td>
<td>Occupants are more tolerant of raised summertime temperatures than in sealed buildings.</td>
<td>The margin is quite small. Windows need to have a reasonable outlook, work well, and be easy to operate.</td>
</tr>
<tr>
<td>6.2</td>
<td>Occupants like to adjust windows and blinds (but not too often).</td>
<td>This improves satisfaction by permitting rapid alleviation of discomfort when it occurs.</td>
<td>A. Access routes to windows may reduce efficiency of space use, and if blocked may reduce comfort.</td>
</tr>
<tr>
<td>6.3</td>
<td>More chance of putting local problems right by fine-tuning or local alterations.</td>
<td>Solutions can be tailored to the specific requirement.</td>
<td>Not all organisations will spare the time and money.</td>
</tr>
<tr>
<td><strong>7</strong></td>
<td>For the environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>More sustainable design with a greener image</td>
<td>Reflects well upon all parties.</td>
<td>Unfamiliar territory. Benefits may sometimes be illusory.</td>
</tr>
<tr>
<td>7.2</td>
<td>Potential to reduce energy consumption and related pollutant emissions.</td>
<td>Mechanical systems can be lower-powered and/or run for fewer hours.</td>
<td>Reductions may not materialise if system or operation is inefficient.</td>
</tr>
<tr>
<td>7.3</td>
<td>Potentially a longer building life with less premature obsolescence and scrapping.</td>
<td>Provided that the strategy is right.</td>
<td>Ready adaptability might encourage early scrapping of some elements (but these may be a relatively small part of the whole).</td>
</tr>
<tr>
<td>7.4</td>
<td>Potential to use modular items of plant, which can be redeployed or sold after use.</td>
<td>Offers rapid, tailored response to changing needs.</td>
<td>But needs strategy, standardisation and an active secondhand market.</td>
</tr>
</tbody>
</table>
A2 MIXED MODE DEFINITIONS AND CLASSIFICATIONS

A2.1 Introduction
A2.1.1 THE VARIETY OF MIXED MODE DESIGNS
MM designs can combine natural ventilation with a wide range of mechanical ventilation and cooling systems, potential or actual. At one end of the scale there may be no mechanical systems at all, but merely strategic provision for adding them in one or more ways, for part or all of the building. At the other end, a building may be fully AC, but planned so that in different circumstances all or part could function with less (and possibly even no) mechanical assistance. An enormous variety of mechanical services may be installed and combined with natural ventilation in many ways - in space, in time, working together, working alternately, and so on.

A2.1.2 IS CLASSIFICATION WORTHWHILE?
Given this potential variety, to attempt a detailed classification may be troublesome. In addition, key features of MM are adaptability and opportunism, so buildings (or parts of them) may alter in classification as they evolve in operation and use. Should the term MM apply to all buildings which incorporate more than one ventilation and cooling system? Or would this debase the currency? Might it be better to talk about MM systems, which combine natural and mechanical ventilation and cooling systems (or system options) in the same space? The MM idea is not only for engineers, it can also affect the whole approach to building procurement, marketing, design and management. It could be an integral part of the response to an increasingly uncertain world in which buildings can no longer pretend to be precise solutions to carefully-measured and unchanging briefs. To paraphrase a comment on education for business by Handy [17, page 193] - perhaps MM systems should be seen as “starter kits which can help the occupants to work out their own solutions to their own predicaments”.

A2.1.3 THE DESIRABILITY OF SOME CLASSIFICATION
People find it useful to consider buildings (or parts of them) in the major groupings of NV, AC, and to a lesser extent MV. In the property market, these terms have associations with not only the ventilation and cooling system, but with a whole group of features which tend to be associated with the mental image of a specific type of building - and which affect its market value. The general term is qualified where necessary, e.g: partially AC. Those really interested can find out more if they wish (for example: VAV with LPHW perimeter heating, gas-fired steam humidification, maximum eight air-changes per hour, allowance for 25 W/m² equipment heat gains, and so on), but at a first pass (except perhaps for the air-conditioning type) these details are much less important.

On balance, it appears to be very useful to have in common parlance a single all-embracing term such as MM (and it is probably too late to change it) to describe buildings which combine openable windows with mechanical ventilation and cooling systems, and which are more readily adaptable (though often less powerful, at least in their basic form) than the traditional exemplars. Given that that the market uses only two or three terms at the moment, seeking to add more than one looks far too ambitious! More detail can come in the small print.

For marketability, the general term would also be an umbrella for a group of desirable attributes (as outlined in Chapter A1), and not just an approach to ventilation and cooling services. Indeed one can argue [25] that MM should become the normal state of things (as for lighting), with NV and particularly full AC the special cases! MM attributes could be promoted not as the middle ground but as superior - at least in the right circumstances.

A2.1.4 APPROACH TO A POSSIBLE CLASSIFICATION
Section A2.2 outlines the existing classification of MM buildings by Max Fordham & Partners (MFP) [3]. In Sections A2.3, known MM buildings are reviewed in relation to these definitions, considering in particular their design intentions and features, and any major physical and operational changes which have occurred in use. Section A4 then puts forward some propositions for discussion. More details can be found in Appendix X.
A2.2 MFP’s mixed-mode definitions and classifications

A2.1 ORIGIN OF THE DEFINITIONS
A2.1.1 The most detailed classification of MM buildings: Contingency, Concurrent, Changeover and Zoned was developed by Max Fordham & Partners (MFP) under the EnREI programme [3]. These definitions are outlined below, with some comments on their interpretation and implementation. Other definitions are discussed in Appendix X.

A2.2.2 CONTINGENCY
In its most common form, contingency design is a building designed to be naturally-ventilated (for example along the lines discussed in the CIBSE Applications Manual [1]), but which also has a clear contingency plan (or plans) for adding mechanical ventilation and/or cooling if this proves to be necessary. At the opposite end of the scale, a sealed air-conditioned building may have the potential to revert to a less energy-dependent form of operation, for example if planned for natural ventilation (and having suitable openable windows etc. - even if initially they are locked shut), or some form of concurrent or changeover operation. Where the initial aim is to rely entirely upon natural ventilation, very careful attention to passive measures and to heat gain avoidance will be necessary, and window design becomes critical.

A2.2.3 CONCURRENT
This is the commonest form of hybrid, in which mechanical ventilation - with or without cooling - operates in parallel with openable windows. Often the mechanical system suffices, controlling draughts and air quality and removing heat, but people can open the windows if they want to. The systems need to be complementary, not antagonistic. Site studies however suggest that mechanical systems are often too powerful, not very efficient, and run much more than necessary and than the designers anticipated. Guidance material would help to identify some of the reasons for this, and permit some of the problems to be identified and avoided.

A2.2.4 CHANGEOVER
Natural and mechanical systems are available and used as alternatives according to need, but do not normally operate at the same time. Some examples include:
- Seasonal changeover, for example where windows are openable in mild weather but locked shut in winter, when mechanical ventilation is used to meet required air quality standards, avoid draughts and possibly save energy by using heat recovery.
- Night cooling, with natural ventilation during the day, and mechanical at night to remove excess heat built up in the fabric. This is useful where windows cannot be left open, or where air is passed over the structure to enhance heat storage effects.
- Local changeover, with window detectors to switch off nearby air-conditioning or comfort cooling units when the window is opened.

In practice it can be difficult to implement centrally-managed changeover design intentions reliably, owing to their complexity; an absence of input information to make an informed choice; poor or non-intuitive user interfaces; or adverse occupant reactions to systems which change capriciously (at least to them) and trigger some irritation to which they had adapted in the former operating mode - for example by moving their desk. Consequently changeover systems frequently default to concurrent operation, usually with increased energy consumption and sometimes with worse performance. The risk of such difficulties may be rising as progressively more complex operating strategies are validated by computer models.

A2.2.5 ZONED: with different services in different parts of the building: for example comfort cooling locally for hot spots (probably a special case of contingency design), or in parts of the building (say) with a deeper plan, high solar gains or limited opportunities for natural ventilation. However, such variations in the servicing of nearby and operationally similar spaces in the same building causes problems for users: careful study and guidance is essential. Another variety of zoning is where services in special areas (eg: restaurants, computer suites, meeting rooms, swimming pools and toilets) differ from those in other parts of the building - but since this is perfectly normal it may not be helpful to classify this as MM.

1 Perhaps a misnomer: recent BRE and BSRIA pressure tests indicate that some recent “sealed” air-conditioned offices in the UK have higher air-infiltration rates than many naturally-ventilated ones!
A2.3 Application of the MFP classifications to some completed MM buildings

A2.3.1 THE BUILDINGS CONSIDERED AND THEIR KEY FEATURES

Table B1 (see Chapter B1) lists MM buildings previously visited by WBA and Table B2 others - built or under construction - which have been described in the technical press. The two tables include their design intentions classified into the four MFP categories; mechanical ventilation rates in air-changes per hour (ac/h) where appropriate; air supply positions; predominant ceiling types (exposed, suspended, or variable - i.e: some of each); and other comments. For the buildings visited, Table B1 also includes notes on the operation and performance in use of the HVAC systems (including the natural ventilation element) in practice, including any changes made.

A2.3.2 CATEGORISATION OF THE BUILDINGS REVIEWED

Key points on categorisation include:

1. Many buildings fall into more than one category, though a single category usually predominates.

2. By far the most common design category is concurrent. It will clearly need the most attention, probably as the prime focus of the proposed CIBSE Applications Manual.

3. Only a few buildings were predominantly contingency designs. The Body Shop [10] is the clearest and best-known example: designed so that conventional (for the time) VAV air conditioning could be added if necessary. Several others (in fact, nearly all with air handling units) had contingency features on a broader BRECSU definition which includes the potential to add cooling coils: however, we have only assigned this feature where the intention was explicit, or if they had some chilling already, which could have been extended easily.

4. Salford Civic Offices - an early 1970s shallow-plan AC office was designed so that its AC could be removed if necessary at some future date. Its centre-pivot windows (with mid-pane venetian blinds) were openable not only for cleaning but as contingency provision. Now the AC is due for replacement they are considering whether to omit it, and in an EnREI study [15] Arup R&D found this to be feasible. The windows were initially locked but were then released following complaints, creating an ad hoc concurrent solution which the staff preferred, partly because the AC was a changeover induction system which did not cope well with mild and fluctuating weather conditions. Several other offices have also reverted to contingency, concurrent or changeover operation following removal of AC.

5. Not including the normal differences in reception areas, toilets, loading areas etc., more than half the buildings were zoned with different types of services in different parts of them. The entry "yes" identifies physically similar areas of office-like space which had different servicing; for example with VAV summer cooling installed only on the solar-exposed facades at Hereford and Worcester County Hall [19], or mechanical ventilation to the offices around the atrium at Policy Studies Institute [18]. The entry "local" means that the zones were for special areas such as restaurants, computer rooms and conference/ training rooms, which would usually have been serviced differently anyway.

6. Changeover operation was most commonly used for mechanical night cooling and for chilling in hot weather (using supply air, fan coils or chilled panels). In some buildings visited - for example Hereford and Worcester County HQ and Refuge House [20] - the seasonal changeover arrangements planned by the designers had often been simplified in practice into concurrent operation, both for greater ease of management and to avoid disturbing or confusing occupants. We think that similar operational changes could well have occurred in some of the newer buildings.
A2.4 Conclusions on definitions

A2.4.1 OVERVIEW
Combining natural and mechanical ventilation and cooling systems is a useful concept and one which we expect to become increasingly widespread. The term mixed mode is already quite well entrenched and we feel it should remain all-embracing and not be restricted to particular types of solution. For a more detailed classification, the MFP system has been reviewed and we think would benefit from some minor alterations. More detailed generic classifications do not seem to be helpful: it would be better to give technical details of the systems.

A2.4.2 GENERAL OBJECTIVES
One thing missing from earlier definitions was a statement of general objectives. We think that all MM buildings and systems will comply with at least one and often all of the following:

OBJECTIVE 1 Longer-lived buildings which can be adapted to changing requirements, standards and priorities, and serviced to meet occupiers’ real needs whilst avoiding wasteful over-provision, unnecessary capital and running costs, or burdens for management.

OBJECTIVE 2 Better occupant satisfaction, by combining the perceived advantages of openable windows with any mechanical servicing necessary to provide suitable levels of health, safety and comfort.

OBJECTIVE 3 Lower energy use and the associated greenhouse gas and pollutant emissions through avoiding the unnecessary provision and operation of mechanical systems at times and in places where natural ventilation could achieve the task more efficiently.

A2.4.3 DIFFERENT CLASSIFICATIONS
The MFP classification: Zoned, Contingency, Concurrent and Changeover has worked well, but some shortcomings have been exposed. A classification system with four separate facets would be theoretically more appropriate (see Appendix X), and leads to the following general definition: Mixed-mode is an approach to ventilating and cooling in which natural ventilation (normally using openable windows) and mechanical ventilation and/or cooling systems are deliberately combined:

1. For the whole building or for parts of it.
2. Actually (with both systems present) or potentially (in building designed for easy addition, removal or alteration of part or all of the mechanical systems).
3. As complementary or mutually exclusive alternatives.
4. If complementary, by operating together or as alternatives.

A2.4.4 RECOMMENDED SIMPLE CLASSIFICATION
In spite of the above, more detailed classification does not seem worthwhile: it would be better to add specific technical details than to seek an elaborate all-purpose classification. We therefore suggest small alterations to the MFP definitions, as outlined below.

Strategically, we suggest the options of zoned, contingency and complementary. Operating modes for complementary systems can then be broadly classified as either:

- Concurrent, where openable windows and mechanical systems operate together.
- Changeover, where the systems may operate in rapid succession but not normally together, except by default.
- Alternate, where a choice, once made (say to close the windows and operate full air-conditioning with humidity control) persists for a long time.

More complex strategies may include combinations of the above. More detailed descriptions can then be provided as appropriate, for example say seasonal changeover with controlled mechanical ventilation in winter, mechanical ventilation with night and comfort cooling in hot weather, and openable windows at other times. Further description of strategic and detailed engineering options will be considered later.

In colloquial terms, however the existing MFP definitions can still be used.
A3 SELECTING MIXED MODE STRATEGIES

A3.1 A strategic flowchart

A3.1.1 THE FLOWCHART

Figure A3.1 is a flowchart which is intended to indicate the appropriate mode of ventilation and cooling for a building or for a zone, using the classification system discussed in Section A2.4.4. The flowchart assumes that the suitability of the building for natural ventilation has already been reviewed, for example using the procedures in the CIBSE Design and Application Guide for Natural Ventilation [1], and particularly its figure 19. It also includes - at least in a rudimentary form - choices both for the building as a whole and for the zones within it.

A3.1.2 DEVELOPING THE OPTIONS

Under these headings, however, there is a wide range of options and possibilities, and it soon gets difficult to separate principles from practicalities. Ventilation and cooling have a variety of different purposes, and these can be met by a variety of different technologies. We therefore now turn to outlining the purposes of ventilation and cooling, together with some methods.

**RESERVED FOR FIGURE A3.1**
A3.2 Purposes and methods of ventilation

A3.2.1 Five main purposes of ventilation

Ventilation has five main purposes, outlined below together with an indication of the normal range of ventilation rates:

V1 To provide sufficient “background” ventilation for air quality and odour control. Today’s good practice in an office is typically 10 litres/second per person [24], though this may be increased for smoking, crowded occupancies, or where there are additional sources of pollution. For a typical occupation density of 14 m$^2$/person [24] and a ceiling height of 2.7 metres, this equates to about one air change per hour (ac/h). For “minimum fresh air” mechanical systems a figure of about 2 ac/h is often used, probably because this permits some smoking and some local increases in occupation density. Recent studies indicate that in many buildings most pollutants originate from the fabric, contents and the mechanical ventilation systems, and not the people. However, to improve conditions further, additional general ventilation has been shown to be much less effective than treating the problems at source: by specification, cleanliness and local extraction.

V2 To provide natural cooling during the occupied period. As a general rule, typical maximum natural ventilation rates in an office are in the range 4 to 8 ac/h. Above this, difficulties tend to occur with draughts, papers blowing about, and so on. Higher rates are practicable in temporarily-occupied spaces such as atria. A maximum of about 6 ac/h is usually the upper limit where mechanical ventilation is used for cooling: beyond this the fan energy consumption is such that some mechanical cooling will often be a more effective and lower-cost solution. To minimise fan power, low-speed operation should also be available outside the peak periods.

V3 To provide natural cooling outside the normal occupied period: in particular “night cooling” or “night purging”. This can remove heat built-up in structure and contents and provide some pre-cooling for the following day. Its effect increases the more the air can “scour” the structure. Techniques range from exposed ceilings, through ventilated raised floors, to airways embedded in the structure: where these surfaces are not exposed to the room they may instead be used to pre-cool the air supply to the room during the day. With normal practical limitations upon secure openable area for natural systems and on duct size and fan energy consumption for ducted mechanical systems, practical night ventilation rates are often in the range 2 to 4 ac/h.

V4 To exhaust heat and/or pollutants from localised sources or areas, for example kitchens, toilets, vending areas and equipment rooms. This enables adjacent areas to be more comfortable with less conditioning. Exhaust air change rates are typically 5 ac/h or more in the spaces concerned. The systems often need to operate for longer hours that in the main spaces, and so independent extract systems are preferable. Good catchment of the air to be extracted is desirable, for example in closed rooms, with exhaust hoods, or with air extracted directly from the equipment concerned.

V5 To act as a carrier medium for mechanical cooling and/or humidity control. This can be either via all-air systems in which the air is treated centrally or via air/water or unitary systems in which the air is recirculated and treated locally. In either case, local air turnover rates in offices are often in the range 4 to 10 ac/h.

Table A3.1 outlines some technical methods of achieving each of these purposes, together with comments on strengths and weaknesses, and other comments. More information on energy-efficient ventilation is available in references [103] and [104].
### TABLE A3.1

**PURPOSES AND METHODS OF VENTILATION: SOME STRENGTHS AND WEAKNESSES**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>STRENGTHS</th>
<th>WEAKNESSES</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V1</strong> BACKGROUND VENTILATION AND AIR QUALITY CONTROL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1A Natural trickle ventilation with automatic control.</td>
<td>Relatively low-cost. Controllable as necessary.</td>
<td>Not widely used or understood.</td>
<td>Heat recovery difficult. Most appropriate for shallow plan spaces and open areas.</td>
</tr>
<tr>
<td><strong>V2</strong> NATURAL COOLING DURING THE OCCUPIED PERIOD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V2N Manually-operated windows</td>
<td>Obvious, understandable, readily adjustable. Different elements may be required for local and for cross-ventilation.</td>
<td>Can be problems with noise, dirt, draughts and security. Better for those sitting near than distant.</td>
<td>Useful safety-valve for discomfort-alleviation. However, occupants do not usually exercise control until they become uncomfortable, so some actions may be taken too late.</td>
</tr>
<tr>
<td>V2A Mechanically-operated windows or ventilators</td>
<td>Automatic control possible in anticipation of need and for the general good. Manual remote control possible without going to a window. Less restrictive on furniture layouts. Less in area for window alterations.</td>
<td>Occupants at their workstations seem to dislike automatic control which perceptibly alters positions of windows (or blinds) in their territory or changes air movement patterns.</td>
<td>Automatic control possible, e.g. for night cooling. Occupants inboard may be given remote control of upper parts of windows. Experience with blinds suggests that if visible operation occurs during occupied hours, user overrides will be essential.</td>
</tr>
<tr>
<td><strong>V3</strong> NATURAL COOLING OUTSIDE THE OCCUPIED PERIOD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3N Manually-operated windows</td>
<td>Simple, straightforward. Modular zoning. Windows opened in the day will tend to be left open overnight.</td>
<td>Possible problems with security, insects, rain or excessive cooling (particularly over weekends).</td>
<td>Hopper fanlights have worked well in several buildings with exposed ceilings, particularly where there are attentive security staff.</td>
</tr>
<tr>
<td>V3A Mechanically-operated windows or ventilators</td>
<td>More precise and reliable operation possible than with manual control.</td>
<td>Additional capital and maintenance costs. Uncertain reliability.</td>
<td>Potentially useful if they can be afforded. Product development may be necessary.</td>
</tr>
<tr>
<td><strong>V4</strong> LOCAL EXTRACTION OF HEAT AND POLLUTANTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V4N Via openable windows</td>
<td>Simple and straightforward, particularly in enclosed rooms.</td>
<td>Somewhat haphazard. May be difficult to leave open at night.</td>
<td>May sometimes be satisfactory for small, closed rooms. Danger of over-cooling.</td>
</tr>
<tr>
<td>V4P Via passive stacks</td>
<td>Simple and straightforward.</td>
<td>Lacks locational flexibility.</td>
<td>Most suitable for fixed facilities such as WCs.</td>
</tr>
<tr>
<td>V4L Via local mechanical extract</td>
<td>Local systems can be sized and controlled according to need.</td>
<td>Local units may not always be easy to accommodate or adapt.</td>
<td>Consider design strategies to permit modular units to be added (and removed) easily.</td>
</tr>
<tr>
<td><strong>V5</strong> CARRIER MEDIUM FOR MECHANICAL COOLING AND/OR HUMIDITY CONTROL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V5 Background mechanical ventilation</td>
<td>Meets internal air quality requirements when windows are closed.</td>
<td>Can be wasteful if one uses large central systems to meet local extended-hours requirements.</td>
<td>Zone both ventilation and cooling carefully in order to avoid the energy waste that occurs when large systems are operated to meet small local demands.</td>
</tr>
<tr>
<td>V1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1 Mechanical background ventilation.</td>
<td>Good control over quantity of air delivered. Tempering and heat recovery possible. Allows facade to be sealed and air conditioning etc. to be added if necessary.</td>
<td>Higher capital cost. Predicted energy cost savings from heat recovery often evaporate in practice once additional ventilation, electricity for fans and heat for air tempering and frost protection are taken into account.</td>
<td>May need zoning, particularly if used to support local air conditioning or heat removal, or if occupancy hours are diverse. Modular, locally/centrally-controlled ventilation units are possible (as at Inland Revenue Nottingham).</td>
</tr>
</tbody>
</table>
VENTILATION AND AIR MOVEMENT
Ventilation is also associated with air movement. Typically velocities of between 0.1 and 0.15 metres/sec can help the atmosphere to feel “fresh”. Higher velocities can provide a useful cooling effect when it is warm, but can be a nuisance if they are perceived as a draught or if they blow things around. It can be difficult to please everybody, and for higher velocities ideally one should be able to choose “where to put the draught”. With natural ventilation, this option is usually only available to people who sit immediately beside windows: not only do they have control, but near the inlet or outlet the location of the draught is less affected by changes in wind direction and by window opening elsewhere. With mechanical ventilation or air-conditioning there is often no choice at all, and many complaints appear to originate from:
- obstructions, clashing airstreams, or loss of Coanda effect, causing air to “dump” locally (but this can also happen with natural ventilation [27]);
- unsuitable air velocities, particularly where furniture arrangements trap stagnant pockets or alternatively do not allow people to vary their seating positions in order to get out of the way of local draughts (or into local airstreams in hot weather);
- floor supply systems, where facilities managers have often had to relocate the outlets further away from desks and into the corridors (or occupants adjust the dampers or put waste paper bins over them);
- varying air distribution patterns with changing load: the control range of many VAV systems has needed to be altered to minimise such complaints.

MM systems are not immune from such problems, both from windows and mechanical systems: for example changeover operation may cause different local problems in each state. However, there may also be benefits: for example a small amount of window-opening in a pressurised building can provide some psychological relief, widening tolerance margins whilst creating little or no draught.

A3.3 Purposes and methods of mechanical cooling
A3.3.1 MECHANICAL COOLING OPTIONS
The purposes of mechanical cooling are fewer than those of ventilation: it is to take out more unwanted heat (and sometimes moisture) than natural or mechanical ventilation can reasonably do. However, the available technologies are diverse. Table A3.2 provides an abbreviated list of mechanical cooling options thought to be of greatest applicability. It also gives comments on their general suitability for use in combination with natural and mechanical ventilation in MM systems. The more innovative possibilities are not included, not because they hold no interest or applicability, but because it is difficult to generalise about them.

A3.3.2 SUITABLE COMBINATIONS
While almost any combination of systems is possible, the most frequent choices tend to be central or zonal cooling via constant volume all-air systems, and local modular cooling via fan-coil units. There is also increasing interest in combining openable windows with displacement ventilation and/or ventilated structures, supplemented if necessary by chilled beams, though as yet there are few UK examples with operational experience.
### TABLE A3.2

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>STRENGTHS FOR MIXED MODE</th>
<th>WEAKNESSES FOR MM</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C1 ALL-AIR SYSTEMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1.1 Constant volume:</td>
<td>If background mechanical ventilation is present, cooling and dehumidification can</td>
<td>Limited cooling capacity. Openable windows may clash and waste energy (but not</td>
<td>Potentially low-cost boost for extreme weather, particularly if combined with floor supply</td>
</tr>
<tr>
<td>minimum air supply,</td>
<td>easily be added to it to boost performance. Can combine with fabric storage.</td>
<td>necessarily very much).</td>
<td>or night cooling. Ground and top floors in particular may need zoning to reduce</td>
</tr>
<tr>
<td>(typically 1 to 3 ac/h)</td>
<td></td>
<td></td>
<td>temperature offsets. 100% fresh air system practicable.</td>
</tr>
<tr>
<td>C1.2 Constant volume:</td>
<td>As above but giving higher cooling capacity.</td>
<td>Fan energy consumption can be high. Energy waste from clashes with window opening</td>
<td>Possible for contingency or changeover mode, but normally there will be more appropriate</td>
</tr>
<tr>
<td>typical air supply 4 to</td>
<td></td>
<td>is more likely.</td>
<td>options. Needs good zoning. For economy, consider two-speed or variable speed</td>
</tr>
<tr>
<td>10 ac/h</td>
<td></td>
<td></td>
<td>systems. Variable recirculation desirable for energy saving.</td>
</tr>
<tr>
<td>C1.3 Variable air volume</td>
<td>Can provide more demand-responsive boost. Could interlock local unit controls to</td>
<td>Potential clashes. Expenses unless used with discretion. More likely to cause</td>
<td>Probably most appropriate for contingency designs or for particular zones or tenancies.</td>
</tr>
<tr>
<td></td>
<td>window opening. Provides local control.</td>
<td>draughts.</td>
<td></td>
</tr>
<tr>
<td>C1.4 Displacement</td>
<td>Fairly simple air tempering and control requirements. Can also benefit from cooling of</td>
<td>Turbulence from natural ventilation will tend to undermine the displacement effect.</td>
<td></td>
</tr>
<tr>
<td>ventilation</td>
<td>floorslab.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>C2 AIR-WATER SYSTEMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2.1 Fan coil units (FCUs)</td>
<td>May be used ad hoc for local comfort cooling. Do not necessarily need fresh air</td>
<td>Condensate drainage (unless windows are shut and supply air is available and</td>
<td>Potentially useful both for local ad hoc cooling and for changeover operation. Relocatable</td>
</tr>
<tr>
<td></td>
<td>supply. Can be interlocked to windows. Good local control.</td>
<td>dehumidified).</td>
<td>FCUs with plug-in connections are possible. Possible problems with chilled water</td>
</tr>
<tr>
<td>C2.2 Unit air-to-water</td>
<td>As FCUs, but do not require central chiller but merely heat rejection circuit. Heat</td>
<td>As FCUs. Heating mode probably unnecessary. Local control not as good as for</td>
<td>sizing and efficient operation to suit dispersed loads.</td>
</tr>
<tr>
<td>heat pumps (e.g.</td>
<td>recovery potential.</td>
<td>chilled water.</td>
<td></td>
</tr>
<tr>
<td>Versatemp)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2.3 Induction units</td>
<td>Most suited to concurrent or changeover. Good local control, particularly with VAV.</td>
<td>Probably relatively expensive. Not suited to ad hoc loads.</td>
<td>Reportedly used successfully in Germany. Probably limited application in the UK. Best</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>for concurrent operation.</td>
</tr>
<tr>
<td><strong>C3 UNITARY SYSTEMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3.1 Through-the wall</td>
<td>Traditional ad hoc solution.</td>
<td>Messy, noisy. poor air distribution.</td>
<td>Not normally appropriate in the UK.</td>
</tr>
<tr>
<td>units</td>
<td></td>
<td>Where do you put the condensers?</td>
<td>Not normally ideal. Careful architectural thought is needed to control unit, condenser</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If the system is altered, refrigerant will tend to be lost.</td>
<td>and pipework location. Adverse environmental impact of refrigerants.</td>
</tr>
<tr>
<td>C3.2 Split units.</td>
<td>Useful ad hoc solution.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3.3 Multi-split units</td>
<td>Useful zonal solution for supplementary comfort cooling.</td>
<td>High charge of refrigerant. Not as readily adaptable as FCUs after fitting.</td>
<td>Potentially useful for zones with local permanent requirements, but not as adaptable as</td>
</tr>
<tr>
<td>(viz VRV)</td>
<td></td>
<td>Refrigerant loss on alteration.</td>
<td>C2.1 or C2.2. Adverse environmental impact of refrigerants.</td>
</tr>
<tr>
<td><strong>C4 STATIC COOLING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4.1 Embedded coils</td>
<td>Useful for lowering radiant temperatures.</td>
<td>Limited cooling capacity.</td>
<td>Needs to be done throughout at the beginning. Interesting for low-energy designs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>requiring some cooling.</td>
</tr>
<tr>
<td>C4.2 Chilled ceilings</td>
<td>Little maintenance required in the room. Potentially good local control.</td>
<td>Relatively expensive. Condensation risk if windows opened or supply air is not</td>
<td>Limited applicability.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>dehumidified. Any advantage of exposed soffits is lost.</td>
<td></td>
</tr>
<tr>
<td>C4.3 Chilled beams</td>
<td>As chilled ceilings, plus good for local ad hoc spot cooling.</td>
<td>Condensation risk if windows opened or supply air not dehumidified in humid</td>
<td>Additional cooling capacity available with ventilated or powered chilled beams. Chiller/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>summer weather.</td>
<td>chilled water sizing problems as for FCUs.</td>
</tr>
</tbody>
</table>
A3.4 Provisional conclusions on MM strategies

A3.4.1 HOW MUCH FURTHER CAN ONE GO?
The above discussion can help to establish possible strategies for ventilation and cooling and the constituent components. However, to go much further in general terms becomes increasingly difficult as the number of permutations blossom. Further development is probably best undertaken in project-specific terms between designers and their clients.

A3.4.2 A PRACTICAL APPROACH
Amongst the wide range of possibilities, some are of particular practical or topical interest at present. Part B - Mixed Mode in Practice - therefore attempts to identify the principal concerns of today and the opportunities for the near future, and to discuss issues which may be of particular importance to the achievement of robust, effective and efficient MM designs.
B1 Introduction

B1.1 This part of the report outlines features of MM buildings (largely offices) that we are aware of either through direct experience (nearly half have been visited by team members), via colleagues or through the literature. It outlines some of their design features, relates them to the MFP classification, and identifies common characteristics. For the buildings visited, it also includes comments on changes made and problems encountered. This helps to identify some of the design and management issues to be discussed in Part C. All buildings included are either occupied or under construction: design studies and unbuilt designs are not included.

B1.2 All the buildings outlined are in the UK. A review of Continental European practice is also recommended: MM is common in some countries and we have already visited a few examples. However, design requirements and market conditions can be very different from those in the UK: for example with higher space standards, and often quasi-domestic situations with many individual perimeter rooms. Objective data is also highly elusive.

B2 Characteristics of existing designs

B2.1 MM BUILDINGS PREVIOUSLY VISITED BY WBA
On previous projects, WBA has visited 27 MM buildings, many of which have been surveyed in some detail. Some of their features are summarised in Table B1. The first page of this:
- Summarises the design intentions of their ventilation and cooling systems under the MFP classification.
- Notes the main air supply location: ceiling, floor, wall or natural (or “none” for contingency designs currently with natural ventilation only).
- Notes the predominant ceiling type: suspended, exposed, partially suspended and varies (some of each).
- Notes the heating system, mostly perimeter radiators or convectors.
- Identifies other key points.
- Notes changes to their design and operation which have occurred in use.
- Comments on these and other issues.
- Makes reference to any publications.
On the second page of Table B1, some key features are summarised.

B2.2 OTHER MM BUILDINGS IDENTIFIED
Table B2 lists other MM buildings identified, categorised as in Table B1, and with notes on some key features. Most of these are either under construction or have been completed within the past three years - on average they are eight years younger than those in Table B1. Most are owner-occupied or pre-let, three are speculative, and many of the others have also had to take some account of investor and property market requirements.

B2.3 CLASSIFICATION OF THE DESIGNS
Over three-quarters of the buildings visited and about half the newer designs were designed for concurrent operation. For the newer buildings, concurrent remains the most common operating strategy but changeover is more common. However, experience with the older buildings suggests that in practice changeover systems are not always controlled as the designers anticipated, see B4.3. Several buildings were zoned, with additional or independent servicing. A few had deliberate contingency strategies, including one from the 1970s with contingency to remove air-conditioning, and which may soon be activated.
**TABLE B1** MIXED-MODE BUILDINGS VISITED BY WBA: DESIGN INTENTIONS AND CHANGES DURING USE

<table>
<thead>
<tr>
<th>BUILDING</th>
<th>Predominant modes are in bold type</th>
<th>DESIGN INTENTIONS</th>
<th>NOTES</th>
<th>CHANGES IN USE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akoz UK Headquarters and Training Centre, Milton Park, Oxon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barclays Bank Regional Head Office refurbishment, Reading</td>
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<tr>
<td>Body Shop HQ, Littlehampton</td>
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<tr>
<td>BRE Low Energy Office, Garston (upgraded)</td>
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<tr>
<td>British Aerospace Space Systems, Stevenage</td>
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<tr>
<td>Civic Offices, Salisbury</td>
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<tr>
<td>Computer Science D-block, York University</td>
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<tr>
<td>Courage Head Office, Ashby House, Staines</td>
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<tr>
<td>Guardian Newspapers, Farnborough Road</td>
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<td></td>
</tr>
<tr>
<td>Hereford and Worcester County Hall</td>
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<tr>
<td>Inland Revenue, Nottingham</td>
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<tr>
<td>Lloyds Insurance, Cheltenham</td>
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<tr>
<td>Meadow District Council Offices, Shipton Mal felton-Upon-Avon</td>
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<td></td>
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<tr>
<td>Polytechnic Institute, London NW1</td>
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<tr>
<td>Pozaic House, Peterborough</td>
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<tr>
<td>Provincial Insurance, Kendal</td>
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<tr>
<td>Refuge House, Winslow</td>
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<tr>
<td>Research Machines, Milton Park, Oxon</td>
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<td></td>
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<tr>
<td>RMC Headquarters, Staines</td>
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<td></td>
</tr>
<tr>
<td>Scottish Office, Victoria Quays, Leith, Edinburgh</td>
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</tr>
<tr>
<td>Solid State Logic, Bletchley, Oxon</td>
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<td></td>
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<tr>
<td>South Glamorgan County Hall, Cardiff</td>
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<tr>
<td>South Northamptonsire District Council, Towcester</td>
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<tr>
<td>Tanfield House, Edinburg</td>
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<td></td>
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<tr>
<td>Weidmuller, Kings Hill Business Park, Kent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constable Terrace housing, UEA Norwich</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**REFERENCES**

1. Numbers in the "Design Intentions" columns give the approximate hours per day of any mechanical ventilation systems
2. Room temperature set points are given for each building in the table below.
3. The "Changes in Use" column indicates any changes to the original design intentions.
4. The "Comments" column provides further information about the building and its use.
<table>
<thead>
<tr>
<th>Project, Location</th>
<th>Energy Use/y (kWh/m²)</th>
<th>Area (m²)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akzo UK Headquarters and Training Centre, Milton Park, Oxon</td>
<td>3.46</td>
<td>23,300</td>
<td>Office</td>
</tr>
<tr>
<td>Barclays Bank Regional Head Office refurbishment, Reading</td>
<td>3.67</td>
<td>2,000</td>
<td>Office</td>
</tr>
<tr>
<td>Body Shop HQ, Littlehampton</td>
<td>3.42</td>
<td>12,300</td>
<td>Office</td>
</tr>
<tr>
<td>BRE Low-Energy Office, Garston (upgraded)</td>
<td>3.67</td>
<td>1,300</td>
<td>Office</td>
</tr>
<tr>
<td>British Aerospace Space Systems, Stevenage</td>
<td>3.67</td>
<td>3,000</td>
<td>Office</td>
</tr>
<tr>
<td>Civic Offices, Salford</td>
<td>3.85</td>
<td>2,500</td>
<td>Office</td>
</tr>
<tr>
<td>Computer Science D-block, York University</td>
<td>3.78</td>
<td>3,000</td>
<td>Office</td>
</tr>
<tr>
<td>Courage Head Office, Ashby House, Staines</td>
<td>3.67</td>
<td>1,200</td>
<td>Office</td>
</tr>
<tr>
<td>Guardian Newspapers, Farringdon Road</td>
<td>3.85</td>
<td>2,000</td>
<td>Office</td>
</tr>
<tr>
<td>Hereford and Worcester County Hall</td>
<td>3.78</td>
<td>1,300</td>
<td>Office</td>
</tr>
<tr>
<td>Inland Revenue, Nottingham</td>
<td>3.67</td>
<td>1,500</td>
<td>Office</td>
</tr>
<tr>
<td>Lloyds Insurance, Chatham</td>
<td>3.85</td>
<td>1,800</td>
<td>Office</td>
</tr>
<tr>
<td>Mendip District Council Offices, Shepton Mallet</td>
<td>3.85</td>
<td>1,200</td>
<td>Office</td>
</tr>
<tr>
<td>NFU Mutual &amp; Avon Group HQ, Stratford-upon-Avon</td>
<td>3.67</td>
<td>1,500</td>
<td>Office</td>
</tr>
<tr>
<td>Policy Studies Institute, London NW1</td>
<td>3.78</td>
<td>1,300</td>
<td>Office</td>
</tr>
<tr>
<td>Posford House, Peterborough</td>
<td>3.85</td>
<td>1,200</td>
<td>Office</td>
</tr>
<tr>
<td>Provincial Insurance, Kendal</td>
<td>3.67</td>
<td>1,800</td>
<td>Office</td>
</tr>
<tr>
<td>Refuge House, Wilmslow</td>
<td>3.78</td>
<td>1,500</td>
<td>Office</td>
</tr>
<tr>
<td>Research Machines, Milton Park, Oxon</td>
<td>3.67</td>
<td>1,500</td>
<td>Office</td>
</tr>
<tr>
<td>RMC Headquarters, Staines</td>
<td>3.85</td>
<td>1,800</td>
<td>Office</td>
</tr>
<tr>
<td>Scottish Office, Victoria Quays, Leith, Edinburgh</td>
<td>3.85</td>
<td>1,500</td>
<td>Office</td>
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<tr>
<td>Solid State Logic, Begbroke, Oxon</td>
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<tr>
<td>South Glamorgan County Hall, Cardiff</td>
<td>3.78</td>
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<tr>
<td>S Northamtonshire District Council, Towcester</td>
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<td>1,500</td>
<td>Office</td>
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<tr>
<td>Tanfield House, Edinburgh</td>
<td>3.78</td>
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</tr>
<tr>
<td>Weidemuller, Kings Hill Business Park, Kent</td>
<td>3.85</td>
<td>1,500</td>
<td>Office</td>
</tr>
<tr>
<td>Constable Terrace student housing, UEA, Norwich</td>
<td>3.78</td>
<td>1,200</td>
<td>Office</td>
</tr>
</tbody>
</table>

Note: Table B1 is based on data from various buildings across the UK, and includes energy use, area, and type of occupancy. The data is presented in a tabular format for easy reference.
## TABLE B2 OUTLINE OF MIXED-MODE BUILDINGS REVIEWED IN THE TECHNICAL PRESS

<table>
<thead>
<tr>
<th>BUILDING</th>
<th>DESIGN INTENTIONS:</th>
<th>NOTES</th>
<th>OUTLINE OF MIXED-MODE BUILDINGS REVIEWED IN THE TECHNICAL PRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Table B2</strong></td>
<td><strong>Weekly energy use:</strong></td>
<td><strong>Annual energy use:</strong></td>
<td></td>
</tr>
<tr>
<td>#</td>
<td>Project</td>
<td>Type</td>
<td>Client</td>
</tr>
<tr>
<td>---</td>
<td>--------</td>
<td>------</td>
<td>--------</td>
</tr>
<tr>
<td>1</td>
<td>3 The Square, Stockley Park</td>
<td>See notes. When hot. Cold 3 Med NV Hot 6.</td>
<td>Manually-controlled double-glazed sash windows onto corner conservatories, with blinds on conservatory side. Contingency MV can be cooled; ceilings (market requirement) can be removed. Solar protected by conservatory roofs.</td>
</tr>
<tr>
<td>2</td>
<td>Addison Wesley Longman, Hatfield</td>
<td>MV in winter 7 ac/h Meeting K/ing A/C.</td>
<td>Varying form with cross-ventilated, courtyard and central atrium arrangements. No detailed information available.</td>
</tr>
<tr>
<td>3</td>
<td>Avon &amp; Somerset Constabulary, Portishead</td>
<td>Yes. MV 7 ac/h Local chilled beams.</td>
<td>9 m central street. Floor supply. Chilled beams, lake cooling. High and low level windows. Not yet occupied.</td>
</tr>
<tr>
<td>4</td>
<td>Barclaycard, Northampton</td>
<td>Yes. MV 37 Chilled AC in hi IT areas.</td>
<td>More information being sought from British Gas.</td>
</tr>
<tr>
<td>5</td>
<td>British Gas, No 1 Leeds City Office Park.</td>
<td>Yes.</td>
<td>Central atrium between two office &quot;tongues&quot;. Nil and LL windows + trickle vents. Additional night MV system 5 ac/h+atrium windows. Summer daytime MV only once building is warm. Can add shunt ducts over cellular offices.</td>
</tr>
<tr>
<td>6</td>
<td>British Gas, Loughborough Science Park</td>
<td>Yes. MV 7 ac/h Ceiling fan coils.</td>
<td>9 m deep linked blocks with courtyard.</td>
</tr>
<tr>
<td>7</td>
<td>British Gas, Thames Valley Park, Reading</td>
<td>Yes. MV 5. Night cool pri NV.</td>
<td>Finger plan with some linking aria. Top hung windows, possibly motorised. Cooling available on main air supply. Was pre-let to British Gas, but now spec owing to organisational changes.</td>
</tr>
<tr>
<td>8</td>
<td>BSIF, Chiswick</td>
<td>Yes. MV 3. Inter-lock.</td>
<td>Overlaid refurbishment of lower block including fattiches with external weather louvres. Microswitch on fanlight cuts off under-cill fan-coil unit.</td>
</tr>
<tr>
<td>9</td>
<td>Charles Aid Foundation, West Malling</td>
<td>Yes. MV 4. Chilled beams planned.</td>
<td>Upgrade options of chilled beam, FCU and VAV considered [31]. Chilled beam most economical. Lightsheaves abandoned.</td>
</tr>
<tr>
<td>10</td>
<td>Defence Procurement Headquarters, Bristol</td>
<td>Yes. MV 7 ac/h Cooling supply air.</td>
<td>Mixture of cross-ventilated and double galleries with central atria. No detailed information available, but could be obtained from Hoare Lea.</td>
</tr>
<tr>
<td>11</td>
<td>DTI refurbishment, Westminster</td>
<td>Yes. MV 7 ac/h</td>
<td>Soc glazing with vented/inter-pane blinds. Trickle vent (0.2-0.5 ac/h) + stack exhaust (0.4-0.8 ac/h) + floor supply (0.5-1 ac/h) with VS fans (0.8-3 ac/h). CO2 control. Chilled ceilings (0-55% when on). Night cooling.</td>
</tr>
<tr>
<td>12</td>
<td>Elizabeth Fry Building, University of East Anglia</td>
<td>Yes. MV 4 max</td>
<td>Termodock hollow core slabs. 3-speed AHUs. 24 hr ventilation. Reversing flow regenerative heat exchanger. Triple glazed low-E. No perimeter heating. Includes lecture and seminar rooms. All items 0.97 ac/h at 50 Pa.</td>
</tr>
<tr>
<td>13</td>
<td>Equity and Law, 175 Corporation Street, Coventry</td>
<td>Yes. MV 7 ac/h</td>
<td>TI-in (and turn?) windows over perimeter reverse cycle heat pumps. No detailed information available. Reviewed as a possibility for BRECSU case study but not visited.</td>
</tr>
<tr>
<td>14</td>
<td>Gatishelde Civic Offices</td>
<td>Yes.</td>
<td>Cross-ventilated courtyard plan. Local AC in council chamber, committee rooms, restaurant, bar and Word Processing rooms. MV in atrium, basement and central cores.</td>
</tr>
</tbody>
</table>
| 15 | IBM Software laboratory, Hursley Park, Portsmouth | See notes. When hot. Cold 3 Med NV Hot 6. | ATM modular fan-coil units interlocked with windows. Offices mostly cellular, but with high IT levels. "Core" depth with some internal rooms. No detailed information available, but could be obtained from Proced.
### TABLE B2 OUTLINE OF MIXED-MODE BUILDINGS REVIEWED IN THE TECHNICAL PRESS

<table>
<thead>
<tr>
<th>Building</th>
<th>Design Intentions</th>
<th>Annual energy use:</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WkM2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>kWh/m2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predominant modes are in bold type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numbers in the &quot;Design Intentions&quot; columns give the approximate air changes per hour of any mechanical ventilation systems.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Inland Revenue, Durrington Bridge House, West Sussex</td>
<td>MV 1.5/4 ac/h</td>
<td>Automatic hopper windows with manual windows underneath. Atrium wall is solid, with wide openness. Night cooling as necessary by auto NV plus AHUs through floor void in off-peak period. Sometimes over-cooled.</td>
<td></td>
</tr>
<tr>
<td>17 Inland Revenue, East Kilbride</td>
<td>Yes, MV 7 ac/h</td>
<td>Echelon plan. All orientations. Some atrium stack. Triple-glazed pivot windows with mid-pane blinds, plus motorised hopper windows in most areas. MV has steam humidifiers.</td>
<td></td>
</tr>
<tr>
<td>19 JEL factory/office, Stockport</td>
<td>Yes, MV 7 ac/h</td>
<td>Mechanical transfer of hot air from solar façade to production area in mild weather; hot air exhausted in hot weather. Windows openable at any time.</td>
<td></td>
</tr>
<tr>
<td>21 Judge Institute, Cambridge</td>
<td>Yes. MV 7 ac/h</td>
<td>Parts naturally vented.</td>
<td></td>
</tr>
<tr>
<td>22 Leith Academy, Edinburgh</td>
<td>Yes. MV 7 ac/h</td>
<td>Some added local AC.</td>
<td></td>
</tr>
<tr>
<td>23 Marston Books, Milton Park</td>
<td>See notes</td>
<td>NV with Colt Interactive Window System, motorised (not automated) top panel and adjustable light shelf. Ceiling has grilles to access floatable mass (for theory see [47]). Floor void - flat roof available for contingency MV/code.</td>
<td></td>
</tr>
<tr>
<td>24 Oxfordshire County Hall refurbishment</td>
<td>Night cooling</td>
<td>In 15% area AC retained</td>
<td></td>
</tr>
<tr>
<td>25 Powys County Hall, Llandrindod Wells</td>
<td>MV 1.5/3</td>
<td>Local HT pump + DX units</td>
<td></td>
</tr>
<tr>
<td>26 Powys County Hall, Llandrindod Wells</td>
<td>MV 1.5/3</td>
<td>Two galleries with linear union. BECS-controlled atrium windows. Tempered MV winter. NV with MV/cooling if needed otherwise. Swirl diffusers. LT heat bus for floor, radiant &amp; air htg + heat rejection. Hot egr not clustered.</td>
<td></td>
</tr>
<tr>
<td>27 Powys County Hall, Llandrindod Wells</td>
<td>MV 3.5</td>
<td>Draft article for Building Services never published: currently mislaid.</td>
<td></td>
</tr>
<tr>
<td>28 RSPB, Sandy</td>
<td>Yes. MV</td>
<td>Sash windows. Ducts embedded in floor slab. Intake via vegetation and underground duct. Bulkhead &amp; atrium extract with heat exchanger.</td>
<td></td>
</tr>
<tr>
<td>29 Scottish Nuclear, East Kilbride</td>
<td>Yes, MV 7 ac/h</td>
<td>AC/VRV + Split inboard</td>
<td></td>
</tr>
<tr>
<td>30 University of Lincolnshire</td>
<td>Yes, MV 7 ac/h</td>
<td>VRF in core areas of S and W-facing open plan offices. Individually-controlled split heat pump units in directors' offices and meeting rooms.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>See Comments.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### REFERENCES

- [47] for theory.
B3 Characteristics of the buildings

B3.1 PLAN DEPTH
Most MM buildings have a plan depth of 12 to 15 metres from outside wall to outside wall or to atrium, though in some designed for concurrent operation the depth is increased to 18 m and sometimes much more. However, at depths over about 20 m the openable windows tend to be more for psychological relief.

B3.2 CEILING HEIGHTS
Many MM buildings have relatively generous ceiling heights in the range 2.7 to 3.3 metres and increasingly with exposed or semi-exposed ceilings, sometimes with downstand beams or undulations and additional height into the coffers. It is now becoming generally agreed that it is false economy to attempt to minimise floor-to-ceiling heights: generous heights both enhance the passive ventilation (and daylighting) and provide space to add mechanical systems where required.

B3.3 BUILDING FORMS
Figure B1 is a simple classification of common building forms, with and without atria and conservatories. Each has a three-letter code which is used in Tables B1 & B2. These include:
1 Linear plans, often cross-ventilated. Occasionally (1A) these have a buffer space on one side as a climate moderator or noise barrier. This space need not be continuous: for example a design study of the refurbishment of Temple Way House [94], used added bay windows as both noise barriers and ventilation stacks.
2 Courtyard plans. These are useful, compact forms which permit most of the space to be cross-ventilated. Where there are a lot of cellular offices, the dead spots near the corners of the courtyard can be used if necessary for cores, equipment rooms and so on. The atrium form 2A can be very economical, with added interior space and the roof paid for largely by savings in the specification of the courtyard walls and windows.
3 L-shape. Useful on odd-shaped sites. The corner atrium (3A) although generally less economical than a central one, can be a useful amenity, reception and buffer space on sites not large enough for a central atrium. There are no examples of this in the Tables.
4 Ladder. Two parallel (or nearly parallel) linear strips with cross-links. It is suitable for large buildings over about 10,000 m$^2$ and can provide sufficient external area for natural ventilation whilst having a more compact internal circulation system than a single courtyard form. Sometimes one or more of the courtyards and re-entrants are roofed-over, as in 4A. Alternatively, there may be a continuous atrium down the middle, with cross-links inside it, as in 4B. We call these “street” (where the atrium floor also serves as the main circulation route) and “gallery” (where most of the circulation occurs around it). Some long buildings (for example the Scottish Office) have combinations of courtyards, streets and galleries in these internal spaces.
5 Block. The plan is often too deep for natural ventilation alone but MM can sometimes help to avoid there being full AC.
6 Tower. While these are sometimes shallow enough for cross-ventilation, wind effects are often more severe, giving special problems with window design.
7 Finger. A central spine (at the top) has two or more wings running off it. In 7A some or all of the spaces between the fingers may be wholly or partially covered over.

B3.4 ATRIA AND CONSERVATORIES
Atria and conservatories, though still in the minority, are growing in popularity. They can allow buildings to be more compact, provide useful amenity and buffer spaces, and reduce heat losses. They can also assist natural and mechanical ventilation strategies, although there are indications that in atrium buildings - and at least away from the external windows - occupants are less tolerant of increased summertime temperatures than in comparable cross-ventilated buildings: so calculated comfort benefits could be illusory. Atria may also reduce heating, lighting and air tempering requirements, though designers can be too optimistic about this: in practice their success is variable. Effective low-energy atrium design will not be discussed here because a comprehensive publication is currently being drafted for BRECSU [95].
FIGURE B1: SOME TYPICAL BUILDING PLAN SHAPES

Without atrium or conservatory:

1. Linear
2. Courtyard
3. L-shape
4. Ladder
5. Block
6. Tower
7. Finger

With atrium or conservatory:

1A. Buffered Linear
2A. Atrium
3A. L-atrium
4A. Ladder + atrium
4B. Street or gallery
7A. Webbed Finger

Without atrium or conservatory:

1. Linear LIN
2. Courtyard CRT
3. L-shape ELL
4. Ladder LAD
5. Block BLK
6. Tower TWR
7. Finger FIN

With atrium or conservatory:

1A. Buffered Linear BUF
2A. Atrium ATR
3A. L-atrium LAT
4A. Ladder + atrium LAA
4B. Street or gallery STR/GAL
7A. Webbed Finger WEB
B3.5 POPULARITY OF BUILDING SHAPES
The majority of MM buildings identified are linear cross-ventilated (but including some cellular offices), followed by blocks. In the older buildings, courtyard plans were also popular, with its variant the ladder for larger buildings. In the newer ones, the courtyard and ladder are losing ground to the street/gallery, the finger (or its U- or V-shaped principal component), and the atrium. which is also an exhaust air path, for mechanical systems and/or by natural buoyancy, sometimes with wind assistance. In the past there has been perhaps too much emphasis on stack ventilation on still summer days, which are in fact rare in the UK. The atrium form emerged in design studies in the UK in the late 1980s and early 1990s, and was largely anticipated in the naturally-ventilated Gateway II building [68]. The street form emerged from northern European studies and practice at the same time. A few buildings do not fit the classification, for example cruciform and T-shaped local authority offices at Towcester and Oxford which are really just variations on a linear theme. The more unusual forms are:
- The triangular PSI, in which a small central atrium was used very effectively to reduce the apparent depth of the building.
- The cruciform Stockley Park building, with bridging conservatories: at one level a back-to-back cluster of L-shapes, but with complex opportunities for ventilation paths across the building from shaded to sunny atria.

B3.6 TYPICAL MECHANICAL VENTILATION SYSTEMS
In the older buildings, mechanical air supply, when fitted, is most often from the ceiling and sometimes from the floor or the perimeter. In the newer ones, floor supply predominates (this becomes economic when raised floors are necessary for cable distribution), and displacement ventilation may be possible - though this is more often claimed than realised. This can then permit an exposed (or partly exposed) ceiling, which further increases thermal inertia, although direct extraction of heat from the lights becomes more difficult. A few buildings also have ductwork embedded in the structure in order to increase thermal inertia and the effectiveness of mechanical night cooling.

B4 Characteristics of the engineering systems
B4.1 THREE DIFFERENT APPROACHES
In the engineering of the VAC systems, three distinct approaches can be discerned: Traditional, Integrated and Opportunist. These are outlined below.

B4.2 THE TRADITIONAL APPROACH
The mechanical system is designed more-or-less as mechanical ventilation, air-conditioning or comfort cooling for a sealed building, but often somewhat less generously sized or more crudely zoned to take account of the contribution of the openable windows to fine-tuning, to occupant tolerance, or to restricting the operation of the mechanical system to the times and conditions in which it is really needed. This tends to be a relatively expensive approach and perhaps best suited to changeover operation, though concurrent operation is also possible, particularly if it can be done at low fan speed - which can give large savings in fan energy consumption. In Tables B1 and B2 these approaches are coded as follows:

- CAC Central all-air air-conditioning (such as VAV).
- DAC Distributed AC (induction, fan coil, heat pump, spilt) with minimum fresh air.
- MV Mechanical ventilation (typically 4 ac/h or more).
B4.3 THE INTEGRATED APPROACH
The natural and mechanical systems are designed to work together more closely to make up - in a cost-effective, low-energy manner - any shortfalls that might occur if natural ventilation alone was used. For example, mechanical ventilation might be modest in capacity (say 2 ac/h on average), but nevertheless capable of improving air quality in winter; providing additional ventilation to landlocked areas; removing heat from hot areas at source; providing better air movement; and undertaking some night cooling. The coding used in the tables is as follows:
- BV Background Ventilation (typically 2 ac/h during occupancy hours).
- BV/MV Multi-speed ventilation, with a low speed of 3 ac/h or less.
- MNV Mechanical Night Ventilation/daytime natural ventilation.
- TC Trickle-charged (typically 2 ac/h or less, 24 hours, as with Termodeck).
- WW “Whole Works” - elaborate changeover strategies.

B4.4 THE OPPORTUNIST APPROACH
The base building is quite lightly-serviced, perhaps with natural ventilation openings only, as in contingency designs (CON), or with background mechanical ventilation (as in BV or TC above). Where necessary, local supplementary mechanical ventilation or cooling (SC) can be added in a modular form - for example by fan-coils, reverse-cycle heat pumps, chilled beams or direct-expansion units. While recent years have seen some use of relocatable units with quick-release connectors to spine distribution systems, we see be considerable scope for more ingenuity and ultimately some standardisation in this area.

B4.5 FREQUENCY OF OCCURRENCE OF APPROACHES
Representation among the buildings identified to date is as follows:

<table>
<thead>
<tr>
<th>Approach</th>
<th>OLDER</th>
<th>NEWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical ventilation</td>
<td>MV</td>
<td>9</td>
</tr>
<tr>
<td>Distributed air conditioning/comfort cooling</td>
<td>DAC</td>
<td>6</td>
</tr>
<tr>
<td>Whole works</td>
<td>WW</td>
<td>0</td>
</tr>
<tr>
<td>Multi-speed mechanical ventilation</td>
<td>BV/MV</td>
<td>4</td>
</tr>
<tr>
<td>Background mechanical ventilation</td>
<td>BV</td>
<td>1</td>
</tr>
<tr>
<td>Trickle-charged</td>
<td>TC</td>
<td>2</td>
</tr>
<tr>
<td>Mechanical night ventilation</td>
<td>MNV</td>
<td>1</td>
</tr>
<tr>
<td>Central air conditioning</td>
<td>CAC</td>
<td>1</td>
</tr>
<tr>
<td>Mechanical plus local supplementary cooling</td>
<td>MV+ SC</td>
<td>1</td>
</tr>
<tr>
<td>Natural plus local supplementary cooling</td>
<td>NV+ SC</td>
<td>0</td>
</tr>
<tr>
<td>Contingency designs</td>
<td>CON</td>
<td>2</td>
</tr>
<tr>
<td>Insufficient information/difficult to classify</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>TOTALS</td>
<td>27</td>
<td>30</td>
</tr>
</tbody>
</table>

B4.6 DISCUSSION OF APPROACHES
The buildings identified are almost equally split between traditional and integrated approaches, with only a few opportunist examples. However, opportunism is also widespread in terms of *ad hoc* additions of ventilation and cooling to naturally-ventilated buildings. In both the older and newer buildings, mechanical ventilation dominates at relatively high air change rates, and fan energy consumption can be high - very high in some instances. After that comes minimum fresh air (1 to 3 ac/h) plus distributed cooling by fan-coils and so on.

While the more integrated approaches are more sparsely represented, in total there are nearly as many as the traditional group. The most significant trend is a move away from multi-speed to whole-works approaches - presumable a consequence of the increased power of computer modelling and of control systems - though experience suggest that the WW strategies may well become simplified in operation.
Some common problems

B5.1 OVER-RELIANCE UPON OCCUPANTS
Some designs expect occupants to react differently with changing conditions: for example if they get hot in mild weather they should open the windows, but in hot weather they are supposed to close them and let the mechanical system do the job. Occupants, however, usually prefer things to work in one particular way and find it difficult (and often do not want) to vary their habitual behaviour in order to satisfy the designer’s expectations, let alone to achieve the optimum balance between environmental and energy performance. In addition, they are often poorly-informed, both about how the building works and what they should be doing at any particular time. Some designs also expect individuals to act not in their own interest but for the common good - for example to open windows on the north side of the building to act as air inlets to remove heat from the south. In practice, this is unlikely to happen: people only tend to take control actions once they reach their “threshold of discomfort” [65]. Designers should seek to make their intended operating strategies obvious, convenient and effective. Where this is not possible, and whilst more deliberate occupant education is desirable, one should also consider means of informing the user - for example an indicator showing that it would be better not to open the window. Occupants should not be expected to take control actions where they personally do not perceive the need for them. They should also not be expected to undertake them too often [72].

B5.2 INAPPROPRIATE RELIANCE UPON AUTOMATION
To avoid some of the problems with occupant behaviour outlined in B5.1, designers are attempting to automate natural ventilation, and in particular window-opening. While to our knowledge occupant response to such systems has not yet been studied, experience with automatic control of lights and solar blinds [66, 67] suggests that occupants are likely to object to seemingly arbitrary step-changes in system operation, and that automatic control action should be gradual and imperceptible (conversely, response to occupant over-rides should be rapid - preferably immediate - and noticeable!). Perhaps the ideal automatic changeover control takes place when the space is empty (e.g.: for night ventilation), or in distant and “unowned” places (for example atrium rooflights). Something which operates in the occupant’s own territory and creates a draught (or removes a breeze) is not likely to be welcomed! Great care - and more study - is required to integrate occupants and control systems effectively.

B5.3 CHANGEOVER SYSTEMS MAY DEFAULT TO CONCURRENT OPERATION
In the older changeover designs already visited, the management had often found concurrent operation more convenient or more acceptable (see Section A2.3.2), for example with mechanical ventilation operating at times when natural-only had been predicted, or heated and/or chilled water circulating to terminal units whether it was really needed or not. This is perhaps not surprising in the changeable UK climate, and because people may object to alterations in local comfort contours when systems change their states. Since changeover strategies are more widespread in the newer designs, it will be interesting to find out whether this still happens. Recent visits by WBA suggest that it will, and we fear that if anything the tendency of systems to default to ON is becoming more widespread: and the consequences for the buildings’ low-energy aspirations may be serious. Indeed, we fear that improved modelling and control systems capabilities may be leading designers to propose operational strategies with a whole range of changeover points. BSRIA’s guidance ([105], pages 10-12) is a case in point. We fear that such complex strategies could easily prove to be not only too difficult technically to implement in practice (this is certainly WBA’s experience on designs upon which we have been asked to comment), but could also alienate the occupants. Meanwhile, we suggest that designers aim for simple basic “starter” strategies which can be upgraded as necessary and appropriate as the management gets to understand how the building really works. They should also to avoid excessive energy consumption when concurrent operation happens, for example by giving priority to low-speed operation. If for some reason extended concurrent operation would be particularly unnecessary or wasteful, then control and monitoring systems should be programmed to avoid it, or at least to raise “clash alarms” which rapidly alert management to unnecessarily wasteful operating conditions.
B5.4 ARE ALL THE FEATURES ESSENTIAL?
For example, Tanfield House, an extremely deep-plan air-conditioned building, had openable sash windows at the perimeter. However, only a small proportion of the occupants were near them, the windows could not contribute much to ventilation or cooling, and they also opened not directly to the outside air but to a buffer space (“not real air”, as one occupant said). In a recent survey [21] the management (and most but not all of the occupants) did not regard these windows as helpful. Nevertheless, they were potentially valuable as a contingency; and the upper sashes were also used under automatic control as the inlets for smoke ventilation. Such measures could also provide relief and reassurance, so improving the “forgiveness” of the design, see section C5.9. Further research is required.

B5.5 PROBLEMS WITH NIGHT COOLING
Often night cooling was not used as the designers had intended, giving higher peak temperatures and/or unnecessary running hours. Peak summertime temperatures hovered near the threshold of discomfort, although with optimum use of the systems (albeit sometimes requiring attention to commissioning, control and maintenance) they could have been lower. Reasons for the shortfall included:

- Few complaints. In practice most building managers tend to be driven primarily by the need to minimise bad complaints, rather than to optimise performance. They are therefore unlikely to strive to improve something which occupants regard as acceptably good - or at least not unacceptably bad - even if it could have been significantly better. The conclusion is that it makes little sense for designers to strive to wring the last drop out of system performance if this requires more management attention, and particularly if such measures add complication and run a risk of reducing occupants’ tolerance margins or increasing the possibility of failure.

- Insufficient perceived benefit for the management to feel it worth running the system.

- Additional expense (or perceived expense) of running the systems - often we found poor understanding of the likely impact of an operational decision on energy consumption and cost. For example, one manager was reluctant to run mechanical night ventilation owing to a fear of increasing maximum demand electrical charges. In fact, the fans were very economical at low speed; the MD was during the day; and the MD charges were zero in the summer months.

- Insufficient zoning: often systems were designed to cool the whole building - or at least the areas served by a particular plant - without noting that some places might need more cooling than others. It was then impossible to remove enough heat from some areas without others - and typically ground floors - becoming too cool next morning.

- Operational difficulties: sometimes controls and interlocks were set up principally for one mode of operation and baulked at another, or at a changeover transition. Most commonly this was a clash between mechanical night ventilation and low limits on supply air temperatures;

These points will influence the guidance and technical recommendations offered.

Durrington Bridge House, which was monitored by BSRIA [105] has alternative natural and mechanical night ventilation. The mechanical system is used in “bad weather”; in rain or when the wind was above 25 km/h - which was for about 30% of the monitored period. BSRIA found that the natural system, using motorised hoppers, was just as effective as the mechanical systems, which used the floor void but started-up later to take advantage of night rate electricity and also suffered from heat pick-up. On 25% of the days monitored, however, the building was over-cooled by the night ventilation and boiler preheat became necessary! The mechanical ventilation was seldom needed to meet daytime cooling requirements and BSRIA felt that it might not be necessary if suitable passive winter ventilation could be provided. Alternatively, to reduce energy requirements and avoid heat pick-up, it might be changed to a pull-through system using the natural ventilation inlets and atrium extract fans.
B5.6 OUTSOURCING
Increasingly organisations subcontract their security, facilities management (FM) and plant maintenance to others. Unfortunately, the contracts often do not include operational responsibilities which the designers may have taken for granted - and which may be quite difficult to fulfil without an intimate knowledge of the occupying organisation and what people are doing, almost from minute to minute. Taking examples from two prestige buildings which WBA has surveyed recently:
- The FM contractor subcontracted controls maintenance to a systems house some 20 miles away from the site. The people on site do not even have access to the BEMS time schedules. Needless to say, most of the engineering systems run constantly.
- The design idea in a “low energy” building (completed in 1995) was that occupants telephoned a “help desk” if they wanted the services adjusted - even the lights above their workstations! The FM contract required the help desk to be manned from 0830 to 1730. Any services wanted in the evening cannot be over-ridden manually and so get left on “just in case” until the late night security shut-down after the cleaners leave.

B6 § Conclusions
B6.1 MAJOR THEMES
Clear themes which come through from this review of current practice include the need for:
- Clear strategic approaches;
- Seamless integration of systems which complement each other rather than clash.
- Systems which are not unnecessarily complicated and which do not have unreasonable expectations or make unreasonable demands of occupants and management.
- Avoiding wasteful energy performance, for example by taking care that systems are not too powerful, inefficient, fight each other; or are on too much.
- As part of the above, reviewing the necessary amount of mechanical ventilation. Sometimes it seems to have been over-provided and occasionally it may have been unnecessary, except perhaps locally or as part of a contingency strategy.
- Improving controls: for occupants, for management, and for effective energy-efficient operation.
- Clearer standards and generic exemplars.
- For some types of MM building, perhaps less plant as a permanent (or semi-permanent) part of the building and more which can be readily adapted and exchanged.

For all varieties of MM, simple and ingenious methods of providing the required adaptability could provide inspiration for designers and their clients. Some options have already been outlined in reference [11], but concepts need to be developed, clarified and illustrated.
C PRINCIPLES OF DESIGN AND MANAGEMENT

C1 Introduction

C1.1 WHY CONSIDER MIXED MODE?
This part of the report discusses principles of design and management of mixed-mode buildings and systems. The reviews in Parts A and B suggest that the purposes of mixed-mode designs can be summarised as:
- **Adaptable**: to different occupiers, to changing requirements, to an uncertain future.
- **Usable**, without unnecessary reliance on management.
- **Healthy and comfortable**, but without unnecessary reliance on mechanical systems.
- **Cost-effective**, not wasting money on unnecessary equipment, energy or labour.
- **More sustainable**, with less resource and energy waste and less associated pollution.

The challenge is to stop them becoming mixed-up!

C1.2 IMPROVING EFFECTIVENESS
To combine natural and mechanical systems appropriately to achieve the required results with a minimum of human and natural resource inputs makes sense in societal, commercial and ecological terms. However, this does not mean minimum inputs across the board, for instance:
- more design effort will be necessary in order to help reduce subsequent inputs of materials, energy and management;
- more investment in the building will be needed in order to save on the services;
- although the building services will usually cost less than air-conditioning, investment will be needed to improve their efficiency, responsiveness and adaptability.

C1.3 THE STORY SO FAR
The review in Part B indicates that MM already has a significant presence. Most of the buildings identified work reasonably well, though with some disappointments, particularly in controls and human factors. Energy consumption is often higher than predicted, even for many (though not all) of the newer buildings. Nevertheless, and as reported in the review of BRECSU’s office case studies [2], owner-occupiers and government organisations have often obtained buildings which are well-liked, less expensive than alternative air-conditioned designs, and usually lower in energy consumption. Some developers are now dipping their feet in the water: usually - but not always - with pre-lets.

C1.4 DIFFERENT VARIETIES OF MIXED MODE
Few of the MM buildings reviewed fit neatly into a single MFP category. As MM moves into the mainstream (as is confirmed by looking at a few recent issues of Building Services - the CIBSE Journal), it is surely right for solutions to be as broad as the imagination. Nevertheless, one can identify several strong themes, including:

- **Robust, simple, upgradeable buildings**, often with heavyweight brick, concrete or stone facade construction, cross-ventilation, insulation somewhat better than Building Regulations, and exposed, or semi-exposed ceilings. Their sophisticated window systems are often fairly modest in area (say 20-35% of external wall) with solar protection and two or more openable elements, the upper of which may be automated, or at least designed to be left open overnight. They are often contingency or zoned in the MFP classification. Marston Books [46, 47] is a good recent example.

- **Trickle-charged buildings.** *Concurrent* designs, with very high levels of insulation and permanently-running low-capacity mechanical ventilation with high-efficiency heat recovery. Windows tend to be relatively small in area (15-25%) but high-performance, often triple glazed, low-E, perhaps Argon-filled, and with inter-pane blinds. Perimeter heating may then be unnecessary, as at the Elizabeth Fry Building [56, 69]. While openable, the windows are primarily safety-valves, and a single element - often casement or tilt-and-turn, suffices. Night cooling is available automatically as necessary from the 24-hour running. Additional low-capacity cooling may be provided for enhanced summertime performance by traditional means, groundwater, evaporative cooling (usually into the exhaust air duct with heat exchange), or embedded pipes. The ultimate in trickle-charging is perhaps a sealed unrefrigerated building which doesn’t need the windows to open at all, as intended in the New Parliamentary Building [73]!
Floor-supply schemes. In buildings which need raised floors for cable distribution, it is usually practical and cost-effective to use the floor void for air distribution, increasing its depth if necessary. The void may also contain, or allow for, trench heating at the perimeter (usable area lost to perimeter radiators, convector and terminal units means that many speculative AC buildings don’t have perimeter heating, but comfort is usually the worse for it), plus ducts, pipes, and fan-coil or heat pump units underfloor (though these are somewhat inconvenient to maintain). With the services concentrated in the floor, one can expose all or part of the ceiling to improve thermal inertia further, though this makes it more difficult to extract the heat from the lights. Night cooling then becomes important, sometimes natural but usually at least part mechanical in order to help remove heat from the floor void and to cool the incoming air the next day. Sometimes displacement ventilation is attempted, but more commonly “swirl” mixing diffusers are used, probably because far fewer are required, and this works out considerably cheaper. Where windows are opened, the displacement effect also tends to be compromised (though even windows with high and low level openings work partly on the displacement principle).

Wind and buoyancy-assisted designs. Stacks, wind towers, atria and conservatories are added to assist the removal of air. This has led in particular to a new generic building form with a central atrium or street, flanked by office galleries each some 12-18 m deep. In the market, this type of building is in the most direct competition with the air-conditioned model. Consequently, perhaps, it has inherited some of its features - in particular relatively lightweight and highly-glazed external walls and a fairly substantial mechanical ventilation system, often with some cooling. The obligatory raised floor is almost invariably used for air supply. Proposed operating strategies may be concurrent or changeover, and are sometimes rather complex. Although such complexity may be justified by the size of the building (typically upwards of 5000 m² nett), the power of its BEMS, and the likely level of facilities management skills, post-occupancy surveys suggest that it could prove troublesome in practice [6].
C2 Good practice design principles

C2.1 SOME KEY POINTS

Some simple rules for achieving a good and energy-efficient design include:

1  A good brief
The best buildings tend to be the product of a good building team/client relationship, with requirements, constraints and aspirations (but not solutions) clearly expressed in a written brief. The brief can start short, evolve as a record of the progress of ideas, solutions and agreed requirements, and also help to inform third parties and new team members about the purpose of the scheme. The final clear statement of requirements can be refined to assist specification, be referred to in the building contract, and be used to help to ensure that the objectives are met. Part of it can also be incorporated in operation & maintenance manuals. This is difficult for speculative buildings, and while there are ways in which the process can be improved, the market also needs to develop confidence in MM exemplars.

2  Get the loads down
Prevention is better than cure! Use building form, orientation and fabric effectively to stabilise internal temperatures and to avoid unwanted heat gains and losses through windows and solid elements. Avoid unnecessary internal heat gains and pollutant inputs by minimising the source strength and providing local cooling and air extraction if necessary. Reduce lighting loads by efficient systems, good control and effective use of daylight. Some common methods are summarised in Table C3.1: this includes many points from reference [8], pages 7-12.

3  Make good use of passive potential
Where possible, straightforward “fit and forget” measures are preferable. These include:
-  Avoiding unwanted heat losses and gains as discussed above.
-  Appropriate siting and orientation of the building, for example turning its back to a noisy road, being distanced by landscaping or car parking, or protected by berms, buffer spaces, or other buildings.
-  Developing plan, section, elevation and construction to make good use of natural ventilation, (see reference [1] and other publications) and natural light.

Within the scope of this study, it is impossible to discuss all the available techniques. However, the key issue of window design in MM buildings is discussed in Chapter C3.

4  Choose appropriate standards
The imposition of precise but ultimately somewhat arbitrary standards can unnecessarily increase the cost, complexity and energy-dependency of a building. For example, many 1980s offices were unnecessarily AC (or the AC was over-sized) because internal heat gains from office equipment had been grossly over-estimated. Sometimes received standards on temperatures and noise levels - which the client may not even understand - may force designers straight into a sealed building (believe it or not, WBA was asked to comment on one such brief which had been developed for the administration of an organisation dedicated to energy-efficiency!!). It is necessary to seek good information, let the appropriate standards develop as part of the briefing/design dialogue, and where there is uncertainty try to plan for a range and not be dominated by the worst case. MM is well suited to contingency and adaptability strategies, which seek to avoid wasteful over-provision while having appropriate robustness to guard against irreversible failure. Essentially, it becomes a form of insurance.

5  Comfort is context-dependent
Comfort standards are also not absolute; different people prefer different things and some fine-tuning is desirable. Standards must also be kept under review as the design develops, because the design solution and management style proposed may also influence what is appropriate. Looser standards may suit where people to have the opportunity to alleviate discomfort quickly and simply when it occurs, for example by closing a blind, opening a window, adjusting a thermostat, taking off a jacket, moving their seat or screen, or lifting the telephone - at least if the facilities manager or automatic system at the other end is able to respond rapidly [5].
<table>
<thead>
<tr>
<th>ITEM</th>
<th>ACTIONS</th>
<th>CAUTIONS</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Reduce infiltration heat losses.</td>
<td>Better airtightness.</td>
<td>Needs careful detailing, site quality and preferably pressure testing.</td>
</tr>
<tr>
<td>5</td>
<td>Reduce unwanted solar gains.</td>
<td>Simplest (and quite common) to use facade orientation within 30° of N-S.</td>
<td>Avoid north side being gloomy.</td>
</tr>
<tr>
<td>6</td>
<td>Reduce unwanted window gains/glare</td>
<td>Modest window area.</td>
<td>Needs careful treatment.</td>
</tr>
<tr>
<td>6.1</td>
<td>Consider internal blinds.</td>
<td>Little reduction in heat gains. May obstruct operation if inward-opening.</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Consider fins or overhangs.</td>
<td>Daylight and view restricted.</td>
<td></td>
</tr>
<tr>
<td>6.3</td>
<td>Consider mid-pane blinds.</td>
<td>Don't suit all window types.</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>Consider tinted glass. (But usually better to use a smaller area of clear glass).</td>
<td>Seldom sufficient to control sun glare. No longer &quot;real&quot; daylight.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Review occupancy gains.</td>
<td>Use realistic figures. 14 m²/person common today.</td>
<td>There may however be clusters of higher density.</td>
</tr>
<tr>
<td>8</td>
<td>Reduce heat gains from lighting.</td>
<td>Don't over-light: 350 lux in VDU offices? Less in circulation areas etc.</td>
<td>Some people may require more: consider adjustable or task lighting.</td>
</tr>
<tr>
<td>8.1</td>
<td>Choose efficient lamps and luminaires and appropriate circuiting.</td>
<td>Expense.</td>
<td>Lowered efficiency may be necessary for comfortable, decorative effect.</td>
</tr>
<tr>
<td>8.2</td>
<td>Make good use of daylight, particularly at perimeter and in common and circulation areas.</td>
<td>Maximum daylight may be a fragile strategy in workspaces: glare and blinds down.</td>
<td></td>
</tr>
<tr>
<td>8.3</td>
<td>Avoid lighting use when people are out or daylight is sufficient.</td>
<td>But maintain pleasant environment for those who remain.</td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>Provide effective lighting controls.</td>
<td>With good manual over-rides.</td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>Exhaust heat from luminaries.</td>
<td>May need suspended ceilings etc..</td>
<td></td>
</tr>
<tr>
<td>8.6</td>
<td>Reduce internal gains from office equipment and other appliances.</td>
<td>Select low-energy equipment.</td>
<td>Seldom a building design decision.</td>
</tr>
<tr>
<td>8.7</td>
<td>Avoid equipment being left on unnecessarily. Select auto-slumber equipment if appropriate (but check standby load and switch it right off where possible).</td>
<td>Seldom a building design decision.</td>
<td>Consider dedicated supplies with the rest off overnight.</td>
</tr>
<tr>
<td>8.8</td>
<td>Corral shared equipment into areas with local extract or cooling.</td>
<td>If local systems need to run out-of-hours, keep them separate.</td>
<td>Good for vending, copiers, shared printers, file servers, comms..</td>
</tr>
<tr>
<td>9</td>
<td>Spread the load over 24 hours</td>
<td>Expose thermal mass of ceilings etc. to reduce temp. swings.</td>
<td>Heat needs to be removed overnight. What if extended occupancy?</td>
</tr>
<tr>
<td>9.1</td>
<td>Expose thermal mass of floors.</td>
<td>Winter preheat time and energy consumption may be extended.</td>
<td>Usually needs ventilated raised floor. People may not like it. Presence detection may bring systems on unnecessarily.</td>
</tr>
<tr>
<td>10</td>
<td>Avoid general defaults to ON</td>
<td>Consider presence/absence detection.</td>
<td>Cautionary points discussed later.</td>
</tr>
</tbody>
</table>
Service the remaining loads effectively
Where possible, choose the simplest and the most efficient means of doing the job, and consider ranges and probabilities while developing the design. Engineering techniques need to be developed to deal better with variable and diversified ventilation and cooling loads - as happens for electrical systems. Where possible, systems should be designed to be self-balancing and able to be adapted easily to changing patterns of load - for example to accommodate an area with an above-average ventilation requirement perhaps by slightly “robbing” nearby, less-demanding areas. Note that there are many aspects to in-use efficiency: not only the efficiency of the item, but also the efficiencies with which the item follows the load, and the the load follows the demand (see chapter D4). If possible, local and abnormal requirements should be serviced separately, or otherwise large systems may have to operate wastefully to look after them: the tail-wags-the-dog syndrome! Remember that the lowest-energy state of most active systems is OFF!

Control and manage the systems effectively
This means systems which not only work well in the engineering sense but are understandable and usable by occupants and management. Usable controls should be visible and readily accessible to occupants, where possible at the point of need; easy to use; and clear - preferably intuitively obvious - in what they are doing. The outcomes of any control action should also be rapid and unambiguous. Similar principles apply to manageability, although at a different scale. Some general principles are discussed in reference [66] and a classification of users and spaces is considered in reference [67]. An important objective is to avoid systems defaulting to ON, which all-to-easily becomes their most convenient operating state.

Include appropriate facilities for metering and fault-detection
Management need to be able to review performance against their own targets, industry benchmarks and past performance, and be aware if a component or system is not working properly. Sub-meters should be fitted in particular to large individual items of plant, to plant and equipment in unusually high (or low) energy areas (for example in offices to computer rooms, restaurants, and large car parks) and to suitable cost centres. In spite of comprehensive fault detection on today’s BEMSs, to date very seldom have these included performance monitoring against design and management objectives for the system. For example, for mechanical night cooling it would be useful to know whether the supply air was coming in more than say 3°C above outside air temperature - as it often did in monitored buildings [8].

Have an effective handover
It is well known that pressures for handover often squeeze building services commissioning programmes, and that systems and controls are not checked and tuned in the ways that the engineers had intended. Whilst adding to the pleas for effective commissioning, it is also important that the industry aims to deliver robust, adaptable MM systems which are made as easy as possible to set-up, to fine tune and to alter. In addition, the design intentions need to be made clear to management, to individual occupants, to operation and maintenance contractors, and to those who may adapt, equip and alter the building, including space planners and interior designers. Requirements to be written into outsourcing contracts also need to be made clear. If possible there needs to be a contingency fund to undertake “sea trials” and to pay for any small alterations which are likely to prove to necessary once the building comes into use.

Don’t be too clever!
Avoid unnecessary complication. Simple and straightforward solutions often work best. In attempting to optimise the design, one should take great care to consider the downside risk of improvements which offer only marginal benefits, particularly where they require high levels of input by the operator, or place unrealistic expectations upon the occupants.
C3 WINDOWS IN MIXED-MODE BUILDINGS

C3.1 INTRODUCTION
Windows and other natural ventilation openings are important and often complex components of NV and MM buildings. Not only must they fulfil the ventilation requirement without admitting excessive amounts of noise, rain, dust or insects, but they also needs to be durable, secure, look good, provide a view, admit daylight, control glare and solar gain, and limit unwanted air infiltration and heat loss. Sometimes these features can clash, for example with blinds obstructing the air path.

C3.2 THE NEED FOR AND EXERCISE OF CONTROL
Most of the above tasks also require a high degree of control: usually manual but increasingly motorised and sometimes automatic. An important issue is who controls what and how. Recent studies [27, 65, 66, 67, 72, 74] suggest that:

i People will tend to do what is easiest and closest to hand, for example they will be more likely to open the lower window if the upper one is less accessible, or to switch on the light rather than raising the blind. If possible, designers should endeavour to make the action they desire the most obvious and convenient one for the user. If this is not possible, a different system or some form of automation may be desirable.

ii In open-plan spaces, people immediately beside the windows tend to feel significantly more comfortable and in control than other occupants. Even where arrangements are made for those inboard to reach their window and operating mechanisms easily, they frequently feel inhibited in doing so. Furniture layouts with desks under windows make access to the window difficult for anyone, even the occupier of the desk.

iii Adverse effects of windows, and in particular glare and draughts, are most felt by the people more remote from them, who are both less in control and may be affected by several, some of which may also be quite distant from them and their immediate working group. To improve conditions and to alleviate discomfort, remote control of upper windows and blinds from inboard workstations needs more consideration. This may also permit automation to enhance performance, particularly outside normal working hours.

iv Occupant surveys indicate that automatic control of blinds and lights is resented if their operation is perceptible and rapid [67]. We think it very likely that there could be a similar occupant response to automatic control of windows for ventilation, though this needs to be reviewed. Where such control is applied, the provision of suitable and accessible over-ride facilities for occupants is essential.

v Automatic blinds and lighting control have seldom been interlocked. This has caused lights to be switched off when blinds were also shut, and consequently most or all the lights are often kept on whatever the daylight. Modern systems where individual luminaires dim in response to local light levels can help to resolve this problem, but appropriate system settings are not easy to determine.

vi People tend not to take control actions until they experience a crisis of discomfort [27]. Then they require rapid, preferably instant, response. From the engineering point of view, individual action is often rather extreme and too late. For example, mechanical night ventilation in the BRE Low Energy Office did not reduce peak temperatures as much as predicted, because with the cooler start people delayed opening their windows until later in the day, by which time the outside air had little or no cooling effect.

vii Inertia in individual and particularly group behaviour not only reduces comfort but often also wastes energy. For example, in an open-plan office, once a blind has been lowered to counteract glare, it tends to stay down. Sometimes this inertia can be an advantage, as when windows opened during the day remain open and so provide night cooling, as at NFU [58]. However, such windows need to be secure, and often separate from the main window, or they will be shut by cleaners, security, or possibly
the occupant when leaving the building. One also needs a means of shutting them if the building gets too cool. Good security guards do this, but they seem to be increasingly rare: perhaps another consequence of the outsourcing culture. Such operation can also be very labour-intensive.

C3.3 WINDOW SYSTEMS FOR VENTILATION
Chapter 4 of reference [1] contains a review of ventilation components, which will not be repeated here. Instead we concentrate on how these components can be, and have been, brought together to serve different purposes in windows in MM buildings.

C3.4 PURPOSES AND METHODS OF VENTILATION
Purposes and methods of ventilation were summarised in Table A3.1. The following are most appropriate for natural ventilation:
V1 Background (trickle) ventilation.
V2 Daytime ventilation and cooling (this may need different elements for local and for cross-ventilation).
V3 Night ventilation and cooling.
Usually high and low-level openings will be desirable to promote single-sided ventilation, for example in a cellular office. These may either be two separate elements, or be combined in centre-pivot, sash and sliding projecting windows.

For each purpose there are three main choices in MM buildings:
i Whether to use natural and/or mechanical systems.
ii If natural, whether manual and/or mechanised and automated.
iii Whether a single window element can undertake several of the required functions.

C3.5 HOW MANY VENTILATION ELEMENTS SHOULD A WINDOW HAVE?
For straightforward usability, there is much to be said for each function being assigned to a separate element: say an unobtrusive trickle ventilator; a readily-operable main window-preferably with high- and low-level openings, and an identifiably separate, secure, weathertight and possibly mechanised and automated element for night and cross-ventilation. To reduce capital costs, one wants as few elements as possible, and it may be difficult to justify elements which duplicate a function which the mechanical systems present are able to do - except perhaps as part of a contingency strategy.

C3.6 MM WINDOWS IN PRACTICE
To attempt to undertake all three functions naturally using a single-element window tends to work in small rooms only - and then often not very well. In multi-occupied spaces, and where there is cross-ventilation, limited controllability usually becomes a problem. In practice, many MM buildings have two-element windows, commonly:
i At high level (or occasionally at low level) small hopper, top-hung or sliding-projecting fanlights, or centre-pivot louvres. These are used variously for cross-ventilation, night ventilation and background ventilation, and usually have some form of mechanical operating mechanism. In MM buildings completed in the last two years, some have been motorised and frequently automated, the exception being Marston Books. Motorised gear can offer finer control at small openings than most manually-operated equipment. Under suitable control, automation can give a better distribution of air in the space, as all windows can be opened a little bit. Under manual control it is more likely that a few will be open a lot.

Occasionally the windows also have fixed vision panels underneath or in between them.
C3.7 WINDOWS IN BUILDINGS DESIGNED FOR CONCURRENT OPERATION
Some systems designed for concurrent operation - for example Refuge House, Solid State Logic, and the two buildings at the University of East Anglia - have only single-element windows. Here presumably the design intention was that the mechanical systems would do most of the job (controlled ventilation in winter, cooling air in summer, and pollutant and unwanted heat removal at all times) with the windows being primarily for psychological relief, emergencies, short periods of rapid ventilation, and perhaps to provide a breeze on still, summer days.

C3.8 TRICKLE VENTILATORS
In the MM buildings studied, trickle ventilators are rare. Often they are redundant because the mechanical systems provide the required background ventilation. At other times they have been deemed unnecessary. EnREI surveys also revealed that occupants may not understand them - though once their purpose had been explained by the surveyor the occupants used them more effectively: simple education can bring great benefits! However, in well-insulated well-sealed buildings with significant internal heat gains the main windows may not be able to provide well diffused, draught-free background ventilation in cold weather:

i) They may not be opened sufficiently, and less air will get in by infiltration than people anticipate from traditional practice. This may not matter if the occupants regard the air quality as acceptable, provided that there are no insidious pollutants which they can not sense.

ii) If they are opened, there may be more draughts because the air inlets are more localised. With reduced fabric heat losses in better-insulated buildings, more ventilation will also be needed to carry away any excess heat which before would have been lost by conduction, and there will also be less vigorous heat output from radiators etc. to temper the draught.

On the other hand, and as mentioned in [46], trickle vents left open cause energy wastage overnight and extend preheat periods, although one can obtain self-actuated temperature, pressure and humidity sensitive ventilators which provide some degree of passive control. In buildings that are naturally-ventilated in winter, there may also be a case for automated trickle ventilators. Sometimes it may also be desirable to bring in the air behind the perimeter heating, as more frequently happens in Northern Europe.

C3.8 WINDOWS AND PLANNING MODULES
In owner-occupied, pre-let and public sector buildings, occupiers have a clearer knowledge of their needs. In such buildings is is often possible to use larger planning modules - see Tables B1 and B2, where values between 2.4 and 3.6 metres are common. This scale permits discrete tall windows, which can provide good views and daylight distribution, and incorporate traditional devices such as splayed reveals to increase apparent width, improve sight-lines and reduce contrast glare (though in practice splays may be obscured by curtains and blinds - which may or may not have a similar effect). The areas of wall between the windows are useful, for example, to park curtains, as a backdrop to VDU screens, and to illuminate at night to improve the appearance of the interior.

C3.9 WINDOWS IN SPECULATIVE DEVELOPMENTS
Speculative developments usually require a finer module to suit uncertain internal planning requirements, as is also evident from Tables B1 and B2. In the late 1980s, some letting agents’ preferred modules were as small as 1.2 or sometimes 0.9 metres. However, this became regarded as too fine and today’s BCO specification [24] recommends 1.5 m. To have one window for each module of this size can create rather fussy and repetitive elevations: and although sometimes alternate modules can be glazed, continuous bands of “ribbon” windows (or ribbons with every fifth or sixth module opaque at the column line) are favourite solutions. However, to stop these these becoming rather mean “vision slots” the window area often climbs above the “safe territory” 25-30% of wall area - with consequent problems of solar gain, and a tendency to lightweight, curtain walled construction, with heat-reflective glass and often increasing the need for mechanical cooling. If natural ventilation is used, then quite elaborate external solar protection may be needed: sometimes this in not practical or affordable - not only because of its capital costs and maintenance requirements, but also on account of town planning regulations, in respect of both appearance and plot ratios based on gross external area.

2 Though with less certainty today than a few years ago. Sometimes the building procurement system (unwittingly or deliberately) also takes little account of their views
C3.10 DAYLIGHT, BLINDS AND SOLAR CONTROL
A useful rule of thumb is that daylight will only be adequate at points from which the sky can be “seen”, so potentially the most useful daylight comes from the top of the window, and glazing below desk-top level is virtually useless. Unfortunately, however, sky and sun through the top of the window can be powerful sources of glare. In traditional situations with rectilinear plans and paper-based based tasks one could achieve satisfactory relationships, at least for most of the time. However, with VDU screens the problems of both reflected glare and high illuminances means that daylight, sky and sun glare often has to be controlled [90].

C3.11 WINDOW CONTROLS
The degree of control appropriate will depend upon the tasks the window need to perform, and the people who are affected by it. The main controls required will be of ventilation, solar gain and glare/radiation/privacy. It is usually best for the final group of functions to be under individual occupant control, either using a supplementary device or an over-ride facility on any automatically-controlled blinds. Sometimes blinds and ventilation clash. Essentially:

1 The person beside the window needs to feel in sufficient control of it. This means being able to exercise both fine and coarse control functions, and to choose whether or not they sit in the draught. It should be simple and straightforward for the occupant to make all the adjustments the designer anticipates will be necessary. This may need remote control facilities, especially for high level fanlights etc..

2 The person remote from the window seldom feels in much control of it. This tends to introduce high inertia into the system: nothing changes until the threshold of discomfort is reached. There is then often a violent state change - for example a window is opened wide or a blind is lowered. This is then followed by a more inertia until someone else becomes really uncomfortable and makes another state change. At the end of the day, or the beginning of the next one, the windows and blinds may be returned to their normal default state by the occupant, cleaning or security staff but frequently they stay where they are until someone else finds the situation intolerable and intervenes.

3 Some things are better motorised and controlled automatically - but where possible with local manual over-rides - and this often applies to high-level windows. Potentially the automatic systems can set the necessary default states, provide supplementary features such as the control of natural night ventilation (or natural make-up air for a mechanical exhaust system), and over-ride control by people deep into the office - who are often inconvenienced by glare and draughts from upper windows.
C4 INTEGRATING NATURAL VENTILATION AND MECHANICAL SYSTEMS

C4.1 THREE FORMS OF INTEGRATION
Section B4 identified three forms of integration:
1 Traditional. Where the mechanical system is designed more-or-less as mechanical ventilation, air-conditioning or comfort cooling for a sealed building.
2 Integrated, where the natural and mechanical systems are designed to work together more closely - for example with mechanical night ventilation; or top-up cooling under very hot conditions.
3 Opportunist, where the base building is quite lightly-serviced, and extra mechanical systems are added when and where necessary. At the minimum, this is the contingency approach with no mechanical systems at all.

WE HAD HOPED TO WORK UP SOME OPTIONS FOR THESE SYSTEMS IN DETAIL, BUT THERE HAS NOT BEEN TIME SO FAR, AND INDEED THIS MAY BE MORE APPROPRIATE FOR THE NEXT PHASE OF THE WORK.
C5 Comfort and control

C5.1 THE AMBITION
MM systems endeavour to deliver the best features of naturally-ventilated and mechanically-conditioned buildings. The level of ambition will of course vary with the system adopted: for example one would not expect a naturally-ventilated contingency design to deliver more than a naturally-ventilated building (though the MM design might possibly be better thought-through) but one might expect complementary designs to.

C5.2 THE BEST OF BOTH WORLDS?
In a complementary design, one might reasonably hope to combine the closer control achievable by mechanical systems with the passive potential (at least in mild weather) and the wider tolerance margins that occupants have where they can open the windows. This could permit:
- Better air quality in winter (and less dusty, particularly in summer) owing to mechanical background ventilation and local extraction of heat and pollutants, and improved ventilation efficiency (for example with displacement ventilation).
- Better thermal comfort in winter owing to the absence of draughts from windows.
- Better thermal comfort in summer owing to heat removal by night ventilation, possibly coupled to fabric energy storage, and potentially higher air velocities with agitation by the mechanical supply.
- Widened occupant tolerance of environmental conditions in all seasons owing to the ability to open windows.

C5.3 THE WORST OF BOTH WORLDS?
On the other hand, one might fear:
- Poorer air quality owing to pollutants introduced by the mechanical ventilation system.
- Discomfort from difficult-to-control air movements from the mechanical system.
- Unwanted heat gains in the mechanical system.
- Clashes in performance between the natural and mechanical systems.
- Uncertain occupant attitudes and perceptions.
- Unrealised ambitions owing to system, control and management faults.

C5.4 SOME EMPIRICAL EVIDENCE
To date there have been few studies of comfort and control in MM buildings, but we have obtained a small amount of information from Building Use Studies' Ltd's (BUS's) database of occupant questionnaire survey findings in 54 buildings, largely offices. The sample includes 4 MM buildings. One of these is a naturally-ventilated contingency design. The other three are concurrent designs with relatively high air change rates of 4 to 6 per hour: two with mechanical ventilation and one with underfloor VAV air-conditioning. The sample also includes four buildings with “advanced” natural ventilation (ANV), all but one incorporating tall spaces with stack and/or wind-assisted exhaust ventilation.

C5.5 OVERALL COMFORT
C5.5.1 Figure C5.1 is a distribution curve of average overall comfort score (on a seven-point scale from 1=unsatisfactory to 7=satisfactory) versus percentile. The continuous horizontal line at just above 4 (actually 4.04) represent the median score, and the dotted lines above and below it the 25th and 10th percentiles.

C5.5.2 Previous analysis of this distribution curve (then with a smaller number of samples) revealed that in terms of occupant perceptions of overall comfort there was little to choose between NV and AC buildings, although both the best and the worst examples in the distribution tended to be air-conditioned [99]. Similar conclusions have emerged from recent studies by BSRIA and the University of Wales/University College London.
C5.5.3 The new buildings however tell a different story, with overall comfort in the MM buildings tending to be in the upper quartile and with all but one of the ANV buildings being well below the median. Before too much is read into these findings - which are on the verge of being statistically significant at the 5% level - one must point out that the solutions are very diverse and that previous studies [e.g: 88, 99] have underlined the importance of the management dimension. The ANV buildings required more effort on the part of occupants, management (and indeed designers and contractors) to work well, while the MM buildings with concurrent operation had more power to spare, albeit often at the expense of some of their claimed energy-efficiency (only the contingency example in these surveys was good in this respect). The MM buildings in the BUS sample - with the exception of the least comfortable one - also had more responsive and service-driven facilities management than the ANV buildings.

C5.5.4 Of the four MM buildings, interestingly the complementary designs with concurrent operation (of mechanical ventilation without chilling) were less comfortable. The technical surveys revealed that there were good reasons for this: in the worst the management and maintenance was poor (being organised from a central BEMS station in head office several miles away) and the mechanical systems were not operating as designed, even though the BEMS and its operators said that they were! In the other, design and commissioning faults meant that the ventilation air was considerably warmer than that outside - typically by about 3°C and night cooling was not effectively operated - so the indoor temperatures were considerably higher than they should have been. It is instructive that the simple, open-planned (with few cellular offices) naturally-ventilated contingency design around a central courtyard performed so well from the occupants’ point of view. This casts some doubt on the claims for advanced natural ventilation in many offices (and possibly the need for it, though ANV can allow buildings to be deeper in plan). The best building (though only just) for overall comfort was a deep-plan office with AC and openable windows. However, given the good performance of the contingency design, one wonders whether all the effort was justified, particularly because the AC building was in a cooler part of the country, and its energy consumption was high!

FIGURE C5.1
DISTRIBUTION OF OVERALL COMFORT SCORES    Source: Building Use Studies Ltd
C5.6 SUMMERTIME TEMPERATURES
Figure C5.2 shows a similar percentile plot of summertime temperatures. Again, the ANV buildings perform relatively poorly. The poorest MM example was the one with the technical and management faults.

FIGURE C5.2
DISTRIBUTION OF SUMMERTIME TEMPERATURE SCORES  Source: BUS Database

C5.7 AIR QUALITY
Figures C5.3 and C5.4 show summer and winter air quality. For the MM buildings, the summer air quality and temperature rankings are very similar, though one of the ANV buildings rates highly in both summer and winter. In winter, the contingency MM building does not perform quite so well, perhaps justifying calls for controlled background ventilation. One concurrent MM design does quite poorly in winter, perhaps because it has local downblow fan-coil units with partial recirculation.
FIGURE C5.3
SUMMER AIR QUALITY  
Source: Building Use Studies Ltd (BUS)

FIGURE C5.4
WINTER AIR QUALITY  
Source: Building Use Studies Ltd (BUS)
C5.8 CONCLUSIONS ON OVERALL COMFORT
Although the sample is small and more information is required, the results are encouraging: MM buildings of several varieties do seem capable of delivering above-average performance on overall comfort - albeit often at some additional energy cost (though not in the contingency design). Anecdotal experience from other MM buildings suggests the same and - although not using comparable questionnaires - BSRIA’s survey results at the MM Refuge House were also relatively good [102]. However, some of the benefits of MM may be related to the motivation of the procurer and of the occupant as much to the building and system type itself. It may also illustrate the relative robustness of the concept in relation to ANV.

C5.9 FORGIVENESS
“Forgiveness” is an index under development by Building Use Studies Ltd (BUS) and WBA to attempt to identify the degree to which people are prepared to accept the conditions in their building. For example, if the building is attractive, congenial or well-managed, or responds rapidly - even if not entirely effectively - to requirements, one might expect occupants to give it the benefit of the doubt. The simple index we are working with to date is the ratio of the overall comfort score, on a 7-point scale, to the arithmetic mean of the individual scores for winter temperature, summer temperature, winter air quality, summer air quality, noise and lighting. Hence a forgiveness of 1.1 means that the overall score is 10% higher than might have been anticipated. Figure C5.5 shows the distribution curve for forgiveness. Extraordinarily, the three MM buildings are at the very top of the range (although BUS tells us that they have just been topped by a new entry to the database) whilst the ANV buildings, although still forgiving, are nearer the middle. The most forgiving building is the concurrent design with the disappointing mechanical ventilation system (see C5.5.4): here influences such as the control and management of the building, the presence of opening windows, or the general ambience appeared to have been having a very positive mitigating effect.

FIGURE C5.5
FORGIVENESS
Source: Building Use Studies Ltd (BUS)

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3 Unfortunately, forgiveness scores are only available for three out of the four buildings of each type: in the other two, one question used was slightly different, making the results not strictly comparable.
C5.10 CONCLUSIONS ON SUMMERTIME TEMPERATURES
Whilst the performance of the MM designs is variable, the ANV examples are uniformly disappointing both in relation to the median and to the contingency MM example. Why might this be? The work of Humphreys in the 1970s [100] revealed that occupants of “free-running” buildings tended to prefer indoor temperatures which varied in relation to those outdoors, while in sealed buildings their preference fell within a fixed and more limited range. This and similar work has been used, correctly in our view, to justify more relaxed internal temperature standards in naturally-ventilated buildings. It appears that this tolerance is a consequence of both psychological and physiological dimensions, for example:

i In schools, Haigh [65] found that people put up with the environment they had until a threshold of discomfort was reached.

ii In offices, similar behaviour was detected [5]: once uncomfortable, people wanted rapid response: it did not matter how they got it. Moving about, adjusting a window, twiddling a knob, or ringing the manager all seemed to be equally good at improving perceived control - provided that the response was rapid and effective.

iii Baker and Standeven [101] identified other fine-tuning processes which they termed adaptive opportunity.

The issue seems to be that where people become uncomfortable and lack both adaptive opportunity and rapid response, their tolerance range for environmental conditions narrows. This applies to all buildings, not just AC ones. It seems that several ANV and MM buildings could have fallen into this trap: in seeking to reduce summertime temperatures, the measures promoted have also unwittingly decreased occupants’ adaptive opportunities and tolerance margins! A recent study by Oxford Brookes University at the Open University [27] has revealed that even in a shallow-plan space, the comfort perceptions (and probably tolerances) of those beside and just one seat away from openable windows differ significantly.

C5.11 CONCLUSIONS ON AIR QUALITY
The best buildings for summertime air quality were the more traditional MM types: the AC building with the openable windows available (though in fact not much used) and the NV contingency design. However, in winter the NV design was not so good - although just above the median - presumably because it was difficult to adjust the windows effectively (they did not have trickle ventilators and a night ventilation position was only added after experience in use).

The concurrent designs, other than the AC one, did not perform very well either in winter or summer, although both did have design and management faults. The fairly substantial (4 to 6 ac/h) mechanical ventilation systems therefore do not seem to have been very helpful investments. Since neither building had more exacting plan depths, occupation densities, office equipment gains or external noise levels than the NV contingency design, it might have been better for them to have pursued the contingency route and put the money saved into the better windows, solar control, lighting efficiency, and lighting control that the contingency design had! Alternatively, a low-power, low-volume, full-fresh-air trickle-charge system might have been sufficient, and possibly better.

C5.12 GENERAL CONCLUSIONS
While MM buildings generally appear to be delivering better comfort than average, this may be more a consequence of the attitudes of the managements that procure, occupy and look after them (and their staff), and the design teams that respond to them, than necessarily of the buildings and their engineering systems alone. While the sample size is small, it sows some seeds of doubt about the need for (and performance of) the higher-powered complementary designs with concurrent systems. More modest installations in simpler buildings may be just as good, and even preferable.
C6 Operation, management and maintenance

C6.1 A POTENTIAL PROBLEM
In attempting to combine the best of passive and active measures, MM systems are different and potentially more complex in their operation. However, recent studies are beginning to reveal that many buildings fail because they are too complicated and provide too much of a burden for management.

C6.2 DOES MM MAKE THINGS SIMPLER OR MORE COMPLICATED?
Sometimes MM can make operation simpler, for example with:
- a contingency strategy adopted and some mechanical systems avoided;
- openable windows available which help to increase occupants’ tolerance of internal conditions and allow them to resolve some of their own comfort problems without involving management;
- simple concurrent operation - for example in a trickle-charged design - increases stability and provides some power to spare; and
- demand-activated changeover - for example with window-linked switches or comfort cooling on interval timers - allows systems to be shut-off or boosted, and waste avoided, without explicit management intervention.

However, the more elaborate changeover strategies can be confusing for management and sometimes for occupants, so perhaps it is not surprising that they often default to concurrent operation, and too often in the highest-energy state.

C6.3 DESIGN FOR MANAGEABILITY
While many systems are capable of fine-tuning, it appears to be important for designers to offer simple, robust, manageable, energy-efficient strategies which will achieve most of the objectives without making too many demands upon management. Skilled managers can upgrade these as necessary to higher levels of performance and efficiency as they gain confidence and experience in operating the building. If such a start-up (and fallback) position is not established, then the systems may easily default into much less desirable states, often with items that are marginally necessary running permanently. Some problems of this kind are discussed in Section D4.

C6.4 THE FANTASY OF FLEXIBILITY
Clients and designers are often tempted to seek systems which offer near-infinite flexibility. These can easily become expensive and technically elaborate, and still fail to meet the full range of requirements that materialise. Meanwhile, the routine effort of looking after all the technology usually absorbs a lot of time. A more straightforward, adaptable MM system could well require much less effort, even including special attention to re-configure it (physically or operationally) to changing requirements. However, the effort it does need may be less routine and more difficult to mobilise. For manageability, systems with straightforward adaptability are therefore important goals.

C6.5 THE OPERATIONAL RESPONSIBILITY
Many organisations do not differentiate clearly between operation - making the system work effectively from day-to-day and minute-to-minute, and maintenance - making sure everything is in good order, clean and working properly. Appropriate job descriptions need to be made clear before staff are appointed and maintenance and/or facilities management contracts let.

C6.6 MAINTENANCE REQUIREMENTS
While MM systems are often simpler than full air-conditioning, because elements may be operated only occasionally or intermittently it will be important to check them thoroughly at the appropriate intervals, to test their controls, and to clean them if necessary. Automatic checks on performance and malfunctions are also desirable to ensure correct operation without wastage.
PART D RELATED ISSUES

D1 Introduction
D1.1 This chapter outlines some other issues which may affect the uptake and performance of MM buildings and systems. These include marketability, cost-effectiveness, energy and environmental issues, and health benefits - each of which has its own section.

D2 Marketability
D2.1 INTRODUCTION
The market does not at present really understand what is meant by mixed-mode. However, interest, knowledge and understanding are now growing rapidly as the demand for “greener” buildings increases and more MM buildings are completed, publicised, monitored and discussed. MM buildings have been produced for over 20 years, either in response to specific briefs, or owing to the interest and enthusiasm of at least a few members of the client or building team. As combinations of natural and mechanical systems move into the mainstream - at least in temperate climates such as the UK’s - we think MM will be regarded as completely normal and to labour the point could become unnecessary, and even counter-productive.

D2.2 PROCUREMENT AND TENURE PATTERNS
The older exemplars of MM buildings in Table B1 were built almost exclusively for owner-occupiers and public sector clients. The newer ones include a number of pre-lets: developer buildings influenced by market standards but where occupiers are identified before construction starts and participate in the briefing and design process. Surveys by Building Use Studies Ltd (some were reported in [5]) indicate that pre-letting can produce buildings (including MM ones) which are more energy-efficient and higher in occupant satisfaction than not only speculative buildings (which is perhaps hardly surprising) but also than owner-occupied ones.

D2.3 THE SPECULATIVE MARKET
D2.3.1 Speculative examples of MM are rare. In spite of their potential appeal to a wider market, they are not yet industry-standard products and everyone is fearful of the unknown. As a developer said at a recent conference [75]:
“Green buildings with natural ventilation, non-divisible office space and lower lighting levels are only feasible for owner-occupiers with fixed requirements. For speculative schemes, you have to accommodate unknown users......Institutional investors don’t want to take risks on temperatures and IT loadings. Nevertheless, our buildings allow for conversion to more energy-conscious use later. It costs us more now, but might earn us more later on.”

Whilst embracing a contingency approach to remove air-conditioning, the potential of other varieties of MM do not seem to have been appreciated (or perhaps they were, and rejected).

D2.3.2 In another recent paper [76], developers MEPC say that energy efficient practices can only be given high priority if they increase letting potential or reduce capital cost. They see opportunities for openable windows and a relaxed atmosphere on a green field site, but not in a city dealing operation; and for energy-efficiency in some pre-lets and shell-and-cores, but not in fully-fitted buildings. They note the supply-side conspiracy of letting agents, funders, and developers (aided and abetted by design engineers!) to produce complex and sophisticated buildings, which are then poorly-commissioned and rarely-understood by their occupants and maintenance staff, leading inevitably to higher energy consumption than their predecessors. However, they note that tenants now wise to this are beginning to demand simpler systems over which they have adequate control. They see change coming from tenant pressure; increases in the price of energy; inclusive leases with developers responsible for running costs; regulations; commonly-agreed voluntary benchmarking standards; and less conservatism by engineers in efforts to improve efficiency without adding cost or complexity. Of these they regard tighter legislation as the best bet: demands from occupiers might also do the trick but not, they think, at today’s low fuel prices. In our view MM might square the circle, but only if developed not to become yet another way of introducing unmanageable complexity!
D2.4 A RECENT TEST
To our knowledge, British Gas Properties is the only developer to have completed three significant MM buildings: a small one at Loughborough (which has been occupied for about two years - a second phase is now under construction); a larger one at Leeds, completed at the end of 1995 but not yet let; and a third just completed at Reading. This last was to have been pre-let to British Gas, but is now surplus to their requirements. However, the developers says that their experience in dealing with them as prospective tenants has increased their understanding of the potential and pitfalls of the MM approach, and we hope we may be able to discuss this with them in more detail. At Loughborough we understand there were some initial problems because the tenants were unfamiliar with the systems and had not been operating them as the designers had intended, and there may be lessons to be learned. At Leeds, there was considerable market research into the views of potential tenants: who reportedly did not initially understand the concepts, but warmed to them once they were explained. Since completion, prospective tenants are reported to have been enthusiastic about the building and its low-energy features - though it has not yet been let.

D2.5 THE NEED FOR BETTER UNDERSTANDING
In spite of the considerable and growing interest in MM, it does seem that its principles and potential are not yet fully understood or exploited: they need more careful exploration and explanation. For the speculative market - at present the most cautious - it could perhaps offer the greatest potential returns: the flexibility offered by AC buildings is often illusory (at least at reasonable cost), though the prospect may be sufficient to clinch the deal! On the other hand, problems that this study has begun to reveal suggests that there may be some foundation for the caution about MM - both by the developer and by the tenant, although in the buildings surveyed to date the problems appear more likely to surface in the form of high energy use rather than lower-than-average occupant comfort. More time, care and thought is required before good industry standards emerge. The proposed CIBSE Applications Manual could be a useful part of this process.

D2.6 MARKET POSITIONING
MM’s market positioning may also be wrong: most people - including building professionals - often see it occupying a rater foggy middle ground between NV and full AC, while in fact it could - and indeed seems to be becoming - mainstream. In marketability terms too, MM could often be seen and promoted as superior to NV or AC, and offering the best of both. Potentially this could reward all parties:
- the developer, with a more profitable and more widely marketable building;
- the tenant, with a more robust, adaptable, cost-effective building;
- the investor, with a better long-term capital asset, better able to meet changing and uncertain requirements;
- the occupant, with a better internal environment; and
- society, with longer-lived buildings with reduced environmental impacts.

D2.7 PROVISIONAL CONCLUSIONS ON MARKETABILITY
The traditional pattern of uptake of new technologies tends to be an S-curve, with typically some 50 years from initiation to complete acceptance - particularly where social and attitudinal change is also required. First the innovators, then the pioneers, then more rapid growth in the market, followed by reinforcement as standards are agreed and the industries and institutions who at first questioned and opposed the innovation begin to climb on board and reinforce the trend. MM concepts, spawned by the energy crisis in the early 1970s are now some 20 years old and beginning to enter the rapid growth phase. However, they are still somewhat diffuse, and need focusing. It would also be worth asking developers, managers, owners and occupiers of mixed-mode buildings whether they would have the same again another time.
**D3 Cost-effectiveness**

**D3.1 CONSTRUCTION COST LEVELS**
While traditionally NV buildings have been considerably cheaper than AC ones, the difference is partly a consequence of building type, rather than the AC itself. In many MM buildings, the occupier wants all the attributes of AC - raised floors and so on, but without full AC - so the cost gap is much narrower. Designers and developers may also want to deliver a similar external appearance too (viz: the attractiveness of glassy curtain walls in some recent MM buildings), even though this will tend to increase summertime temperatures and require complex mitigation systems. In addition, the spatial efficiency of MM may be lower, both in terms of the amount of floorspace that can be put on the site [36] and in the efficiency with which that space can be used. For example, access to windows requires space, and may also restrict furniture layouts. While there may be some savings in plant space, its location is often not very suitable for other purposes; and past experience suggests that squeezing floor-to-floor heights in non-AC buildings is not a good idea.

**D3.2 DATA FROM COST MODELS: BUILDING SERVICES COSTS**
Air-conditioned offices today cost typically in the region of £ 1000/m² gross and naturally-ventilated some £ 150/m² less. However, the range of individual figures for each type is wide with budget levels for “prestige” buildings being nearly twice as much as for low-cost offices for letting [97]. Cost models recently-published [77, 78] give typical M&E services subcontract costs of £ 278/m² for speculative commercial urban offices with fan-coil air-conditioning and £ 125/m² for an out-of-town naturally-ventilated office with perimeter heating: the mechanical services elements were £ 143 and £ 32 respectively. The figures exclude main contractor’s profits, attendance, builders work, and contingencies, which would add perhaps 20% to the M&E figures. Although including a basic fit-out, prestige developments and tenant requirements would add to these costs. Indeed, a more recent paper [96] gives ranges of £ 150-175 for plant, £ 90-100 for distribution and £ 200-250 for fitout. Services for MM buildings would be expected to fall somewhere in the middle of this range. For example, [96] indicates elemental costs of £ 135/m² for heating and displacement ventilation (a common choice for today’s MM offices) versus £ 210 for VAV air conditioning.

**D3.3 BUILDING FABRIC COSTS**
Whether the fabric of a MM building costs more is a moot point: although openable windows with solar control devices etc will tend to be added-cost items, in practice the slick, sealed facades of many AC buildings are not cheap and the differences may be small or even negative. For example, in [85] a Dutch developer noted the market was prepare to spend large sums on curtain walling, take on an expensive commitment of having to clean it 4 to 6 times a year, and ending up with the most expensive construction in both capital and maintenance terms, together with the highest cooling loads (or summertime temperatures)! Similar conclusions were reached by Davis Langdon Consultancy in support of the EnREI Passive Solar and Air-Conditioning study [83]: while good, well-controlled windows naturally cost more (though some styles -for example aluminium-clad timber can be highly competitive), well-designed facades need not in relation to market norms for good-quality AC buildings.
D3.4 DATA ON RECENT MM OFFICES
At a recent conference [35], the engineer of British Gas’s MM building in Reading stated that the savings in capital and energy costs between this and an AC office were only about £100 - 150 and £2-3 per square metre respectively. At Ionica, the QS [53] identified a saving of £70/m² (or about 6%) in relation to a traditional air-conditioned building; and Ionica is all-electric, which would tend to have made it slightly cheaper in any event. The cost comment AJ article on Addison Wesley Longmans [91] states costs 5% below the norm, although reduced servicing costs had been compensated by higher envelope costs, including cladding, sunscreens and 1.2% for thermal mass on the upper floors (concrete roof with garden rather than the normal lightweight steel construction). At Leeds City Office Park the architect stated [86] that openable windows had added about 13% to the total cost of cladding and sunscreens. All these figures seem to confirm typical capital cost savings per square metre of some 5% (for a fully mechanically-ventilated solution) to 15% (for a contingency design) in relation to air-conditioned buildings of similar perceived quality standards.

D3.5 DESIGN COSTS
Reference [76] asks for much more up-front design, and states that it is arguably more difficult to design a simple building than a complex one (or should it be a complicated one?). This is confirmed by the architect of the Power Gen building who is reported [53] as saying that a “low-effort” (for the occupier) building probably needed twice as much design effort as a standard speculative office block - though we imagine that this effort was as much in the quality of the team and of the thinking as in raw time spent.

D3.6 PROVISIONAL CONCLUSIONS ON COSTS
MM designs will normally be a little cheaper than AC buildings of a similar quality standard, although they can be more expensive than basic AC buildings. While they may be (and have been) attractive to owner-occupiers, the public sector, and as pre-lets, in the speculative market they could be bad investment value unless they command greater, or at least similar, rentals to AC buildings. Alternatively developers and investors with a longer-term view can regard MM design as an insurance premium which is likely to reduce future risks of obsolescence and unlettablity or increase the prospect of higher future rental income and/or capital value. However, work will need doing on both increasing the perceived and actual value of this approach and on developing more adaptable, robust and cost-effective solutions - for example using contingency design principles.
D4  Energy and environmental benefits

D4.1  INTRODUCTION
MM designs offer the prospect of lower energy consumption, costs and greenhouse gas and pollutant emissions than AC ones, simply because their HVAC systems should be lower-powered and on less. The MM buildings chosen for the EEO/BRECSU Office Case Studies certainly confirmed this for the normal services of HVAC and lighting (though in several, special areas such as computer rooms and restaurants necessarily added to total consumption), as illustrated in the comparison graphs of energy consumption, energy costs and carbon dioxide emissions in Reference [2]. While the VAV air-conditioned One Bridewell Street [79] performed equally well, it was very much the exception - particularly in its quality of management - and in subsequent studies over the last six years WBA has still not found a fully air-conditioned building which matches it.

D4.2  WHERE MIGHT THE SAVINGS COME FROM?
The main energy savings would be expected to be for fans and cooling. In highly-insulated trickle-charged buildings with high-efficiency heat recovery systems there is also a prospect of savings in heating: though in terms of cost and carbon dioxide emissions electricity tends to be the more important item. In monitored buildings in the UK to date, any predicted CO₂ savings from added mechanical ventilation and heat recovery have frequently evaporated once the extra energy consumption and CO₂ emissions associated with the fans and other parasitic losses have been taken into account. There are several reasons: more ventilation than natural; the need for preheat on cold mornings (even sometimes in warm weather); parasitic losses (in particular the fan electricity consumption with its high cost and CO₂ overhead) and the high risks of un-noticed wastage. However, the potential is definitely there.

D4.3  ASSOCIATED EFFECTS
In more “natural” environments with openable windows, one also often finds lower lighting energy use than in sealed air-conditioned buildings. While the reasons for this are complex, (for example AC buildings tend to have deeper plans and more intensive occupancy) it does appear that the better outside awareness provided by openable windows can encourage people to make less use of the lights.

D4.4  ENERGY DATA FROM EXISTING MM BUILDINGS
Figures D4.1 and D4.2 put together the information we have to hand on annual energy consumption (see tables B1 and B2) and associated CO₂ emissions. They include data from twenty-four MM buildings: all offices except for Solid State Logic (office/light industrial), Constable Terrace (student residential - with consequently a high domestic hot water consumption), and Elizabeth Fry (university teaching). The information comes from disparate sources - some quite old - including BRECSU/EEMD case studies, buildings considered and rejected for these case studies, EnREI studies, PROBE surveys, articles in Building Services - the CIBSE Journal, and WBA’s private communications. The measurement conventions are not entirely consistent: for example the classification of end-uses varies, and some data is for building or HVAC services only. While for the majority of the buildings the floor area denominator is treated area, for other it may be gross area - which is typically 5-15% greater and will falsely reduce the energy consumption indices.

D4.5  COMPARING THE DATA
As revealed in the EEO/BRECSU office case studies [2], energy consumption indices fall into a wide range which depends partly on what is happening in the building. In particular, buildings with a high proportion of cellular offices and individual rooms tend to use less energy because the environment is more “domestic”, passive measures are more readily usable, and the occupant is more in control. Conversely, in more open and deep-planned spaces, more management is required, it becomes much more difficult to determine what individuals really need, and systems tend to default to ON. In addition, the larger buildings tend to contain special areas with more intensive energy use, for example restaurants, computer and communications rooms.
FIGURE D4.1 Annual delivered energy consumption by mixed mode buildings (kWh/m²)

Sorted by CO₂ emissions for normal building services purposes (i.e: up to lighting)

- Heating gas
- Hot water gas
- Htg+HWS gas
- Humidification gas
- Heating elec
- HWS elec
- Humidification elec
- Cooling
- Fans + pumps
- Lighting
- Small power
- Other
- Catering gas
- Catering electricity
- Computer room
- Total Elec (gas htd)
- Total elec (all elec)

VAC SERVICES TYPE CODES:
- DAC Distributed A/C (eg: fan coil)
- CAC Central A/C (eg: VAV)
- NV/MV Natural and Mechanical
- MV+LSC Mechanical plus local cooling
- MV Mechanical (> 3 ac/h)
- BV/MV Multi-speed ventilation
- TC Trickle charged

ALL BUILDINGS ALSO HAVE OPENABLE WINDOWS
FIGURE D4.2 Annual carbon dioxide emissions from mixed mode buildings (kg/m²)

- ECON 19 GOOD PRACTICE TYPE 4
  - 4 Ashby House DAC
  - 4 Tanfield House CAC
  - 4 Provincial Insurance NV/MV
  - 4 Lloyds Chatham MV+LSC
  - 4 RMC Head Office MV
  - 4 South Glamorgan County Hall MV
  - 4 Hereford/Worcester MV+LSC
  - 4 Scot Office (design, act. more) BV/MV
- ECON 19 GOOD PRACTICE TYPE 2
  - 3 Leeds City OP (design:low?) WW
  - 2 Mendip DC (prelim) MV
  - 2 Gateshead Civic Offices NV+Z
  - 2 Charities Aid Foundation (design) BV
  - 3 Ionica (design, actual much higher) WW
- ECON 19 GOOD PRACTICE TYPE 3
  - 3 Equity & Law (estd) DAC
  - 3 Solid State Logic MV
  - 2 South Northants DC DAC
  - 2 Weidemuller (ht+fan only) TC
  - 2 Refuge House DAC
- ECON 19 GOOD PRACTICE TYPE 1
  - 1 Constable Tce (nb: student HWS) TC
  - 1 Policy Studies Institute NV/MV
  - 1 Elizabeth Fry (preliminary) TC
  - 1 BRE LEO, upgraded CON

VAC SERVICES TYPE CODES:
- DAC Distributed A/C (eg: fan coil)
- CAC Central A/C (eg: VAV)
- NV/MV Natural and Mechanical
- MV+LSC Mechanical plus local cooling
- MV Mechanical (> 3 ac/h)
- BV/MV Multi-speed ventilation
- TC Trickle charged
- BV Background vent (< 3 ac/h)
- WW Whole works (multi-step)
- NV+Z Natural + zoned
- CON Contingency
- ALL BUILDINGS ALSO HAVE OPENABLE WINDOWS

Sorted by CO2 emissions for normal building services purposes (i.e: up to lighting)
• Policy Studies Institute is disappointing on the heating side. This was pointed out in the EEO case study [18], and is related to poor control and in particular to refurbishing its elderly and oversized cast-iron boilers, and converting them from gas to oil, rather than replacing them with newer technology.

• Even after allowing for its high hot water consumption (which arises from a combination of use patterns, inefficient generation, and insufficient water conservation measures), Constable Terrace just fails to make the grade. The reason is that more (electric) heating was used than expected, owing to additional window opening (partly because of smells recirculated by the mechanical ventilation system) and the need for boosting during partial occupancy in vacations when there was less heat to recover than anticipated. It is difficult to achieve emissions targets with electrically-heated buildings in the UK because of the high CO\(_2\) overhead of electricity generation. Designers and their clients and advisers should be cautious when importing techniques and technologies from other countries where a high proportion of renewable and/or nuclear energy is used to generate their electricity, and where natural gas is not readily available as a competitive and relatively clean heating fuel.

D4.10 WHAT HAS BEEN ACHIEVED IN TYPE 2/3 BUILDINGS?
Carbon dioxide emissions at Weidemuller (with very high fan energy consumption) Solid State Logic (with high lighting and fan energy consumption) and Equity and Law (insufficient information but probably high), and we understand Ionica exceed the Type 3 GP benchmark. Others do much better, with Mendip and Gateshead around or just below the Type 2 GP benchmark. While Charities Aid Foundation and Posford House lie just below the Type 3 GP benchmark, this is somewhat disappointing because they appear to have planning and occupancy characteristics more similar to Type 2 buildings. Perhaps they could have pursued a contingency or trickle-charged route.

D4.11 WHAT HAS BEEN ACHIEVED IN TYPE 4 BUILDINGS?
Many of the Type 4 buildings have achieved the ambition to provide a Head Office environment with similar or lower emission levels than Good Practice for a standard Type 3 air-conditioned office - which in itself we have found that very few air-conditioned offices achieve. In particular:

• There is a tight cluster: RMC, South Glamorgan, Hereford/Worcester and Refuge with very similar levels of emissions (typically 67 kg/m\(^2\)) - up to the top of the lighting bar: 23% and 37% respectively below the relevant parts of the Types 3 and 4 GP benchmarks. Perhaps this should be a new standard? However, in all these buildings lighting energy consumption (average 42 kWh/m\(^2\)) is high: with today’s technology performance in the 20 - 30 kWh/m\(^2\) region should be attainable in this type of building.

• NFU [58] is unusually low in its consumption and emissions. There seem to be three main reasons for this:
  - A two-speed ventilation system which during the day is normally operated concurrently at low speed, giving large savings in fan energy consumption.
  - Reasonably well-controlled daylight, low design illuminance levels, and relatively good (for its time) central and local lighting controls.
  - Practical facilities management experience which abandoned mechanical night ventilation in favour of natural ventilation through the relatively secure high-level hopper windows. MFP’s EnREI studies [8] found this to be effective. This parallels BSRIA’s findings [105] on Durrington Bridge House.

• Lloyds Chatham and Provincial Insurance have higher consumption, but only for lighting. These schemes date from the 1970s and have not benefited from today’s more efficient technology and lower illuminance standards.

• Design targets for the Scottish Office were somewhat higher than the measured levels at NFU, largely owing to the inclusion of refrigeration to meet higher estimated internal gain levels. However, early operating experience suggests that the targets may have been optimistic.

• In spite of claims, Ashby House and Tanfield House essentially perform as typical air-conditioned head offices and no energy benefits from the MM approach are discernible.
D4.12 ENERGY USE FOR HUMIDITY CONTROL
When ECON 19 was being prepared, most AC offices had abandoned humidification owing to the legionnaires’ disease scare, and so its energy use was not included in the benchmarks. It is now creeping back, particularly with VDU legislation and the increasing use of full-fresh-air systems. Of the buildings included, only South Glamorgan and Tanfield House have humidification: packaged electric steam and central gas-fired steam respectively. Energy consumption by humidification is very variable depending on the standards adopted: at Tanfield a minimum level of 45% RH was expensively maintained with a gas consumption of 90 kWh/m$^2$. South Glamorgan used it only in cold, dry weather with an estimated electricity consumption of 5 kWh/m$^2$ (or a CO$_2$ equivalent of about 17 kWh/m$^2$ of gas). However this electricity was probably very expensive as it would have been likely to have added to the wintertime maximum demand charges. Some recent studies suggest that added moisture often creates as many problems as it resolves, at least until RHs fall below 25-30%; and in cold climates wintertime RHs very much lower than this are routinely accepted. Advice on appropriate levels, provision and operation of humidification would be desirable.

D4.13 ENERGY CONSUMPTION BY FANS
Perhaps the key to energy efficient design of MM buildings is to minimise the energy use by the fans. This is the product of four numbers:

1. The design air change rate, or rates, in ac/h or l/sec per m$^2$. For a typical ceiling height in recent MM buildings of some 3 metres (including the volume of air in coffers etc.), 1 ac/h is equivalent to 1.2 l/s per m$^2$.
2. The specific fan power (for supply and extract combined). For ducted mechanical ventilation and air-conditioning, this typically falls in the range 1 to 4 Watts per l/sec. Unducted systems, and multi-speed ducted systems operating at low speed, can use less than this.
3. The hours of use of the system. This can range from a few hundred hours a year for on-demand night ventilation, at Durrington Bridge House and York University’s Computer Science Laboratory, to 8760 hours per year on continuously-operating trickle-charged systems such as Termodeck at Weidemuller and Elizabeth Fry.
4. The proportion of the total floor area which has mechanical ventilation.

D4.14 A GEOMETRIC PROGRESSION
In good MM design, one should aim to keep all four numbers above low, as the multiplier effect - for both good and ill - can be tremendous. As a general rule, the higher the air change rate, and the more sophisticated the system, space restrictions, noise attenuation and air resistance through added features such as heat recovery devices increased the specific fan power. In addition, the higher the air change rate the more people are likely to notice the difference between the system operating or not, which may reinforce the tendency to default to ON. There may also be technical problems which reinforce this.

For example, one building WBA visited had a mechanical air change rate of 6 ac/h at a specific fan power of 4 Watts per l/sec, giving an installed fan power of 28.8 W/m$^2$. For various reasons, including the sensitivity of the plants in the atrium to solar gains at weekends, this system defaulted to ON and ran continuously, giving a massive annual energy consumption of 250 kWh/m$^2$ of office area (or some 170 kWh/m$^2$ of treated area) with some additional consumption from boost extract ventilation to 10 ac/h in hot weather.

A more recent example is the trickle-charged Weidemuller. Here the continuously-running ventilation had a specific fan power of 3 W/l.s and chalked up an annual consumption of 78 kWh/m$^2$ [92]. Most of the cooling influence of this system was also devoted to counteracting fan gains and other forms of heat pick-up, rather than cooling the building! The Elizabeth Fry Building reportedly performs much better, though [92] quotes a specific fan power of 2 W/l.s, while the increasingly widely-accepted norm for an energy-efficient building is a maximum of 1 W/l.s. [28, 73, 104, 108]. Admittedly this can be difficult when there are a lot of filters, heat exchangers etc in the air stream, but an absolute maximum of 1.5 W/l.s is recommended. Values less than 1 W/l.s can be achieved on low-speed operation, as at NFU.
D4.15 CONCLUSIONS ON ENERGY AND ENVIRONMENTAL BENEFITS
While MM buildings can provide benefits, they require attention to detail in strategy, design and management and are often somewhat fragile. As a general rule, the good practice design principles set down in Section C2 need to be followed carefully. The proposed CIBSE Applications Manual could illustrate in some detail the application of these and other principles to the design of different varieties of MM building.

D4.16 AVOIDING WASTEFUL OPERATION
Designers, reasonably enough, tend to be optimistic about their proposals. However, recent studies emphasise the importance of minimising the downside risk of potentially good ideas. Without care and circumspection, these can very easily turn into “nuisance” features and technologies which can prove baffling or annoying to the occupant, difficult to understand and to manage, and to have unintended consequences - frequently for excessive energy use. Some of the problems regarding comfort and control have already been outlined in Section C5. Below we list some generic problems which often lead to energy wastage.

C4.17 COMMON CAUSES OF ENERGY WASTAGE
Many buildings suffer problems which tend to reduce performance and/or increase energy consumption - with systems either defaulting to “ON” when they could have been off (or at least at substantially reduced output), or operating inefficiently. The energy consequences of these tend to be most severe in the more sophisticated and highly-serviced buildings, which until recently have tended to be AC. However, the more complex MM buildings are at risk of similar afflictions. The root cause of the problems is often poor usability of complex systems, with the following generic causes:

i  *The “tail-wags-the-dog” effect,* where whole systems are brought on to service small loads, for example a central chilled water system servicing a few 24-hour machine rooms (in one installation the energy used at night by the pumps alone was over five times the cooling load). The same thing may happen with central ventilation systems, as discussed in D4.14. Suitable local self-contained or supplementary systems should be used; or if the main systems are zoned the central plant needs to be designed and controlled so that it can operate efficiently at small fractions of its full load.

ii  *Unwanted operation,* when systems run long hours or constantly because the controls have been over-ridden for some unusual purpose and not reset afterwards; or because automatic controls (eg: frost thermostats or hidden hardware or software interlocks) bring on systems unnecessarily owing to poor setting, calibration or programming; or as a result of changes whose repercussions have not been fully appreciated. Suitable fault detection should be incorporated, for example by reporting the running hours of devices and systems during periods when they are programmed to be off.

iii  *Unintended operation,* when systems activate (or fail to de-activate) themselves when not required, often outside the occupied period. Anticipatory systems (eg: for optimum start, night cooling, or reservoir charging/discharging) are particularly prone to this. Ideally, hours should be logged and compared with heuristics of likely predicted requirements.

iv  *“Embedded” system malfunction,* where systems no longer improve performance or save energy, and may even increase it as a result of parasitic loads (see below). Examples include heat recovery systems which break down un-noticed (or continue to operate when cooling is required); “free” cooling and enthalpy control systems, which often introduce the wrong proportions of outside air; and unnecessary heating (through recirculation, letting-by or even deliberate heating) of air intended for night cooling (and sometimes during the day too). Ideally performance of such systems should be automatically monitored against the design intentions.

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4 The term “embedded system” is used to describe one which is installed to improve economy but which does not necessarily or immediately affect perceived performance.
Parasitic losses are particularly common with embedded systems. For example extra fan power is required to drive air through heat exchangers; heat recovery from chillers usually reduces refrigeration efficiency and additional fan and pump power may be required for heat rejection and redistribution. These parasitic loads are nearly always electric - with a high cost and CO\textsubscript{2} emissions overhead - and can often be present whether or not heat is being recovered, hence eating into any improvements and savings. Designers should attempt to reduce these losses to a reasonable minimum and if possible to avoid them entirely when energy is not being transferred, for example by switching-off and/or by-passing the device concerned.

Antagonistic losses usually take the form of heat fighting cool, for example heat being recovered unnecessarily when systems are in free or mechanical cooling mode; simultaneous humidification and dehumidification; or (particularly common with MM systems) mechanical systems competing with air coming through the windows. System state and performance should be monitored and clash alarms reported.

D5 Health issues

D5.1 At this stage it is difficult to say much about health issues. People often say they feel healthier in NV buildings even though in theory MV and AC should provide better air quality. Recent studies have shown that there is some sense in this, and not only psychologically: mechanical systems can not only introduce, recirculate and distribute pollutants, but if poorly designed, cleaned and maintained they can harbour and generate pollutants of their own. There is also no mechanical equivalent of throwing open the windows for “shock” or “rapid” ventilation.

D5.2 On the other hand, some insidious air pollutants, such as radon, cannot be sensed, and well-designed mechanical systems can ventilate with greater effectiveness than natural ones, particularly in cold (or very hot) weather in which increased levels of natural ventilation would carry energy penalties. Potentially there seem to be health benefits in trickle-charged MM buildings in which a small amount of high quality mechanical ventilation can not only maintain minimum levels of air quality but help to achieve thermal stability and to remove localised pollutants at source.

D5.3 The intermittent operation of some mechanical systems might cause health problems, in the same way that the greatest likelihood of legionnaires’ disease from cooling towers was on start-up after a long idle period when the bacteria had had a chance to multiply. Unused mechanical supply systems could potentially fester with dust, puddles, vermin etc. and spring into life distributing the remains about the building. Attention to hygiene in design, operation and maintenance is likely to be come increasingly important for all mechanical ventilation systems, in MM buildings and elsewhere.

D6 Conclusions on related issues

D6.1 Under all the four headings considered here, we have discovered areas of good prospects but somewhat uncertain knowledge and understanding. There is a clear need for further study, both on developing the ideas and on understanding the performance of existing MM buildings and the opportunities for and methods of improvement.
E NEXT STEPS

E1 Overview

E1.1 A SHORT HISTORY
This study has identified a wide variety of MM buildings. The first wave was designed for the private and public sectors as a response to the 1970s energy crisis. By the mid-1980s - and with a few notable exceptions - MM had been somewhat eclipsed by the rise in information technology and over-estimates of its likely heat gains, rising prosperity, falling fuel prices, and the institutional standard of VAV air-conditioning. However, in the 1990s concerns about the environment, value for money, no-frills adaptability and occupant health have created a surge in interest, and there are even a few speculative examples.

E1.2 ARE MIXED MODE BUILDINGS ACHIEVING THEIR OBJECTIVES?
We have identified three main objectives for all MM buildings. These are summarised below, together with comments on the extent to which we think they are being met.

1 Longer-lived buildings which can be adapted to changing requirements, standards and priorities without wasteful over-provision or unnecessary costs. As yet there is little evidence, except on capital costs, which for buildings already equipped with complementary mechanical ventilation are reported as typically 5% less than comparable air-conditioned buildings, sometimes rising to as much as 15%, particularly for contingency designs with few mechanical ventilation and cooling services.

2 Better occupant satisfaction by combining the perceived advantages of openable windows with any mechanical servicing necessary. There is some indication that people are more tolerant of environmental conditions where they can open the windows. However, occupant questionnaire surveys in recently-completed buildings with advanced natural ventilation indicate that all is not well, and that what tolerance there is accrues primarily to those who are near and in direct control of the windows. In general, MM buildings seem to do considerably better. However, the samples are not yet large enough to be statistically significant. We have also found that good managements tend to procure better buildings and manage them and their staff better, so there may well also be knock-on effects.

3 Reductions in energy use and associated emissions by avoiding the unnecessary operation of mechanical systems at times and in places where natural ventilation could meet the requirements more effectively. Although there are some successes, meeting this requirement without approaching the energy consumption levels of comparable air-conditioned buildings is proving to be more difficult. In practice many ventilation systems are oversized, not very efficient, and operate for more hours under worse control than the designers had predicted, bringing additional running costs and extra heating, cooling and particularly fan electricity consumption. While poor management is often blamed for this, we think the reasons are much more deep-seated.

E1.3 WHAT IS GOING WRONG?
As yet there seems to be insufficient understanding of the following major issues:

i How to achieve adaptability cost-effectively. Many buildings appear to be overserviced and insufficiently adaptable. Sometimes moneys might have been better spent on reducing unnecessary heat gains than on providing ventilation plant to mitigate them.

ii How occupants and management really behave. In hindsight, design expectations of occupiers often seem to have been unrealistic. Better briefing and consultation is not the complete answer to this: client and designer can unwittingly connive in creating false expectations. There is no substitute for monitored pilot projects, plus post-occupancy surveys to improve industry awareness generally.

iii What can go wrong with systems which are supposed to be energy-efficient. This ranges from basic efficiency (in many MM buildings the specific fan power is far too high) to more rigorous analysis of possible failure modes and their implications.

iv Appropriate design of controls, which work well and are effectively usable by occupants and management.
E2 What needs doing next?

E2.1 MORE INFORMATION
While this report has established a framework for thinking about MM buildings, it is short on information and exemplars. In terms of information, we think it would be very useful to undertake rapid building appraisals with energy, occupancy, and management surveys on a number of more recently-completed MM buildings. In the first place these could be along the lines of the current series of PROBE studies for Building Services - the CIBSE Journal. Follow-up monitoring might be required in a few cases.

E2.2 BUILDINGS TO SURVEY
Many in Table B2 would be of interest, and in particular:
- BSI Chiswick: a refurbished tower block with interlocked fanlights and fan coils.
  * Elizabeth Fry Building, University of East Anglia. One of the first trickle-charged buildings which appear to be fulfilling its promise.
- DTI refurbishment, Westminster. A rather elaborate MM strategy: how well is it working in practice for occupants, management and energy?
- IBM Software Laboratory, Hursley Park. Another building with interlocked fan coils. Energy may be difficult to measure because the building - on a large site - might well not be sub-metered.
- Inland Revenue, Durrington Bridge House. What seems to be a fairly straightforward atrium building which BSRIA said could possibly be even simpler. Can it?
- Inland Revenue, East Kilbride. An interesting form with a number of variations. Do these affect occupant perceptions?
- John Menzies, Edinburgh. A good-looking but relatively simple design. But have too many of the frills been removed?
  * Marston Books, Milton Park, Abingdon. A simple contingency design. Some other contingency designs have done as well as the mechanically-ventilated examples without the cost, complexity and energy consumption of the mechanical systems. Will this?
- Powergen, Coventry. A potentially interesting, relatively simple design, and one which reportedly did not need its chillers to operate last summer.

We understand that some monitoring is already occurring (or is about to occur) in the asterisked buildings, but this may need to be enhanced. Information from other monitored buildings, in particular Inland Revenue Nottingham and Ionica should also be included.

E2.3 BETTER EXEMPLARS
A study is recommended of the potential for MM design, both reviewing past exemplars and current ideas and looking at generic possibilities for the future. It should include ideas for contingency building shells and for the “drop-in” services which might be added to them. It should also consider trickle-charged designs and methods of increasing their capacity to deal with additional heat gains and ventilation requirements quickly, easily and if possible reversibly. Its report would be developed into a well-illustrated publication which would help to raise awareness of the potential whilst identifying the process and the pitfalls.

E2.4 A MARKET SURVEY
This would include expectations of and attitudes to MM buildings, both of those who have been concerned with them as procurers, designers, occupiers, commissioning engineers, managers and letting agents, and of the wider community.

E2.5 EXPLORATION OF CRITICAL FEATURES AND DETAILS
Certain aspects, and in particular windows, controls and control interfaces, are critical to the success of many MM buildings. A detailed study is suggested of the best means of achieving critical goals, for example effective low-energy night ventilation.
E3 The CIBSE Applications Manual

E3.1 In this report we have identified - directly and indirectly - more than enough material for a CIBSE Applications Manual, and many reasons why such a manual could be valuable. We think it would be helpful to start drafting this as quickly as possible - by doing so (and by reviewing it) we think that the gaps in the arguments would become most rapidly apparent. These could then be used to direct any further research and investigation beyond that outlined in Section E2.

THIS SECTION WILL BE EXPANDED FOLLOWING DISCUSSIONS WITH THE PROJECT OFFICER AND THE ADVISORY GROUP.
Appendices
APPENDIX X
A REVIEW OF MIXED MODE DEFINITIONS

X1 INTRODUCTION

X1.1 This appendix includes some arguments which underlie the discussion on definitions in Chapter A2 of the main report. The Max Fordham & Partners’ (MFP) definitions: contingency, concurrent, changeover and zoned, [3] are repeated for convenience, other definitions introduced, and some conclusions drawn.

X2 THE MFP DEFINITIONS

X2.1 CONTINGENCY designs are ones in which mechanical systems can easily be added (or removed) if this proves necessary. At one end of the scale comes naturally-ventilated buildings or spaces (designed for example along the lines discussed in the CIBSE Applications Manual [1]), which have a clear contingency plan (or plans) for adding mechanical ventilation and/or cooling if required. At the opposite end, a sealed air-conditioned building may be designed with the potential to revert to a less energy-dependent form of operation, for example if it is planned for natural ventilation (and having suitable openable windows etc. - even if initially they are locked shut), or for some form of concurrent or changeover operation (see below).

X2.2 CONCURRENT is the most common form of hybrid, where mechanical ventilation - with or without cooling - operates in parallel with openable windows. Normally the mechanical system suffices, controlling draughts and air quality and removing heat, but people can open the windows if they want to. The systems must be complementary, not antagonistic. Site studies however suggest that mechanical systems are often too powerful, not very efficient, and run much more than necessary and than the designers anticipated.

X2.3 CHANGEOVER: Natural and mechanical systems are available and used as alternatives according to need, but do not normally operate at the same time. Some examples include:
- Seasonal changeover, for example with windows openable in mild weather but locked shut in winter, when mechanical ventilation is used to meet required air quality standards, avoid draughts and possibly save energy by using heat recovery.
- Night cooling, with natural ventilation during the day, and mechanical at night to remove excess heat built up in the fabric. This is useful where windows cannot be left open, or where air is passed over the structure to enhance heat storage effects.
- Local changeover, where window detectors switch off nearby air-conditioning or comfort cooling units when the window is opened.

In practice it can be difficult to implement changeover design intentions reliably (apart perhaps from local) owing to their complexity; an absence of input information to make an informed choice; poor or non-intuitive user interfaces; or adverse occupant reactions to systems which change their operating mode capriciously (at least to them). Consequently changeover systems often default to concurrent operation, nearly always with increased energy consumption and sometimes with worse performance - at least in engineering terms.

X2.4 ZONED, with different services in different parts of the building: for example comfort cooling locally for hot spots (probably a special case of contingency design), or in parts of the building (say) with a deeper plan, high solar gains, or limited opportunities for natural ventilation. However, such variations in the servicing of nearby and operationally similar spaces in the same building can cause problems for users - either through jealousies or because the different systems require different user behaviour: careful study and guidance is essential. Another variety of zoning is where services in special areas (eg: restaurants, computer suites, meeting rooms, swimming pools and toilets) differ from those in other parts of the building - but since this is perfectly normal it may not be helpful to classify this as MM.
X3 SOME OTHER DEFINITIONS

X3.1 CIBSE NATURAL VENTILATION APPLICATIONS MANUAL [1]
This quotes the MFP definitions, but also mentions seasonal mixed mode.

COMMENT: We consider that seasonal can be regarded as a special case of changeover, and in general terms a changeover can occur for any reason.

X3.2 D ARNOLD [2]
This states that MM is a strategy which attempts to combine the best features of both natural ventilation and air conditioning, in holistic designs which treat building and services equally, using different features of the systems at different times of the day and the year. For most of the year, MM is seen as operating in natural ventilation mode, perhaps with mechanical ventilation coming on if air quality deteriorates or the temperature gets too high. Once the natural systems became inadequate to restrict the rise in temperature during the day, mechanical systems would provide “just enough” cooling - by free cooling, mechanical refrigeration, or night cooling and fabric thermal storage. Suitable trade-offs are discussed in the paper.

COMMENT: We regard this as a restrictive definition, although the paper identifies some useful objectives and procedures for certain changeover systems. While “just enough” is a useful and desirable principle, evidence from case studies suggests that in practice the changeover points are not always easy to identify, and that people can be inconvenienced by the changeover itself - when temperature, air movement and required user behaviour can alter for no apparent reason. Most managements therefore tend to run mechanical systems more liberally and concurrently than the designers ever anticipated.

X3.3 D BRAHAM [13]
This author chooses an even more restrictive definition, of openable windows for the daytime, mechanical underfloor ventilation for overnight cooling when necessary, and controlled ventilation with heat recovery in winter - again a variety of changeover system. He differentiates this from “passive heating and cooling”, a concurrent system which uses year-round mechanical ventilation with heat recovery, hollow core slabs, and openable windows. He also includes a changeover mode which has supplementary cooling in very hot weather.

COMMENT: We regard all three options as variations on two of the MM themes.

X3.4 BRECSU [8]
On page 18 this suggests that many mechanically-ventilated concurrent designs fall into the contingency category, because cooling coils could be fitted in the air-handling units, or sensible cooling could be added in the rooms to which some mechanical ventilation was also available.

COMMENT: While this is a reasonable interpretation, the original intention of MFP’s contingency definition was to indicate buildings with latent potential but not able to exploit it immediately, either because:
- there was no need, e.g: a building which could cope for the moment with natural ventilation
- there was no hardware in situ; for example in a naturally-ventilated building with space provision only for future mechanical systems; or
- it would be unsuitable (for example for a space which had openable windows but for the time being needed to be sealed and air-conditioned - perhaps to meet exacting environmental standards).

In response to the BRECSU point, we consider that all varieties of mixed-mode are to some extent contingency designs, because part of their main purpose is to be more easily adaptable to meet changing circumstances. This point will be incorporated in some general objectives, see Section X6.2.
X4 DISCUSSION OF THE DEFINITIONS

X4.1 GENERAL OBJECTIVES

We recommend that the definition of MM is kept broad, and not restricted as suggested by some authors in Section X3. However, more detailed functional and technical classifications will be helpful, as of course they are for all types of system. Whatever their classification, MM buildings can be seen as seeking to achieve some, and often all, of the following objectives:

1. Longer-lived buildings which can be adapted to changing requirements, standards and priorities, and serviced to meet occupiers' real needs whilst avoiding wasteful over-provision, unnecessary capital and running costs, or burdens for management.

2. Better occupant satisfaction by combining the perceived advantages of openable windows with any mechanical servicing necessary to provide suitable levels of health, safety and comfort.

3. Reductions in energy use and the associated greenhouse gas and pollutant emissions through avoiding the unnecessary operation of mechanical systems at times and in places where natural ventilation could meet the requirements more efficiently.

X4.2 RE-ASSESSMENT OF THE MFP DEFINITIONS

The MFP definitions are already in the public domain (for example in references [1], [3], [6], [8] and [14]), have proved useful, and work well despite some shortcomings. To change them too much could well confuse people: we think it would be better for them to evolve through interpretation, development, and practical application. Possible shortcomings requiring attention are discussed below.

- WHEN SHOULD A BUILDING RATE AS MM?
  In our view a true MM system should combine natural and mechanical servicing options in one and the same space. For a building to be called MM, such an approach would be widespread. Where it is not, parts of the building can still be designed on MM principles.

- THE FOUR MFP TERMS ARE NOT MUTUALLY EXCLUSIVE
  The review in Part B indicates that the four terms: contingency, concurrent, changeover and zoned do not in fact describe distinct choices, but classification facets, of which more than one may be present. A multi-faceted classification is needed to take account of this.

- AT WHAT SCALE SHOULD THE TERM CONTINGENCY APPLY?
  To the whole building (as MFP originally intended), to some zones only, or to small-scale system modifications as suggested by BRECSU - like the added cooling coil in an existing AHU? We prefer the original definition, possibly taken down to the zone. With the general objectives in X 4.1, a fine-tuning capability (like the added coil) is fundamental to the whole idea of MM.

- WHAT ABOUT CONTINGENCY TO REMOVE PLANT?
  Is a strategy to remove mechanical systems (like the AC at Salford) different from one to add them (as at Body Shop)? Not really, but this needs more consideration, both on grounds of marketability and perhaps to avoid a possible back-door route to full air-conditioning.

- SHOULD ONE DIFFERENTIATE BETWEEN CONCURRENT & CHANGEOVER?
  This distinction seems to be more real to designers than in practice. The systems available in a building tend to be operated in the manner that management and occupants finds most convenient or reliable, and which leads to fewest problems and complaints. The key feature of both concurrent and changeover is that natural and mechanical systems are both present at the same time and are complementary in operation. Whether they are operated at the same time, as alternatives, or at all, is ultimately a management choice. We suggest that the distinction is retained, but to describe operating modes rather than as a fundamental element of building or system classification.

- DO WE NEED EXTRA TERMS TO DESCRIBE ENGINEERING OPTIONS?
  This might include concepts such as perhaps upgradeable (say for the cooling coil) and modular (where additional units such as fan-coils can be easily added). It is not yet clear whether this would be helpful.

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Footnote:
3 Occupant surveys by BUS suggest that in group situations the situation of least complaint is not necessarily optimal. It is often that of least change and may even border on the threshold of discomfort.
X5  PROPOSED CLASSIFICATION FACETS

X5.1 We think that one can classify MM using four separate facets, each with two choices, as outlined below. In naming them here, words from MFP’s definitions have deliberately been avoided for the time being.

X5.2 FACET 1  WHOLE or PART?
This facet relates closely to MFP’s *zoned* classification. However, buildings containing differently-serviced zones but not designed with the potential for ready interchangeability or parallel running would not strictly count as MM.
Alternatively, one could omit this facet and instead apply the classification not to the building as a whole, but only to those parts of it which claimed to be MM.

X5.3 FACET 2  ACTUALLY or POTENTIALLY?
This is MFP’s *contingency* classification, which may be applied to the whole building or to individual areas (but see point 1 above).
Explicit recognition of such latent potential is particularly important at the point of sale. If the thought and investment devoted to the contingency strategy is not valued by the market (be it customer or investor), nobody (except the odd enthusiast) will have the incentive to do it. The potential to alter or upgrade systems and subsystems is covered by the general attribute of adaptability, and does not appear to be essential to this aspect of the classification. However, this will be reviewed later.

X5.4 FACET 3  COMPLEMENTARY or MUTUALLY EXCLUSIVE?
If complementary, natural and mechanical systems are both physically present and operationally available, subject to management, control system or user choice (see point 4 below). In the *mutually exclusive* option, the choice of one system or the other stands until there is good reason for change - for example a major alteration in occupancy or equipment levels; and the change might well require some physical alterations.
We think that this facet can probably be discarded, with mutually exclusive treated as either:
- a special case of zoning or contingency planning; or
- where natural and mechanical systems are both present, but the choice between the two is a long term-one, it could be regarded as an extreme case of changeover, in which the changeover option was seldom exercised.

X5.5 FACET 4  IN PARALLEL OR ALTERNATELY?
This is the last facet because it is a matter of operational choice. *Parallel* is similar to MFP’s *concurrent* option, and *alternate* to MFP’s *changeover* option and to Reference [1]’s *seasonal* definition. This is a useful distinction but should not be a primary means of classification. However, an understanding of these choices, and the related opportunities and pitfalls, is essential to the engineering of systems in which natural and mechanical systems are effectively and economically combined.

X5.6 A FULL DEFINITION
A full definition, which takes account the four proposed classification facets, could be:
*Mixed-mode is an approach to ventilating and cooling in which natural ventilation (normally using openable windows) and mechanical ventilation and/or cooling and air-conditioning systems are deliberately combined:
1 For the whole building or for parts of it.
2 Actually (with both systems present) or potentially (in a building designed for easy addition, removal or alteration of part or all of the mechanical systems).
3 As complementary or mutually exclusive alternatives.
4 If complementary, by operating in parallel or alternately.*
X6 CONCLUSIONS ON DEFINITIONS

X6.1 USE OF THE TERM ‘MIXED MODE’
Although more restrictive definitions have been proposed, we recommend that the term ‘Mixed Mode’ is used to describe the full range of combinations of natural and mechanical systems. Recommended general objectives for such buildings and systems are as follows:

1. Longer-lived buildings which can be adapted to changing requirements, standards and priorities, and serviced to meet occupiers’ real needs whilst avoiding wasteful over-provision or unnecessary capital and running costs.
2. Better occupant satisfaction by combining the perceived advantages of openable windows with any mechanical servicing necessary to provide suitable levels of health, safety and comfort.
3. Lower energy use and the associated greenhouse gas and pollutant emissions through avoiding the unnecessary provision and operation of mechanical systems at times and in places where natural ventilation could achieve the task more efficiently.

X6.2 DIFFERENT CLASSIFICATIONS
The MFP classification: Zoned, Contingency, Concurrent and Changeover has worked well, but some shortcomings have been exposed. A classification system with four separate facets would be theoretically more appropriate, but rather than changing everything we recommend using the insight this brings to make minor alterations to the MFP definitions. A more elaborate classification does not seem worthwhile: more information would be imparted by adding specific technical details.

X6.3 RELATIONSHIP TO THE MFP CLASSIFICATION
The faceted classification makes four choices:

1. Whole or Part? MFP’s zoned term can be retained to describe buildings which contain a variety of natural and mechanical systems. However, to be termed a MM system, natural and mechanical systems must be combined in the same space.
2. Actually or potentially? MFP’s Contingency term can be retained for strategic options. Tactical options (such as adding a cooling coil) are covered by Objective 1.
3. Complementary or Mutually Exclusive? We recommend using the term Complementary to describe all situations where natural and mechanical systems are available together in the same space. Mutually exclusive can be considered as an extreme case of a Changeover operating strategy. However, the distinction can be useful in making strategic choices, see Section A3.1 of the main report.
4. In parallel or alternately? For complementary systems, MFP’s concurrent and changeover are just two of a variety of possible and frequently interchangeable alternative operating strategies. Although one could attempt to classify the whole range of options in general terms, we do not think that this would be helpful. Instead, we think it would be better to ensure that the specific strategy or alternatives were set down clearly for the building or space concerned.

Some people already limit the term mixed mode to describing complementary situations, but we regard this as too restrictive because it excludes zoned and contingency options.

X6.4 RECOMMENDED SIMPLE CLASSIFICATION
Strategically, we suggest the options of zoned, contingency and complementary. Operating modes for complementary systems can then be broadly classified as either:

- Concurrent, where openable windows and mechanical systems operate together.
- Changeover, where the systems may operate in rapid succession but not normally together, except by default.
- Alternate, where a choice, once made (say to close the windows and operate full air-conditioning with humidity control) persists for a long time.

More detailed descriptions can then be provided as appropriate, for example say seasonal changeover with controlled mechanical ventilation in winter, mechanical ventilation with night and comfort cooling in hot weather, and openable windows at other times. However, as a shorthand, the original MFP 4-way classification may still be used.
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Figure from Probe report: Overall occupant survey scores for comfort by ventilation type
Probe and BUS reference database

Notes
Average Overall score
A score based on the average scores of the following seven summary variables.
TSOver Summer temperature
TWOver Winter temperature
AirSOver Summer air quality
AirWOver Winter air quality
LtOver Lighting
NseOver Noise
ComfOver Overall comfort

Average Overall percentile
A percentile based on the Average Overall score.

Example
TAN scores an average of 4.73 on the seven summary variables. When converted to a percentile this evaluates to 97. Thus TAN is in the top 5% of the dataset by this criterion.

Scales
Type A. Best on right

Ventilation types
NV Natural
ANV Advanced natural
MM Mixed mode
AC Air conditioned

Interpretation
For the average percentile variable, all dataset buildings have been a) ranked into order from worse to best (left to right on bottom axis); b) split into four ventilation types c) plotted showing rank against average percentile. The buildings in the top right of the graph are “best” by these criteria.