Development of a Decision Support System for the Design of Good Indoor Air Quality in Office Buildings

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ABSTRACT

Office buildings are complex entities. Design decisions can affect the quality of the indoor air (IAQ) throughout the life of the building. Poor IAQ affects approximately 30% of all office buildings and is ranked within the five greatest risks to human health in developed countries.

Despite a vast and growing body of scientific literature on IAQ, there is a large gap between the current knowledge and the application of this knowledge in building practices. The USA Environmental Protection Agency identified a high priority need for design and educational tools to assist building designers who are not experts in IAQ issues to create healthy buildings. In this study a Decision Support System (DSS) for the design of good IAQ in office buildings was developed.

The DSS leads building designers through a structured question database on building attributes that affect IAQ. Full justification for each design decision is given in order to prompt designers to select building features that lead to low indoor concentrations of volatile organic compounds, gaseous pollutants, microbiological contaminants and respirable particulates. The DSS was developed for new office buildings in New Zealand conditions, with either natural or mechanical ventilation.

An exisiting methodology for the development of DSS was used. The problem was approached from the perspective of the building users under the broad headings of site and external factors, building envelope, building infrastructure, interiors, and heating ventilating and air-conditioning. Each of these topics was subdivided into finer layers of detail until conclusions on the potential impact of each building element on the IAQ could be inferred.

The hierarchy for decision-making placed highest priority on the elimination or reduction of pollutants at source. Opportunities for pollutants to enter from outside

or spread within the building were also controlled. If either of these strategies were not found acceptable, then mitigation techniques were recommended.

A panel of independent national and international experts validated the DSS for correctness and completeness. The reviewers reported that the system was very comprehensive, drew correct conclusions and would assist building designers without IAQ expertise, to design office buildings with good IAQ. The DSS was also considered to have a significant educational component for users.

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Appendix 9 Conference paper 2: Phipps R.A., Wall G.L., Laird I. (2001) Decision support for healthy office building design. International Council for Research and Innovation in Building and Construction, International Congress. Wellington, New Zealand, 2nd – 6th April 2001

LIST OF ABBREVIATIONS

AHU	Air handling unit
AI	Air intake
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
BRI	Building related illness
CAV	Constant air volume
CFD	Computation fluid dynamics
CIB	Council for Research and Innovation in Building and Construction
DSS	Decision support systems
EPA	Environmental Protection Agency
ES	Expert system
ETS	Environmental tobacco smoke
HEAD-Start	Healthy Environments – Alternative Designs
HEPA	High efficiency particulate air
HSE	Health and Safety in Employment Act
HVAC	Heating ventilating and air conditioning
IAQ	Indoor air quality
ISIAQ	International Society of Indoor Air Quality and Climate
MMMF	Man-made mineral fibre
NIOSH	National Institute of Occupational Safety and Health
PM	Particulate matter
PM_{10}	Particulate matter within the size range less than 10μm
$PM_{2.5}$	Particulate matter within the size range less than 2.5μm
$PM_{7.5}$	Particulate matter within the size range less than 7.5μm
RA	Return air stream
SA	Supply air stream
SBS	Sick building syndrome
SVOC	Semivolatile organic compounds
TLV	Threshold limit values
TVOC	Total volatile organic compounds
VAV	Variable air volume
VDT	Visual display terminals
VOC	Volatile organic compounds
VVOC	Very volatile organic compounds
WHO	World Health Organisation

1 INTRODUCTION

Office buildings are complex entities. A vast number of decisions need to be made and coordinated by the architectural and engineering practitioners during the design stage. The quality of the decisions made in this period can affect the quality of the indoor environment throughout the life of the building.

1.1 The Significance of Indoor Air Quality

Three international evaluations of the relative risks of environmental problems have identified poor indoor air quality (IAQ) among the five greatest risks to human health (United States Environmental Protection Agency, 1987; United States Environmental Protection Agency, 1990; Presidential and Congressional Commission, 1997). This is largely due to the duration of exposure to indoor air pollutants as citizens of developed countries spend, on average 90%, of their lives indoors. Also, indoor environments have frequently been found to have concentrations of Volatile Organic Compounds (VOCs), gaseous pollutants, microbiological contamination and respirable particulates at levels detrimental to human health (Maroni et al., 1995).

The World Health Organisation (WHO) estimated that 30% of new or retrofitted commercial office buildings cause health problems for their occupants (World Health Organisation, 1982). A comparable level of symptom reporting was also found in studies of New Zealand office buildings (Phipps et al., 1999; Cleaver et al., 2000).

Health problems associated with unhealthy indoor environments are classified either as Sick Building Syndrome or as Building Related Illness, depending on whether or not a specific causal agent can be identified.

Sick Building Syndrome is a diffuse range of symptoms for which no specific causal agent can be identified. The definition of Sick Building Syndrome symptoms differs between authors but the most widely accepted list is that developed by a working panel from the World Health Organisation (1984), which includes the symptoms of:

- Sensory irritation of the eyes, nose and throat; such as pain or a feeling of dryness, smarting, stinging, hoarseness or voice problems,
- Neurotoxin and general health problems; such as headache, mental fatigue, reduced memory, reduced capacity to concentrate, sluggishness, dizziness, intoxication, nausea or vomiting and tiredness,
- Skin irritations; such as pain, reddening, smarting or itching sensations or dry skin,
- Nonspecific hypersensitivity reactions; such as running nose or eyes, asthma-like symptoms among non-asthmatics or sounds from the respiratory system,
- Odour and taste sensations.

It is apparent that the occupants of some buildings suffer from a higher incidence of illness than is normal or acceptable. Although seldom life threatening, the symptoms of the SBS can be debilitating for those affected. Sick Building Syndrome (SBS) symptoms typically appear soon after a sensitised person arrives in the building, and diminish after departure (Raw, 1992).

The term Building Related Illness (BRI) is used to describe specific illnesses, symptoms or conditions for which the causal agents are characterised by clinical evidence, laboratory tests or identifiable exposure to pollutants. BRI includes hypersensitivity conditions, such as hypersensitivity pneumonitis, allergenic asthma, allergenic rhinitis, Pontiac fever and humidifier fever. By definition, it also covers symptoms arising from exposure to elevated levels within a specific building of toxins (carbon monoxide, formaldehyde, nitrates etc.) or irritants (fibreglass dermatitis).

While SBS and BRI are separate entities, there are many similarities between the building conditions that allow the casual agents of each to be propagated (Hodgson, 1992). Indoor Air Quality is a term that encompasses the indoor airbourne concentrations of the causal agents of SBS and BRI, and is more widely used.

Poor IAQ became an issue after the 1974 energy crisis, when energy efficient measures included cutting ventilation to 2l/s/person. This coincided with new construction techniques that reduced the leakage of air through the building envelope. The reduction in the supply of fresh air and infiltration limited the removal of contaminated air or pollutants generated within the building. SBS has not, however, disappeared following a subsequent increase to the ventilation rate to 10l/s/person and it is apparent that other factors are involved (Mendell, 1993).

Recent decades have seen concurrent increases in the use of building materials, furniture, finishes and office appliances that emit or host pollutants. Many reconstituted wood products, paints, carpets and adhesives release VOCs, such as formaldehyde, into the room air. Water leaks and spills, condensation and standing water all provide ripe opportunities for microbiological contaminants to propagate. Fine particulates generated within or outside the building are also incriminated as a cause of SBS (Godish, 1995).

Economic pressures, coupled with the flexibility of open plan layouts, can lead to an increase in the density of people, appliances and other sources of pollution, often exceeding the pollutant load that the building was designed to accommodate. Consequently, the total pollutant load increases, without modifications to the building's systems to counteract it.

There is no simple solution to this multi-faceted problem. Indeed, there are frequently few outward differences between a healthy and a sick office building (Mendell, 1993).

Poor IAQ and SBS can also be a burden to employers who contend with the reduced productivity of their employees, and who may face the risk of litigation for failure to detect or avoid problematic conditions.

Productivity is not easy to quantify, but there are many reports of poor, unhealthy office environments adversely affecting actual and perceived productivity (Holtom, 1990; Fisk & Rosenfeld, 1997). Except in extreme cases, SBS seldom leads people to take sick leave. However, they frequently leave work early or take longer breaks, which equate to an average of 14 minutes' lost time per day. In a typical office building, the salary bill for just one year substantially exceeds the purchase cost of the entire building (Nathanson, 1995a). Consequently, cost-cutting measures which impact on the health of the office environment are false economy. Increasing employee productivity by an average of five minutes per day will in one year pay for the costs of designing, constructing and maintaining an efficient and healthy workplace. Many organisations are reporting that productivity gains in excess of 20 minutes per day can be achieved by improving the IAQ and healthiness of the office environment (Fisk & Rosenfeld, 1997). As salaries and employee benefits are usually 100 times greater than total building operational costs, such as rent and energy, it is obvious that small improvements in employee productivity can lead to large gains (Fisk & Rosenfeld, 1997).

While poor IAQ in office environments affects the well-being and productivity of office personnel, the risk of litigation is further incentive to increase the healthiness of the office environment. In the United States, SBS and poor IAQ have been frequently found to constitute legal grounds to force building owners to upgrade their building, or allow lessees to prematurely break their lease. The United States has also seen several multimillion-dollar claims upheld against the employer for damages where employees have suffered loss or injury (Davis, 1997).

While the magnitude of SBS litigation in New Zealand is much smaller, there are several recent cases that should serve as notice. Two of these used Accident Rehabilitation and Compensation Insurance Act 1992 (ARCI) legislation and judgements in both cases found that the employees had become unwell as a result of their work environment and that compensation was payable. In Mallia vs. ARCIC (1996) it was found that elevated concentrations of formaldehyde emissions arising from alterations to part of the office, but remote from the employee's place of work, caused permanent voice loss. In Ray vs. ACC (1997) the judge found that unidentified problems in the office environment caused permanent nervous system problems for the claimant. The buildings occupied by Hagley Community College, Christchurch, the Nurse Maude Agency - also in Christchurch - and the Porirua City Council are a few of the other examples of New Zealand buildings which have been investigated for poor IAQ.

In New Zealand the health and safety of the workplace is governed by the Health and Safety in Employment (HSE) Act 1992. This Act places specific duties to provide a healthy and safe place of work on all employers and persons who are responsible for a place of work. This includes building owners, designers, contractors, and all other parties who contribute to the procurement and operation of the building. To date there have been no attempts to use the HSE Act for sick office environments, however a recently completed legal thesis has suggested that this legislation is an applicable action for cases of SBS (Miles, 1998).

1.2 Indoor Air Quality Standards

New Zealand Standard 4303:1990 Ventilation for Acceptable Indoor Air Quality (Standards Association of New Zealand, 1990) is reproduced from ASHRAE Standard 62-1989 Ventilation for Acceptable Indoor Air Quality (ASHRAE, 1989) with minor amendments to suit New Zealand conditions and legislation.

Both Standards have two procedures for ventilation design: the Ventilation Rate Procedure and the Air Quality Procedure. The Ventilation Rate Procedure attempts to achieve acceptable air quality by recommending ventilation with outdoor air specified quantity to the space, which, therefore, is "deemed to provide acceptable indoor air quality". For office buildings, the recommended rate is 10l/s/person in general areas, and 7l/s/person in reception areas. The Air Quality Procedure attempts to achieve good quality indoor air by controlling known and specific contaminants. The Air Quality procedure is based on air quality criteria, which are not part of the standard but are included in a "for information purposes only" appendix. Ventilation engineers can use whatever amount of outdoor air they deem necessary as long they can show that indoor concentrations of contaminants are held below recommended limits. Ventilation systems designed using the Air Quality procedure are expected to provide less than 10l/s/person unless there are known contaminants within the space (NZS 4303:1990).

ASHRAE Standard 62-1989 has been criticised by Seifert (1995) because it fails to answer two major questions:

- Is acceptable good enough?
- Is ventilation the best way to achieve good indoor air quality?

Standards are, by definition, a minimum standard rather than "best" or even "good" practice. They have a political dimension, in that their preparation is subject to pressure from various interest groups. The result is often a compromise between scientific knowledge and political will (Seifert, 1995). Political pressure is an important consideration in the regulation of air quality in office buildings, where the cost and benefits accrue to different parties. For example, the financial benefit of constructing a building with a relatively low cost building envelope that could leak is borne by the building developer or owner, while the cost of any resulting health problems is borne by the lessee, occupants and health care funders.

At a recent forum of building code writers, held at the Council for Research and Innovation in Building and Construction (CIB) Congress 2001, it was evident that the worldwide approach to performance-based codes was that solutions deemed to be "acceptable" are the minimum acceptable practice rather than desirable solutions (Duncan, 2001). One building regulation writer expressed the opinion that a building which precisely meets the requirements of the code could be regarded as the worst possible acceptable building (Beller et al., 2001). Further, as the process of preparing a standard and gaining industry consensus can be drawn out, the knowledge within a standard can lag behind the frontiers of science.

The high prevalence of SBS symptoms in buildings, which have been designed in accordance with building standards suggests that there are interactions and mechanisms that are outside the scope of the regulations. Mendell (1993), after a review of six large studies linking ventilation rates and health outcomes, concluded that ventilation rates below 10l/s/person were associated with increased risk of SBS symptoms, but higher rates of symptoms had also been found in buildings with ventilation rates in excess of 20l/s/person - that is, twice the recommended rate. The large inconsistency between buildings suggested that ventilation is not the only factor affecting the health of the indoor environment (Hanssen, 1993; Godish, 1995).

Further, many causes of unhealthy buildings still require more research (Mølhave, 1996). A keynote address by Seppänen (1996) on the function of ventilation standards for providing acceptable indoor air quality cited the incompleteness of the current knowledge on VOCs, microbials and some particulates as a hindrance to the formulation of satisfactory ventilation standards.

Seppänen (1996) presented a draft of a European pre-standard for dimensioning ventilation rates. This pre-standard suggests four procedures; the most conservative method uses pre-specified ventilations rates per person of 10, 7 and 4l/s/person depending on use category; the next method pre-specifies lower ventilation rates per floor area of 2.0, 1.4 and 0.8l/s m^2 assuming the building is constructed and furnished with low emitting materials. The third method is based on calculations of CO_2 concentrations, with permissible levels of 460, 660 and 1,190ppm respectively. The final method uses a rational distribution of airflow based on calculated pollutant loads using separate formulae to determine comfort and health pollutants concentrations. Variables factored into the equations include acceptable contaminant concentrations, ventilation efficiency, generation of pollutants, and contaminant concentrations at the air intakes.

The primary disadvantage of this latter method is the unavailability of data to complete the equations. Other significant limitations include the large quantity of resources required to calculate the pollutant loads, and requirements for specialist training and handling of interactions from factors where the knowledge is incomplete, such as cleanliness of the air handling system (Seppänen, 1996). It is anticipated that calculation of pollutant loads could be the preferred design procedure for greater precision in the use of ventilation systems once the knowledge of pollutant generation and building interactions is further advanced.

Design procedures that can address total pollutant load in buildings are required. Some eminent indoor air quality researchers (Berglund et al., 1992; Raw, 1992) have promoted the "total stress theory" which states that it is the body's response to the stress from an accumulation of indoor air factors as well as other work-related stressors that cause indirect physical stress responses. Mølhave (1990) suggested that headaches might occur as a secondary body mechanism in response to stress from the body's attempts to override the unwanted sensory information and to maintain protective reflexes. Berglund et al. (1992) were in general agreement with this theory. Consequently, a healthy building design needs to reduce the total concentration of all pollutants within the indoor environment.

1.3 The Need for Indoor Air Quality Design Assistance

While a vast body of literature has identified that exposure to pollutants within an office building can cause or aggravate ill health, several leading authors have identified the fact that this knowledge is not being integrated into common practice (Bascom, 1997; Turner, et al., 1999; Maroni & Seppänen, 2000).

The need to equip building designers with more knowledge on the creation of healthy indoor environments has been recognised as a high priority in the Indoor Air Quality research agenda developed by the US EPA (United States Environmental Protection Agency, 2000). The first two of the five goals listed in the agenda are the education of design professionals in IAQ issues, and development of processes and systems to support the "whole design" of healthy buildings. This document discusses the need for tools to assist building designers, who are not experts in IAQ, to design indoor environments that avoid ill effects.

A void exists between indoor air quality research and practitioners in a variety of disciplines who could utilise the information (El Daisty & Olson, 1993). A lack of accessibility to good scientific information on factors that affect the air quality of the office environment has been given as a reason for the low uptake by building designers (Levin & Hodgson, 1996).

Numerous prominent authors (Sundell, 1994; Bascom, 1997; Turner et al., 1999) have highlighted the poor knowledge transfer and uptake of IEQ research into the practices of building design and operation. Turner et al. (1999), in a plenary presentation at the International Healthy Buildings/IAQ conference in Washington DC, USA stated "We have enough knowledge to go beyond what is commonly undertaken in practice." Bascom (1997) reiterated this sentiment and stated that there is "poor fit between research and reality".

Further, with many other important design aspects, such as capital cost, aesthetics and energy efficiency, competing for the attention of the design team, few building design professionals give due consideration to IAQ and healthy design (Levin, 1991).

Despite a clear need, there are currently no healthy office building design tools that examine the whole building available.

Many design tools have been developed to support different aspects of the building's environmental design; analysis of the embedded energy, and computational fluid dynamic modeling for natural or mechanical ventilation strategies are two application topics. Environmental design tools range from simple systems that can be used by designers who are not experts in the particular application domain, to sophisticated packages which require specialist training in the use of the design tool and/or application domain.

A design tool to support the creation of office buildings with good IAQ has long been considered necessary to bridge the gap and facilitate information transfer between the research community and the designers. An approach that emphasises the inter-relationships of all components and factors of the building, including the larger environment and the occupants, has been suggested as the strategy for healthier buildings (Stockton et al., 1991).

Decision Support Systems were the type of design tool that was considered most suitable for this application (Mehandjiska-Stavrena, 1998).

1.4 The Nature of a Decision Support System

Decision Support Systems (DSS) have been defined by Moore & Chang (1983) as an *extensible system with intrinsic capability to support ad hoc data extraction, analysis, consolidation and reduction as well as decision modeling activities.* Education of non-expert users is also considered to be an important component of DSS as this supports future decision-making (Turban, 1992; Klein & Methlie, 1995). Moore and Chang (1983) considered the ad hoc nature to be an essential element of DSS which are to be used for planning and design problems, as these are largely unstructured activities, with procedures which can be difficult to pre-specify. The currency, accuracy and precision of the data incorporated into a DSS can be de-emphasised on the grounds that design and planning should be insensitive to minor discrepancies in data (Moore & Chang, 1983). Siegel (1986) recommended the use of DSS in applications, such as environmental design, where a non-rigorous solution approach can give acceptable answers without getting lost in detail. He recommended a qualitative simulation approach to determine solutions based on predefined constraints and the application of non-rigorous empirical knowledge.

A DSS does not attempt to model the exact, complete or deterministic behaviour of all components of the system, but enables the users of the system to make appropriate decisions from the data available (Siegel, 1986).

A DSS which provides quantitative support is more suited to the application of the design of healthy buildings than are other, more precise artificial intelligence structures, as there are still many gaps in the IAQ science - including a lack of knowledge of non-linear and synergistic interactions of the causes of IAQ problems.

For example, it is known that approximately 2000 different VOCs at low concentrations can be present in an office environment. The health risk of most, but not all, of these VOCs is known when they are considered individually, and these data are usually expressed as short- and medium-term exposure limits. However, there are very few data on the combined health effects of mixtures of VOCs and different experts have concluded that it is still not known if the health risks are simply additive, or have compounded effects. The concept of Total Volatile Organic Compounds (TVOCs), that is the sum of fifteen important indoor VOCs, is the method frequently used for evaluating mixtures of VOCs in non-industrial environments. It is accepted that this approach is far from accurate, and even the authors of the method advise cautious use and interpretation of TVOCs (Mølhave & Neilson, 1992). However, the TVOC approach is widely used, as it is the best method currently available (Mølhave, 1996).

Further examples of deficiencies in the precision of the current knowledge include the adsorption/reemission dynamics of VOCs in sink materials, the compounded health risks from VOCs and particulates, and the effect of non-steady state environmental conditions on the propagation of fungi or behavior of VOCs. The health risks for many respirable particulates and fungi are also unknown (Bienfait et al., 1992). These examples are indicative of the complexity of the interactions between IAQ factors and the need for solutions that are correct, without implying scientific precision. Consequently it is not considered possible to produce precise design rules (Seppänan, 1996).

1.5 DSS for Good IAQ in Office Environments

HEAD-Start (Healthy Environments - Alternative Designs) was the mnemonic given to the DSS which is the result of this thesis. It was developed to support designers of new office buildings, who are not experts in healthy building science or IAQ, to start considering the implications of their design decisions on the quality of the indoor air.

After extensive consultation with other developers of building design tools it was established that the work undertaken for this research should be focused on the development of the logic of a healthy IAQ office building design tool (Clark, 1993). It is, however, anticipated that the production of a software programme will follow as a natural consequence of this research, at a later stage.

HEAD-Start has been developed for New Zealand conditions. The New Zealand climate is temperate, with high rainfall, relative humidity and wind runs. Workplaces are free from tobacco smoking, and the geological structure is free from radon (Robertson et al., 1988). New Zealand Standard 4303:1990 Ventilation for Acceptable Indoor Air Quality is the governing indoor air quality standard.

The outdoor air is reasonably uncontaminated, compared to many metropolitan areas in other countries (Fischer, 2000). Auckland and Christchurch are the predominant exceptions, where the outdoor concentrations of the nitrogen dioxide, carbon monoxide and respirable particles have been shown to frequently exceed the limits established by the WHO. Generally, the effects of industrial emissions are decreasing, as “dirty fuels” are phased out and cleaner production processes are more commonly used, however some sites are still exposed to localised industrial pollution. The growing vehicle fleet is the predominant source of outdoor pollution. The three-month averages of benzene were often found to exceed the outdoor reference concentration of 12 mg/m^3 at sites along busy roads and traffic impacted areas of some New Zealand cities (Fischer, 2000). High concentrations of pollutants have been found trapped in climatic inversions, which is a problem particularly in Auckland and Christchurch.

The design of healthy office environments requires the integration of most building disciplines including architecture, mechanical engineering, interior design, cladding design and building physics, as well as many other related sciences such as microbiology, toxicology, epidemiology and materials science. This system focuses primarily on the architectural domain but incorporates other disciplines where appropriate. A multidisciplinary approach is necessary as the boundaries between domains are often blurred and ill defined and the interface between disciplines requires co-ordination. Case studies have identified many examples of poor co-ordination between disciplines, leading to poor indoor air quality. An example of this is rubbish compactors located adjacent to air intakes (Angell & Daisey, 1997).

HEAD-Start does not attempt to be the primary design tool for the design of the building services and should be used in conjunction with other engineering design packages for the modelling of airflows and component specification.

HEAD-Start is not intended to replace specialist skills, in-depth analysis of selected parameters or advanced modelling techniques. While techniques such as computational fluid dynamic analysis for modelling airflows are valuable for the examination of specific problems, they cannot holistically address the IAQ implications and interactions of all components and factors within the building.

Conversely, a design tool which addresses the implications of all building systems to the level of detail of a modelling package would require the resources of a large research team or effort equivalent to ten PhD theses (Clarke, 1993). This opinion was based on his experience with the development of computer-aided tools for the design of buildings with passive solar energy strategies. Following the advice of Professor Clarke, the scope of this thesis was limited to the development of the logic structure and content of a Healthy Office Building design tool, excluding software production.

In order to provide a workable context for the identification and mitigation of indoor pollutants it was necessary to place some boundaries around the problem domain. The system was limited to new constructions, with either natural, mechanical or hybrid ventilation systems. New Zealand office buildings are predominately low to medium scale with only two cities having buildings over twenty floors. All indications suggest that this trend will continue in the perceivable future (New Zealand Property Institute, 2001).

Remote discharges of pollutants into the outdoor air that could be communicated with the building are included in the system. However, it was necessary to exclude some risks which - although they may be manifested within a building - originated at a distance and are best mitigated at source. For example, the system does not attempt to control any effects from residues of pesticides on food that might be brought into the building, but considers pesticides that are used within the building or used near the building and could be walked indoors on footwear.

The system has been designed for the activities and building components typically found in office buildings. While similar circumstances arise within other types of buildings such as schools, homes, hospitals, hotels and museums, the risks and methods for reducing exposure to indoor pollutants vary with building type, use and occupant activity.

Childcare facilities were excluded from the system as childcare accommodation in New Zealand is seldom linked with office space. Children also have a higher toxic reaction to VOCs and microbiological contaminants due their body mass, metabolism and closer proximity to flooring materials (Angell & Daisey, 1997; Bascom, 1997). Therefore, IAQ design criteria for children require separate consideration and are not covered in this project.

Personal control, perceptions of comfort and other "softer" design issues that have an element of human psychology have not been included in this version of the system, but could be included in later developments.

The knowledge embedded in HEAD-Start could be applicable to the renovation of many existing buildings. However the inspection, remediation of existing conditions and integration with older style construction types should be considered case by case. Further, design criteria for the renovation of existing structures would increase the number of unknown variables, which would add complexity and could compromise the accuracy of the recommendations.

Other aspects outside the bounds of the domain are: -

- Financial, energy consumption, or durability implications.

- Lighting and acoustic environment.
- Thermal comfort.
- Emotional and psychological responses to personal control, colour, space and form.
- Electromagnetic fields, radiation and ionization.
- Ergonomics considerations.
- Environments suitable for people with hyper-sensitivitie and allergies.
- Building commissioning and management.

1.6 Research Aim

To develop a decision support system to assist building designers, who are not experts in IAQ, to make decisions that lead to the design of new office buildings suitable for New Zealand conditions, such that the new buildings provide indoor air quality that is healthy for the majority of the occupants.

In order to advance this aim, the following activities were undertaken:

- An extensive review of the current knowledge on the building elements and conditions that comprise a healthy IAQ,
- Development of a conceptual model which provides a IAQ solution approach that is common across all pollutant types,
- Development of criteria for the design of office buildings with good IAQ including;
    - Concentrations of gaseous contaminants, such as carbon dioxide, carbon monoxide, oxygen, ozone, nitrous oxides, and sulphurous oxides within acceptable standards in all occupied areas,
    - VOCs, such as formaldehyde, below appropriate standards or guidelines in all occupied areas,
    - Low concentrations of biological and microbiological contamination in and around the building,
    - Low concentrations of respirable particulate matter in all occupied areas,

    - A thermal environment that does not cause conditions detrimental to the four objectives above,
- Development of a text-based version of a DSS to assist building designers to select building features, materials and systems which lead to healthy IAQ in office environments,
- Development and incorporation in the DSS of an IAQ educational component within the system for long-term decision support for the users,
- Validation of the DSS for correctness and completeness.

1.7 Research Perspective

This research is undertaken from a Product Development perspective. Consequently, the research effort was predominantly invested in the development and content of the DSS. Architectural and mechanical engineering elements are incorporated into the development of the system where required.

1.8 Structure of the Thesis

The thesis is presented in two volumes. The first volume contains chapters on the aims of the research, literature reviews, methodology, results, discussion of results and conclusions. The literature review on IAQ issues, which is extensive by necessity is presented in chapter 2. Chapter 3 provides a review of issues on the design and validation of a DSS. The methodologies used for development and validation of the DSS are given in Chapter 4. The common solution approach, design criteria, and results of the validation exercise are presented in Chapter 5, and the impacts of these are discussed in Chapter 6. The conclusions of this research are given in the final chapter.

The second volume contains appended material, including the completed DSS (HEAD-Start), two peer-reviewed conference papers written on the conceptual framework of the system, instructions and report forms for the reviewers, and the names and affiliations of the experts interviewed in the knowledge acquisition phase of the research.

2 LITERATURE REVIEW – INDOOR AIR QUALITY

This chapter presents the key points from the literature reviewed on factors affecting indoor air quality and criteria for the design of healthy office environments.

Over 1000 research papers published in this field within the last 20 years were reviewed. Results from small studies with limited statistical power were disregarded. Where contradictory results were identified in the literature, all available views of the material were reviewed.

New Zealand research was included wherever it was available. Research on some ambient pollutants was found, but indoor air quality data were sparse.

2.1 Indoor Air Quality and Factors Affecting the Design of Healthy Office Buildings

The first section presented is a brief review of the impact of ventilation on IAQ. There were many hundreds of papers on this topic, and ventilation was frequently suggested as the primary solution to IAQ problems (Maroni, 1995).

The section on ventilation is followed by a review of the impact that contaminants have on the indoor environment, and how these contaminants are manifested in an office building. The contaminants that are typically found in unhealthy indoor air are VOCs and other gas phase pollutants, biological and microbiological contaminants and airborne particulate matter (Maroni et al., 1995). These factors are interrelated, and interactive (Raw, 1992). VOCs are gas phase pollutants, but due to their characteristics (source and emission patterns) they are discussed and treated separately from other gaseous pollutants. Many microbiological organism release both airborne particulates and VOCs, but for ease of comprehension they are also addressed separately. The thermal environment is reviewed within each pollutant section to the extent that temperature and humidity impact on the generation of each contaminant.

2.1.1 Ventilation

Mechanical ventilation has been implicated as a significant contributor to problematic conditions in several hundred field investigations (Woods, 1988; Robertson et al., 1989; Seitz, 1990; Turner & Binnie, 1990). These four reports present summaries of the results from hundreds of investigations, where deficiencies in the buildings' design and commissioning - as well as the operation and maintenance of the environmental services - were frequently found. Design problems include inadequate fresh air capacity, poorly located outdoor air inlets, poor distribution of supply air within and among spaces, and limited access for maintenance and cleaning of the system. Heating, ventilating and air-conditioning systems (HVAC) systems were found to be a source of contamination (Seitz, 1990; Turner & Binnie, 1990), and the reasons for this are discussed in more detail by each pollutant source.

Mechanical or natural ventilation systems are typically designed to deliver sufficient fresh or recirculated air to maintain a comfortable air temperature rather than to maintain indoor air quality. When the room temperature is close to the ideal temperature, it is tempting to conserve energy by reducing the fresh air or ventilation rate. In many instances, particularly with Variable Air Volume (VAV) systems, this may have the additional undesirable effect of reducing the flushing and dilution of indoor pollutants, and can cause an accumulation of contaminants (Roberts, 1991).

Maroni et al. (1995) and Liddament (2000) both consider that IAQ in office buildings can fall below acceptable standards where the ventilation system is being asked to perform functions beyond its primary role. The primary role of ventilation is the dilution and removal of pollutants that are unavoidably emitted into the indoor spaces. This principally includes the metabolic pollution generated by the occupants and pollution generated by the essential activities of the occupants. However, ventilation is frequently expected to remove gaseous and particulate pollutants that have been introduced into the indoor environment without sufficient regard for their impact on IAQ (Liddament, 2000).

The debate on whether buildings that are naturally ventilated are healthier than those that are mechanically ventilated has waged for many years in public and scientific fora (Tucker et al., 1992). A British study of 4373 people in 47 buildings showed that buildings with mechanical ventilation were among both the highest and the lowest ranking on a building sickness index (Burge et al., 1987; Wilson & Hedge, 1987). All the naturally ventilated buildings surveyed had an average, or above average, score, while the mechanically ventilated buildings presented both the healthiest and most unhealthy building sickness scores. From this and other similar studies, it was concluded that the problem is not just mechanical ventilation per se, but how the system is designed, commissioned and managed, as well the ventilation systems' interaction with other building factors (Raw, 1992).

Natural ventilation can be supplied to office buildings either intentionally via openable windows and doors, grills and louvres or ventilation chimneys, or unintentionally via leakage through the building envelope (Limb, 1993).

Maroni et al. (1995) identified some difficulties which exist in achieving acceptable IAQ with natural ventilation. They cited the potential for interstitial condensation to be caused during winter, where outgoing air deposits moisture in the building envelope. They also identified the fact that under natural ventilation strategies the flow of air is governed by the size and location of the openings, the wind and temperature forces and occupant activities – and, consequently, it is unpredictable and highly variable. As a result there will be periods of both over- and under-ventilation. The latter can lead to elevated indoor concentrations of pollutants. They also suggested that it would be difficult to ensure that outdoor air was adequately distributed to all areas of the building.

Natural ventilation systems, however, manage to avoid the sanitation problems that can occur with an HVAC system (Bearg, 1993), and can provide acceptable indoor air if the outdoor air is also low in contaminants (Limb, 1999)

It is also possible that the mechanical plant is providing adequate ventilation within the space, but that the air is either short-circuiting the occupants' breathing zone, or bypassing parts of the office space. The cause of this is often poorly designed or badly positioned diffusers, or imbalances in the air pressure relationships (Godish, 1995).

Short-circuiting can also occur with inappropriately positioned partitions or desk screens. Studies using Computational Fluid Dynamics (CFD) analysis and tracer gases have both shown that in open plan offices, screens should not exceed 1500mm in height, to allow for effective room air mixing (Menzies, 1993). Evidence is inconclusive whether a 100mm gap at the bottom of the partition also aids air circulation (Strobridge & Black, 1991).

During the energy crisis of the 1970s', the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) ventilation standard reduced the required level of fresh air supply to a minimal 2 l/s/person to eliminate body odours but conserve energy. Experience showed that this level was insufficient to maintain adequate IAQ, and it was subsequently increased to 10 l/s/person (ASHRAE, 1989). In a study of ventilation rates and the prevalence of SBS symptoms, Mendell (1993) observed that people in buildings with ventilation rates below 10 l/s/person had significant numbers of symptoms, while those in buildings above this level didnot. He concluded that a ventilation rate below 10 l/s/person was an SBS risk factor. Clean, clear indoor air is generally bad air diluted to a point where it is not a problem (Nathanson, 1995b), but it will not always resolve IAQ problems unless other control measures are also utilised.

Hedge et al. (1993) cited numerous authors who have shown that increasing the ventilation rate from 2 l/s/person to 10 l/s/person might have only marginal benefit for indoor air quality and thermal comfort. Hedge et al., concluded that:

> "poor indoor air quality is often the result of dynamic and multi-factorial processes, and attempting to resolve these only by increasing the ventilation often fails to eliminate complaints."

Mendell (1993) and Godish (1995) also reported this effect.

The effect of increasing ventilation rates above 10 l/s/person on symptom reporting has also been considered in many studies. However, the results have been conflicting (Hanssen, 1993).

The apparent contradiction between the findings noted above can be explained by Liddament's (1999) observation that ventilation is only one component in the IAQ equation. However, it is generally agreed that a high air exchange rate is required to dilute and displace the contaminants that accrue in occupied office accommodation.

Providing an adequate supply of "outdoor air" is not necessarily the same as "fresh clean air". Adequate indoor air is very difficult to achieve if the outdoor air has a high concentration of ambient pollutants (Limb, 1999) or if the ventilation system draws air from an area location with a high localised concentration of pollutants. The National Institute of Occupational Safety and Health (NIOSH) of the USA conducted many hundreds of IAQ investigations and reported that cases of re-entry or cross-contamination of pollutants from an adjacent building, or spaces within a building, occur in about 10% of cases (Seitz, 1990). These problems are considered easiest to resolve at the design stage (Godish, 1995).

2.2 Gas Phase Contaminants

2.2.1 Carbon Dioxide

Carbon dioxide (CO_2) is widely considered to be a reasonable measure of the concentration of bioeffluents, which are by-products of respiration, within the space. However, it is a very crude measure of ventilation efficiency, as sources of pollution - such as emissions from building materials - can be masked by reliance on measurements of CO_2 levels alone (Nathanson, 1995b). As a rough guideline, fresh outdoor air has an average CO_2 level of 350ppm, acceptable indoor air has up to 800ppm, and stale indoor air has over 1000ppm (Nathanson, 1995a). CO_2 in its own right is not considered to be toxic until about 3000ppm, however, at high rates it will displace the supply of oxygen (Nathanson, 1995b).

CO_2 levels can be considered as a rough measure of dilution of other contaminants only if there are no extraordinary or strong sources. Hodgson (1992) reported the results of field studies where the levels of CO_2 failed to show any significant correlation with levels of health symptoms. He concluded that ventilation rates alone in a building are not a good indicator of IAQ. Godish (1995) also reviewed numerous studies that have failed to identify a relationship between CO_2 levels and SBS symptoms.

A ventilation rate of 10 l/s/person should maintain a CO_2 level of 800ppm (Bearg, 1993). A recent trend in the ventilation control of some buildings is the moderation of the air supply system based on CO_2 sensors, which are set to deliver outdoor air at a rate sufficient to maintain the internal CO_2 concentration below a set point of either 800ppm or 1000ppm. However, linking the ventilation rate to the increase in indoor concentration over outdoor concentration can deliver an incorrect quantity of outdoor air given that the outdoor CO_2 concentration can range from 300 – 450ppm (Bearg, 1993). While this shortcoming is not as arbitrary as delivering outdoor air based solely on thermal comfort criteria, it still runs the risk of delivering an under-supply of outdoor air.

2.2.2 Carbon Monoxide

Carbon monoxide (CO) is one of many chemicals generated from combustion of fossil fuels. It is an odourless, colourless, tasteless and non-irritating, but lethal, poison (O'Reilly et al., 1998). The severity of health effects increases with the duration of exposure, concentration and activity level/breathing rate. Air drawn, or rising, from carparks and areas with idling vehicles has been shown to be a significant source of CO in office buildings (Bearg, 1993).

The New Zealand Workplace exposure limit is 25ppm for an 8 hour period, and the short-term ceiling limit set by NIOSH is 200ppm (Appleby, 1999). The ambient guidelines are regularly exceeded in some New Zealand cities, when high concentrations of traffic emissions coincide with certain weather conditions, such as climatic inversions or still weather preventing dispersion of the pollutants (Fischer, 2000b).

2.2.3 Nitrogen Dioxide

Nitrogen dioxide is mainly generated from combustion sources, including vehicles, burning of heating fuels and industry (Commission of the European Communities, 1989).

Vehicle emissions are by far the predominant source of nitrogen dioxide in New Zealand's urban areas. Ambient concentration peaks exceed the 100 $\mu g/m^3$ 24-hour guideline in Auckland's traffic-congested urban areas with increasing frequency, as traffic activity grows. Pollution in the urban air of Christchurch has also exceeded the guideline during cold winters, due to high emissions and strong climatic inversions (Fischer, 2000b).

Indoor concentrations of nitrogen dioxides typically arise from unvented or incorrectly vented gas combustion appliances, tobacco smoke and admittance of outdoor levels. European studies have measured indoor levels with an average concentration of 0.1ppm with peaks up to 2.1ppm (Commission of the European Communities, 1989). Emissions from combustion processes can be significantly reduced with cleaner technologies and appropriate design and maintenance (Molina et al., 1989).

2.2.4 Ozone

Few long-term data are available on the ambient concentrations of ozone in New Zealand. However, it is known that the ambient guidelines were frequently exceeded in the early 1980's, but such high ambient concentrations have not been repeated in recent years (Fischer, 2000a).

Ozone found in office buildings has typically originated in the outdoor air, however, photocopiers, laser printers, some air cleaners and UV lighting can be indoor sources (Godish, 1995). A few investigations have linked "wet" process type photocopiers with the generation of ozone within office environments (Taylor et al., 1984) although this has not been substantiated in other studies (Raw, 1992). As ozone is a very reactive compound, indoor concentrations vary with UV light levels, as well as the absolute concentrations and ratios of nitrogen oxides and VOCs (Maroni et al., 1995).

2.2.5 Sulphur Dioxide

Sulphur dioxide is emitted during combustion processes especially the burning of coal. Levels of ambient sulphur dioxide are seldom monitored in New Zealand, however, they have been found to be well within the guidelines when they have been measured (Fischer, 2000a). The risk of harm from sulphur dioxide levels in New Zealand office buildings is considered to be very low, unless there is a localised point source such as a coal-fired boiler.

2.2.6 Radon

Radon, along with its daughter products, is considered to constitute the third largest cause of lung cancer in the USA and also present health risks in many other countries. Overseas studies have reported indoor residential concentrations of ^{222}Rn up to 8000 Bq/m^3 (Nazeroff et al., 1988).

Radon is not considered to be present in New Zealand at concentrations of concern. A report on research conducted by the National Radiation Laboratory in New Zealand concluded that New Zealand has a geological structure that is free from radon (Robertson et al., 1988). Robertson et al., conducted a survey of radon in residential structures and found indoor residential concentrations of ^{222}Rn range from

31.2 to 59.6 Bq/m^3. The researchers reported that the natural gamma dose rate and peak radon concentrations were very low compared to those found in other countries.

2.2.7 Sewer Gases

Sewer gases are a mixture of odoriferous and toxic gases and may also contain bioaerosols. As they are usually lighter than air, they accumulate in traps and bends and can be admitted into a building if a trap or vent pipe fails (Bulleyment, 1999)

In infrequently used sewer or waste water lines, it is reasonably common for a water sealed trap, which is installed to prevent gases from the sewage line from flowing back into the building, to have failed (Bearg, 1993). This has been found to be a problem in the waste water traps installed below condensate trays, where the water seal can dry out during the heating season and directly admit sewer gases into the air supply (Seitz, 1990). This can be remedied by priming the trap with a trickle feed of clean water to replenish the water seal in the trap. A water-sealed trap fitted to a condensate tray within an air handling unit (AHU) can also fail if high air pressures within the AHU push the water over the bend in the seal, and deep traps are recommended (Bearg, 1993).

2.2.8 Summary of Control of Gaseous Pollutants

The majority of gaseous pollutants are generated outside of office buildings, with vehicle emissions in carparking areas, combustion processes and some office equipment being the exceptions. Emissions, from vehicle activity close to the building, are readily entrained into the indoor air, and their exclusion requires careful attention by designers. This includes avoidance of openings or well-ventilated buffer zones between vehicle areas and building openings. Emissions from heating sources such as boilers are best dealt with at source with cleaner processes and correct exhausting.

Most interior sources of gas phase contaminants can be controlled by reduction of emissions at the source, direct exhausting of emissions to the outside and improved general ventilation. The first option is considerably the most effective control measure (Molina et al., 1989). Exhausting of gases requires that sufficient replacement air from a clean, dry source is made available (Bearg, 1993).

2.3 Volatile Organic Compounds

Investigations show the ubiquitous presence of Volatile Organic Compounds (VOCs), Semi Volatile Organic Compounds (SVOCs) and Very Volatile Organic Compounds (VVOCs) in office air (Brown et al., 1994; Wolkoff, 1995). The term "VOCs" is frequently used in the literature to encompass many categories of volatility where distinction is not critical (Meckler, 1996). VOCs exist mainly in the gas phase at the temperatures and humidity encountered in indoor environments (Nielsen et al., 1997). Over 300 VOCs have been found in indoor air at concentrations greater than 1 ppb (Berglund et al., 1986). These include formaldehyde, benzene, xylene, styrene, phenols, acetone, toluene, trichlorethylene and 4- phenylcyclohexene (4-PC) (Wolkoff, 1995).

In non-industrial environments the number of different VOCs found in air samples can typically vary between 50 to 300 with many of these being difficult to measure and isolate from other VOCs at low concentrations (Knöppel & Wolkoff, 1992). Each individual compound seldom exceeds a concentration of 50 $\mu g/m^3$ which is 100 - 1000 times below occupational exposure limits (Hodgson et al., 1994).

Indoor concentrations are generally higher than outdoor (Wallace, 1991), but usually lower than threshold limit values (TLV) or irritation thresholds. They are frequently above odour detection levels (Bienfait et al., 1992). Therefore, in indoor environments exposure to single compounds, except for formaldehyde and acrolein, is usually considered "non-reactive", but additive or synergistic effects from multi-chemical exposure are considered very important (Wolkoff, 1995).

VOCs are widely considered to be casual agents of poor IAQ because of the following factors:

- Many are irritants and/or can cause central nervous system symptoms typical of SBS (Tucker, 1991b),
- They are found in stronger (typically x200) concentrations in indoor air than in outdoor air (Hodgson et al., 1994),
- As so many VOCs are simultaneously present they may react additively or synergistically to induce symptom responses. The cumulative health risk for combinations of VOCs found in indoor air is unknown (Mølhave, 1996),
- Commercial environments tend to expose the occupants to longer periods of more complex mixtures of chemicals than those which are found in industrial settings (Nathanson, 1995b),
- Exposure to VOCs can occur simultaneously with other risk factors, such as microbial contamination (Knöppel & Wolkoff, 1992),
- A high temporal exposure dose, such as after the laying of new carpet, can cause some previously healthy individuals to become sensitised, and they will subsequently experience symptoms at substantially lower doses. (Mølhave, 1996),
- Irritation effects, such as irritated mucous membranes, generally have steep dose–response relationships (Cometto-Muniz & Cain, 1992),
- Comfort and productivity issues within the office environment require stricter limits than those needed to protect health. (Nathanson, 1995b).

In office buildings, occupants are exposed to many chemicals simultaneously and serially; whereas industrial workplaces have a limited number of hazardous substances that are required to be controlled (Levin, 1990).

Levin (1989) conceded that there is insufficient knowledge of the health and irritation effects of VOCs at very low levels, and that there are difficulties in interpreting the effects of multiple simultaneous exposure to many low VOC concentrations makes selection of “good” materials very difficult for product specifiers.

2.3.1 Guidelines and Standards for VOCs

The chemical composition of the air in offices has been a concern only since the mid-seventies and has generally not been the subject of regulation (Seifert, 1992). Consequently, there are few specific guidelines for VOCs in office environments. The application of industrial standards, such as occupational health limits, to non-industrial indoor environments has been criticised as it under-represents the continuous exposure from typical indoor chemicals and the need to protect from irritations (Pierson et al., 1991). A pragmatic "indoor $\text{value}_{24\text{hr}}$" of 1/40 x occupational health value has been suggested (Nielsen et al., 1995) and generally adopted by the scientific community. Canadian Public Works (1993) have set 1/500 of the occupation health limit as a target for its buildings, with 1/100 as the action level for instigating further investigations. They have based this level on the rationale that occupational health limits were set to protect industrial personnel, where the office environment has more physically vulnerable occupants, including pregnant women, older personnel, and people with pre-existing heart or lung diseases.

A further difficulty with the occupational health limits is that as they are legally enforceable, and therefore must be based on solid evidence produced by medical research and documented exposures and effects. This has been possible only for five or six hundred VOCs. Consequently, the remaining 90% of VOCs are unregulated and notification on material data safety sheets is not required.

Research by Mølhave (1986) found a relationship between symptoms typical of SBS and an aggregate measure of VOC's. They proposed a measure, Total Volatile Organic Compounds (TVOC's), which consisted of a cocktail of 22 VOC's, excluding carcinogens, commonly found in non-industrial indoor environments. TVOC concentrations are typically found in office air in the low parts per million. Mølhave (1990) defined a dose response relationship between symptoms and exposure to TVOC mixtures (Table 2-1).

Table 2-1 Proposed dose response relationship between discomfort/health effects and exposure to TVOC mixtures

(Mølhave, 1990)

TVOC concentration (mg/m^3)	Response	Exposure range
<0.20	No effects	Comfort range
0.20 - 3.0	Irritation/discomfort possible	Multi-factorial exposure range
3.0 – 25.0	Irritation and discomfort; headache possible	Discomfort range
>25.0	Neurotoxic effects in addition to headache	Toxic range

These TVOC dose/response guidelines have been widely accepted by many IAQ practitioners and researchers as a convenient indicator of VOC concentrations in indoor air. The TVOC measure bypasses the difficulties with establishing the effect of an infinite number of combinations of VOCs which are currently beyond the realms of science (Tucker et al., 1992).

A pertinent complication has arisen with the application of TVOC guidelines, as other users have adopted differing definitions of compounds measured and used different analytical techniques, such as direct read flame ionisation or photo-ionisation detectors (Gammage et al., 1989).

It is acknowledged, however, that this measure has limitations. Following numerous studies in controlled chamber tests using varying mixtures of VOCs at varying exposures, Mølhave and Neilson (1992) have cautioned against the use of the TVOC concept as a generic indicator of building health risk. In further work, Mølhave (1996) subsequently failed to identify any consistent link between health effects and TVOCs levels. Mølhave concluded that TVOC is a crude measure as it does not differentiate the magnitude of toxicity or specific chemical properties of various

VOCs, nor does it distinguish the presence of particularly toxic compounds such as benzene. Mølhave stated that TVOC "cannot be used to assess the intensity or acceptability of (health) effects" but conceded that it is the best of the available methods for determining the probability of non-specific immediate and delayed sensory irritation. Further, in the absence of a better method, there is validity in the earlier findings by Mølhave and Neilson (1992) and that exposures below 0.2mg/m^3 TVOCs appear to be without importance for the air quality, and that exposures above 3.0mg/m^3 seem to cause some effect.

However, compliance with the guidelines noted above does not guarantee the exclusion of health effects, as guidelines by nature cannot represent the synergistic effects from exposure to multiple doses of individual VOCs or even TVOC in conjunction with other types of contaminants (Seifert, 1992).

2.3.2 Formaldehyde

The most common VOC in the office environment is formaldehyde (Berglund et al., 1992). Formaldehyde is ubiquitous in the indoor air, due to its prevalence in many construction products such as particleboards, adhesives, some types of insulation, paints, and in many office products, building maintenance products and tobacco smoke (Strobridge & Black, 1991; Jensen et al., 1995; Wolkoff, 1995). It is readily photo-oxidised in sunlight to form carbon dioxide and its half-life under the influence of sunlight is short (Knöppel et al., 1995).

Formaldehyde produces symptoms typical of SBS: stinging or burning of any exposed parts of the body (skin, eyes, respiratory tract), headaches, tiredness, neurological disturbances and nerve problems (Nathanson, 1995b). These symptoms can be produced at concentrations in the 0.05 - 0.50ppm range. The WHO threshold guideline (Table 2-2) and the California Air Resources Board recommend formaldehyde levels below 82ppb (100 μg/m^3) and 50ppb (62 μg/m^3) respectively. Building investigations have often found formaldehyde levels in excess of these guidelines (Spengler & Sexton, 1983).

Table 2-2 Formaldehyde exposure levels and symptoms

(WHO, 1990, in Nathanson, 1995b)

Health effects	Median (mg/m^3)	Range (mg/m^3)
Odour detection	0.1	0.6 – 1.2
Eye irritation	0.5	0.01 – 1.19
Throat irritation	0.6	0.1 – 3.1
Biting sensation in nose and throat	3.1	2.5 – 3.7
Tolerable for 30 minutes	5.6	5 – 6.2
Danger to life	37.5	37 – 60
Death	125	60 - 125

The formaldehyde levels in Table 2-2 are for healthy young males, whose symptom responses are considered to be lower than those of other sectors of a typical office population (Nathanson, 1995b).

In a controlled chamber experiment, Falk et al. (1993) found that significant swelling of the nasal membranes occurs for sensitive individuals after only two hours' exposure to formaldehyde at 60ppb ($73\mu g/m^3$). In the Office Illness Project of Northern Sweden, Sundell et al. (1993) observed that formaldehyde levels above 25ppb ($31\mu g/m^3$) were a significant indicator of skin and mucous membrane symptoms. They reported a significant relationship between the depletion of VOCs from the air intake to the room air and the prevalence of SBS symptoms. They observed also an increase in formaldehyde levels as TVOCs decreased, suggesting that formaldehyde was being generated from other lost VOCs.

Relatively low formaldehyde levels have been found in office and institutional buildings with a high incidence of SBS symptoms, often in the range of 10 - 40ppb (12 - $50\mu g/m^3$). Consequently, a working group of the Commission of European Communities (Molina, 1989) has suggested that formaldehyde in isolation may not be of consequence, but rather that it is a contributor by potentiation of other factors.

Mixtures of different VOCs at remarkably low levels are capable of acting synergistically to elicit neural behavioural responses (Mølhave & Neilson, 1992).

2.3.3 Benzene

A longitudinal New Zealand study found that urban concentrations of ambient benzene were comfortably low, except in areas with traffic congestion (Fischer, 2000a). As for other ambient gaseous compounds, it is possible for benzene to be entrained into the outdoor air drawn into a building if the air intakes are placed within the air strata containing traffic pollutants (Bearg, 1993; Limb, 1995; Limb, 1999).

2.3.4 Indoor Sources of VOCs

Building materials, office furniture and equipment and consumer and cleaning products are consistently cited in the literature as strong indoor sources of VOCs (Black et al., 1993; Nielsen et al., 1994). Field investigations (Seifert et al., 1989) have identified that building materials and human activities/consumer materials are significant sources of emissions of VOCs and contribute VOCs to the office environment at an approximate ratio of 1:1.

2.3.4.1 Emissions from Building Materials

Emissions from building materials can be classified as primary pollutant sources which include emissions of free VOCs, or secondary emissions which include pollutants formed by chemical or physical reactions, hydrolytic decomposition, oxidative degradation and reemission of adsorbed VOCs (sink effect) (Wolkoff, 1995). Many laboratory studies and field investigations have measured emissions from building materials and the results differ between studies depending on the type of chamber, analytical methodology and environmental conditions (Brown et al., 1994). However, while there are differences in the reported emission concentrations, types of VOCs and decay rates there is general consensus on which types of new materials are sources of VOCs (Reponen et al., 1991).

Most primary emissions occur from new construction and finishing materials within weeks to months of exposure to the air (Berglund et al., 1982; Wolkoff et al., 1991; Berglund et al., 1992; Rothwieler et al ., 1993; Brown et al., 1994) but can take over 12 months to decay to acceptable levels (Farant et al., 1992; Clausen, 1993). The decay of emissions varies considerably with material type and environmental conditions, however, emissions from new construction and finishing materials routinely dominate the primary emissions for the first twelve months of the life of a new building (Wolkoff, 1995).

The strength of the source is obtained by multiplying the area of the material with its emission rate. A material with a large surface area will have higher emissions than the same volume of the same product in a dense mass (Wolkoff, 1995).

Wet construction products such as paints, wall or floor material adhesive, sealants including silicone, wood stain, floor varnishes, water and solvent-based adhesives contribute significantly more to VOCs in buildings than do dry products (Mølhave, 1990; de Bortoli & Colombo, 1993; Brown et al., 1994). However, dry products including - vinyl, rubber, many types of textile flooring, particle and fibreboards, polyurethane foam, vinyl wallpaper, and plywood - have all been identified as sources of VOCs (Mølhave, 1990; Brown et al., 1994).

The major sources of formaldehyde in office buildings include furniture, counter tops, desk screens, room dividers and cabinets made from particle and fibreboard products (medium density particleboard, plywood, and hard board). Formaldehyde can also be released from acid cured finishes on wood and some paints (Godish, 1995).

Chang et al. (1997), who conducted a comparison of the effect of substrate on VOC emission from latex paint, found that emissions from paint applied over a stainless steel substrate were 90% complete within 2 weeks via primary phase emissions. However, the VOCs from the same paint applied over gypsum plasterboard were initially adsorbed into the substrate, but were subsequently released as secondary emissions for at least 11 months, and long-term experimental data suggest that this process could continue for 3.5 years. This study concluded that as most experimental investigations of emissions from adhesives and paints used stainless steel rather than porous materials, there could be widespread underestimation of the longevity of the emissions of VOCs.

2.3.4.2Occupant Activity

VOCs can arise from the activities of the occupants, such as photocopying, laser printing (Wolkoff, 1995), using carbonless copy paper (Godish, 1995), dry process photocopiers (Brown, 1999), correction fluid, storage and handling of printed materials and processed paper (Wolkoff & Nielsen, 1993) and personal care products and fragrances (Wallace, 1991; Wolkoff et al., 1992). Environmental tobacco smoke is a strong point source of numerous VOCs, including aldehydes (formaldehyde and acrolein), benzene, styrene, aliphatic-hydrocarbons, 3-vinylpyridine, 2- and 3-picolines (Walsh et al., 1984; Wallace, 1991; Berglund et al., 1992).

Emissions from occupant activities tend to dominate the VOC profile of office buildings after the emissions from the new construction materials have decayed (Wolkoff, 1995).

VOCs emitting from human activities are often point sources and are emitted close to the occupants. They also have large temporal fluctuations of the concentration patterns, which can temporarily increase the occupants' exposure and confound measurements (Rodes et al., 1991). In field investigations, VOC levels have been found to fluctuate on an hourly and daily basis and occupant activities are thought to contribute largely to these fluctuations (Wolkoff et al., 1991). Rodes et al. (1991) also found a concentration gradient of VOCs near the breathing zone, which could be associated with personal care products and occupant activities. It is possible that laser printers, photocopiers, and some other office equipment generate formaldehyde (Wolkoff et al., 1992). Rodes concluded that office equipment is often underestimated as a source of pollutants.

2.3.4.3Outdoor Sources

Although a lesser contributor to the concentration of indoor VOCs than indoor sources, VOCs which originate outdoors have been found to infiltrate buildings, depending on geographic location (Nagda et al., 1991; Daisey et al., 1994). Geographic factors include adjacent traffic patterns, neighbouring activities, soil characteristics or prior contamination of the site. Not surprisingly, these studies found that high ventilation rates led to high indoor concentrations of TVOCs when outdoor concentrations were high.

A prominent outdoor source is emissions from nearby passing traffic or idling vehicles. Their entry route is primarily via infiltration or incorrectly located air inlets, however, lift shafts (Weschler et al., 1990; Weschler et al., 1992; Limb, 1993; Daisey et al., 1994) and crawl spaces and service ducts (Wolkoff et al., 1991) have also been found to admit externally generated VOCs. Low internal vapour pressures can also drive VOCs from contaminated soil through leaks in the basement structure (Kliest et al., 1989).

Building investigations have revealed instances where the air supply inlets for a building are adjacent to the exhaust air grill or laboratory exhausts from either the same, or a neighbouring, building (Wolkoff, 1995) or adjacent to, or downwind of, leaking underground storage tanks or sewer gas vents (Godish, 1995). These would lead to re-entry of exhausted air and entrained VOCs.

2.3.5 Sink Effect

VOCs are adsorbed onto other surfaces, such as fleecy materials (Chang et al., 1997) and dust particles (Gebefugi, 1989; Wilkens et al., 1993; Hirvonen et al., 1994; Wolkoff & Wilkens, 1994) and these can be reemitted at later stages when the boundary air concentration is lower than the concentration within the material. This phenomenon is called the sink effect and prolongs the residence of VOCs in indoor air considerably longer than the time required for primary emissions, particularly of SVOCs, to decay (Berglund et al., 1992).

Two Danish and Finnish studies (Nielsen, 1987; Jaakkola et al., 1994) found a close correlation with the fleece factor (area of textile surfaces in a room/room volume) and shelf factor (area of open filled up shelving/room volume) with reported levels of SBS symptoms. They concluded that the interaction of VOCs with the adsorptive properties of textiles and open storage of paper is an important contributing factor to SBS.

In a typical office, VOCs emitted from occupants' activities will be adsorbed into fleecy and shelf surfaces during the working day. The sorption process is reversed at night when the equilibrium between sorbed and room air VOCs is reestablished (Jorgansen & Bjorseth, 1999). If the ventilation system is shut off at night, the reemitted VOCs will be concentrated in the room air to await the occupants the following morning. Nielsen (1988) found that VOCs were removed from the room if the ventilation system were operated overnight with the heating on.

Investigations of problem buildings have found that it takes a long time for formaldehyde concentrations to diminish after removal of the source material due to the re-releasing of sorbed compounds in other textiles and porous materials (Nielsen, 1988; Nielsen et al., 1997).

VOCs absorbed onto dust particles, which are subsequently either deposited on skin or inhaled, produce alternative exposure mechanisms which need to be considered (Wolkoff, 1995). Kirchherr et al. (1992) confirmed that water soluble VOCs, such as formaldehyde, were readily carried on the surface of dust particles. Several authors have suggested models to limit the sources of VOCs in buildings. Bayer and Black (1988) suggested criteria for selection of low VOC emitting materials such as solid wood and metal, while Tucker (1991) promoted specification of low emitting office materials by TVOC emission criteria.

Mølhave (1991) identified a 16-fold increase in VOC levels upon reactivation after an overnight shut down of an HVAC plant. He postulated that the increased level was generated from the dust layer in the ducting that had acted as a sink for VOCs. Godish (1995) found a similar result.

2.3.6 VOC Interactions and Dynamics

Temperature affects the vapour pressure and diffusion coefficients of the emitted VOCs and has a large impact on the rate of emissions of VOCs (Wolkoff, 1995). Large temperature rises frequently occur during the course of a typical day from solar radiation on surfaces, especially dark surfaces, and from heating sources.

The glue in urea formaldehyde resin boards can degrade and emit gas phase formaldehyde, especially under the influence of heat and moisture (Nielsen, 1988). The emissions of formaldehyde doubled for every 7°C rise in temperature within the range of 14-35°C, and they will also double if the relative humidity increases from 30% to 70% at 22°C.

Seifert et al. (1989) measured increases in certain VOCs emitted from latex-backed carpet at higher temperatures, but Sollinger et al. (1994) didnot observe increases in emissions at higher relative humidities. This latter result is expected, as it is difficult to generalise for other VOCs due to differences in volatility and polarity at elevated temperatures (Wolkoff, 1995).

Building characteristics, such as ventilation conditions and wind direction, contribute to the variability and temporal nature of VOC emissions, due both to the infiltration of outdoor pollutants and to the effectiveness of the removal of indoor pollutants (Mølhave, 1991). Wind is usually the major driving force of infiltration, so infiltration of many types of contaminants is a particular problem at windy sites or sites with localised air turbulence such as wind tunnels (Meier, 1994). Weschler et al. (1992) observed that indoor ozone levels fluctuated with the time of day and this may influence the types and strengths of indoor VOCs.

Many studies have found that TVOC levels increase as the air exchange rate is decreased (Nagda et al., 1991; Godish, 1995), however, the converse is not true if there are strong sources within the indoor spaces (Mølhave, 1991). Increased ventilation changes the vapour pressure around a source material, and this can cause emission rates of formaldehyde and many other VOCs to increase (Reponen et al., 1991; Tichenor & Guo, 1991). A six-fold increase in ventilation can cause a two-fold rise in formaldehyde emissions and it is presumed that the same phenomenon occurs for other gas-phase contaminants emitted by diffusion (Godish, 1995). Nielsen (1988) and Tucker (1991b) found short-term increases in formaldehyde emissions from particleboard and other pressed wood products, in response to increased ventilation rates. This effect was studied in more detail by Reponen et al. (1991), who concluded that high air exchange rates increased short-term emissions of formaldehyde, as the concentration of free formaldehyde in the particleboard decreased more rapidly, causing temporary increases in the indoor concentrations.

2.3.7 Source Control

Source control is undoubtedly the best way to achieve low indoor levels of VOCs (Seifert, 1992; Maroni et al., 1995; Bower, 1997). Several authors have suggested models to limit the sources of VOCs in buildings. Bayer and Black (1988) suggested criteria for selection of low VOC emitting materials such as solid wood and metal, while Tucker (1991) promoted specification of low emitting office materials by TVOC emission criteria. Care should be taken to avoid using construction materials that are likely to release quantities of VOCs (Levin, 1987; Tucker, 1990). Many studies have been conducted to measure the vapour-phase emissions of common building products (Mølhave, 1990; Mølhave, 1991; Tichenor & Guo, 1991; Wallace, 1991; Black et al., 1993; Jensen et al., 1995). Data from these and many other studies have led to initiatives for labelling schemes for the "safe emitting products"

The labelling scheme proposed by the US EPA (Tucker, 1990) is based on manufacturers' and suppliers' data and attempts to model indoor concentrations and occupant inhalation exposure. Tucker's proposed model aims to maintain TVOCs below 5 mg/m^3 with every source contributing less than 0.5 mg/m^3. However, in part due to political and economic objections from product manufacturers, this scheme has not been adopted as US EPA policy.

The government of the state of Washington, USA (Black et al., 1993) has embarked on a programme for healthier new and renovated state buildings, where manufacturers of materials, furnishings and finishes are required to provide emission profile data with their tender price. Designers and builders of the State's buildings are required to develop and implement an indoor source control plan for all materials, furnishings and finishes. Emission standards for key pollutants are required to be met as follows - formaldehyde (below 61μgm^3), TVOCs (0.5 mg/m^3), 4-PC (1ppb), and particles (50μg/m^3). In addition, all emissions of regulated pollutants and chemicals with specified threshold limit values must be below the regulated criteria. The programme requires these criteria to be met within 30 days of installation.

To minimise the sink effect, the Washington State Healthy Buildings programme allows only the least feasible amount of wet materials (paints, adhesives, sealants etc.) and prohibits the installation of adsorbent materials, such as carpets and furnishings, until all wet materials have been allowed to dry. All dry products must be air-out or preconditioned prior to installation.

The State of California, USA (Haywood & Wesoloski, 1993), proposed less stringent voluntary guidelines for reducing VOC emissions in new and renovated office buildings. Measures include:

- Selection of low VOC emitting materials,
- Isolation of construction zones in partially or fully occupied buildings,
- Scheduling of construction and furniture installation to minimise VOC elevation of VOC prior to occupancy,
- Delaying installation of adsorptive materials until after drying of wet materials and processes,
- Using low emitting housekeeping and maintenance materials,
- Building bake-out prior to occupancy.

The Danish Ministry of Housing (Wolkoff & Nielsen, 1993), has made advancements in protocols for assessing the IAQ impact of materials. Consideration is given to chemical emission over time, and modelling the health impact, with the principal objective being to determine the number of months necessary for a product to reach an acceptable concentration for mucous membrane irritation and odour detection.

Levin's VOC reduction approach focused on selecting the correct products, with modifications where necessary, special installation procedures to minimise VOC transference, and judicious operation of the ventilation system. Levin found that placing the responsibility for providing "clean" materials and data of emission on the product manufacturers was the most effective method (Levin, 1987; Levin, 1989; Levin, 1996; Levin & Hodgson, 1996).

Since hundreds of products are used in most construction projects, careful attention should be given when selecting materials with the greatest potential for causing harm, especially those with a large surface area, such as textile, floor coverings and treatments, insulation, ceiling systems, office workstations and workstation partitions (Levin, 1989; Levin, 1996). Using floor area as a reference, the relative surface area of floor coverings can represent a fraction to 200%; ceiling tiles that form the base of a return air plenum represent 200%; and workstation partitions can equate to 200-300%. Shelving can represent 5% – 100% (Etkin, 1992).

In addition to careful selection of materials, Levin (1996) recommended that temporary and special ventilation should provide large quantities of full fresh air via doors, operable windows, stairwells and emergency exits after installation of wet or VOC emitting processes or products. This will minimise the sink effect and help prevent a cycle of adsorption and re-release of VOCs. Levin also recommended that potential "sink" materials, such as the upholstered furniture, should not be installed in the office until VOC emmissions have diminished to acceptable levels. Other authors (Tucker, 1991a; Wolkoff, 1995), have also cited adequate flush-out periods and increased ventilation of new buildings prior to occupancy as important strategies for reduced exposure to short-term emissions of VOCs from construction materials.

Pre-installation conditioning of materials has been cited as a beneficial control technique. Prior to installation, components such as carpet should preferably be unrolled and aired off-site, and not wrapped in a plastic bag from the time of manufacture to allow free VOCs to be released outside of the new building (Public Works Canada, 1993; Levin, 1996). Levin recommended that construction materials be aired to allow VOC emissions to reduce to acceptable levels before the space is occupied. Liddament (2000) also advised that the return air ducts should be sealed during construction, to prevent airborne VOCs entering and being adsorbed in the ventilation system.

To aid the selection of appropriate control mechanisms, Wolkoff (1995), advocated the categorisation of the time patterns of emissions as continuous (regular or irregular) or discontinuous, and the spatial patterns as point source or distributed. This was based on earlier work undertaken by Otson and Fellin (1992), who characterised VOC emissions from building materials and occupant activities as temporal (either short- or long-term), and spatial (point or distributed). Levin (1992b) added to this model by distinguishing temporal emissions as either constant, periodic/occupational, or episodic. In particular, the model allows for the appropriate operation of the ventilation to coincide with the generation or presence of pollutants.

2.3.8 Source Isolation

It is well established that elimination is better than a cure. However, if pollution sources are unavoidable, then they should be isolated from the occupied areas (Bower, 1997). Levin (1990) recommended locating pollution-generating activities or equipment - such as printing, food preparation and photocopying - away from occupied spaces, and providing controls to the airflow to prevent cross-contamination.

Godish (1995) identified design considerations as a useful strategy to complement the selection of low VOC materials. These include site selection, architectural planning and ventilation control issues. Godish stressed that good IAQ design starts prior to site acquisition, with the selection of a site in a neighbourhood physically removed from ambient pollution problems. Further, architectural planning can reduce indoor concentrations of VOCs by physically isolating building openings - especially outdoor air intakes as well as unintentional infiltration points away - from vehicle parking areas, loading docks, pedestrian drop-off points or thoroughfares (Limb, 1995; Limb, 1999). Buffer zones between VOC sources and occupied areas were also identified as effective architectural control measures (Liddament, 2000).

Air flow isolation strategies include installation of local exhausts adjacent to point sources, and maintaining areas with pollutant sources at a negative pressure relative to the remainder of the building (Liddament, 2000). However, investigations have shown that the actual air pressure relationships within the building are frequently contrary to the designed intent due to the malfunctioning of fans, fans being turned off or idling, and the stack effect and therefore the use of fans to maintain air pressure relationships cannot be relied on as a means of protection (Bearg, 1993).

The stack effect is a natural phenomenon where the buoyancy of warmed indoor air causes the air to rise and escape through penetration in the upper parts of the building. When the outside air is colder than the interior, air exfiltrates at upper levels and replacement air is drawn in through penetrations in the lower levels. The reverse process can occur to a lesser extent in mechanically cooled buildings during summer. The stack effect is more pronounced with higher temperature differences between inside and outside and building height. It cannot be avoided, but can be modified by the building design (Wilson & Tamaru, 1968).

Air entering at lower levels can cause draughts, and entrain VOCs, particulate matter and other contaminates present in the vicinity of the building's openings. The flow of air can also draw pollutants from the lower levels of the building to the upper levels, which can increase the concentration of pollutants at the upper levels (Bearg, 1993). Airflows from the stack effect can overwhelm intended air pressure relationships.

Often changes in the air pressure balance of the building can allow contaminants to enter the building or be transported around the building from contaminated sources. These can be temporal events, such as infiltration through the building skin due to low night temperatures, or high wind pressures preventing the exhausts from expelling air (Liddament, 2000).

The air from vehicle zones should be isolated from circulation routes, such as lift shafts and stair wells, by a vestibule or air lock, or alternatively treated with positive air pressure to prevent spread of vehicle exhaust throughout the building (Limb, 1993).

In a lesser number of investigations, the air at the supply inlet has been contaminated from failure of flue gases to rise because of strong negative pressures in buildings (Godish, 1995). Mechanically ventilated buildings are usually maintained at a slight positive pressure; consequently infiltration is minimal when the fans are operating.

2.3.9 Removal of VOCs

The ventilation characteristics and adsorption/desorption characteristics of materials determine the removal of VOCs (Wolkoff, 1995).

Ventilation is not a panacea for strong VOC sources in the building (Liddament, 2000). It is possible to have a building with an excess of 20 l/s/person of outdoor air and still have air quality problems (Godish, 1995).

2.3.9.1 General Dilution Ventilation

General dilution ventilation is the most common, and frequently the only, contaminant removal measure employed in office buildings (Levin, 1991). The general ventilation theory states that under static or constant emissions of contaminants, a 50% decrease in the concentration can be achieved from doubling the ventilation rate. A further 25% reduction of the original value can be achieved by a further doubling of the air volume. The theory states that the converse should also be true.

However, it has been found that dilution ventilation is not as effective as the theory predicts (Godish, 1995). As discussed previously, emissions of VOCs vary in response to environmental conditions such as temperature, relative humidity and ventilation rates, and this confounds the applicability of dilution theory to the removal of VOCs (Godish, 1981).

Depending on the conditions, VOCs may continue to be emitted from building materials until the vapour pressure from solvents and other chemicals in the materials has reached equilibrium (Mølhave, 1995). This can take up to two years from the time of construction or when the materials are exposed to air (Chang et al., 1997). Notwithstanding inefficiencies with general dilution, ventilation rates should be held at high levels until the chemical concentrations have receded (Levin, 1996; Levin & Hodgson, 1996). If only one part of a building has been fitted with VOC-emitting materials, care needs to be taken to prevent air cross-contamination from this area to other parts of the building or other sink materials. Consideration should be given to ducting this area as an air-conditioning zone separate from the remainder of the building, including separate air handling unit and filters, until VOC concentrations have subsided (Bearg, 1993).

The effectiveness of ventilation for removing pollutants, including VOCs, is dependent on a number of factors. These include the:

- Difference in temperature between the supply air temperature and room air temperature,
- Type and positioning of the supply and exhaust terminals,
- Shape and volume of the space,
- Sources of heat within the space,
- Injection velocity of the supply air and,
- Location of objects within the space.

Displacement ventilation has been found to be the most effective ventilation strategy for removing contaminants compared to in- room mixing and other ventilation strategies (Skaret & Mathisen, 1982). They found that locating the supply air terminals just below the ceiling and the extracts just above the floor achieved the most effective ventilation during the heating cycle. The opposite locations of the supply and extract terminals were optimised during the cooling cycle.

Night time ventilation has been proved effective in certain circumstances for reducing indoor air pollution without increasing building operational costs (Dix, 2000). The building can be flushed with very high volumes of full fresh air during the night to dilute the pollutants that have accumulated from occupant activities and building materials emissions during the day. This has the added advantages of utilising cooler, less humid and cleaner night air, and off-peak energy rates (Bearg, 1993).

2.3.9.2Building Bake Out

Building bake out has been suggested to accelerate the emission of VOCs. Building bake out is the practice of raising the indoor air temperature of a newly completed building for several weeks prior to occupation. This is very energy intensive, and the high temperatures can cause damage to the HVAC plant and some building materials. Experience has also shown that bake out simply tends to drive VOCs from one material to another, rather than permanently eliminating them from the building (Levin, 1992a). Levin found that although VOC levels were initially significantly reduced, they rose again when the vapour pressure of the VOC in the sink material altered. Controlling contaminants by bake out is no longer considered to be an effective remedy for removing the emissions from high VOC materials (Rothwieler et al., 1993; Cutter Corp, 1993).

2.3.9.3Air Cleaners

Air cleaners can be used to reduce VOCs from the ventilation air stream. Activated charcoal filters are the most commonly used and can be installed in the HVAC system along with the dust filters, or in-room units in the office space. Charcoal filters can be designed to remove most VOCs or specific chemicals. Filter specification is a problem as there are no standard methods for testing and ranking chemical filter performance (Kinkead, 1990). The weight of the charcoal or carbon filter gives a very rough assessment of the capacity for the filter to absorb VOCs. The maximum absorbency is approximately 20%, that is, 100g of charcoal can remove only 20g of VOCs from the air. There are currently no standard approval methods for testing the performance or replacement requirements of activated charcoal air cleaners (Nathanson, 1995b)

Some species of plants are able to absorb quantities of VOCs from the air and lock them into their root structure (Woods et al., 1997). However, to rely entirely on plants for air cleaning would require a large quantity of plants (Raw, 1992). Depending on the maintenance regime, living plants may also be a source of contamination either through the application of pesticides or by microbial propagation in wet soil and surrounding materials caused by incorrect watering (Burge, 1990).

2.3.10 Summary of Control of VOCs

Most VOCs found in office environments originate indoors from new construction and furnishing materials, and occupant activities. VOCs from construction and furnishing materials typically have high emission rates for the first month after they are exposed to air, and can continue at a decreasing rate for several years. The selection of materials that have low emissions of VOCs is undoubtedly the most reliable method of ensuring low concentrations of VOCs in the indoor air.

Outdoor sources generally make a lesser contribution and are typically associated with vehicle activity. Selection of a site and location of openings away from major concentrations of vehicle activity are effective and passive means to reduce the contribution of VOCs from outdoor sources.

If the emissions from VOCs cannot be excluded from construction materials then other mitigation strategies to reduce the occupants' exposure to these pollutants need to be addressed. The ranked order of effectiveness of these strategies starts with isolating the occupants from the material or emissions, through to removing the VOCs from the air. Preconditioning of materials prior to installation has been recognised as an effective method to isolate the peak emissions from construction and furnishing materials. Breaking the "sink" cycle is also an important component of removing VOCs from the indoor air.

Grouping together occupant activities which are VOC emitters and maintaining physical isolation and/or negative air pressure can help to isolate strong sources of VOCs.

The greatest attention should be paid to materials and processes that are closest to the occupants' breathing zone and/or have the largest surface area from which to emit VOCs. The health effects of the specific VOCs emitted are also very important, and compounds that are carcinogens, toxic or sensory irritants should be avoided.

Air cleaners can assist the removal of VOCs, but a lack of performance standards and precise details of how much of the room air is actually drawn through the air cleaner limits their effectiveness.

2.4 Biological Contaminants

Microbiological contaminants found in indoor environments include viruses, bacteria and fungi spores and their products (bioaerosols). Bioaerosols of concern to the healthiness of the indoor environment include mycotoxins and endotoxins, fungal fragments and spores, macromolecular dust (MOD) and other metabolites (Burge, 1995).

Contamination from biological sources has been shown to cause epidemics of BRI, such as humidifier fever, hypersensitivity pneumonitis, Legionnaires' disease and asthma, which can be confirmed with a clinical diagnosis. Humidifier fever and hypersensitivity pneumonitis are flu-like conditions that can be traced back to heavily contaminated HVAC systems and other wetted building materials. Humidifier fever can be caused by exposure to bacterial endotoxins or non-pathogenic amoebae from cold mist humidifiers. Hypersensitivity pneumonitis is thought to be caused by a variety of mould species, including thermophilic actinomycetes (Godish, 1995).

2.4.1 Fungi

Counts of fungal spores are frequently elevated in office air. As such, moulds and their antigens represent a major source of air contamination and potential human inhalation exposure. The health effects from fungi are of great consequence to IAQ. Fungi can produce toxic products and evoke symptom response through a number of physiological mechanisms (Samson et al., 1994).

Typically 6% - 15% of the population become sensitised to the antigens from the sporesof fungi and develop allergic-type reactions (Miller, 1992). The likelihood of developing an allergy to fungi is related to the time and quantity of exposure. Allergy reactions - such as sore throats, coughs, bronchitis and wheezing - frequently affect the respiratory system, and can also cause eye and skin irritation, ear infections and headache. Once a person has sensitised they can react at relatively low exposure even across different species of moulds.

Fungi species typically found in office buildings include *aspergillus, penicillium, alternaria* and *cladosporium*. The *Aspergillus* genus of *A. fumigatus, A. terrus* and *A. flavos* can cause a condition known as aspergillosis. Aspergillosis is an invasive lung disease that is particularly difficult to treat. Personal characteristics and certain kinds of medication influence susceptibility to this pathogen.

2.4.1.1Conditions For Fungal Growth

Spore counts in non-contaminated buildings can vary between 0 - $10^4/m^3$ per species (Miller, 1992). Fungal spore counts in buildings with natural ventilation often emulate the spore count in outdoor air. Fully air conditioned buildings, with well maintained systems can have viable mould counts that are lower than outdoor levels. However, there are many sites for amplification of fungi within buildings, especially the HVAC system (Burge, 1990).

Any combination of moisture (including high relative humidity) and organic dust can provide an ideal site for fungi propagation. Humidity greater than 70% is optimum for fungi growth; however, most species can tolerate lower water availability if temperatures are warm (Miller, 1992). There can be sufficient water present in a substrate to support microbial growth even if the moisture is not visible or the relative humidity is low (Pasanen et al., 1991). Fungi can grow at very low ambient relative humidity levels if there is moisture available within the host material. Therefore, sites with repeated or persistent condensation and leaks should be considered as being at risk of fungi colonisation (Pasanen et al., 1991).

Nutrients are not a limiting factor in office buildings, as there is always sufficient organic material to supply the nutrient requirements of fungi, except in sterilised special use environments (Nathanson, 1995c).

The optimum temperature for fungi propagation is 20-30 C°, however, some species can survive in a broader range of 10-40 C°. These thermal conditions are obviously prevalent in office buildings. Pasanen et al. (1991) found that temperature was not a limiting factor on the growth of fungi on building materials as they could grow at temperatures below 10 C°.

Michel et al. (1991) and Douwes et al. (1998) studied β(1-3) – glucan levels in house dust and found no correlation with either room temperature or relative humidity. They both concluded that environmental parameters measured in the centre of a room are poor indicators of the condensation potential on poorly insulated materials. They surmised that the temperature of a surface, and hence its condensation potential, is a more critical factor.

The nutrient supply, water replenishment, temperature, and the presence of other organisms influence the growth of fungi and moulds in liquids, such as those found in humidifiers and condensate trays. Unless limited by the application of biocides, bacteria and yeasts have a faster growth rate than fungi, and will scavenge nutrients from the liquid medium. This will inhibit fungal growth, unless large amounts of complex organic matter are also present (Miller, 1992).

Many species of fungi are capable of producing very large quantities of spores in a short period. Most fungal spores are in the 2 - 100 micron range. They are readily airborne, making them cause significant reactions in the mucous membranes and respiratory system. Their wide variations in size and shape will cause a wide range in the length of time they will remain airborne following disturbance. Spores of *Aspergillus* and *Penicillium* can remain viable for more than twelve years in typical office conditions (Miller, 1992). Consequently there are always viable spores present in an office building, which can amplify when conditions, namely sufficient moisture, are present (Nathanson, 1995c)

Some moulds have the physiological properties to grow on almost any organic material, provided there is sufficient water. This can include glass, petroleum products, paint, rubber, textiles and electrical equipment (Miller, 1992). The presence of viable microbial spores on building substrates is normal and inevitable (Burge, 1990).

2.4.2 Sources of Fungi and Dissemination

2.4.2.1 Outdoor Sources of Fungi

Most fungi produce spores that are designed to become airborne and transported on air currents. Consequently the outdoor air has an abundant source of fungal spores and outdoor air is the primary source of all microbial growth (Lavoie & Comtios, 1993). The types and concentrations vary with seasonal, diurnal and geographic factors (Burge, 1990). These spores can freely penetrate through the building envelope through open windows and doors, and mechanical air intakes: they can also infiltrate through small penetrations as well as being carried in on clothing and footwear.

Outdoor levels are highest near ground level, where dense vegetation or piles of leaf litter are close to the building (Kozak et al., 1978). Air intakes and openings in the building envelope near these sources represent an increased risk of contamination within the building (Limb, 1995). Lakes, streams and wetlands in the immediate vicinity have not been found to be a risk factor for microbial contamination. However, birds roosting in areas close to any penetration of the building envelope, especially air intakes, has been found to be a focus for fungi and other allergenic matter (Burge, 1990). Commercial composting sites that are frequently disturbed should also be considered potential bioaerosol sources.

2.4.2.2 Indoor Sources of Fungi

No interior environment is completely free of fungal spores, and indoor concentrations tend to emulate outdoor levels, especially in non-airconditioned buildings (Burge, 1990). Air-conditioned buildings that have good filtration, well maintained HVAC systems and no indoor sources of fungal contamination, tend to have substantially lower levels of fungi than are present outdoors (Liddament, 2000).

Fungi can proliferate almost anywhere in and around the office environment where there is a source of moisture and nutrients. Frequently colonised sites include condensate trays, filters, porous acoustic insulation, potted plants or any building materials that have been affected by recent rain leaks, flooding or condensation. Areas where there is the potential for dampness, such as basements, kitchens and bathrooms or condensation-prone areas should be regarded as a potentially strong source of bioaerosol (Burge, 1990).

The building dynamics which contribute to the formation of condensation are varied. Areas of the building envelope with thermal bridging, where warm air comes into contact with an uninsulated area of the building envelope, are common sites for fungi to colonise (Morey, 1996).

The stack effect also indirectly contributes to condensation during periods of cool weather. When warm indoor air exfiltrates through the construction at the upper levels, interstitial condensation can occur as the water vapour contained in the air cools below the dew point within the wall cavity. The extent of the condensation depends on the quantity and initial moisture of the airflow, and the temperature gradient within the construction. Condensation from exfiltrating air increases with building height, indoor air humidity and cooler winter temperatures (Wilson & Tamaru, 1968).

2.4.2.3Mechanical Services

Ventilation systems are often reservoirs or amplification sites for microbial growths (Morey, 1988). Sufficient moisture and nutrients are typically present within many sites of the HVAC system. All sites where moisture, condensate or dampness could occur should be either eliminated or very carefully controlled.

Sites were water could sit, such as condensate trays, should have their bottom surfaces sloped towards a drain to prevent water ponding. Ample depth to the tray, or a secondary overflow tray to prevent inadvertent flooding, is advisable. Condensate trays should be drained into the building's waste water drains and the water seal trap may require priming with water to prevent stagnation or drying out during periods of infrequent use of the cooling system (Bearg, 1993).

The potential for inter-duct condensation is greatest within the first three metres beyond the cooling deck where the air is close to saturation point, and around obstructions including bends (Pejtersen, 1997). Cooling coils should be designed for zero droplet carry over and insulation in the ductwork within three metres of the chilling plant should always be avoided (Pasanen et al., 1993). Inter-duct condensation can also occur when air within the duct cools below the dew point, where the duct is uninsulated or passes through a cold area.

Condensation can be caused within the ventilation system by procedures such as the typical energy saving measure of shutting off the ventilation system at night (Pasanen et al., 1993). Vapour that is contained in the ventilation system at the time of shut off, or that re-enters the duct from the rooms, can condense and wet the internal surfaces (Morey, 1996).

The rough surfaces of internally lined acoustic duct liner can harbour particulate matter which has not been arrested by the air filters, or has infiltrated from leaks downstream of the filters (Reinhardt, 1991). Dust in the duct will increase the moisture holding capacity of the duct liner, as well as providing a nutrient source (West & Hansen, 1989). If the internal surfaces of the ventilation systems are also loaded with microbial spores then a ripe host environment for propagation of fungi is created (Morey, 1988; Gyntelberg et al., 1994). As fungal spore germination can occur within five hours of condensation forming, then there can be sufficient time during an overnight shut-down of the ventilation system for spore germination and amplification (Pasanen et al., 1993).

Once a microbial source reservoir has been established, dissemination of microbial material throughout the building can readily occur. The rush of air upon restarting the ventilation system is particularly effective at liberating microbial matter (Foarde et al., 1996). Air velocity of 5-6m/s in a duct has been found sufficient to liberate *Penicillium* and *Aspergillus* spores (Pasanen, 1996). Subsequent drying of the contaminated duct, which is inevitable when warm air is pushed through it, appears to promote the release of spores into the airstream (Samson et al., 1994).

2.4.2.4MVOCs and Metabolites

As fungi metabolise they can produce carbon dioxide, VOCs and SVOCs, such as alcohols, aldehydes, aromatic hydrocarbons and carboxylic acids. Over 500 microbially produced VOCs (MVOCs) have been identified, with ethanol as the dominant compound produced by moulds (Wilkens et al., 1993). Many MVOCs are highly toxic (Wessen et al., 1994; Morey., 1996). MVOCs are mainly produced from a few species and are commonly identified by a “mouldy” or musty smell (Miller, 1992). Samson (1985) and (Miller et al. 1988) have identified MVOCs as a potential health risk, especially in causing acute respiratory symptoms. Little data are available on the health risks of long-term exposure (Health and Welfare Canada, 1987).

In a study of water-based paints, Norbäck et al. (1995) found concentrations of MVOC in 5 out of 20 applications, and concluded that water based paints can represent a source of hidden microbial activity. The highest concentrations were found in an ecologically friendly paint that was claimed to be free of VOCs, biocides and chemical additives.

Some fungi, such as certain species of *aspergillus* and *penicillium,* will produce mycotoxins and antibiotics as secondary metabolites. Mycotoxins are concentrated in the fungal spores and have been found at concentrations up to 200 000ppb. It is well established that mycotoxins cause illness including indigestion and intoxication in humans (Wessen et al., 1994; Morey, 1996). Some mycotoxins are very potent carcinogens, and have been linked with cancer of the liver (Seneviratne, 1996). Mycotoxins have a very high molecular weight and consequently are not volatile. They are likely to become airborne only in a particulate phase, suggesting that human exposure is most likely to occur through inhalation of contaminated dust, spores and fungal fragments. Nasal congestion is a likely symptom of exposure to airborne mycotoxins (Samson, 1985).

Fungal irritation can also be caused by (1-3) - β - glucan, which is a constituent of the fungal cell wall. Nasal congestion, skin redness, and headache can be caused by (1-3) - β - glucan, at exposure levels akin to that found in an office environment (Rylander, 1993).

In addition to toxins per se, fungi can produce a mixture of compounds, such as ethanol, which can act as synergyisers. Although these compounds may be benign in their own right, they can greatly increase the potency of other toxins (Wicklow, 1989, in Miller, 1992).

2.4.3 Bacteria and Viruses

Although bacteria can cause extremely severe acute symptoms, they have been cited as a problem of lesser prevalence than fungi for two reasons. Firstly, while fungi proliferate in damp conditions, bacteria require full water immersion to reproduce; and bacteria do not produce the huge quantities of spores that are needed for the fungal growth cycle. Exposure to bacteria is usually via inhalation of aerosols of infected water or person-to-person communication. Inhalation of dust-borne bacteria is an infrequent transmission mechanism (Health and Welfare Canada, 1987).

Many authors have reported the significance of airborne transmission of diseases such as influenza, some common colds, measles, chickenpox and tuberculosis (Burge, 1995; Morey, 1996). Tuberculosis is becoming a major health concern due to the rise in drug resistant strains (Hoak, 2000).

Legionella is a bacterium which is propagated in warm water rich in organic matter. This can be dispersed through a building's air-conditioning system, and will produce flu-like symptoms and pneumonia in a human host. Symptoms can range from mild to fatal. Humidifier Fever, which is related to *legionella* bacteria, but is less severe, is caused by an allergic response to airborne bacterial allergens or endotoxins of many Gram-negative bacteria.

Several investigations (Rylander, 1993) have been conducted, which compare both the viable and total bacterial counts in healthy and "sick" office buildings, schools and daycare centres. These studies showed few conclusive trends, apart from high levels of *actinomycetes* in many problem buildings. *Actinomycetes* are similar to fungi in their growth patterns and structure, and are commonly found in the soil. Rylander measured *actinomycetes* in 70% of problem buildings at levels ranging from 2 - 240 CFU/m^3. However, a*ctinomycetes* were observed in only a few healthy buildings.

2.4.3.1 Sources and Disseminators

Bacteria are present in buildings, typically at rates comparable to outdoor air except where there is a site for amplification and communication. Often this is a waterborne site, such as condensate trays and cooling towers (Burge, 1987).

Humans are a primary source and disseminators of bacteria. Dissemination can occur through coughing, sneezing and talking (Houk, 1980). Depending on the relative humidity, temperature and droplet size, airborne bacteria droplet nuclei can remain suspended as aerosols for considerable periods of time. Whilst suspended, they can spread throughout a room, and even between rooms although their concentration is diluted with increased distances from the source (Burge, 1995). Bacteria transmitted from this biological mechanism are typically Gram-positive bacteria, such as *staphylococcus, micrococcus and streptococcus*. Research findings are currently inconclusive as to whether or not aerosol bacteria can be transmitted via air-conditioning systems (Hoak, 2000).

Indoor concentrations of viruses and many bacteria are intrinsically linked to human occupant density and skin shedding rates. The risk of indoor disease transmission is low unless either the ventilation is poor or an extremely contagious pathogen is present (Burge, 1990).

Viruses have been observed to persist for up to eight weeks on non-porous surfaces depending on the relative humidity, temperature and the wavelength and intensity of light, and longer on porous mediums (Mbithi et al., 1991).

Resilient flooring can be a reservoir for microorganisms that are subsequently readily released into the air. Carpeting appears to trap organism more firmly, but it provides more favourable conditions for survival. It is also more difficult to clean effectively, and the cleaning process can reaerosolise the organisms (Cox, 1987). Organisms that remain viable present a risk of secondary exposure if shaking, vibration or vacuuming disturbs the substrate. Direct contact transmission (hand to mouth) also occurs if a person touches a contaminated surface (Burge, 1990).

Water is a frequent and well-documented source of infectious microorganisms. The exposure mechanism is either through digestion, hand-to-mouth contact or inhalation of aerosolised water droplets containing viable matter (Burge, 1995).

Air intakes adjacent to, or downwind of, cooling tower mists from either the same or a neighbouring building are always considered a risk factor (Morey et al., 1990). Cooling tower water that is not properly treated can create an ideal environment for bacteria to amplify, after which theyr are readily disseminated (ISIAQ, 1996). They can be entrained into the building if there are openings nearby. The biocides used to treat the water can also be a source of contamination if the mist is entrained in the airstream (Nathanson, 1995c).

2.4.4 Mammalian, Avian and Insect Allergens

Dander (mainly feline and canine) has been found in many office buildings even when the host animal is not present, as it can be carried into the office on clothes and personal effects. It can cause irritation of the skin, eyes, respiratory tract and mucous membranes of sensitive individuals (Luczynska, 1995). Cat allergen (*Fel d* I) is carried on extremely small particles and is readily carried between environments on clothing and resuspended. Dog allergen (*Can f* I) is thought to be carried on larger particles and be less readily airborne (Luczynska, 1995).

Rodents and birds and their faecal deposits are common biological pollutants in office buildings. Bird droppings can harbour some exceptionally pathogenic fungi (Bearg, 1993) and all roosting opportunities should be eliminated, especially near air intakes (Nathanson, 1995c).

Cockroaches can survive wherever there is sufficient moisture. They can rapidly move throughout a building seeking moisture and favourable habitats (Squaillace, 1995). Investigators suspect that cast skins, whole bodies, eggshells, faecal particles, and saliva are all potent sources of allergens (Lehrer et al., 1991). Cockroaches secrete their allergens on their bodies and adjacent surfaces. Cockroach allergen can become airborne with little disturbance (Squaillace, 1995). Cockroach populations can be reduced with the application of pesticides, however, reinfestation is common and allergenic material and excreta may remain in the indoor environment for long periods.

An extensive review of the literature on the effects of insects found that large proteins from biological organisms caused occupational asthma (The Commonwealth of Massachusetts, 1988). In particular, insects and insect parts were found to be a potent allergen causing acute and sometimes severe respiratory and other discomfort, with long-term exposure leading to chronic conditions.

Dustmites are not generally as prolific in office environments as they are in homes (Cunningham, 1996). A few instances of house dust mites in some UK office buildings have been reported, but this is an unusual finding (Raw, 1993). Dustmites, or rather their faeces, are highly allergenic and can cause asthma and other allergy-type symptoms. Dustmites can live and breed anywhere there is a warm, humid environment and a ready source of dead human skin scales. To control dustmites it is important to limit the water availability in porous materials, maintain the room air relative humidity below 65%, control condensation and ensure regular and thorough cleaning of building surfaces (Cunningham, 1996).

2.4.5 Control of Microbiological Aerosols

2.4.5.1 Material Selection

Materials selection can help limit microbial growth (ISIAQ, 1996). Microorganisms need water and nutrients to grow, and removing one, or both, of these factors is the key to preventing their multiplication (Burge, 1990). As most building substrates contain sufficient quantities of either carbon or nitrogen to support opportunistic microbial growth, limiting water availability is essential. This includes the avoidance, or thorough drying, of wet construction processes and finishes, such as wallpaper paste and paint (Tucker, 1991a).

Newly poured concrete can take 7-10 years to lose all construction moisture, although the majority of free moisture will have evaporated within 60 days of pouring, depending on environmental conditions, the thickness and density of the concrete, casting and post casting treatments (Murdock & Brook, 1979). The installation of resilient or porous finishes or linings, which could, respectively, prevent the drying or absorb moisture from green concrete, should be delayed for at least 60 days after pouring (Tucker, 1991a).

Ideally, any materials with the potential to become damp should be made of non-porous materials that limit water absorption. However, even non-porous materials can provide suitable habitats for microbial survival (Burge, 1990), but will at least have a lower gross moisture availability if wetting is only spasmodic. Ease of cleaning, including good access, and smooth, wipeable surfaces are recommended (Burge, 1990).

2.4.5.2Environmental Control

Limiting the ambient levels of water vapour has been shown to be another important factor in the control of microbial growth. High relative humidity will lead to condensation on cold surfaces and will permit hygroscopic materials, including skin scales in dust, to absorb sufficient moisture to support microbial growth (Burge, 1990; Lavoie & Comtios, 1993). A few grams of atmospheric moisture per m^{-3} of air can produce high moisture contents in materials at low temperatures during winter, on cool evenings and cold parts of the building (ISIAQ, 1996).

Flannigan (1992) disproved the widely held misconception that maintaining the relative humidity below 70% will reduce the likelihood of microbial growth. He found that microbial growth is possible at 60% relative humidity and room temperature of 20°C, if the wall temperature is less than 15°C. Further, if the relative humidity is above 70%, then water availability within construction materials is frequently sufficient to support the growth of even very hydrophilic microorganisms if there is sufficient nutrient supply.

A study of the psychometric parameters affecting the propagation of dustmites found a similar result in that the environmental conditions within the micro-zone of habitation dominated the room air conditions. The humidity of the air nearest host surfaces and the temperature of host materials had a large influence on water availability, hence dustmite growth (Cunningham, 1996).

Although water availability is the primary factor affecting the germination, growth and sporulation of fungi, there is evidence to suggest that species, temperature, nutrient status of the substrate, pH and elapsed time are additional contributing factors (Morey, 1996).

Most experimental work on the environmental factors affecting microbial growth on building materials is limited by the assumption of steady state conditions, and more work is required to observe the influence of relative humidity and temperature cycling (ISIAQ, 1996).

2.4.5.3Building Design

Microbiological contamination is most easily controlled at the time of design and construction (Burge, 1987). The following preventative measures should be included in the building design:

- Elimination of moisture inclusion routes,
- Elimination of interstitial condensation through adequate insulation of wall cavities and appropriate installation of vapour and air barriers,
- Elimination of condensation on ducts and pipes through insulation,
- Avoidance of overcooling of interior spaces (Morey, 1996).

Moisture which feeds microbial activity can be forced into wall cavities via a number of leakage mechanisms, of which the most difficult to resolve is wind-driven rain. Leakage of commercial claddings is a significant problem, which can be avoided with proper attention to design, architectural detailing and construction (Brookes, 1998). Advanced cladding design systems, such as rain screen and/or pressure equalisation, offer greater protection against rain penetration, especially in high wind zones and for large buildings (Brookes, 1998).

Rain which partially penetrates the building envelope can go unchecked (Brookes, 1998) and cause interstitial microbial contamination. Rain penetration can be minimised by use of non-porous claddings and air seals within the wall construction (Garden, 1963; Brookes, 1998).

Within an hour, the first drops from a leak can germinate previously dormant organisms and allow them to continue growing in insulation, wood and building dust and interior materials (Burge, 1990).

Latta (1973) concluded, after investigating many buildings with moisture problems, that it is almost impossible to prevent moisture from the inside of a building penetrating the envelope via diffusion or air leakage. He identified the fact that building envelope designs which are "fail safe", that is, they allow moisture that has partially penetrated a wall to drain and/or ventilate to the exterior, is preferable to the installation of vapour barriers within the exterior envelope.

Elimination of standing water on the roof of the building and on balconies or other horizontal surfaces has been identified as a means to minimise the formation of colonies on the exterior of the building envelope and greatly assists moisture exclusion (Brookes, 1998). This can be achieved by providing sufficient slope for self-drainage to all horizontal surfaces, and limiting cracks and pores that can hold water.

Metabolites and spores from mould growing within the building envelope cavities can infiltrate the interior spaces through small penetrations in the interior lining. This can be driven by negative indoor air pressure, from the stack effect, extraction fans, furnaces and unbalanced air circulation patterns or high exterior wind pressures (Gravensen, 2000).

Moisture can also be driven into the building envelope and infrastructure from interior sources (Miller, 1992). Mechanisms which promote interior sources of inter-cavity moisture include:

- Positively pressurised ventilation,
- Stack effect positively pressurising the upper levels forcing moist air though small penetrations,
- Incorrectly installed vapour barriers,
- Thermal bridging where localised uninsulated areas of the envelope permit interstitial condensation to form,
- Overcooling of materials close to air outlets during the cooling cycle,
- Distribution of cold air or water in uninsulated ducts and pipes.

To reduce the risk of condensation on interior surfaces, Lstiburek (1994) has suggested that the mechanical cooling system should supply air with a dew point of at least 12-14°C. He also found that condensation could occur when poorly positioned air-conditioning diffusers or leaky air supply ducting blow cold air onto an adjacent surface, creating a localised cold spot.

2.4.5.4Building Services

The building services represent a significant potential for microbial contamination due to the frequent presence of standing water or moisture (Australian/New Zealand Standard 3666:1995, 1995). Standing water can occur at many sites within the cooling system, and usually presents a microbial problem (ISIAQ, 1996).

Air washers, humidifiers, dehumidifiers, cooling coils and cooling towers are intense sources of biological contamination. Theses devices are frequently moist to saturated, and organic dust entrained within the air that is in contact with, or passing over, these devices provides the nutrients for microbial growth (Loyd, 1992). The resulting contaminated airflow can directly feed into the supply air stream and contaminate the occupied areas (Miller, 1992).

Bioaerosols generated by cooling towers and sanitary drains may enter buildings through the exterior air inlets. Wet cooling towers should be located 7.5m (preferably 15m) from all air inlets and other building openings, and downwind from prevailing winds and wind patterns around buildings which could entrain cooling tower mist (Morey, 1996). Inlets located at ground level may become contaminated by herbaceous plant debris (Lavoie & Comtios, 1993) and to avoid both this and infiltration of other pollutants, they should be located at least three storeys above ground level (Bearg, 1993).

Filtration of the ventilation air stream with clean, dry and well-maintained filters can reduce indoor fungi levels (Miller, 1992). However, filters can also be a source of microbial contamination, especially when they are located close to the outdoor environment, where they inevitably collect moisture, fungal spores and sufficient organic material, dirt and debris from the outdoor air to support microbial growth (Pejtersen, 1997). Filters are always contaminated with microorganisms (Burge, 1987). To minimise the growth of microbes, every attempt should be made to keep filters permanently dry and the microclimate around the filters needs to be kept below 65% relative humidity (Burge, 1990).

Spores captured or settled in filters and other parts of the ventilation system can be disturbed and released back into the air stream (Miller, 1992). Levels of fungi spores can be elevated downstream of the filters by aggressive air movement and disturbance of filters, duct liners and settled dust. It is, therefore, important to minimise the disturbance or transfer of this matter into the air stream by controlling the vibrations from the mechanical plant at ventilation start up (Pejtersen, 1997).

Upgrading the filtration system to limit the nutrient supply to HVAC components and ducts downstream of the filters can also limit microbial contamination (Morey, 1988). The installation of cut-off switches, which prevent the ventilation system from being operated if the filters are not correctly fitted, has also been suggested as a means of limiting nutrient supply in ducting (Miller, 1992). Reinhardt (1991), and Lavoie and Comtios (1993) showed that improved filter maintenance also contributed to limiting microbial growth in downstream ducts and fans.

Biocides are not recommended for controlling microbial growth on filters, as biocides, by nature, are toxic to living organisms and should not be permitted in the air supply. These also have limited effectiveness as they will cull only bacteria and not fungi, and a layer of dust can block the bacteria's contact with the biocide (Burge, 1990).

It has been found in numerous field investigations that porous duct liner insulation is an amplification site for mould and other microorganisms (Morey & Williams, 1990). *Penicillium* and thermophilic actinomycete levels were found to be 2-3 fold higher in porous duct liner than outdoor levels. Morey and Williams found that if porous duct insulation was wet, downstream mould levels were high. However, if it was dry, high levels were found only following disturbance of the insulation material. They concluded that a significant risk of microbiological contamination could be avoided by prohibiting internally insulated ducts. Morey and Williams (1991) advised that air baffles should be used instead of internal insulation to absorb HVAC plant noise and prevent it from being transferred through the ducts. Double skin ducts with sandwich insulation are the preferred option to avoid condensation forming on inner or external surfaces of ducts in response to temperature differentials (Pejtersen, 1997).

Infiltration of some dirt and moisture to the HVAC system is inevitable, therefore the presence and configuration of access points to permit inspection and cleaning of the duct interior is highly desirable as a monitoring strategy (Foarde et al., 1996). Access to all system components including the plenum, heating and cooling coils and fins, humidifiers and filters, for inspection and cleaning should be provided (Morey & Williams, 1990).

2.4.5.5 Isolation

Isolation is seldom an effective method of removing the risk of person-to-person communication of infectious diseases in office buildings. Frequently, the infectious person is unaware of the nature of a serious illness during the transmissible stage, and infected people often continue to occupy the work place even when they know they have a contagious disease, such as influenza (Burge, 1995). Personal protective equipment, such as masks or respirators, are obviously both impractical for the office setting and seldom warranted.

Isolating areas with microbial contamination from occupied areas is a difficult strategy to achieve in practice in office buildings, as fine spore particles can readily disperse around buildings on air currents (Foarde et al., 1996). Strategies used in clean rooms to maintain a low concentration of microbial spores – which the provision of a constant supply of relatively higher pressure of highly filtered air - are, however, not feasible in office environments.

2.4.5.6Filtration

One method of removing airborne spores from indoor air is filtration of the air supply or room air. Filtration devices can effectively remove many kinds of infectious particles and microbial contamination from the air that passes through the filter. The effectiveness is dependent on the pore size of the filter media. While high efficiency filters (93-97% dust spot) can remove virtually all infectious particles, the more commonly used 34 – 45% dust spot are not effective (Burmester & Witter, 1972). Filtration devices can remove microbial contamination only when the contaminated air actually passes through the filter. Therefore, filters do not offer protection from microbes that are generated within the room or downstream of the filter, infiltrate through openings other than the filtered airstream, or by-pass a leaking filter (Burge, 1990).

Filtration devices can either be located in a central area, typically the HVAC plant, or installed as smaller decentralised units located in the occupied areas.

The efficiency of filtration is also dependent on the strength of the in-room source, and the efficiency of room air mixing so that all the room air passes through the filter without stagnant areas (Loyd, 1992). Emissions of infectious aerosol are characteristically spasmodic and have spatial concentration peaks, which means that filtration is unlikely to protect people closest to the infectious source (Burge, 1995).

Vacuum cleaners should be fitted with high efficiency filters to avoid resuspending microbiological and allergenic material back into breathing air (Nathanson, 1995c).

2.4.5.7Dilution Ventilation

Dilution ventilation from a clean, dry source of air can reduce the indoor concentration of bioaerosols unless there are strong indoor sources (Burge, 1987). Brundage et al. (1988), in a large multiyear study of army personnel, found a 50% higher risk of acute respiratory disease among recruits accommodated in new barracks with closed windows, low rates of outdoor air and high recirculation, compared to cohorts in accommodation with frequently opened windows, high fresh air and low air recirculation.

At very low ventilation rates, susceptible people have a risk close to 100% of being infected with tuberculosis-causing agents (Riley & Nardell, 1993). However, dilution ventilation can reduce this risk to 20%, but dilution sufficient to reduce the risk below 20% would compromise thermal comfort and be very energy intensive. It is assumed that dilution ventilation is equally effective for control of other infectious particles.

2.4.5.8Control of Organisms

Control of relative humidity to a level where many infectious agents are damaged has been frequently addressed as a simple means of control. However, in practice, few microorganisms share a useful relative humidity range (Burge, 1995).

Disinfection of surfaces is a widely practiced control method for many hygiene circumstances. This is seldom practical in the office environment due to the large number of surfaces, many of which are porous, and the amount of clutter with paper work (Foarde et al., 1996). Surface disinfectants can cause contact allergenic reactions to sensitive individuals whose bare skin touches the treated surfaces (Fink, 1978). It has been suggested that some HVAC surfaces, which are infrequently wetted, can have immobilised biostatic agents incorporated into their surface construction (Loyd, 1992). This has been found to inhibit the growth of microbial colonies and this treatment method has been advanced as having a lower risk than sprayed disinfectant, as the biocidal agents are not aerosolised (ISIAQ, 1996)

Burge (1990) has cautioned against the use of biocides to control microbial contamination, as they are not always effective and pose other health risks. Most biocides used in indoor environments can become separated from the host material and become airborne. They may be a greater health risk than the microorganisms they were meant to kill (Burge, 1990). Biocides are toxic to living cells and irritations and toxic reactions can occur following the aersolisation of these chemicals into the indoor air (Nathanson, 1995c). Reliance on the constant use of biocides can result in the mutations of resistant populations of microbes which, in turn, leads to the need for stronger biocides (Burge, 1990).

Dirt and organic films that have accumulated on surfaces treated with biocides can also isolate the microorganisms from the biocides. Further, some cleaning agents may cause inactivation of the biocides (Burge, 1990).

2.4.6 Summary of Control of Biological Contaminants

It is inevitable that viable spores of many toxic and allergenic microorganisms will be present in most areas of office buildings. There are numerous opportunities for the right conditions, including sufficient nutrients and moisture, to support their propagation.

Avoidance of microbiological problems is significantly more effective than remedial actions. Therefore, great care needs to be taken in the design of office buildings to limit the availability of free moisture and nutrients. Areas with a high moisture risk include:

- The HVAC system, especially the control of reservoirs of water, saturated air coming into contact with cold or porous surfaces or obstructions, and condensate from cooling system,
- The building envelope, especially the control of leakage through the cladding and around the penetrations, thermal bridging and condensation control,
- Ablution and food preparation areas, including the extraction of steam, and control of standing water, spills and overflows.

Efforts should also be made to limit the supply of nutrients. Mechanisms include efficient filtration systems, specification of easily cleaned finishing materials and surfaces, avoidance of roosting sites for birds and habitats for insects and cockroaches etc..

Effective filtration and dilution ventilation with clean air can significantly assist the control of the indoor concentrations of many bioaerosols, where there are no strong internal sources. Reliance on biocides is not recommended where there is a possibility that these could be communicated with the occupied areas.

A graphical summary of conditions identified in the literature, as either lessening or compounding the risk of microbial contamination, is shown in the following figure.

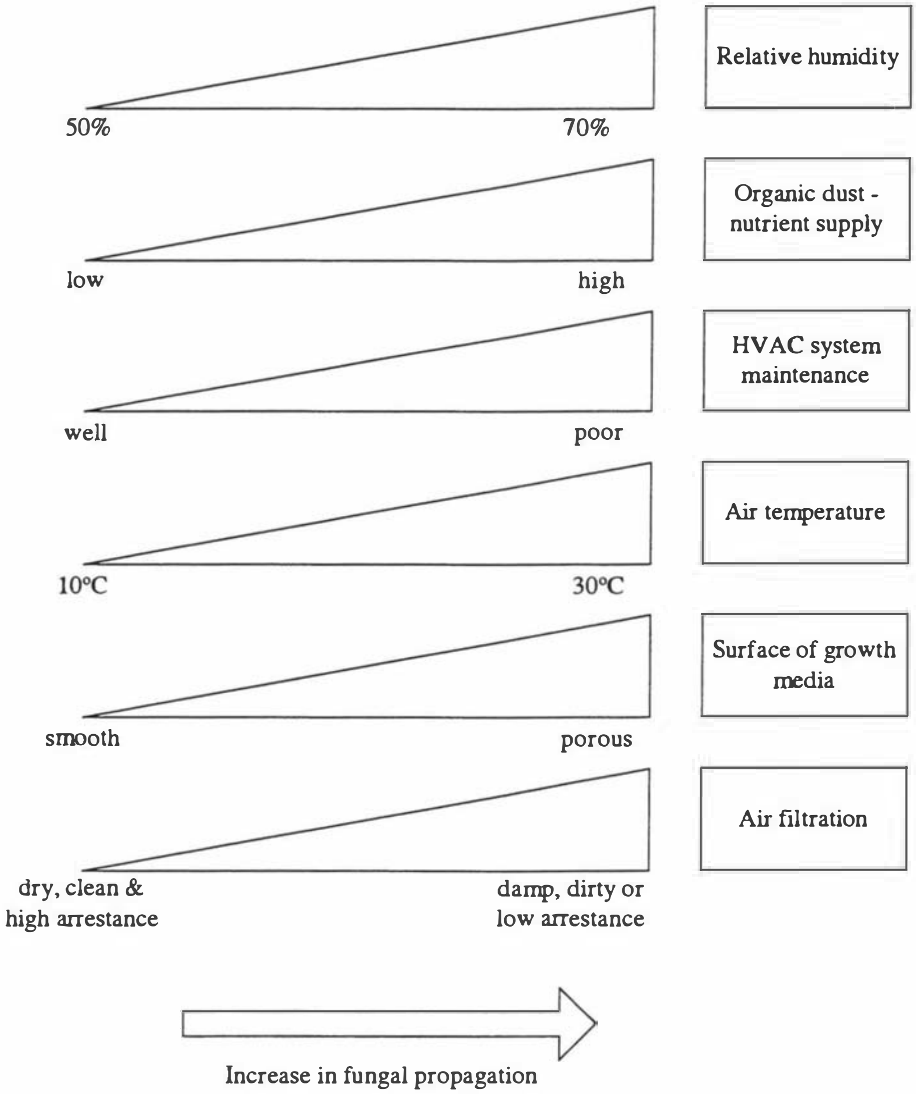

Figure 2-1 Conditions for the alleviation or propagation of fungal matter

2.5 Particulates

Airborne particulate matter is a generic term for discrete solid or liquid droplets of varying chemical composition and size. Particles can contain heavy metals, acids, biological and biogenic material as well as other organic and inorganic materials (National Research Council, 1998).

Many authors have expressed increasing concern regarding the contribution which particulate matter (PM) has on IAQ (Dockery & Spengler, 1981; El-Shobokshy & Hussein, 1990; Wallace, 1991; Boender, 1994). Particles are especially of concern if they are within the respirable range of less than 10μm (PM_{10}) in diameter. Respirable suspended solids (RSP) are considered a health risk due to their ability to penetrate the human lung (Boender, 1994) and remain airborne for considerable periods (Hanley et al., 1994).

Typically, PM exists in the atmosphere with a distribution of sizes clustering around a fine and a coarse peak, which occur between 0.1-1.0μm and 2-10μm respectively. Fine particles have a suspended lifetime of days to weeks and can travel many 100s to 1000s of kilometres, while coarse particles have an airborne life of minutes to hours and travel 10s of kilometres (Wilson et al., 1995, in (Wilson & Spengler, 1996a)). Fine particles readily penetrate buildings, persist for long periods and few indoor environments offer protection against inhalation of fine particles (Seaton et al., 1995)

Seaton et al. (1995) considered that the fine particles found in urban air offer a considerably higher acute health risk than do coarse particles found in industrial settings. This is due to the interactions with the lower alveolar, which exacerbate lung disease and can coagulate blood, thereby increasing the risk of acute episodes of cardiovascular disease in susceptible individuals.

2.5.1 Sources of Particles

2.5.1.1 Outdoor sources of particles

Outdoor ambient levels are elevated in locations close to high industrial activity and high volume traffic routes (Jamriska et al., 1999). Poor pollution control of industrial exhausts is another common outdoor source. Combustion exhaust from boilers and flume stacks adjacent to buildings are entrained into buildings either via intentional air intakes or infiltration through the envelope and contribute significantly to indoor concentrations (Lioy et al., 1985; Godish, 1995; Limb, 1995).

Fine particles generally originate from high temperature processes such as fuel combustion, tobacco smoke and atmospheric reactions such as photochemical smog (Wilson & Spengler, 1996b). Coarse particles tend to originate from resuspended soil or road dust, sea salt, pollen, mould spores, plant and animal parts. Particles may be emitted directly from these sources or formed in the atmosphere from gaseous precursors such as sulphur dioxides and nitrogen oxides (National Research Council, 1998). Outdoor levels are particularly high when temperature inversions trap pollution close to the ground. This effect is most marked in valleys and coastal regions.

The chemical composition of the fine fraction of urban pollution is half carbon, which is likely to have other chemicals adsorbed onto the surface, and half salts, mainly ammonium sulphate and ammonium nitrates (Seaton et al., 1995).

2.5.1.2 Indoor Sources of Particles

The indoor level of PM results from the interactions of many variables including contaminant source, physical and chemical properties of the source, building characteristics, the ventilation system and cleaning practices (Raw et al., 1991). Indoor dust consists of many differing types of particles of differing sizes, and compounds absorbed on the surface of the particulates.

Colome et al. (1990) found that indoor PM_{10} concentrations were similar to ambient concentrations unless there were significant indoor sources such as environmental tobacco smoke (ETS). Morawska et al. (1998), using an advanced size classification system, observed a close correlation between indoor and outdoor particle concentrations in hospitals. Likewise, Ozkaynak & Spengler (1996) and Ozkaynak et al. (1996) found that the fine particle aerosols from the outdoors readily penetrate into the indoor environment. These studies consistently show that fine particles infiltrate through the building envelope as well as entering via openings.

Further to the studies noted above, Yocom & McCarthy (1991), observed that indoor concentrations of PM_{10} tended to be higher than outdoors, and they highlighted the significance of indoor sources.

ETS has been repeatedly shown to be the single most dominant indoor source of particles (Dockery & Spengler, 1981; Sheldon et al., 1989; Leaderer et al., 1990; Baechler et al., 1991) and the elimination of ETS in buildings is the most effective means of control. Following an intensive review of 14 epidemiological studies from many countries, the US EPA classified second-hand tobacco smoke as a significant cause of lung cancer in non-smoking individuals and found no evidence of a safe threshold level (United States Environmental Protection Agency , 1994).

Biological materials, such as spores, moulds, miscellaneous plant by-products, bacteria, viruses, and insect parts and their by-products have been identified as significant components of indoor particle matter (Dockery & Spengler, 1981; Leaderer et al., 1990).

Occupants and their activities were also found to be significant generators of particles. Movement by the occupants was shown to disturb settled particles, which raised the airborne concentration (Baechler et al., 1991). Particle sources typically found indoors and associated with occupant activities include:

- Hair, skin cells, debris from clothing,
- Photocopy dust,

- Tracked in soil and road dust,
- Drink and food residues,
- Combustion particles from gas or other combustion space heating,
- Water heating and cooking appliances,
- Disturbance of fragments of building materials, such as asbestos, gypsum plaster, cellulose, man-made mineral fibres, textiles and glass (Dockery & Spengler, 1981; Sheldon et al., 1989; Leaderer et al., 1990; Baechler et al., 1991; Yocom & McCarthy, 1991; Raw, 1993; Kemp et al., 1998)

Asbestos and many other types of man-made mineral fibres (MMMF) have attracted considerable amounts of research (Hedge et al., 1993). As asbestos is not used in new construction it is not covered in this review.

Gross (1982), in a review of health effects from fibreglass exposure, identified a link with upper respiratory symptoms, such as nasal congestion, cough, sore throat, troubled breathing and chest pain. Fibreglass is a contentious health issue, and there is disagreement amongst scientists and manufacturers on its potential risk (Gross, 1982; Ridout, 1993; Cutter Corp, 1994). It has been found to cause cancer when injected into mice, however, this is not a usual type of exposure, and there is debate on the applicability of the results.

Several authors have associated settled dust concentrations of MMMF with SBS symptoms. Hedge et al. (1993a) observed a significant correlation between settled MMMF levels and symptoms, but no correlation with airborne concentrations.

Fibreglass from the insulating lining of ventilation ducts is of concern as the fractured particles are in the sub-micron respirable range and are generally coated with phenol formaldehyde, which is a potent irritant (Garnys, 1995). Fibreglass from duct lining has been found to cause many respiratory symptoms, although only low levels were measured in the breathing zone of occupants residing in a building with internally insulated ducting breathing zone (Newball & Brahim, 1976).

Fibreglass and other MMMF are widely used for thermal and acoustic insulation in construction materials. Studies have shown that mechanical damage of materials made from MMMF can fracture and liberate particles (Verbeck et al., 1981; Hedge et al., 1993). These papers reported that particles were liberated due to air erosion acting on exposed MMMF used for acoustic insulation in supply ducts or the return air plenums. Godish (1995) reported that air erosion could also liberate MMMF particles from the acoustic insulation in air handling units, reheat boxes, variable air volume mixing and diffuser boxes, as well as ceiling tiles which serve as the lower surface of return air plenums. Hedge et al. (1993) found movement of acoustic ceiling tiles could release particles when they are lifted for access to the ceiling void services, or when the tiles move slightly due to air pressure differences in the room from doors opening or operation of the HVAC system. Particles liberated from ceiling tiles are of concern, as they can be composed of fibrous glass, mineral wool or cellulose and frequently contain fire-inhibiting compounds (Godish, 1995).

Resin binders and latex or vinyl coatings are usually added to fibrous insulation to stabilise it from shredding. Godish (1995) reported from field investigations, that fibrous duct materials eventually undergo physical and chemical degradation. He associated this with high temperatures, high air velocities, reactions with airborne contaminants such as ozone, microbial growths and aging. Shedding has not been found in airborne samples drawn during laboratory testing of new fibrous duct board (Schneider, 1986), but this may be due to the absence of the degradation forces mentioned above.

A high "fleece factor" and a high "shelf factor" represent indoor sources of particulate matter (Skov et al., 1987; Wilson & Spengler, 1996a). The fleece factor is the ratio of fleecy surfaces, such as carpets and upholstery, to smooth, non-porous surfaces, while the shelf factor is a ratio of open storage of paper to other room surfaces. The risks associated with these two factors are partly linked with the ease of cleaning as well as contributing to the sources and sinks for dust. Fractions of fibres from fleecy materials can splinter off, adding to the particulate count within the space. Also, high levels of fleecy surfaces and open storage of papers are readily available sinks to absorb free VOCs and other particles. Skov et al. (1987) showed that the fleece factor and shelf factor were strongly correlated with SBS symptoms.

This theory was strengthened by findings from an interventional study conducted by Raw (1993) which showed symptoms could be reduced by thorough cleaning of paperwork stored on open shelving. Similar studies (Schneider et al., 1993; Tan et al., 1995; Kemp et al., 1998), also concluded that poor and infrequent housekeeping practices and building maintenance procedures exacerbated indoor suspended PM.

In a detailed study of eight ventilation systems, Pejtersen (1997) found that rotary heat exchangers, humidifiers and filters were major pollution sources. They attributed this to dust in the filters, rather than to the filter material itself, and the pollution load increased with longer HVAC operating times and accumulated levels of dust. The dust loading was observed to increase the particle load within the supply air, as well as forming a suitable habitat for microbial contamination.

2.5.2 Personal Exposure

A building occupant's exposure to particles is directly related to the indoor airborne concentration arising from indoor sources and infiltration of outdoor PM (Ozkaynak et al., 1996). Several authors (Hedge et al., 1993a; Raw, 1993; Ozkaynak & Spengler, 1996) have reported that in addition to background indoor levels, occupants are exposed to a cloud of particles resuspended by their activities, such as disturbing papers. Consequently, personal exposure to airborne particles can be 3-5 greater than sampling would indicate. Mamane et al., (1993) showed that personal exposure to indoor PM could be 50% higher than parallel airborne exposure counts, due to personal clouds of resuspended matter. Occupant activities were found to contribute up to $10\mu g/m^3$ in particulate concentrations per person, except for particles smaller than $1\mu m$ which were closely correlated with outdoor particle concentrations, but not occupant activities (Luoma & Batterman, 2001).

The number of particles in each size range is more important than the total count of the particles (Wilson & Spengler, 1996a). Counting particles by mass as opposed to quantity is misleading as this underexpresses the effect of the smaller, more problematic particles and this has been a confounder in much of the reported research (Etkin, 1995; Ozkaynak et al., 1996).

2.5.3 Particles and Building Parameters

Ozkaynak & Spengler (1996) found that many building parameters have a strong influence on the occupants' exposure to respirable particles. These parameters include volume, air exchange rate, filter efficiency, surface materials, dust loading, activity levels, room use patterns and frequency of cleaning. Air exchange rates can dilute the concentrations of indoor PM as well as directly admitting ambient particles.

The size of particles determines the probability of infiltration through the envelope. Large particles are either excluded or readily settle once inside a building. Ozkaynak et al. (1996) found, in an experimental study, that particles less than 10μm could infiltrate a building as readily as non-reactive gases. These results suggest that if outdoor ambient particle levels are high, then they pose a considerable risk to indoor environments. This study also suggests that it is possible to limit this exposure by decreasing infiltration and increasing the efficiency of the filtration.

2.5.4 Particle Size and Health Effects

The size, shape, density and reactivity of particles determines how far they can be transported and how they react with the human body. Airborne particles and fibres are a source of irritation to the eyes, skin, respiratory passages and other soft tissue. The health effects are also dependent on the velocity of breathing (Etkin, 1995).

Skin and eye tissue that is exposed to particles can be irritated, regardless of the particle size. Most large particles (11-10μm) and 60-80% of inhalable particles between 5-10μm are trapped in the nasopharyngeal region but can cause irritation to the airways. Particles of less than 3.0μm are most biologically detrimental, as they are respirable and are able to bypass the natural filters in the respiratory/nasal passages and penetrate deep into the lung cavity (Wilson & Spengler, 1996a).

2.5.5 Particle Behaviour

The respirable fraction of particles penetrates beyond most HVAC systems and air filtration units. They are also inclined to remain suspended in the breathing zone for long periods, and once settled are readily disturbed, (Wilson & Spengler, 1996a).

Mechanisms such as condensation, coagulation, combustion, and resuspension affect the particle size and formation. Very humid conditions will cause the fine fibres to agglomerate, increasing their disposition rate. Very low air humidities (below 30% relative humidity) will cause particles to become electrostatically charged and more readily attracted to humans, particularly to individuals working close to visual display terminals (VDT's). Franke et al. (1997) found that a rise in relative humidity decreased personal exposure to PM and presumed this was due to coagulation and settling of fine particles.

2.5.6 Macromolecular Organic Dust

The Danish Town Hall study (Skov et al., 1987), identified the fact that potentially allergenic material in dust was significantly associated with an elevated incidence of mucous membrane irritation and general symptoms. It indicated that the qualitative aspects of dust, in particular the macromolecular organic dust (MOD) fraction, was of significance (Skov et al., 1987; Wilkens et al., 1993).

MOD includes human serum albumin, proteins, rigid carbohydrates, DNA molecules, and fragments of skin scales and dander. Gravesen et al. (1993) identified human serum albumin as a predominant constituent of MOD. It is suggested that human serum albumin acts as a carrier for endotoxins, mycotoxins and other inflammatory or toxic reactors. Human serum albumin also has the potential to bind with formaldehyde to produce sensitising antigens and antibodies in humans (Gravensen, 2000).

The health effects of MOD were further investigated in a second study conducted in Danish Town halls (Gyntelberg et al., 1994), which found there was significant statistical correlation between the prevalence of bacteria, MOD, and histamine liberation. Gyntelberg et al. identified a positive correlation between the ratio of the particulate content in dust to other components (human fragments and fibres), and the prevalence of general symptoms. There was a threefold increase in the risk of general symptoms such as fatigue, heavy headedness and headache with high levels of gram-negative bacteria, which also strongly related to hoarseness and sore throats. General symptoms were approximately twice as high with a high particulate count, and the symptoms of eye and nose irritation also increased.

Carpeting, in conjunction with poor cleaning practices, has been implicated as a reservoir for MOD (Skov et al., 1990; Franke et al., 1997).

2.5.7 Particles and Gas Phase Pollutants

As particles have a large exposed surface area, VOCs, VVOCs and other gaseous pollutants are able to adhere to them through such forces as electrostatic attraction and surface tension (Skov et al., 1987; Gebefugi, 1989). Consequently, dust particles are frequently a reservoir for pollutants, which increases the adverse effects on health , and exposure mechanism and duration of these compounds.

Small particles in the size range <3.0μm can lodge deep in the lung cavity and deposit on the lung tissue any compounds and microbes that they have absorbed. These compounds and microbes can be solubilised and cause a concentrated point of cellular irritation or damage, which is thought to be more harmful than free gaseous VOCs (Garnys, 1995).

Researchers (Wilkens et al., 1993; Wolkoff & Wilkens, 1994) have shown that saturated aldehydes, carboxylic acids and hydrocarbons, as well as aromatic and aliphatic hydrocarbons, are common in indoor dust. These compounds can be reemitted from the surface of PM at a later stage depending on the environmental conditions (Nielsen et al., 1997). Skov et al. (1987) advised that high concentrations of gas phase pollutants and particles are a combination which should be avoided.

Hirvonen et al., (1994) identified the fact that unstable compounds attached to particles can be decomposed and released when the dust comes in contact with hot surfaces, such as radiator heaters, reheat coils, and light fittings. Desorption occurred mainly between 50 - 150°C, and the oxidation process occurred at higher temperatures. These compounds can lead to irritants and malodours. It has been suggested that thermal decomposition of dust can have a significant effect on IAQ (Hirvonen et al., 1994).

Levels of VOCs and TVOCs in the dust were strongly correlated with heavy headedness and lack of concentration, which is similar to the dose/symptom effect that Mølhave (1991) found from VOCs and TVOCs in-room air.

2.5.8 Particles and Microbiological Contaminants

High concentrations of settled dust provide a favourable habitat for fungi. As dust is hygroscopic, it can absorb and hold moisture in addition to providing sufficient levels of organic nutrient matter. West and Hansen (1989) advised that particle levels within the ventilation ducting and on all HVAC components should be carefully controlled and monitored to prevent amplification of fungi. Numerous studies have found the relationship between dust and fungi within the air-conditioning system (Pejtersen, 1997), and it is surmised that the same relationship occurs in other parts of the building (Foarde et al., 1996).

2.5.9 Guidelines and Standards for Indoor Particulate Matter

Worldwide there are few guidelines and fewer standards for particulate levels in office environments. These are summarised in Table 2-3 below.

Table 2-3 International Standards and Guidelines for Particulates

(Wilson & Spengler, 1996)

Agency	Standard	Category
ASHRAE	50µg/m^3	Indoor air exposure guideline, average annual (PM_{10})
ASHRAE	150µg/m^3	Indoor air exposure guideline, 12 hour average (PM_{10})
Japanese Government	150µg/m^3	Indoor air standard for office buildings ($PM_{3.5}$)
Canadian Government	150µg/m^3	Indoor air exposure guideline, one-hour exposure ($PM_{2.5}$)
Canadian Government	40µg/m^3	Indoor air exposure guideline, long-term exposure ($PM_{2.5}$)
US EPA	150µg/m^3	Outdoor National ambient standard, 24 hour average (PM_{10})
US EPA	50µg/m^3	Average annual ambient standard (PM_{10})
US EPA (proposed)	25-85µg/m^3	Average, 24 hour ($PM_{2.5}$)
US EPA (proposed)	15 -30µg/m^3	Average, annual ($PM_{2.5}$)
OSHA	5,000µg/m^3	Occupational exposure guideline, respirable fraction
ACGIH	10,000µg/m^3	Occupational exposure guideline, 8 hour (PM_{10})

2.5.10 Particle Source Control and Removal

Reducing indoor concentration of particles can be achieved via a combination of five basic strategies:

- Reducing the intake and infiltration of particles into the building,
- Reducing the internal sources of particles,
- Reducing airborne concentrations by dilution with clean ventilation air,

- Reducing surface concentrations by source control and effective cleaning practices,
- Removing airborne particle concentrations from indoor air by capture (Etkin, 1995; Franke et al., 1997).

Fine particulates are the most difficult to contain as they readily move through building envelopes and between occupied areas (Dockery & Spengler, 1981). Isolation is not considered a reliable method for particle control and it is very difficult to reduce their infiltration (Wilson & Spengler, 1996a). Decreasing the area of unfiltered openings in a building will somewhat reduce the opportunities for particles to enter the indoor environment. It is important to limit unfiltered openings adjacent to strong outdoor sources of particulate matter, such as:

- Rubbish compactors and food disposal areas,
- Vehicle parking, thoroughfare or docking areas,
- Tobacco smoking areas,
- Combustion process extracts and flues (Wilson & Spengler, 1996a).

The fresh air intake for a building should draw air from the cleanest possible source. This is generally at roof level away from street dust and vehicle emissions of particles and other gaseous, combustion waste products from vehicles, especially carbon monoxide (Bearg, 1993; Rock & Moylan, 1999). Air inlets located at street or basement level, may lead to entrainment of high concentrations of particles and other outdoor contaminants, especially particles. The air intake should not be located near a loading dock or carpark. Wind flow patterns around the building should be noted, as air-currents can transport contaminants considerable distances. Bearg (1993) suggested that wind tunnel tests, that are routinely conducted during the design of high-rise buildings, should also be used to evaluate the path of air and possible entrainment sources prior to the air intake.

Openings at street levels to should be avoided so as to preventthe entry of high concentrations particlate matter from street dust and traffic emissions, and should ideally be located in the upper two thirds of the height of the building (Bearg, 1993; Limb, 1995).

Physical separation can be the most effective and reliable means of providing isolation from outdoor pollution sources (Limb, 1995). However, the physical separation can be broken if any openings exist near the external source (Rock & Moylan, 1999).

Positively pressurising the air within the building relative to the source is necessary to prevent the entry of particles. However, in practice, difficulties frequently arise when the relative internal air pressure drops due to ventilation fans being switched off, relative air pressure differentials contrary to the desired conditions due to the stack effect or high wind pressures outside the building (Billings & Vanderslice, 1982; Gorman, 1984). Extracts have also been found to function as air intakes when the building fans are not operated during weekends and holidays (Godish, 1995). These four forces can lead to entrainment of particulate matter.

Localised low-pressure zones can occur in the wake of a lift car, drawing in gas-phase and particulate matter from adjacent zones. This is a major pathway for entrainment, when areas adjacent to the lift well are a source of contamination, such as a carpark, truck dock, rubbish collection space or laundry (Tamura & Wilson, 1967; Limb, 1993).

The concentrations of particles generated by occupants and their activities can be reduced by controlling the quantity or level of activity of the source from which they originate (Godish, 1995). This applies to activities such as paper handling, food preparation and mechanical damage of construction materials and textiles. Low concentrations of ETS can be achieved by banning smoking in buildings (Berglund et al., 1992), as is the case in New Zealand office buildings.

Where reduction of PM at the source is not feasible, then isolation of the particle generating activity, such as confining photocopying to designated areas, and deployment of removal strategies can help to contain and remove particles originating indoors (Bearg, 1993).

It is important that the air from spaces designated for particle generating activities does not become entrained in other parts of the building (Godish, 1995). This is a particular concern with tobacco smoking (Ozkaynak et al., 1996) and can even occur when the designated smoking space is outside the building.

Consequently, as with all other external sources, consideration should be given to reverse air pressure relationships when mechanical ventilation systems are turned off or when wind pressure or temperature causes buildings to become negatively pressurised (Gorman, 1984).

Chao et al (1998) observed that heavy rain, washed particulate matter from the ambient air, and a 20% decrease in indoor particle levels could be achieved in less than one hour during periods of heavy rain, if the ventilation during this period was high. Chao et al. suggested that flushing the building with high air exchange rates following heavy periods of rain was one method to reduce indoor concentrations of airborne particles. However, there are obviously climatic limitations to placing too much reliance on this method. Franke et al. (1997) also observed a decrease in the infiltration of airborne particles during periods of rain, but an increase in the amount of particulate matter, primarily soil, that was tracked in on shoes. This debris had the potential to be suspended into the air at a later time.

Kemp et al. (1998) also identified the fact that pedestrian entrances function as entry points for particulate matter and concluded that levels of biological materials, tracked in soil and road dust could be reduced by providing frequently cleaned and heavily textured walk-off mats inside all building entrances. Where outdoor air concentrations of particulate matter were low, increasing the ventilation rate can reduce indoor concentrations and conversely, decreasing the supply of outdoor air could raise indoor levels (Owen et al., 1992).

Particulate concentrations can also be controlled with diligent cleaning and selection of appropriate finishing materials (Raw, 1993; Franke et al., 1997; Kemp et al., 1998; Kildeso et al., 1998). This includes installation of HEPA (High Efficiency Particulate

Air) filtration in vacuum cleaners to prevent resuspension of PM, and the selection of materials which do not fragment or hold dust particles. Raw (1993) and Kemp et al. (1998) found that "normal" vacuum cleaners fitted with low efficiency filters contributed to an accumulation of particulate matter. Kemp et al. also found that occupant behaviour, such as covering work and floor surfaces with paperwork, prevented cleaners from gaining access to these surfaces, and concluded that careful furniture design and office layout can facilitate effective cleaning and reduce surface particle concentrations.

The two main types of filters are media filters and electrostatic filters (Beck, 1990). The two main locations for capturing particles from indoor air are filtration within the HVAC plant and filtration within a room (Croxford et al., 2000).

Within the particle range of 0.01μm to 0.3μm the filtration efficiency of media type air cleaners is highly dependent on the size of the particles (Hanley et al., 1994). The filter efficiency rating of media filters is usually determined by the ASHRAE 52.1-1992 standard which tests for atmospheric dust spot efficiency and arrestance of particles by weight (as opposed to a count) (Nathanson, 1995a). As the arrestance test includes particles up to 80μm in size, larger particles can bias the results to the larger and easily captured particles and allow 90% of fine particles to pass through (Beck, 1990). Manufacturers' data usually present the best-case scenario of averaged, loaded or clean filters, which can also bias the reported efficiency of the filters and may overstate the performance of the filter (Owen et al., 1992).

Fractional filter tests have been shown to present a more accurate presentation of efficiency of filters over all size ranges (Lee & Liu, 1980; Hanley et al., 1994). Smaller particles generally penetrate further through media filters. However, particle behaviour causes some exceptions. For example, Hanley et al. (1994) found that HEPA filters were least efficient for particles in the 0.2 – 0.3μm range, but were efficient for both smaller and larger particles. Particles larger than the pore size of the filter were collected either by the sieving mechanisms, or by inertial impaction and interception, while smaller particles (less than 0.2μm) underwent bombardment by air molecules and diffused to the filter fibres (Croxford et al., 2000). However, there are economic and performance issues that are barriers to the specification of HEPA filters as standard components of building air-conditioning systems.

Pleated media filters are more efficient than pad filters, typically having efficiency ranges between 25-55% and 5-10% respectively (Nathanson, 1995b). Bag filters should be supported to prevent them from vibrating and releasing particles when the HVAC system is started (Bearg, 1993).

The flow rate also contributes to the efficiency of media type filters. The efficiency for particles less than 0.1μm was seen to decrease with increased flow rate due to the particles having less time to diffuse onto the filter media (Hanley et al., 1994). However, the reverse was observed for particles above 0.1μm, as the higher inertia of the particles increased the impaction efficiency. A higher air volume flow rate reduces the efficiency of electrostatic cleaners (Hanley et al., 1994).

For most types of media filters the efficiency of the system usually increases with the dust loading. Hanley (1992) found charged fibre filters were an exception, as the initial layer of dust inhibited the charging of the particles.

Jamriska et al. (1999) observed that buildings located near busy traffic routes will need to be fitted with filtration systems up to 80% to 90% efficiency to achieve indoor concentrations that comply with the US EPA standard for $PM_{0.7}$ and smaller. The authors suggested that this result is also applicable to other outdoor sources of particulate matter.

Correct sealing of filters and filtration systems has been established as an important criterion for obtaining optimum performance from all types of filters so that air does not bypass the filtration system (Woods, 1987; Beck, 1990). Methods to prevent this include installing gasket seals around filter frames, and tight-fitting closing latches.

Significant impediments to the effectiveness of all types of filtration are the distance between the source and the filter and the exposure to the occupants en route. Instances where this distance and exposure are considerable include:

- Particles generated in the HVAC system downstream of the filtration unit (Leaderer et al., 1990; Morey & Williams, 1991),
- Biological contaminates produced and amplified in the condensate trays and porous insulation (Morey, 1996),
- Shedding of fibrous glass and other particulate phase materials associated with the duct liner or return air plenum (Morey & Williams, 1990).

These situations support the argument for introducing filtration close to the occupied environments and several studies have found that it is possible to reduce the exposure to particulates and airborne microbes within the office by installing efficient in-room filtration devices (Shaughnessy et al., 1994). Several researchers (Hedge et al., 1993a; McCarthy et al., 1993) have found that small desk-side HEPA filtration units are effective for reducing particle counts within the microenvironment of the workstation as well as a spill-over to surrounding areas. These units have been found to reduce 80% of $PM_{2.5}$ particles of both indoor and outdoor origin and reduce the effect of the personal cloud. Hedge et al. (1993b) found a significant decrease in SBS type symptoms (lethargy, dry skin and headache) and a 61% reduction in certified sickness absence when open plan workstations were fitted with personal breathing zone filtration systems. A reduction in airborne concentrations was also found following the installation of electrostatic filters in the breathing zone of open plan offices (Croxford et al., 2000).

In an in-room HEPA filtration study, Abraham (1999) found that the system reduced the counts of fine particles, but performed less efficiently in a real situation than the 99.97% efficiency achieved in a testing laboratory. Although HEPA filtration units close to the occupants' breathing zone is useful for reducing the concentration of fine particles, Abraham concluded that it is vital to eliminate respirable particles at source.

Contrary to the studies noted above, Raw (1993) conducted an interventional investigation examining the effect on symptom reporting from various particle removal strategies and observed no benefits were gained from installing air filters in-rooms. Liddament (2000) stated that desk-top filters were no substitute for the correct supply of ventilation air and that filter efficiency needed to be rated EU8 or higher to accomplish any significant reduction in pollutants.

Maintenance is important for all types of filters. The filters need to be kept dry to prevent them from becoming a host breeding ground for mould and bacteria. They also need to be regularly cleaned and replaced (Liddament, 2000).

2.5.11 Summary of Control of Particulate Matter

There are many sources of particulate matter both within and outside an office building. Measures to control the ingress of particles ideally start at a macro level with the selection of a site away from high concentrations of particles, and include locating all openings in the building envelope remote from localised high concentration zones. In a mechanically ventilated building, the concentration of particles entering the building from outside can be further reduced by the installation and correct operation of an efficient filtration system and maintaining the building at a positive air pressure relative to the exterior. Filtration systems located within the mechanical plant room are not, however, able to remove particles generated downstream of the filters or entering through other openings in the envelope. In-room filtration systems and the design of surfaces to facilitate thorough cleaning of deposited particles are methods that have been found to be effective for removing particles that reach the occupied areas.

Fine particles pose both the greatest risk to health and challenge to control, as they can readily migrate into and around an office building, take longest to settle, are easily resuspended and can penetrate most filtration systems.

Particles have been found to cause numerous respiratory and heart complaints. However, their risk to health increases when they occur in an environment rich in

VOCs or microbiological contaminants, and these compounds can be adsorbed on the surface of the particles, thus changing the exposure mechanism and health effects of the VOCs.

2.6 Comprehensive IAQ Solution Strategies

Source control comprises several principles depending on the nature of the polluting agent or problem. Several authors have stressed the fact that prevention is infinitely better than a cure (Billings & Vanderslice, 1982; Maroni et al., 1995; Bower, 1997).

This view is aligned with the general occupational, safety and hygiene approach to dealing with pollutants, which employs the following hierarchy of control measures:

- Eliminating or minimising pollutants,
- Substitution with more benign products or systems,
- Enclosing or isolating the process, materials or system,
- Partial enclosure with local air extract,
- Dilution ventilation,
- Personal protection
- Monitoring and surveillance (COSHH, 1987).

This hierarchy is applicable to office environments with the exception of personal protection, as is seldom ergonomically feasible or necessary to wear personal protection equipment in the office environment.

Several authors have expressed variations on this control strategy. Godish, (1989) suggested that non-industrial indoor air source control strategies should include:

- Measures which prevent or exclude the various pollutant emitting materials (sources) in the building environment,
- Elements of the building design or maintenance that prevent or minimise air contamination,
- Treatment or modification of sources - either directly or indirectly - to reduce emissions,

- Physical removal of the source or source materials and replacement with other materials with no, or minimal, effects,
- Measures that prevent the amplification and entrainment of biological contaminates in indoor air,
- Removal of particulate dust from surfaces by cleaning.

There are many instances, such as the stack effect, where the driving forces cannot be removed. In these situations, attention to isolating or reducing the source and pathways becomes more important (Bearg, 1993).

Liddament (1999) presented an approach, whereby the role of ventilation is viewed as a component of the total IAQ equation, rather than as the solution.

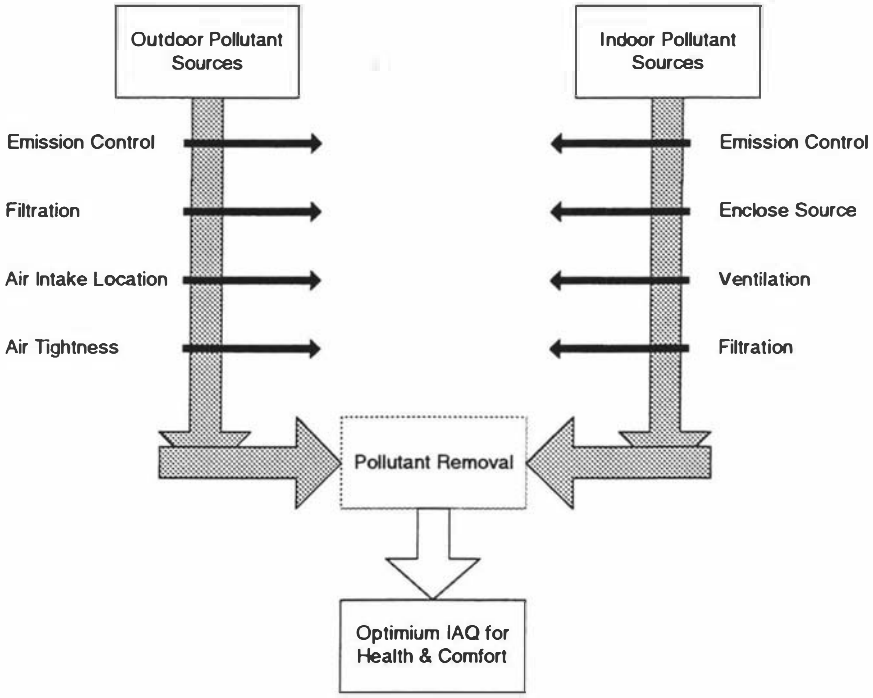

Figure 2-2 Achieving Optimum IAQ

(Liddament, 1999)

Liddament used this figure to illustrate the fact that ventilation represents only a small component in the IAQ chain. He drew attention to the hierarchy of the operations listed, with priority needing to be given to the operations at the top and left of the list, ahead of ventilation.

2.7 Conclusion

The design of a healthy office building requires consideration of the total pollutant load within the building. Healthy office environments are achieved when the indoor concentrations of VOCs and gaseous pollutants, microbiological contaminants and particulates are within acceptable levels.

There is no single solution or even simple formula for the design a healthy building, but there are design criteria that will help achieve this objective. The selection of a site with low outdoor concentrations of pollutants and the elimination of building features that can be sources of pollutants are fundamental design criteria for the creation of a healthy office building. These include reduction of VOC emissions from construction and finishing materials, and shedding or holding of particulates from the same, as well as limiting the ingress of particles from outdoor sources. Care in the building design is required so that low levels of free moisture and nutrients can be maintained throughout the life of the building to limit the propagation of fungi, bacteria and other biological contaminants. Control of gaseous pollutants from indoor and outdoor sources also requires attention in the design of a building.

Priority should be given to eliminating the sources of contaminants which cover the largest area or have the most potent emissions. The spatial and temporal relationships between the pollutants and the occupied areas need to be considered.

Pre-treatment of materials which could emit VOCs or shed particles to reduce the strength of pollutants that could potentially be released into the occupied areas should be conducted prior to materials being installed in the building or the area being occupied.

Where pollutants cannot be eliminated at the source, then other control strategies are required. These include isolating the occupied areas from the pollutants and removal of the pollutants. Methods of isolation include the sealing of materials, installation of physical barriers between the source of the pollutant and the occupied areas and manipulation of air pressure relationships to contain or exclude pollutants from the occupied areas.

Strategies for the removal of pollutants vary between pollutant type and building feature. Particles can be captured by filtration of the airstream or cleaning the building. The effectiveness of filtration and cleaning for removal of particulate matter both depend on the system used and the location. VOCs and gaseous pollutants can be removed by air cleaners, however not all aspects of air cleaning technologies, such as determination of replacement intervals, are well established. The most common methods for removing gaseous pollutants and VOCs are localised extraction and dilution ventilation. Biocides can control sites with microbial contaminants, however biocides by nature are detrimental to all living cells and their wholesale use is not recommended.

Designing for maintenance and the total life of the building are also important considerations. These include low maintenance features, and full access to components requiring attention throughout the life of the building to enable high standards of building maintenance and hygiene.

3 LITERATURE REVIEW - DECISION SUPPORT SYSTEMS

Information on the design of DSS was predominantly published in the 1980's, while more recent literature tended to focus on techniques for knowledge acquisition, programming techniques or specific applications.

Methods of verification, evaluation or validation of DSS were not widely reported in the literature (Klein & Methlie, 1995), except for a small group of papers published between the mid-1980's and early-1990's. Indeed many of the recent textbooks on building decision support systems contained only passing references to verification or validation of the developed tool (Bennett, 1983; Jelassi et al., 1992; Gray, 1994; Klein & Methlie, 1995; Berkeley et al., 1998).

The literature on validation and verification of Expert Systems (ES) was also reviewed and numerous papers were found (Blethyn & Parker, 1990; Gupta, 1991). There are sufficient similarities between certain phases of DSS and ES for some of this literature to be relevant.

Expert systems have been defined as artificial intelligence systems which are designed to perform at close to human expert levels (Gupta, 1991). The development effort of ES systems is divided between the knowledge acquisition and representation phases and the production and testing of the artificial intelligence. Most of the papers on validation of ES focused on methodologies for checking the syntax of the rules and other aspects of the artificial intelligence, rather than the structure and logic of the knowledge. Consequently, these papers were outside the scope of this project.

3.1 Design of a Decision Support Systems

The term "decision support system" was coined in 1971 (Bennett, 1983) and since then the notion of a DSS has been used to describe many types of knowledge repository and retrieval systems (Klein & Methlie, 1995). However, the principal function of a DSS was succinctly described by Bennett (1983) through definitions of the title words:-

- *Decision* emphasises the primary focus on decision-making in the problem situations rather than the subordinate activities of simple information retrieval or processing.
- *Support* clarifies the systems role in aiding rather than replacing the decision maker, thus including those decision situations with sufficient "structure" to permit computer support, but in which executive judgment is still an essential element.
- *System* highlights the integral nature of the overall approach, suggesting the wider context of the user, decision environment and requirement for commonality in the solution approaches.

There are nearly as many definitions of a "system" as there are DSS applications. The following definition has been frequently cited in the DSS literature and there is general agreement between authors that the emphasis on goals is a valid approach:

> A system is a group of element, either physical or non-physical in nature, that exhibit a set of interactions among themselves and interact together toward one or more goals, objectives or ends. (Mittra, 1986)

DSS are considered to be most suitable from problem domains that involve semi-structured or unstructured decision-making processes (Sprague & Carlson, 1989) and where there are insufficient quantitative models to automate the problem resolution (Ginzberg & Stohr, 1982).

They are also suited to assisting the resolution of problems which are partly routine and partly judgemental (Ginzberg & Stohr, 1982). The need to use judgement to decide upon a series of alternatives is an important feature of a DSS. The emphasis of a DSS is to support the users and lead them through the decision-making process, by asking many "what if" questions, rather than automating the decision process or imposing solutions. The DSS should accept input from the user, process it, and then provide output for review. If the output is not satisfactory to the users, then they can continue to work through the alternatives until the desired outcome is reached (Mittra, 1986).

In an assessment of the features of DSS, Alter (1980) stated that an important objective of a DSS is the overall effectiveness of the system in problem resolution. This distinguishes it from other types of information management systems where mechanical effectiveness is emphasised.

DSS are designed to support the decision-making of the user in two ways; the first is the immediate guidance of the implication of the decision at hand, and the second is an educational function to support the longer term decision-making of the user, regardless of whether or not they use the DSS for every project (Bennett, 1983).

Although several textbooks and numerous papers suggested in their titles that they offered guidance on "building" or "developing" DSS, it was found that there was little detailed literature on structured approaches. Most texts recommended that clear definition of the goals and sub-goals was an important first step of the development process (Alter, 1980; Mittra, 1986; Sprague & Carlson, 1989; Klein & Methlie, 1995). After this step, some texts suggested unstructured approaches, such as, trial and error (Sprague & Carlson, 1989), while a few authors recommended more structured methodologies (Siegel, 1986; Turban, 1992). These latter two authors considered structured approaches were more likely to facilitate the development of complete and consistent systems than were ad hoc techniques. The methodologies proposed by Siegel (1986) and Turban (1992) were very similar in essence, with the Siegel model providing more detail. Siegel's method is described in Chapter 4 and was the approach adopted for this thesis.

3.2 Validation of a Decision Support System

Terms used in the literature to refer to checking of the performance of DSS and expert systems included evaluation, validation and verification. These terms appear to have been used almost interchangeably in the literature and this could contribute to the confusion surrounding the validation process. In a paper seeking to clarify this process, O'Keefe et al. (1989) gave the following definitions:

- Evaluation: seeking to assess the systems overall value to problem solving in the subject domain,
- Validation: building the right system; substantiating the view that the system performs correctly,
- Verification: building the system right: substantiating the view that the system correctly implements its specification.

They added that separating performance validation from evaluation could be difficult especially in groundbreaking areas where a reasonable level of performance is difficult to achieve. Many knowledge engineers naturally favour verification of the system's artificial intelligence to validation of its performance, as this is closer to their specialisation.

Moore and Chang (1983) argued that DSS do not need to be validated as their goal is to improve the higher level decision-making rather than the operational efficiency of the system. This comment, however, ignores the need to validate the knowledge representation.

Other DSS developers have argued that as the number of end points increases, the validation plausibility decreases. While the initial knowledge and individual algorithms can be verified, the interactions between the internal elements (frames, rules etc.) become less predictable (Brule & Blount, 1989).

Brule and Blount (1989) suggested that as DSS are typically utilised in domains that are complex, difficult to pre-specify and possess multiple end points, then quantitative assessment of validation results would always be difficult to achieve and potentially meaningless.

Geissman and Schultz (1988) proposed that rigorous validation of ES was not necessary in domains without readily defined models of the knowledge or previous attempts at artificial intelligence. They suggested that something is better than nothing and stressed the evolutionary nature of this type of system. They added that this argument is valid, if it is made explicit just what the system does do and whether or not it does this correctly.

Reasons given in the literature for the infrequency of validations being undertaken, include lack of demand for validations, lack of understanding of the validation process and lack of reliable methodologies (Green & Keyes, 1987; O'Keefe et al., 1989; Gupta, 1991). These authors all said that methodologies for validating expert systems are in need of further development, which leads to a vicious circle where "nobody requires validation as nobody knows how to do it; since nobody knows how to do it, nobody requires it (Geissman & Schultz, 1988). Green and Keyes (1987) suggested that attempting to apply traditional software validation techniques would lead only to further confusion, and proportionately more focus should be placed on the validation of the "truth of the knowledge embedded in the system". They added that the justification of the conclusions was considered as important as the precision of the conclusions.

Many of the validations that have been reported on DSS have been post-installation audits conducted when the system had not met user expectations (Sprague & Carlson, 1989). Sprague and Carlson suggested that poor performance could have been avoided if evaluations and validation had occurred at intervals during the development of the DSS, including prior to the programming stage. O'Keefe et al. (1989) also advocated that ES systems should be validated in stages during the development, with the focus in the earlier stages on direction of the ES with knowledge representation and the reasoning process.

3.2.1 Validation Approaches

The three primary approaches that have been reported in the literature for validating DSS and ES are:

- Review by independent experts,
- Comparison of performance with, and without, the system and,
- Review of tests cases by independent panels of users or experts.

3.2.1.1 Validation by Expert Review

Brule and Blount (1989) reported on their experiences of employing panels of experts to review numerous DSS. They had found a reasonable level of consistency when one expert panel had tested a system, then the DSS was retested by the same or another panel of experts - and cited review by experts as their preferred approach. Although not reported in detail, Brule and Blount made reference to a comparison they had conducted of "review of the system by experts" and "review of test cases by experts" which found the former approach more amenable to detection of omissions and fundamental errors.

Review by experts was promoted by numerous authors including Green and Keyes (1987), Geissman and Schultz (1988) and O'Keefe et al. (1989), as the predominant validation method. O'Keefe et al. (1987) reported that these had been used successfully in several projects to verify the performance of a DSS, however care in the design of the survey was required to limit response bias. Most of these authors mentioned that validating a DSS was a tedious and dry task which could reduce the reviewer's enthusiasm and attention to the task, but none of the authors offered advice on how to address this issue.

A key advantage of expert review surveys is that they can be implemented during the development process, which enables feedback to be incorporated into subsequent design stages. Sprague and Carlson (1989) suggested that expert reviews for large or complex DSS systems should be completed at the end of the knowledge acquisition phase and knowledge representation phase prior to programming. They suggested that reviews by domain experts could be staged to investigate the correctness and completeness of the system's knowledge base in toto, and added that this approach provided the most meaningful validation.

The feedback from experts can be difficult to analyse either quantitatively or qualitatively. Green and Keyes (1987) reported on the validation of a medical diagnostic system by a number of distinguished physicians and found that even the elite evaluators exhibited:

- Prejudice; some experts refused to consider that the system could provide answers as good as theirs,
- Parochialism; experts in different areas applied different criteria and different bodies of knowledge. This can be most pronounced in interdisciplinary domains, which can give wide variations of, and contradictory responses between, experts, and,
- Inconsistency; some evaluators rated answers generated by the ES, which were substantially similar to their own, as unacceptable.

Consequently the experts' responses need to be interpreted with this in mind. In extremely critical domains where failure of the system would be catastrophic, independent validation of the independent experts' comments may be required, however this could compound the advantages and disadvantages of review by expert and is seldom deemed necessary. In most cases the ES designers should be able to objectively interpret failings in the experts' validation data (Green and Keyes, 1987).

Other significant disadvantages of expert reviews include the large commitment of time required of the experts and lack of validity in a quantitative analysis of the survey's results (Green & Keys, 1987; Geissman & Schultz, 1988). Green and Keys used an academic analogy and suggested the results of the experts' opinions should be considered as the grading of a dissertation rather than as the marking of a statistically precise experiment.

3.2.1.2Validation by Comparison of Performance

Atler (1980) and Sprague and Carlson (1989), in papers reporting on their experiences with pre/post installation reviews, suggested that a review of the entire system was cumbersome and recommended the assessment of key performance indicators (KPIs) to measure the impact of the DSS. Gray (1994) supported this opinion and added that as DSS are by nature qualitative systems, then attempting to quantify the qualities of a system and subsequent statistical analysis may be misleading and he cautioned against using engineering paradigms to analyse the results.

Sprague and Carlson (1989) suggested that KPIs worthy of evaluation could be divided into four categories, with each category being most pertinent at certain stages of the development process.

- Productivity measures to evaluate the impact of the DSS on decisions, such as time and cost of making the decision,
- Process measures to evaluate the impact of the DSS on decision-making, such as number of alternatives examined, and time horizon of the decisions,
- Perception measures to evaluate the impact of the DSS on decision makers, control of the decision-making process, usefulness of the DSS, understanding of the problem, and conviction that the decision is correct,
- Product measures to evaluate the technical merit of the DSS, such as product development and implementation costs, response times and mean time to failure.

Sprague and Carlson (1989) suggested eight approaches to assess the impact of the DSS on decision-making. Seven of these approaches were variations of assessment of performance with, and without, the aid of the system under review. There was considerable overlap between the eight approaches, and methods included aspects of event logging, cognitive testing, value analysis, and system measurement. The eighth approach is an attitude survey of key users to verify the ease of use of a completed system. They also suggested surveying other experts to verify the accuracy and completeness of the DSS, but didnot elaborate on when this should occur.

Alter (1980) found that bias in performance with, and without, the aid of the DSS was inevitable due to the lack of a blind control. He argued that this was not considered a problem if the DSS was a business tool, as the objective was an improvement in decision-making rather than apportioning responsibility for the improvement. This argument is not, however, valid in a research context.

A further disadvantage of this approach is the lack of opportunity to validate the system until it is completed and installed (Sprague & Carlson, 1989). This approach is not suitable for validation of DSSs during development or for systems which cannot be readily implemented, and is wasteful of resources if fundamental errors have been made during the development phase.

3.2.1.3Validation by Test Cases

Validation by comparing the results of test cases run through the system and "other methods" available to experts is an approach widely reported for validating ES (Gupta, 1991), where other methods include experimentation, case histories and intuition. In an ideal world there would be a large number of well-documented cases from a number of experts on a complete range of problems from which a stratified random sample could be drawn. However, this is seldom the reality.

Where no new (that is, they have not been used in the development of the system) historical test cases are available then it is possible to have experts create some fictitious cases (O'Keefe et al., 1989). O'Keefe et al. argued that it is very difficult to achieve a range of invented cases that represent a well-stratified random selection. It also increases the effort required from the experts.

Confidence that the system is generating valid results increases with the number of test cases which have been solved with substantially similar results generated by the

DSS and expert. However, the "law of large numbers"[1] does not necessarily apply, as the coverage of the test cases is more important than the number. Consequently the larger the input domain, the more test cases are required to validate the system (O'Keefe et al., 1989).

Validation by test cases is well suited in domains where it is possible to gather a large number of test cases to provide representative coverage for typical decision outcomes, however rare cases will always present a problem and can fall outside of the scope of the validation exercise (Klein & Methlie, 1995).

Test cases are useful for validation of the conclusions generated by the ES but do not uncover errors in the reasoning or subsystems of the system. They are very suitable for validation of systems with a limited number of input variables and conclusions or simple models. Validation of the reasoning process is, however, also recommended at certain stages during the development process (Brule & Blount, 1989).

3.3 Conclusions

DSS are considered to be a very suitable knowledge engineering approach for solving unstructured problems. Their primary function is the support of executive judgment, rather than automation of the decision-making process. Educating the users of the knowledge embedded in the system is a secondary role of the DSS, which is important to support longer-term decision-making.

Validation of DSS and ES is not an exact science, and difficulties compound with the number of possible solutions to the domain problem. Strengths and limitations were identified with all the validation methods discussed in the literature. However,

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[1] The law of large numbers states that certainty that a hypothesis is correct increases with the number of trials with a positive outcome.

validation by expert review was considered the approach most suitable for assessing the correctness and completeness of the logic within a DSS.

4 METHODOLOGY

The methodology used for the development of a DSS for the Design of Healthy Office Buildings had three distinct phases. The first phase was the gathering and assimilation of data on two topics; the first and larger topic being Indoor Air Quality, Sick Building Syndrome and research related to the content of the DSS, which are presented in Chapter 2. The second topic was data on methodologies for development and validation of design tools and DSS (refer to Chapter 3). The second and third phases of this research were, respectively, the development and validation of HEAD-Start. The methodologies for the three phases are discussed in turn in the following sections.

4.1 Knowledge Acquisition and Assimilation

Knowledge for the content of the DSS was gathered by an extensive review of published literature and interviews with national and international experts in IAQ. An intensive postgraduate course on Indoor Air Quality from the University of Sydney was completed. Two International conferences on Indoor Air Quality and an International Conference on Healthy Buildings were attended and the proceedings from other significant IAQ meetings were reviewed.

References to literature and authors were searched in general literature databases, including Medline, Current Contents and Citation Index, and by specialist ventilation/IAQ databases, for example Airbase, which is produced by the Air Infiltration Centre (AIC), Berkshire, UK, and the Buildings and Health database, produced by The Building Services Research and Information Association (BSRIA), Berkshire, UK. Indoor Air and Indoor and Built Environment, which are the two leading journals in this area, were subscribed to and regularly read. Personal consultations with other researchers in this field also assisted in the identification of relevant papers. Identification of criteria for the design of office buildings with good IAQ was the primary focus of the review.

A matrix of the literature cited in the research by subject and author was produced to highlight common research themes, and conversely any areas where little research had been undertaken (Appendix 1).

Seven leading researchers in the IAQ community were identified by their publication record and were interviewed in person (refer to Appendix 2).

Data gathering for the design and validation of the DSS was undertaken by a review of literature published in journals, technical reports and specialist texts. An information science course on Development of Experts Systems from Massey University was completed. Seven individuals with expertise in the development or evaluation of architectural design tools or expert systems were also interviewed. Details of these experts are also included in Appendix 2.

Most of the interviews with experts were conducted using the formal knowledge acquisition model described by Brule and Blount (1989). However, interviews were less structured where the expert was personally known.

4.2 Development of a Decision Support System for the Design of Healthy Office Buildings

Evidence from the literature (Blethyn & Parker, 1990; Turban, 1992; Klein & Methlie, 1995) and expert opinion (Mehandjiska-Stavrena, 1998), suggested that a Decision Support System was the most appropriate approach for achievement of the research objectives. The qualitative nature of the problem domain was a key determinate in this decision.

Other types of expert systems were investigated, and it was found that systems with sophisticated artificial intelligence would add complexity to the development process and limit the validation options.

DSS are capable of managing complex, dynamic problems, whilst providing a relatively simple and transparent structure of the embedded knowledge. This feature supports external validation by peer review of the embedded knowledge of the design tool, compared to other more advanced knowledge engineering approaches where the embedded knowledge is coded into a "black box" and validation by test cases is required.

A methodology for the development of the DSS as described in Siegal (1986) and Turban (1992) was used for this thesis. Seigal identified the need to clearly define the limits of the domain. Identification of a finite number of goals, solution approaches, relationships and factors was another crucial step.

It was apparent from the literature that a systematic solution approach that could be used across all types of contaminants types didnot exist. The vast majority of contemporary office buildings depend heavily on ventilation to control indoor pollutants, however ventilation alone has been identified in the literature as not always being an effective solution (Maroni, 1995). A conceptual model of the IAQ cycle, which encompasses a common solution approach, was developed and presented at two international conferences (Appendices 8 & 9) to subject the fundamental logic of the system to peer review. This IAQ solution approach is presented in Chapter 5.

Seigal's (1986) method required that the problem be broken into manageably sized portions of information by partitioning large sequences of events, concepts and features into progressively smaller groups of related details, until a conclusion on the potential impact on the quality of the IAQ could be drawn. To allow efficient manipulation of the data it was important not to add unnecessary levels and to structure the data to allow for inheritance of common sequences.

The problem was approached from the perspective of the building designer. Context trees were generated for each main section including site and external factors, building envelope, building infrastructure, interior features and heating, ventilating and air conditioning. These topics were subdivided into broad, then progressively finer levels of details on building features about which the building designer would need to make decisions. The conclusions were the potential impact on the generation, communication or mitigation of the concentration of pollutants in the office environment. This was presented graphically as a series of context trees, which showed the subdivision, linking and attributes of building features. The goals and sub-goals were redefined in the framework of the common solution approach, and the design criteria listed in Chapter 5 eventuated from this exercise.

Mapping the flow of logic in the opposite direction, from the conclusions on conditions that could create a source, pathway, driving force or mitigation technique for contaminants, back to the specific building features was also required. These logic flows were presented graphically as inference flow diagrams. Inference diagrams define the path of reasoning or logic employed to resolve the problem. They are structures with the goals or sub-goal at the bottom of the chart, related observable facts at the top and many layers of inferable relationships in between. Flow lines were also added to define the relationships between the many attributes. The inference diagrams were superimposed over the context trees.

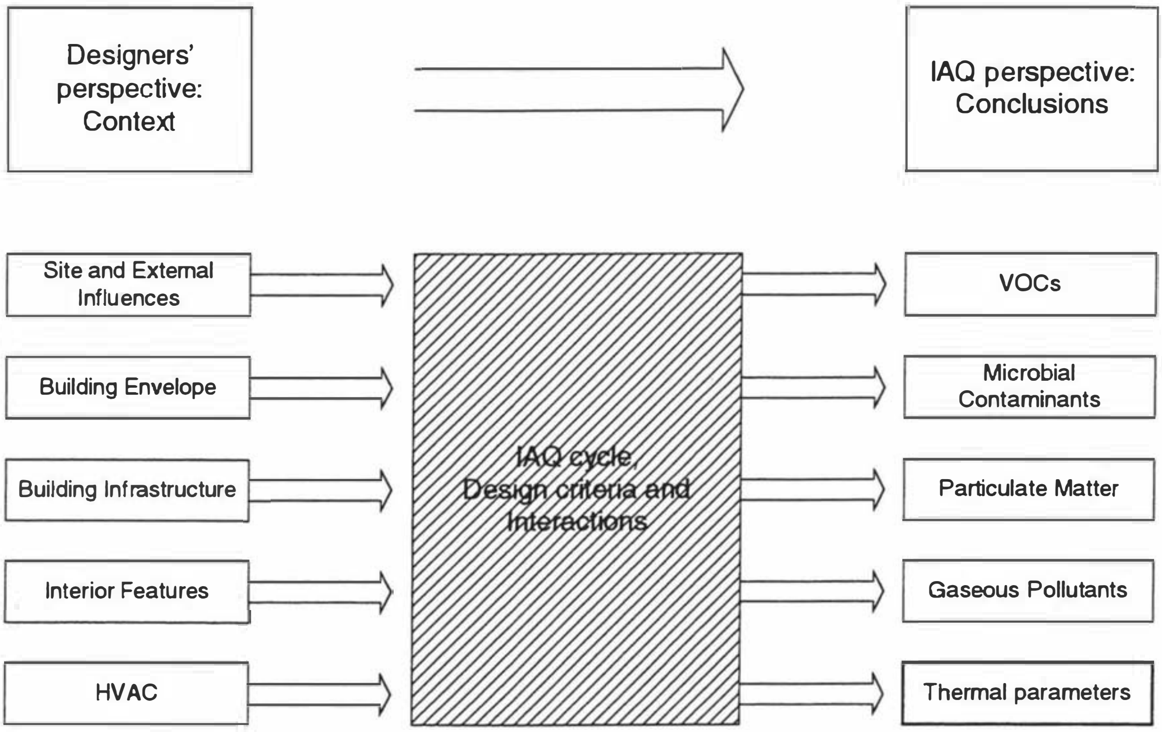

Figure 4-1 Flow of IAQ knowledge from context trees to conclusions

Frequent redrawing and refinement of the context trees and inference diagrams was necessary during the development of the DSS to eliminate redundant branches and levels.

During the development phase it became apparent that clarification of the boundaries of the problem domain was necessary to ensure consistency, completeness and manageability. Cleaning and building hygiene are one example of this. Cleaning and building hygiene issues were initially included in the problem domain as this is a topic identified in the literature as having a significant effect on the quality of the environment (Raw, 1993). However, during the development of the DSS it became apparent that the building features, such as access, that facilitate effective cleaning are a design issue and these have, therefore, been incorporated in the DSS, but the operational aspects, such as frequency of cleaning or method used, were considered to be outside the scope of this thesis.

Generation of the question database was the next stage of the development process. Questions evolved from the context trees. Seigel (1986) stated that questions should be continued until the design options are defined in sufficient detail to form a conclusion. Questions were structured to focus the designer's attention on the aspects and details of the building that potentially affect the healthiness of the indoor environment. A mix of prescriptive and performance style questions was used depending on the particular situation. A predefined selection of response options was added to the questions to limit the potential number of outcomes and give guidance to the user (Seigel, 1986).

Justifications and recommendations, based on the knowledge gained from the IAQ literature and the IAQ cycle solution approach, were added to each question response option. Detailed explanations of the effect that each building feature could have on the IAQ were given so that the external reviewers, and eventually the users, could follow the line of reasoning. The justifications also contribute to the educational requirement of a DSS.

Rewriting of the context trees, questions, justifications and conclusions continued in an iterative manner throughout the development of the system.

Gonzalez and Dankel (1993) introduced a quantitative element to DSS, which they called an Importance Factor. They suggested that Importance Factors, that quantify the importance and contribution to strength of the affect, should be included where possible. They stated that importance factors are derived from the expert's experience and the current knowledge of the domain rather than from a statistical database. They permit the expression of belief in each hypothesis, illustrating the effect of multiple sources of evidence.

Various Expert Shells and DSS software programmes were investigated, but were rejected to allow full transparency of the logic structure. This also allowed the research effort to be focused on the development of the logic and content of the DSS, rather than on production of a software programme. The question database and responses were generated within a spreadsheet to allow transfer to other data management programmes or an expert shell in subsequent stages of the system's development.

4.3 Validation of the Decision Support System

It was considered important that both the fundamental logic of the system, as well as the actual DSS were correct. Each of the validation approaches discussed in Chapter 3 was explored for its suitability for validating HEAD-Start, and the following conclusions were drawn.

The first validation approach outlined in Chapter 3 is the comparison of the results of solving the problem with, and without, the DSS. This approach would test many of the conclusions, but would not test the reasoning embedded within the system. There are also some practical limitations. It would be possible to design matched pairs of office buildings, with one building within each pair being designed with HEAD-Start, one other without, and measure the IAQ by either occupant responses or direct measurement of environmental parameters. This process would take several years and require considerable financial resources. However, evaluation of a small sample of matched pairs of buildings would not test either the breadth or the rigor of the system, and experimental costs would quickly escalate with the number of pairs of buildings. Buildings would need to be occupied to simulate real conditions and this would introduce bias from the occupants' activities. Non-identical microclimates, site attributes, and other confounding factors would need to be very carefully managed. It would not be possible to make the study blind to the designers, and this could introduce some bias. It would also raise human ethics issues, as the occupants of one of the buildings would be subjected to lesser quality conditions.

Validation with test cases would be difficult to achieve due to a lack of documented case history. Test cases would need to be invented and the number of cases required to test the breadth of the system would be very large. As actual results for the invented and test cases would not be available, this approach is at best a comparison of the ability to solve problems using HEAD-Start against the experts' intuitive reasoning. The test case approach would also not validate the reasoning of the system.

Validation using expert review would require the selection of experts from a wide range of disciplines to cover the breadth of the topic. Selection of reviewers can be a difficult process and can introduce bias to the results (Isaacs, 2001). The amount of time required of the reviewers, is a significant disadvantage of this approach.

Having multiple reviewers introduces a problem with consistency of reviewers' reporting styles. A structured report format can help address this issue. Sprague and Carlston (1989) suggested that expert opinions be captured on three,- five or seven - point scales to attempt to quantify the experts' perceptions. Further they suggested the results should be presented as graphical summaries to avoid implying statistical precision.

There are advantages and disadvantages with each of the validation methods. The performance comparison approach was considered the least suitable approach. A fundamental problem with validation by test cases was a lack of existing test cases and a review of fictitious cases would neither provide a comprehensive coverage of the system, nor attempt to validate the reasoning embedded within the system. Validation by expert review would expose the system's logic to critique and allow comprehensive coverage of the breadth and depth of HEAD-Start. Validation by expert review was, therefore, the chosen approach.

As the validation of a DSS requires a large time commitment and is a rather "dry" task, it was considered reasonable to assign only two sections to each reviewer. Reviewers assigned to the HVAC section were not requested to validate any other topics, as this section alone was over 100 pages. Assigning to each reviewer sections that were closely aligned with their particular expertise was also considered helpful.

Parochialism was identified in the literature as being a problem with this validation technique, particularly in domains that crossed discipline boundaries. Isaacs (2000) advised that some reviewers would give negative feedback that was unjustified, and advised that a reality check would be required in the interpretation of the reviewers' comments. To address these potential problems it was considered necessary to allow at least two reviewers per section and a cross-over in sections and reviewers (Table 4-1). Therefore, a minimum of two reviewers per section was considered necessary and more would add to the rigor of the validation process.

Table 4-1 Allocation of reviewers to section topics

Section	Reviewer							
	A	B	C	D	E	F	G	H
Site and external factors	X			X				X
Building Envelope	X	X						X
Building Infrastructure		X	X				X	
Interior			X	X			X	
HVAC					X	X		

In a similar validation exercise, Hand (1999) advised that only approximately 60% of experts invited to review a passive solar design tool indicated that they were available and willing to participate in the process. Hand also found that not all experts who had agreed to review their design tool, actually completed the review process, due primarily to conflict with other commitments.

In order to have all sections of HEAD-Start reviewed by at least two experts, expressions of interest in participating in the review process were sent to twenty IAQ experts. Invited participants were either active in IAQ research, or IAQ consultants with a scientific background.

A balance of Australasian and international reviewers was sought to bring both the knowledge of regional conditions and rigor of international critique. While there is a limited pool of people in Australasia with expertise in the design of office buildings with good IAQ, some narrower aspects of the system are well covered. Seeking experts from outside Australasia could introduce some regional bias due to differences in construction systems and environmental conditions, however this could be addressed in the reviewers' guidelines and interpretation of reviewers comments (Isaacs, 2000).

Experts who were already known to the researchers were selected for inclusion in the review panel. As the review process would require a considerable commitment from the reviewers, it was considered that strangers could struggle to commit fully to unsolicited requests for assistance.

Isaacs (2000) advised of the need to focus the reviewers on specific objectives. He recommended an approach similar to the review of a research paper. The instructions to reviewers from five journals were appraised. While none of these was sufficiently focused for the validation of a DSS, the instructions from the Royal Society of New Zealand (Appendix 3), which publishes three key New Zealand scientific journals, was considered the most comprehensive and provided a starting point for the development of the reviewers' questionnaire

Several texts on survey design were also consulted (Floyd, 1995; Statistics New Zealand, 1995).

Reviewers were asked to focus on the correctness and completeness of the justifications, recommendations and conclusions. The objectives of HEAD-Start were rewritten as questions and reviewers were asked to respond on a five point scale ranging from highly disagree to highly agree. Questions were presented in the order of specific to general. Additional questions such as "Does this section draw correct inferences from the current body of knowledge on indoor air quality?" and open questions on weakest and strongest points and any omissions, were also included to record reviewers' perceptions of the comprehensiveness of the system. A copy of a blank reviewers report form is included in Appendix 6.

Reviewers were also invited to make detailed comments directly on the hard copy of the system if they wished, and to offer any suggestions to improve the science, clarity, succinctness, and quality of presentation.

Lippiatt (2001) recommended that it was important to seek positive feedback where warranted, as in her experience reviewers inadvertently overlooked mentioning the good features, unless specifically requested.

Three colleagues tested the questionnaire and instructions to reviewers for comprehensibility, and minor changes to the questions and layout were made following their comments.

Consideration was given to the ethics of the research. As no research was being conducted on human participants or animal subjects, submission of a research proposal to the Massey University Ethics Committee was not required. The reviewers' comments and scores were coded so that only the principal researchers were aware of the author of each comment. No other ethics issues that needed addressing were identified.

Confidentiality and ownership of the intellectual property issues were discussed with Massey University's New Technology Manager. It was identified that the DSS would have some commercial value once the system was translated into a software aplication, but that it would be premature to attempt to patent the system at this stage of its development. Reviewers were, however, asked to respect the confidentiality of the work done to date.

Reviewers were given a copy of all the sections of HEAD-Start for their reference and so that they could see the fit between the sections. The topics assigned to them were printed on coloured paper so they would be distinct from other sections. A paper describing the philosophy of the system was also provided as background information. A small gift was sent to all reviewers to thank them for their time and involvement.

Reviewers were asked to complete and return their review forms within eight weeks. Reviewers who had not responded within ten weeks were asked if they still wished to participate in the review process or required further assistance. They were sent follow-up reminders or were contacted every three weeks until the review reports were returned.

Graphical summaries of the reviewers' scores were produced. Detailed statistical analysis was not conducted due to the small sample size of reviewers per section. The open questions and reviewers' comments were recorded and analysed. Appropriate modifications or editorial changes were made to Head-Start where necessary.

5 RESULTS

The results of the knowledge acquisition, development and validation of HEAD-Start are presented in this Chapter. Knowledge acquisition involved an extensive review of literature and completion of a series of interviews with experts in the fields of IAQ/SBS and DSS or expert systems. The development of HEAD-Start included structuring the problem domain into a manageable format; the principal result of this activity was the context trees. The indoor air cycle, which was developed to create a common solution approach, and the design criteria are also presented in this section. The results of the development of the question database - including the justifications, conclusions and importance factors, conclude the first part of the Chapter.

The second section of the Chapter contains the results from the validation of HEAD-Start, including the reviewers' evaluations and comments.

5.1 Knowledge Acquisition

Seven individuals with national and international expertise in IAQ/SBS were interviewed. Details of the IAQ/SBS experts interviewed are given in Appendix 2. Four of these experts were from the UK, two were from Australia and the last was from Canada. IAQ issues raised in the interviews were followed up with the relevant published literature and have been included in Chapter 2.

Interviews were also conducted with seven academics with expertise in the development of architectural design tools or expert systems. Five of these interviews were conducted early in the research project and primarily focused on the development process, the remaining three interviews concentrated on techniques for the validation of the system. Details of the experts interviewed for the development and validation of the DSS are also given in Appendix 2. The information gained from these interviews was incorporated into Chapters 3 and 4, as appropriate.

5.2 Development of the DSS

5.2.1 The Structure of Problem Domain

The methodology for the development of the DSS, described in Chapter 4, required the compartmentalisation of the problem domain into manageable levels of detail. The primary result of this activity was the preparation of the context trees and the top two layers of these are shown in Appendix 4. The context trees graphically show the redefined problem domain as well as the structure of the DSS.

5.2.2 The Question Database

Each of the factors identified in the context trees were expanded into questions, structured to lead the users of the DSS to consider the building features and issues requiring consideration. A choice of typical design solutions was given for each question, and every conclusions and justifications on the impact on the IAQ were given for each design solution. The justifications and conclusions were drawn from the information found in the literature review.

Importance factors were added to each conclusion to indicate the contribution that each building factor had on causing, communicating or mitigating an IAQ problem. Importance factors were assigned separately for each of VOCs, particulates, gaseous pollutants, microbiological contaminants and thermal interactions. Importance factors were given on a seven-point scale ranging from –3 to +3. Building features, which were assigned an importance scale of –3 were considered to exert a strong negative impact on either the generation of a source or the pathway of a pollutant. An importance factor of zero was given to building features that had a neutral effect, or for which further information was required before a conclusion could be drawn.

Building features that were given an importance score of +3 were considered to have a strong mitigating effect.

The question database including answers, justifications, conclusions and importance factors is presented in Appendix 5.

5.2.3 The Common Solution Approach: The Indoor Air Quality Cycle

There are many conceptual similarities in the sources, communication between parts of the building and removal strategies of particulate matter, microbiological contaminants, VOCs, and gaseous pollutants. It was deduced from the literature that IAQ problems occur when all of the following major elements of the indoor air quality cycle occur:

- A primary outdoor, indoor or intermediate source of a contaminant;
- A pathway for the transportation of the contaminant to the occupied areas;
- A driving force for the transportation of the contaminant from the source to the occupied areas, intermediate factor or reservoir;
- Occupants or a reservoir within the space.

The level of indoor pollutants can be expressed as the sum of the contaminants generated and communicated to the occupied areas, less those removed via various mitigation techniques. This cycle is illustrated in Figure 5-1.

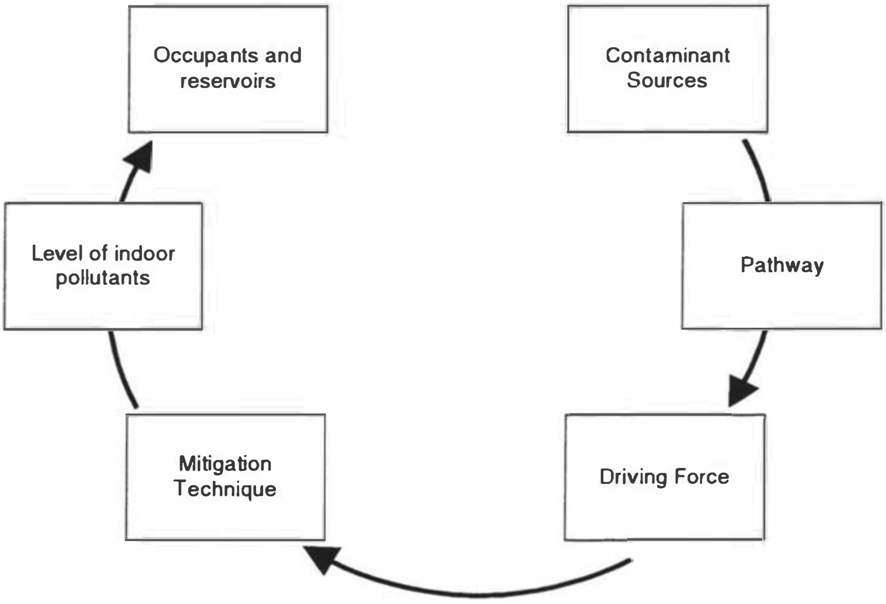

Figure 5-1 The major elements of the Indoor Air Quality Cycle

If any of the above elements are removed then the magnitude of the IAQ problem is decreased. Conversely, the magnitude of the problem will generally be exacerbated if the strength of the source, pathway or driving force is increased. Between the origin of the source and the occupants' exposure to the contaminants there are frequently opportunities to mitigate the problem.

Two papers on the logic of the DSS were presented for peer review at international conferences (these papers are attached in Appendices 8 and 9). The first paper (Phipps, 1997) was presented at the combined ISIAQ Fifth International Conference on Healthy Buildings/ASHRAE Annual IAQ Conference, 1997. This paper was awarded a 2nd prize at this conference. The second paper (Phipps, Wall, & Laird, 2001) was presented at the CIB International Congress, 2001 and was also very well received.

5.2.4 The Design Criteria

The goals for the design of an office building with good IAQ, as detailed in the objectives of this research (Chapter 1), were expanded into a set of design criteria derived from the literature presented in Chapter 2. The design criteria were written in the framework of the IAQ cycle. These design criteria are listed below under the headings of each pollutant type and component of the IAQ cycle.

5.2.4.1 Gases

The objective for gaseous pollutants was:

To have concentrations of gases such as carbon dioxide, carbon monoxide, oxygen, ozone, nitrous oxides, and sulphurous oxides within acceptable standards in all occupied areas.

This objective was expanded into a series of design criteria, which were written within the context of the IAQ cycle discussed above. The design criteria for gaseous pollutants focused on the control at the source of pollutants, the pathways and driving forces by which gaseous pollutants can enter a building or move between spaces. The main mitigation techniques for gaseous pollutants identified in the literature were extraction and dilution ventilation and these are emphasised in preference to other mitigation techniques. The design criteria for gaseous pollutants are listed below.

Gases: source control

- To have a site with low ambient concentrations of gaseous pollutants.
- To have priority given to the avoidance or removal at source of all gaseous pollutants.
- To minimise emissions of gaseous pollutants from indoor sources such as photocopiers and laser printers, sanitary fixtures and combustion processes.
- To have sufficient air supplied to all combustion sources to allow for complete and clean combustion.

Gases: pathways and driving forces

- To have priority given to the emissions of gaseous pollutants which are close to the breathing zone of the occupants.
- To isolate all direct and indirect pathways between occupied areas and areas with concentrations of gaseous pollutants above acceptable standards.

- To have all localised areas with sources of gaseous pollutants, such as carparks and generator rooms, isolated from other occupied areas at all times when gaseous pollutant concentrations from the source are present.
- To have all openings in the building envelope located to preclude the entry of gaseous pollutants from external sources.

Gases: mitigation

- To have localised extraction directly to the outdoors, adjacent to all interior sources of gaseous pollutants, with equal amounts of make-up air from a clean source.
- To have sufficient ventilation to dilute building and occupant generated gaseous contaminants during periods when the building is occupied and leading the occupied periods.
- To have operation of the ventilation synchronised with the emissions of the gaseous pollutants.
- To have good room air mixing for effective dilution ventilation.

The design criteria for the control of VOCs are listed using the same structure outlined above.

5.2.4.2 Volatile Organic Compounds

The objective for VOCs was:

To have VOCs, such as formaldehyde, below appropriate standards or guidelines in all occupied areas.

This objective was expanded into a series of design criteria, which were written within the context of the IAQ cycle. The design criteria for VOCs focused on the control at the source of pollutants, the pathways and driving forces by which VOCs can enter a building or move between spaces, and the mitigation techniques available. These design criteria are listed below under the headings of each component of the IAQ cycle.

Volatile Organic Compounds: source control

- To have a site with low ambient concentrations of VOCs.
- To select construction and finishing materials, furniture and fittings with low or no emissions of VOC and limit the quantity of construction and finishing materials, furniture and fittings which are emitters of VOCs.
- To pre-condition materials which could emit VOCs, before they are installed in the building.
- To have no environmental tobacco smoke within, or where it could be entrained into, the building.
- To have few VOC sinks in areas with materials, activities or processes which could emit VOCs.
- To avoid or restrict the installation of finishing materials which do not require the use of VOC emitting cleaning products.

Volatile Organic Compound: pathways and driving force

- To have priority given to the avoidance or removal at source of emissions of VOC from materials that will be located close to the breathing zone of the occupants.
- To locate all materials, appliances and activities that could emit VOCs, but cannot readily be eliminated from the building, as far as possible from the main occupied areas.
- To isolate all occupied spaces, from other areas with concentrations of VOCs above acceptable standards.
- To isolate all pathways, such as lift shafts, stairwells and ducts, from other areas with concentrations of VOCs above acceptable standards.
- To have all localised areas with sources of VOC, such as print rooms, isolated from other occupied areas at all times when VOC concentrations from the source are present.
- To have all openings in the building envelope located to preclude the entry of VOCs from external sources.

Volatile Organic Compounds: mitigation

- To have sufficient air exchange with fresh air to dilute VOCs emitted from the materials, furnishings and occupants' activities during all intervals when VOCs could be emitted. This includes the first 12 months following the installation of new VOC emitting materials, periods of high indoor temperature when the emission rate of VOCs can increase and during periods of occupant generation of VOCs.
- To have sufficient localised ventilation and extraction directly to the outside to remove emissions from point sources.
- To have good room air mixing for effective dilution ventilation.
- To have air cleaners for removal of VOCs from specific activities and intervals.

5.2.4.3 Biological and Microbiological Contaminants

The objective to control the indoor concentration of biological and microbiological contaminants was expressed as:

To have low concentrations of biological and microbiological contamination in or around the building.

This objective was expanded into a series of design criteria using the IAQ cycle, as previously described. The design criteria for the control of biological and microbiological contaminants are listed below under the headings of source control, pathways and driving forces and mitigation techniques. Emphasise was placed on source control and containment as it was identified in the literature that treatment of building materials which have become contaminated with microbiological organisms is not always effective and complete replacement is generally recommended (Nathanson, 1995b).

Biological and microbiological: source control

- To have a site with low ambient concentrations of biological and microbiological contaminants.

- To minimise the opportunities for moisture to stand in and around the building.
- To minimise the moisture content of materials in and around the building, and maximise the opportunities for materials to be rapidly dried where wetting cannot be avoided.
- To have low admission of viable microbiological matter and nutrients from outside sources or between areas with a high concentration of viable spores, moisture or nutrients and occupied areas.
- To have low available water in all construction and finishing materials, and provision for drying out all wet construction processes within as short a period as possible.
- To have no inclusion of moisture through the building envelope or sub-grade structure.
- To have no interstitial, inter-ducting or room condensation.
- To have no birds roosting near air intakes or within the building.
- To have no rodents, cockroaches or other such pests, and low levels of dustmites within the building or near air intakes.

Biological and Microbiological: pathways and driving forces

- To isolate the occupied areas from air which could be contaminated with bioaerosols.
- To have particular attention paid to the control of moisture and nutrients in parts of the building which are near to or along the air supply stream or the occupied areas.
- To have particular attention paid to the control of moisture and nutrients in parts of the building which are difficult to access.

Biological and Microbiological: mitigation

- To have provision for appropriate cleaning, monitoring, servicing and maintenance of all areas which are subject to wetting or moisture.

- To have provision for appropriate cleaning, monitoring and maintenance of all areas which have a supply of organic nutrients, such as food preparation and consumption areas.
- To have sufficient air changes for dilution of bioaerosols.
- To have good room air mixing for effective dilution ventilation.
- To have high efficiency filtration next to sources of microbiological organisms.
- To have appropriate treatment of all reservoirs of water in, or around the building, to limit the amplification of microorganisms.

5.2.4.4 Particulate Matter

The objective to reduce the indoor concentration of particulates within the office environment was written as:

To have low concentrations of particulate matter, especially respirable and inhalable particles.

This objective was expanded in the same manner as the previous three objectives and the design criteria are listed below under the headings of source control, pathways and driving forces and mitigation techniques.

Particulates: source control

- To have a site with low ambient concentrations of particulate matter and physical separation from particulate generating activities. This includes physical separation from roads, chimneys, industry, and large sources of pollen and leaf mould.
- To have no environmental tobacco smoke within or adjacent to the building.
- To minimise where possible, or contain, particle generating activities, such as paper handling, food preparation and consumption.
- To minimise the quantity of particle generating materials, such as fleecy surfaces including floor coverings, upholstery, screen coverings, window treatments, open shelving and paper storage area, and exposed insulation.

- To have low particulate concentrations in areas with VOC or gaseous pollutants.
- To have low concentrations of particulates within the ventilation ducting and components.

Particulates: pathways and driving forces

- To have low admission of particulates from outside sources, including capturing particles at entrances, and low levels of infiltration of unfiltered air.
- To have no cross-contamination between occupied spaces and areas with combustion sources, including carparks.
- To minimise the quantity of air being drawn into the building from particle-laden sources.

Particulates: mitigation

- To have particle removal mechanisms appropriate to the predicted occupant density, particle load generated by the occupants and predicted external sources of particles.
- To have particle removal mechanisms, appropriate to the construction methods, during construction and prior to occupation.
- To have high levels of particle capture at all times when particle concentrations are above acceptable standards or when the HVAC system is being operated.
- To have low levels of particle re-entrainment and resuspension.
- To have access to all parts of the building which are in contact with the indoor air to enable high standards of cleaning.

5.2.4.5 Thermal Interactions

The thermal interactions objective was written as:

To have a thermal environment that does not cause conditions detrimental to other design criteria.

The thermal interactions objective was expanded into four design criteria. These criteria were not linked into the format of the IAQ cycle as the thermal interactions objective was related to the control of thermal parameters that could cause a thermal environment which was detrimental to the design criteria for gaseous pollutants, VOCs, Biological and Microbiological Contaminants and Particulate Matter. The four design criteria for thermal interactions are listed below.

- To have interior relative humidity between 40 - 60% in all areas of the building.
- To have the surface temperature of the floor, walls and ceiling between 19 and 26°C.
- To insulate the exterior envelope to prevent condensation occurring within the structure, room surfaces or service areas.
- To minimise solar heat gain and heat emitted from office equipment to avoid high interior temperatures.

5.3 Validation of HEAD-Start

Nine of the twenty IAQ experts who were invited to participate in the validation process responded to the invitations. Eight respondents indicated they were willing and available to participate. The ninth respondent responded that he was very interested but currently over-committed.

Of the eight experts who indicated their willingness to participate in the review process, equal numbers were from Australasia and further afield. Two reviewers were from each of New Zealand, Australia and the United Kingdom, and one each from Canada and the USA.

Six of the reviewers had a background in IAQ research. The remaining two were IAQ practitioners, but had a strong interest in keeping current with the latest research. The reviewers represented a broad range of background disciplines, including building physics (1), environmental chemistry (1), psychology (1), architecture (1) and mechanical engineering (4).

Two of the mechanical engineers conveyed their preference to review the HVAC section, and were assigned this section. Sections were assigned to the remaining reviewers depending on their particular expertise and coverage of the sections.

Reviewer B - who had been asked to review the Building Envelope and Build Infrastructure sections - returned the folder and forms within fours weeks of receipt, with a note advising that he would be away for the next three weeks and would not have time to complete the section on Building Infrastructure. This section was subsequently sent to Reviewer C, in order to have all sections peer reviewed by at least two independent experts. Reviewer C made in depth comments on the infrastructure section, but did not return the reviewer's questionnaire. Reviewer A had not completed the review process within eleven months of dispatch of the material. All other reviewers completed all sections as requested.

The sections completed by each reviewer are summarised in Table 5-1.

Table 5-1 Sections completed by each reviewer

Section	Reviewer					
	B	G	D	E	F	H
Site and External Factors			X			X
Building Envelope	X					X
Building Infrastructure		X				
Interior		X	X			
HVAC				X	X	

The level of detail in the reviewers' comments suggested that all of them, with the exception of Reviewers A and B, had committed considerable time and effort to the review process.

5.3.1 Reviewers' Results

Graphical summaries of the reviewers' evaluations are shown in Figures 5.2 – 5.4 below. Reviewers were asked to respond to each question on a scale of 1-5, where 1 was strongly disagree and 5 was strongly agree.

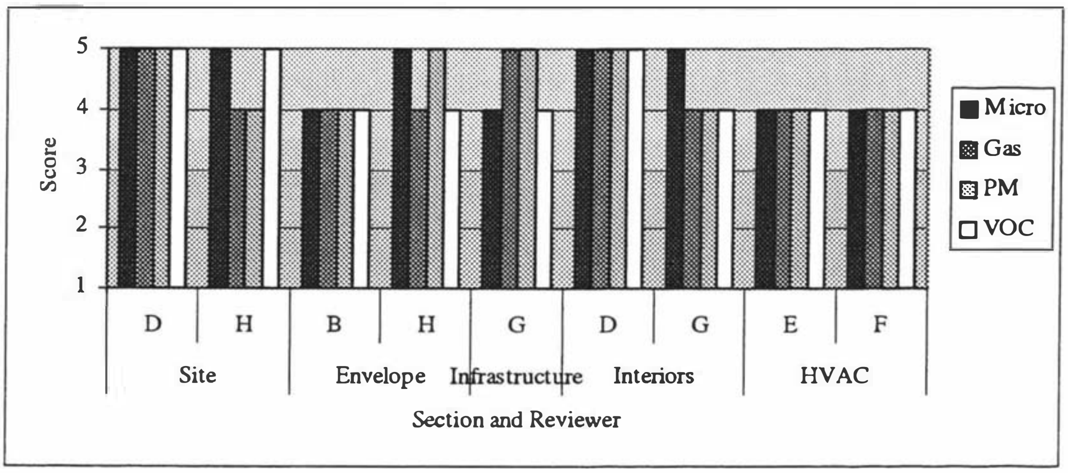

Figure 5-2 Reviewers' responses to "Does (*this section*) adequately identifies how components of the building could contribute to the generation of each type of pollutant"

The aggregated data for each section, showed that the average values assigned by the reviewer's for "identification of pollutant sources" for each of the four pollutant types of microbiological, gaseous, particulate matter and VOCs were, respectively, 4.6, 4.3, 4.4 and 4.3. The values assigned by the reviewers for this question had a range of 4 – 5 out of 5.

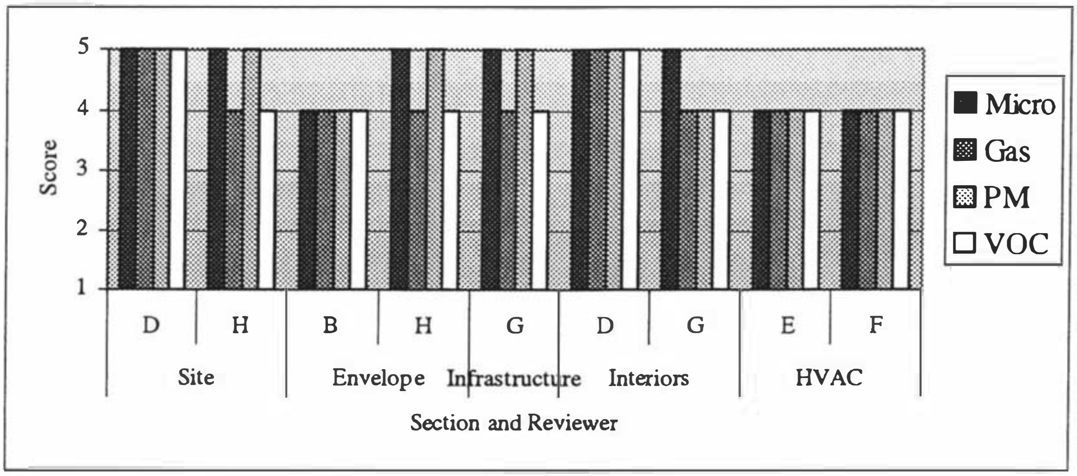

Figure 5-3 Reviewers' responses to "Does (*this section*) adequately identifies how the components of the building could form a pathway for the movement around the building of each type of pollutant"

The averages of the reviewers' responses to the "identification of pathways for the movement of pollutants around the building" across all sections were calculated as microbiological (4.7), gaseous pollutants (4.2), particulate matter (4.6) and VOCs (4.2). The reviewers' responses to this question ranged from 4 to 5 on a 5-point scale.

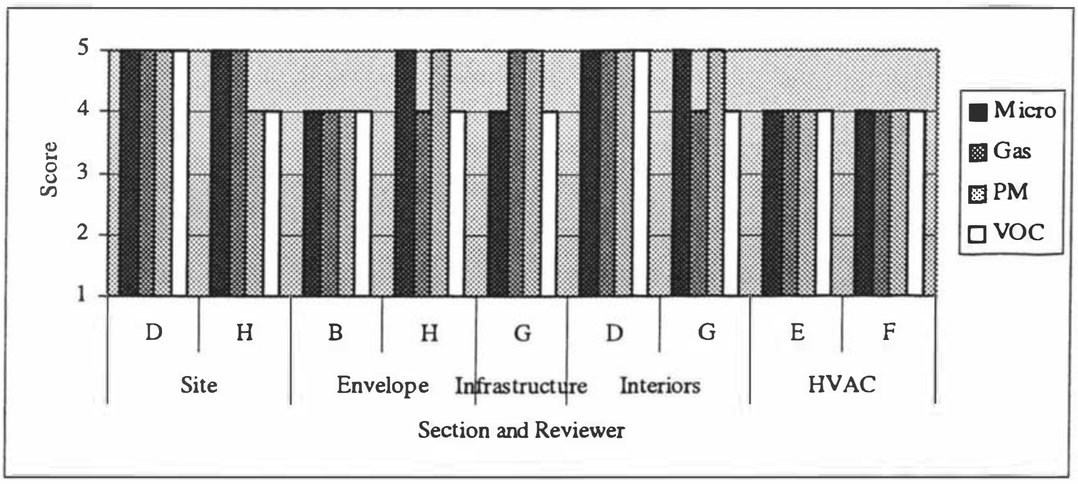

Figure 5-4 Reviewers' responses to "Does (*this section*) draw correct conclusions on the effects which each type of pollutant that originates within the (*section*) can have on the indoor environment"

The average of the reviewers' responses presented in Figure 5 – 4 for each pollutant type were calculated as microbiological (4.6), gaseous pollutants (4.4), particulate matter (4.6) and VOCs (4.2). The scores given by the reviewers' to the above question ranged from 4 to 5 on a 5 – point scale.

The reviewers were also requested to respond on a 5 – point scale to the five questions listed below. Their responses to these questions and the average value given for each question are listed in Table 5-2.

Does this section draw correct inferences from the current body of knowledge on indoor air quality?

- Is this section consistent with the IAQ model described in the attached paper?
- Would this section assist a building designer, who is not an expert in indoor air quality, make decisions which will lead to a healthy office building environment?
- Would this section help educate a designer, who is not an expert in indoor air quality, in indoor air quality issues?
- Is the information in this section is presented in a logical sequence?

Table 5-2 Reviewers' responses to above questions

Section	Reviewer	Draws correct inferences from literature	Consistent with IAQ model	Provides correct assistance for designer	Educates designer	Logical sequence
Site	D	5	5	5	5	5
	H	5	5	5	5	5
Envelope	B	4	4	4	4	4
	H	5	5	5	5	5
Infrastructure	G	4	4	4	4	4
Interiors	D	5	5	4	4	5
	G	5	4	5	4	4
HVAC	E	4	4	5	5	5
	F	4	4	4	4	4
Average		4.6	4.4	4.6	4.4	4.6

The reviewers' responses to the open-ended questions were copied directly from their reports and are listed by each question in the following tables. Several of the reviewers elected to make brief comments in separate communications either verbally or by email. These additional comments have been included in the tables below and the mode of communication is identified with a footnote. Reviewer C made in depth comments on several aspects of the Infrastructure section in a separate email. These comments and a response to these comments are summarised after Table 5 – 5 and briefly discussed in Chapter 6. The comments and responses made by reviewer C are included in full, in Appendix 7.

Table 5-3 Reviewers' responses to "What is the weakest point of this section?"

Section and reviewer	Reviewers' Comments
Site	
D	No detectable weaknesses. This section is an important component of a Decision Support System
H	Nothing, very impressive system
Envelope	
B	Needs a brief introduction which gives overview of structure of programme. Seems a bit long, winded but when programmed this will not be a problem.
H	A bit repetitive in hard copy. Will make great software.
Infrastructure	
G	Given that it is a paper based tool at this stage, the interactions with the designer will improve with the translation to a computer based tool. One element which should be considered is the scaling of decisions, e.g. no of staircases, lifts, etc, could have a marked effect, carparking areas. Same of prioritisation given the scale of the building would be useful.
Interiors	
D	My previous email comment would assist in strengthening this section in a minor way.[2] This section is already very comprehensive.
G	Very impressive. As with previous section, it would be important to include graphical representation of recommendations within the paper

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[2] Reviewer D made two suggestions in a separate email. The first suggestion was to add a separate section on childcare facilities and the second was to amend the justification in the question database on the potential for formaldehyde to be released from particleboard, to include reference to new manufacturing processes which can produce formaldehyde-free particleboard.

	based and computer program to improve the design awareness of the user. The text based method would be improved when translated into a computer.
HVAC	
E	Nothing major – see list of notes and comments on separate sheets
F	Perhaps a listing of actual design/ ventilation/ IAQ standards and guidelines would help the designer. A list of do’s and don’ts.

Table 5-4 Reviewers' responses to "What is the strongest point of this section?"

Section and reviewer	Reviewers' Comments
Site	
D	The section augments the Decision Support Tool for designers in a manner that enables designers to cover ALL the critical issues for a healthy office environment. It is an excellent and comprehensive document. I believe your concept and approach is excellent.[3]
H	Very simple but effective approach – the IAQ cycle is a very useful approach to a complex task.
Envelope	
B	Comprehensive. There is a good logic in question order. Starting with yes/no questions good for user.
H	An appropriate and insightful use of ventilation. ASHRAE 62-1999 revision committee should welcome this approach. Extremely comprehensive.
Infrastructure	
G	Simple language and straight forward nature of recommendations.
Interiors	
D	This section once again provides valuable information in a clear, precise manner and which will enhance the decision support tool for designers
G	Excellent detail within the interiors section, which provides a good overview for design decisions.
HVAC	
E	Impressive comprehensive coverage of the issues – from the major to

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[3] Comments made in separate correspondence.

	the minor- interpreted under IAQ. Much more comprehensive than a similar type of document where we had three senior researchers working fulltime on the project.[4] It is against my principles to give 5/5, but I found I had.[2]
F	Gets into a "process" to assist the designer from start to finish. It is a solid way to get professionals resolving IAQ building / design / systems problems and issues.[1]

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[4] Verbal comment.

Table 5-5 Reviewers' responses to "Does this section have any important omissions?"

Section and reviewer	Reviewers' comments
Site	
D	None. Head-Start is an important initiative for ensuring healthy office buildings. We would certainly use this tool when it has become an electronic version.
H	Nothing missing. Could you add a chapter on radon and ETS for the US market.
Envelope	
B	No
H	Nothing
Infrastructure	
G	Some cam or graphical illustration or guide for designers would be useful to consider.
Interiors	
D	None.
G	No references to computer equipment, task lighting and peripherals apart from photocopiers and fax machines. Mobile phones etc. should be addressed within interior section.
HVAC	
E	More consideration of "advanced natural ventilation systems" Some definition of the terms and possibly a statement of the basic assumptions. Explanations of the rating scale and what it presents. Do ceiling fans matter??

	It is very difficult to think of anything that you have missed out as the system is extremely comprehensive.[5]
F	No – Very comprehensive and complete

A summary of the detailed comments made by Reviewer C on the Infrastructure section, are presented below and given in full in Appendix 7. A summarised response to reviewer C's comments is given in Chapter 6, and a full response is presented in italics following each comment in Appendix 7.

Reviewer C stated that he considered the Infrastructure section was "already very impressive" and the detailed comments were made with the view to further improvement. The majority of Reviewer C's comments were in agreement with the question database, and were either querying New Zealand's construction practices or seeking clarification on the finer detail. Some of the comments related to topics that were not included in the Infrastructure section but were included in other sections of HEAD-Start.

Reviewer C suggested that air pressure relationships should be used to prevent the spread of pollutants between stairwells, toilets, lifts and other occupied areas. He considered that the use of vestibules carried a space penalty and had implications on fire evacuation routes. He also noted that stairwells could be used to either supply naturally semi-tempered air or air extraction. He recommended that locating kitchens/food areas on the top floor of the building would reduce the need for isolating the air pathway between the kitchen and the stairwells with vestibules. Reviewer C also mentioned the importance of cleaning of duct interiors, and the need to place priority on the control of contamination in the HVAC system, rather than the plant room. This reviewer also queried if re-entrainment of contaminants exhausted from the building was covered in other sections.

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[5] Verbal comment

Adding a weighting to the level of vehicle activity in carparks and loading docks was suggested Reviewer C, as this would influence the degree of extraction of exhaust emissions and pathway protection required. Inclusion of the IAQ impact of recycling and re-use storage areas; insulation of infrequently used cold pipes in warm areas; and the need for multiple cleaners cupboards so that cleaners were not tempted to dilute chemicals in the occupied areas were topics that Reviewer C suggested could also be included in HEAD-Start.

Reviewers C asked whether, or not, the designer would have control of the use of storerooms, the specification of printing equipment, the operation of the ventilation and filtration systems, and cleaning of interior surfaces.

5.4 Conclusions of Results

The structured methodology for the development of the DSS was critical. This enabled the topic to be subdivided into manageable segments, as well as providing a framework for consistent treatment of detail between sections and checking for completeness or duplication between sections. The development of the IAQ cycle was a vital component of the framework and enabled the integration of solution approaches that were applicable to the different pollutants types.

Peer review allowed independent critique of both the methodology and completed text-version of HEAD-Start. The methodology was presented at two international refereed conferences and received very positive feedback, and one conference prize.

Different sections of Head-Start were reviewed by seven independent IAQ experts, and were given very comprehensive and positive feedback. The reviewers considered that the IAQ knowledge embedded within HEAD-Start correctly presented the current body on knowledge on IAQ issues, and would assist a building designer who was not an expert in IAQ, make decisions which would lead to a healthy office building. The reviewers responded to these two key questions with an average score of 4.6 out of 5 for both questions. The aim of two completed critiques for each section was achieved for all sections, except the Infrastructure section. The structured reporting form was important to provide consistency and a degree of quantification of the reviewers' responses.

6 DISCUSSION OF RESULTS

The results from the research are discussed in this Chapter. Discussion of the knowledge acquisition phase of the research includes the completeness of the literature and other areas where further published material would support the Healthy Office Building design criteria. The discussion of the development of the DSS and solution approach includes a review of the effectiveness of the development process and the IAQ cycle. The evaluations and comments made by the reviewers during the validation phase, plus a review of the validation process, are the last topics discussed in this chapter.

6.1 Knowledge Acquisition

The literature review provided evidence that there have been many studies conducted on various aspects of IAQ research in the last twenty years (Refer to the Literature Matrix - Appendix 1). Many areas had been well researched, but there were some important gaps in the knowledge.

Areas that have been well researched include emissions of VOCs from materials, propagation of microbiological contaminants under controlled conditions, and concentrations and sources of gaseous pollutants.

Research on respirable particulates in relation to IAQ is an emerging topic. The number of papers published on concentrations and behaviour of respirable particulate matter has increased in the last five years, but there is still a need for additional information on the concentrations and characteristics of particles found in office environments, and studies of the effectiveness of particle removal strategies under real conditions (USA EPA, 1990).

Little research was found on emissions of VOCs from materials under non-steady state environmental conditions, including the diurnal variations in temperature, humidity and airflow, which typically occur in an office building. An area where there appears little published research was on the effects on VOC emissions from finishes with high concentrations of VOCs applied over semi-porous or porous substrates that are commonly found in buildings, such as gypsum plasterboard, wood fibre board and concrete.

New manufacturing processes are aiding the production of construction and finishing materials with lower emissions of VOCs (Gilbert, 2001), and regular updating of data on chemical emissions and their performance under New Zealand conditions would allow the inclusion of specific, rather than generic, advice on material selection.

Data on the effects of non-steady state psychometrics on the growth and viability of microbiological organisms are important to the IAQ in buildings. While only one paper was found on this topic (Cunningham, 1996), this excellent paper showed that only intermittent rises in relative humidity were required to provide favourable conditions for dustmites. No publications on the affects on fungi or bacteria under non-steady state psychometric conditions were found. This could be important in the context of New Zealand's maritime climate, which is characterised by rapid fluctuations in both temperature and humidity.

Research on moisture in housing, which has been conducted in New Zealand, suggests that the risk of microbiological allergens growing in New Zealand's domestic buildings is equivalent to, or higher than, the risk in the UK or Scandinavia (Wickens et al., 1997; Kennedy et al., 2000). While further research specific to the New Zealand context could add clarity to the extent of microbial contamination in New Zealand buildings, there is currently sufficient strong evidence to support the need for measures to remove moisture sources from buildings. Consequently, heating in winter and cooling in summer to control the indoor relative humidity, and removal of additional sources of moisture are vital.

The area where little comprehensive research appears to have been undertaken is the additive and synergistic effects from different pollutants. There are many obvious practical difficulties in conducting research on the health effects and interaction betweens many types of pollutants. Some researchers (Mølhave, 1996), have found difficulties determining the combined health effects from a small set of commonly found VOCs. The difficulties with conducting and validating this research would obviously be compounded many-fold if other pollutants, such as fungi and particles, were also included in an experiment.

While more knowledge on the interactions between IAQ factors would allow greater precision in the prioritisation and quantification of the design criteria and selection of building features, there is sufficient knowledge on the causes of poor IAQ to justify changes to current building techniques. This observation was also made by Bascom (1997), Turner et al. (1999), and Maroni and Seppänen (2000).

6.2 Development of HEAD-Start

The methodology provided a systematic approach, by which to structure both the features of an office building that impact on the indoor air quality, and the design criteria, into manageable portions. Transparency of the logic structure facilitated updating of the question database during the development of the system as new IAQ knowledge was incorporated. It highlighted areas were there was duplication, overlap or gaps between sections. It also allowed crosschecking for completeness and consistency between the literature review and the question database.

Partitioning and subdividing the building features into successive sub-levels of detail until a conclusion could be drawn was a vital stage of the methodology. From a developmental perspective, this was a useful technique and proved a suitable working framework for the development of the DSS. The context trees provided a clear overview of the relationships between building features, and this provided a logical structure from which the question database could be developed. A logical structure for the question database was important to eliminate any duplication or omissions in the content of the DSS. All reviewers scored the logical presentation of the material in the sections, which they reviewed, as either 4 or 5 out of 5, with the average score for this question being 4.6.

The context trees also supported the definition of the questions and responses within the question database. If the justification and conclusions drawn about a design decision on a particular building feature were too complicated to be expressed in a simple IF-THEN style statement, without conditional sub-clauses, then that particular branch of the context tree on the building feature needed to be further subdivided.

Consequently, it was necessary to have a large amount of repetition in the justifications and conclusions between related branches. This increased the size of the hard copy version of the system, but would allow for inheritance of common material and a substantial reduction in size once the system is developed into a software application. Three of the reviewers considered the repetitious nature of the hard copy version as the “weakest point” of the sections reviewed. However, they all also acknowledged that this would be resolved once HEAD-Start was programmed into a computer-based system.

Although all justifications and conclusions were derived from the IAQ/SBS literature, it was not possible within HEAD-Start to consistently cite references alongside the justifications or conclusions. The justifications and conclusions linked to specific building factors constitute the application of the fundamentals established in the research. For example, it is well documented in the literature that moisture is generally the only additional ingredient required in an office building to allow the propagation of fungi (Burge, 1995; Morey, 1996). Some of the sites that are at risk of fungal colonisation, such as exposed porous insulation downstream of cooling coils are well documented (West & Hansen, 1989). From the literature, it does not appear that the research has investigated fungi concentrations in all the specific locations in which moisture could be found, but it follows that all areas with the potential for available moisture, such as refreshment serving areas, and entrance areas where rain water can be walked in, also share the conditions necessary to support the amplification of microorganisms, even though specific references were not available for each at risk site.

Therefore, one of the objectives of the research was to identify all locations with the potential to have available moisture and/or nutrients throughout the life of the building, draw the designer's attention to the risk and suggest healthier alternatives. The reviewers scored the identification of building components which could contribute to the generation of microbial contaminants between 4 and 5 out of 5 with the average score of 4.6. The reviewers also awarded scores between 4 and 5, with an average of 4.6 out of 5 across all sections on the correctness of the conclusions on the effects which microbial contaminants have on the indoor environment.

6.3 The Indoor Air Quality Cycle

6.3.1 Comparison of the IAQ Cycle with Other Solution Approaches

The Indoor Air Quality Cycle presented in Chapter 4 fits neatly with the general occupational health and hygiene approach to controlling pollutants, which employs the following hierarchy:

- Eliminating or minimising pollutants,
- Substitution with more benign products or systems,
- Enclosing or isolating the process, materials or system,
- Partial enclosure with local air extraction,

- Dilution ventilation,
- Personal protection,
- Monitoring and surveillance.

This hierarchy of pollutant control is applicable to office environments - with the exception of personal protection , which is seldom feasible or necessary. This hierarchy helped form the decision-making philosophy used in the HEAD-Start system.

Only two other sets of design criteria for the design of office buildings with healthy IAQ, which encompassed the control of all pollutant types, were found in the literature (Godish, 1989; Liddament, 1999). Godish's (1989) objectives were not given a hierarchical structure, however they fit within the solution approach of the IAQ cycle and design criteria.

Liddament's (1999) "Optimum IAQ" design approach is similar to the IAQ cycle presented in this research, in that it prioritises source control, and isolation ahead of ventilation and pollutant removal. His model had also separated outdoor and indoor sources of pollutants and suggested alternative treatments for each origin of pollutant. Liddament stated that ventilation should be regarded as a component of the IAQ equation rather than as the whole solution, which also is one of the premises of the IAQ cycle developed for this thesis.

The differences between Liddament's model and the IAQ cycle are mainly in the terminology used and prioritisation of elements. Liddament (1999) suggested that the indoor concentration of pollutants generated outdoors should be handled by source control, filtration, location of air intakes and building air-tightness. In the IAQ cycle, the latter two of these four strategies were grouped together under the term of "pathway control", and were placed ahead of filtration, which is considered in the IAQ cycle along with other mitigation techniques.

6.3.2 Implications of IAQ Cycle

The IAQ cycle concept provided a very useful and systematic framework for the consideration of the impact which building features have on the concentration of indoor pollutants. It provided a logical structure for the application of the research findings presented in Chapter 2. Some of the implications of the IAQ cycle and how these were interpreted in HEAD-Start are discussed below.

6.3.2.1 Contaminant Sources

Elimination of the source of pollutants is the preferred design option (Maroni et al., 1995). The question database prompts building designers to identify the pollutant potential of the site, building materials and components. Materials with low emissions and low absorbance of gas phase pollutants, low water availability or porosity in areas prone to dampness, and low shedding of particles are recommended. Where this is not feasible, more needs to be known about the nature of the pollutants in order to determine the most appropriate method of control.

The gas phase pollutant source control models suggested by Seifert and Ullrich (1987) and Levin (1992b), which gave spatial and temporal attributes to contaminant sources, are compatible with the IAQ cycle and provide very useful distinctions to source control strategies and mitigation techniques appropriate for each pollutant source. Spatial attributes include whether the source is distributed, for example VOCs from carpet adhesive, or localised, for example gaseous emissions from a generator. Temporal patterns were classified as constant, for example emissions of VOCs from new construction materials for the first twelve months of the products life; periodic for example emissions of VOCs from the application of resilient flooring polish, and episodic for example entrainment of high concentrations of ambient pollutants during episodes of climate inversions. The proximity of the source to the occupants' breathing zone was a further spatial parameter to be considered (Etkin, 1992). This is an important consideration where VOCs are released from office furnishings and partitions in the close proximity to the occupants' breathing zone. Within HEAD-Start, temporal and spatial patterns are regarded as important distinctions as they prioritise and determine the most suitable technique for source control, containment or mitigation.

In addition, the contaminants interact differently with the indoor environment including such factors as air movement, air temperature, temperature of surfaces, relative humidity, and other contaminants. For example, the emission rate of most VOCs increases in response to increased temperature, relative humidity or air movement (Wolkoff, 1995). HEAD-Start prompts designers to control these indirect parameters.

Ventilation was frequently identified in the literature as the cause of contamination when the ventilation system failed to deliver sufficient air to dilute the level of indoor pollutants. However, in the framework of HEAD-Start, ventilation is considered to play four distinct roles in the indoor air cycle. Firstly, it can be a primary or secondary source of pollutants, such as fungi and bacteria propagated on components of the HVAC system, or emissions of particulates and VOCs from duct liner materials. Secondly, the HVAC system can form a pathway for communicating contaminants generated elsewhere to the occupied areas. This occurs if there is a contaminant source near the air intakes (Godish, 1995), or if contaminants are generated within the ventilation stream (Wilkens et al., 1993). Further, it acts as a driving force by creating air pressure relationships that can move, sometimes unpredictably, or contain contaminants (Bearg, 1993). Finally, it can be a mitigation technique, by dilution and removal of contaminants generated within the occupied area.

Numerous authors (Hanssen, 1993; Godish, 1995) have reported instances where ventilation rates in excess of 15l/s/person failed to address poor indoor air. Increasing the ventilation rate will have little positive impact on resolving IAQ problems if the HVAC system is performing either the first, second or third role mentioned above. Consequently, control of contaminants within the ventilation system is paramount, and emphasised within HEAD-Start.

The reviewers of the HVAC sections both consistently scored the identification of sources of pollutants, with scores ranging from 4 – 5 out of 5 with averages between 4.3 and 4.6 for each of the pollutant types. Further, the correctness of conclusions drawn across all sections also ranged from 4 – 5 out of 5, with average scores for each pollutant type ranging from 4.2 out of five for the section on VOCs to 4.6 out of five for the sections of microbiological contaminants and particulate matter.

6.3.2.2 Contaminant Pathways

Little research has been specifically reported on the effectiveness of controlling contaminant pathways as a means of improving the indoor air. However, there are numerous field studies which have identified detrimental effects of communication of pollutants via pathways (Melius et al., 1984; Kirkbridge et al., 1990; Namiesnik et al., 1992; Godish, 1995). Other authors have identified a positive outcome when a pathway has been interrupted (Hedge et al., 1993a; Kemp et al., 1998; Kildeso et al., 1998).

Devices for breaking pathways include eliminating unintentional pathways such as penetrations in the building's envelope or air circulation routes, and the installation of pathway interruption devices such as physical distance, buffer zones and vestibules.

Contaminant pathways include ventilation ducting, plenums, lift shafts and stairwells, penetrations in the building envelope, the room air, and openings between rooms. Pathways can be direct or indirect. They also have a driving force and a distance factor.

Direct pathways are easier to identify but are not always easier to manage than indirect pathways. For example, fungi growing on the HVAC filters would allow the insertion of a contaminant directly into a pathway to the occupied area. In this situation removing the pathway is not feasible; therefore control at source of microbiological activity within the HVAC services is identified as a critical activity within HEAD-Start. Similarly, diesel fumes from vehicles idling at a loading dock cannot feasibly be controlled at source by relocating the loading dock remotely from the building. However, the indirect pathway from the loading dock, up the lift shaft or other circulation route, to the occupied areas can be interrupted by the installation of a vestibule with self-closing doors and/or the control of air pressure relationships.

A premise incorporated within HEAD-Start is to design the building features so that if a contaminant is generated within the building, then pathway is interrupted in a fail-safe mode. If the above example of vehicle emissions entering the building from a loading dock is explored further, then it could be argued that source control could be achieved by requesting that drivers turn their vehicle engines off whilst loading/unloading at truck docks. However, the building designers, and possibly even the subsequent building managers, may not have control over the behaviour of visiting drivers. Therefore, designing the building without a pathway between the truck dock and other occupied areas provides for a safe barrier in the event that source control fails.

Control of air pressure relationships to limit the migration of contaminants is an alternative commonly used pollutant control technique. However, many cases have been cited in the IAQ literature where actual air pressure relationships are the reverse of the intended airflow due to the stack effect, inadequate commissioning, fan malfunction and many other causes (Bearg, 1993, Godish, 1995). Therefore, other means to restrict contaminant migration were given higher priority within HEAD-Start. Physical separation is a means of pathway control that is permanent and fail-safe, and is recommended where applicable.

The distance of the pathway is an important factor. A short distance between the source of the contaminant and the occupied area, or more specifically the breathing zone of the occupants, limits the opportunities for mitigation of the pollutant. This is critical where dilution ventilation is relied on for the removal of the contaminant. Identification of a short pathway highlights the importance of control of contaminants at source.

Consequently, the selection of materials with a low pollutant potential, where they are to be used in close proximity to the occupants, is emphasised within HEAD-Start.

A principle adopted in HEAD-Start was to break pathways as close to the source of contamination as possible if the pollutant originated from a point source, or close to the occupants if the source is distributed or there are multiple point sources. HEAD-Start pays particular attention to the elimination of pollutants within the HVAC system, as the HVAC system is a very direct pathway through a mechanically ventilated building.

Identification of all opportunities for contaminants to enter and exit the pathway will also suggest the most effective point at which to break the pathway. Attempting to mitigate contaminants generated within the occupied area with devices located remotely will be of limited effectiveness for the controlling the occupants' primary exposure. Centralised devices can, however, reduce the recirculation and accumulation of the same contaminants.

6.3.2.3 Contaminant Driving Forces

Examples of contaminant driving forces include air movement due to the stack effect, wind pressure, and lift car wakes. In reality, it is frequently difficult to control the driving forces as they are often dynamic, unpredictable or unavoidable. Maintaining the occupied area at a higher air pressure than a localised zone with a high concentration of contaminants is a technique used frequently in building designs to offset the pollutants' driving forces. Reliance on maintaining appropriate air pressure can be problematic under certain climatic conditions, or when the mechanical ventilation system is shut off. It is recommended in HEAD-Start that this strategy is best suited for contaminants which have a short-term duration, or the emissions from which coincide with the operation of the mechanical ventilation.

The reviewers rated the treatment of pathways with average scores across all sections of 4.7 for microbiological contaminants, 4.2 for gaseous pollutants and VOCs and 4.6 for particulate matter, and a range of 4 – 5 out of 5 for all contaminant types.

6.3.2.4 Contaminant Mitigation Techniques

Mitigation techniques include; dilution ventilation with clean, fresh air; localised air extraction; filtration and air cleaners; cleaning and hygiene practices; application of biocides.

The average office building relies on ventilation as the primary, if not the only, strategy for achieving good IAQ (Liddament, 2000). While ventilation is invaluable for improving IAQ, it should be used to supplement other good IAQ design strategies. Ventilation systems are typically designed to provide thermal comfort for the occupants during the main hours of occupying the building. The difference between the outdoor and indoor air temperature typically determines the air exchange rate, and any improvement in IAQ is incidental (Maroni, 1995).

However, a ventilation system designed for good IAQ would give equal consideration to both the dilution of pollutants, and thermal comfort (Nathanson, 1995b). This requires consideration of the temporal and spatial attributes of the contaminants. Bioeffluents and other occupant-generated contaminants are typically generated during the occupied periods of the day and distributed throughout the building. Opportunities to interrupt the pathway or driving forces from one area to another are limited, and consequently these sources are suited to removal by standard dilution ventilation. However, occupant activities, such as photocopying, can generate point sources of pollutants that are most effectively removed close to the source with localised extraction.

VOCs are emitted continuously from new construction materials, but the emission rate can increase if the relative humidity or temperature increases. A trickle of ventilation outside the main hours of building occupancy can remove free VOCs to prevent an increase in the indoor concentration, as well as controlling the environmental variables that influence the emission rate. Typically, urban air during the early hours of the morning has the lowest concentrations of particles and gaseous contaminants (Hitchens et al., 2000), and this can be useful to flush accumulated pollutants out of the building.

This philosophical shift in the role of ventilation enables a clearer application of the mitigation strategy presented above. Also, removing reliance from the supply of large quantities of ventilation for the dilution of the contaminants within the space to the control of the source, pathway or deployment of other mitigation techniques allows for more precise use of ventilation. It is suggested in the pollutants' load strategies outlined in ASHRAE 62-1989 and the pre-standard document proposed by Seppänen (1996) that this will reduce the total amount of ventilation required within a building and, consequently, reduce the energy consumed.

The function of air cleaners and filters is self-evident, and specification of high performance components can greatly assist in the removal of airborne particles and VOCs (Reinhardt, 1991). Consideration should be given to installing air cleaners in the occupied areas if strong in-room sources are present, or there are sources downstream of the centralised air cleaners. Buildings with unfiltered air pathways such as natural ventilation also benefit from in-room filtration (Hanley et al., 1994).

Thorough and regular cleaning of the interior of buildings and the ventilation system has been found to improve the air quality (Raw et al., 1991; Schneider et al., 1993; Franke et al., 1997). Designing the building to facilitate cleaning and maintenance is a building design feature recommended in HEAD-Start.

6.3.3 Importance Factors

Importance factors were assigned to all conclusions within HEAD-Start. As acknowledged by Gondalez and Dankel (1993), importance factors are derived from the research findings, but also have a subjective element, which is influenced by the knowledge gained during the knowledge acquisition phase of the development process and the expertise of the DSS development team.

The calculation of the importance factor was relatively simple in relation to the Site and Building Envelope sections of the HEAD-Start, but the IF-THEN logic strings became increasingly more complicated in subsequent sections as the number of prior decisions that contributed to the result increased. This will be simplified when the system is programmed into a software application design tool.

Further research on the accuracy and interpretation of the importance factors is recommended, although this is outside the scope of the current developmental stage of the research. The importance factors currently give an indication of the building feature's impact on causing or resolving IAQ problems, and are useful for comparing the effect of different building elements within a section. Further research is required to develop a robust rating system to compare decisions on the selection of building elements across topic boundaries, such as the IAQ benefits gained from selecting a rain screen cladding system versus displacement ventilation.

There is currently insufficient knowledge on the combined effects of various IAQ pollutants to determine whether or not the importance factors can simply be summed to give either an overall importance score for each pollutant type, or the more sophisticated equations are required to include synergistic interactions.

6.4 Validation of HEAD-Start

6.4.1 Validation Results

HEAD-Start was peer reviewed to determine whether, or not, the system was accurate, complete and met the research objectives. The reviewers were asked a number of specific, general and open questions on the above criteria and their responses to these questions are discussed below. Reviewer C completed a review of the infrastructure section and made detailed comments in a separate communication, but did not complete the standardised report form. The summary of his comments is discussed separately at the end of this section, and addressed in full in Appendix 7.

The questions in the reviewers report form to test the accuracy of the system were:

- Does this section (*under review*) draw correct conclusions on the effects which each type of pollutant that originate within the section can have on the indoor environment?
- Does this section (*under review*) draw correct inferences from the current body of knowledge on indoor air quality?

The reviewers rated the conclusions drawn within each section with averages for each pollutant type of 4.6 for microbiological contaminants and particulate matter, 4.4 for gaseous pollutants and 4.2 for VOCs. The range for all sections and pollutant types was 4 - 5 out of 5.

The correct incorporation of current literature was rated between 4 – 5 with an average of 4.6. There were no discrepancies identified by the reviewers between the knowledge within HEAD-Start and the literature. One of the reviewers, in a separate communication, draw attention to a paper, of which he was a co-author, that was in press on the effects of outdoor concentrations of PM on indoor concentrations. This paper supported the knowledge already within the question database and was added to the literature review. Reviewer C drew attention to another paper, of which he was a co-author, which updated previous research already cited in the background paper.

The completeness of HEAD-Start was evaluated by the reviewers responses to two closed and one open-ended question, as follows:

- Does this section (*under review*) adequately identify how the components of the building could contribute to the generation of each type of pollutant?
- Does this section (*under review*) adequately identify how the components of the building could form a pathway for movement around the building of each type of pollutant?
- Does this section (*under review*) have any important omissions?

The first two of these questions were given scores with a range of 4 – 5 out of 5 and averages between 4.3 - 4.6 and 4.2 – 4.7 respectively. The third question was open-ended, and the reviewers' responses to this question are addressed by each section below.

Site

Reviewers D and H both said there were no omissions from this section. Reviewer H suggested that the section on Sites be extended to include a chapter on radon and ETS so that the system could be used in the United States. While this is outside the New Zealand focus of the current research, this suggestion may be addressed in subsequent developments of this design tool.

Envelope

Reviewers B and H both replied that there were no omissions from this section.

Infrastructure

Reviewer G did not note any omissions from the content of this section, but suggested that graphical illustrations would be useful for designers. This is a good suggestion and it is intended that diagrams showing the potential pathways of pollutants and interactions of pollutants will be included when the system is programmed into a computer application.

Interiors

Reviewer D found this section very comprehensive but suggested that a separate sub-section on childcare facilities be added. Childcare facilities were considered when the boundaries of the problem area were originally defined, but were excluded from this version of the system as few New Zealand office buildings include childcare facilities, and the criteria for designing healthy environments for children are different from those for adults, due to their smaller body mass and closer proximity to flooring materials. Childcare facilities may be added to future stages of this research.

Reviewer D also suggested that mention should be made of new emerging manufacturing processes that enable the production of particleboards with low or no VOC emissions. This is a very useful suggestion, and when independent research is available on the emissions from these low VOC materials, a recommendation to this effect will be included in HEAD-Start.

Reviewer G noted that references to computer equipment, task lighting and mobile phones were not included in the interior section. The main pollutants emitted from computer equipment and mobile phones are electromagnetic fields and radiation (Godish, 1995). Lighting, electromagnetic fields and radiation were all deliberately excluded from the scope of the study in order to manage the size of the DSS and to focus on air quality issues. It is anticipated that subsequent stages of development will see the DSS expanded to include lighting and personal control issues.

HVAC

Reviewer E suggested that more material on advanced natural ventilation systems, such as wind chutes and chimneys, could be included in the DSS. This was considered during the development of HEAD-Start, but not included due to the specific design and modelling required for every site and building, which are best considered using specialised natural ventilation simulation and design tools.

Reviewer E also suggested that some definition of the terms, basic assumptions and explanation of the rating scale could be included. These were not presented in the current version where the focus was on the accuracy and completeness of the logic of the DSS. It is intended that these will be included in the computer-based version.

This reviewer also queried if ceiling fans had the potential to spread dust that had settled on the blades and insect excrement into the room air during operation. This is a good point, but no references in the literature were found to suggest that the impact on IAQ from ceiling fans had been researched. Ceiling fans could possibly be added to subsequent versions of HEAD-Start once research on their impact on IAQ has been published.

Reviewer F responded that there were no omissions from the HVAC section and that it was very comprehensive and complete.

All the reviewers who completed the validation process volunteered the opinion that the system was comprehensive. Five of these reviewers went as far as to describe it as "very", "extremely" or "impressively" comprehensive.

The primary aim of this research was to develop a DSS which would assist a building designer who was not an expert in IAQ to make decisions which would lead to the design of an office building with good IAQ. Reviewers were asked whether or not HEAD-Start achieved this goal for each of the sections that they reviewed and they responded with scores between 4 – 5, with an average of 4.6 out of 5. Reviewers also volunteered comments such as:

- "Gets into a "process" to assist the designer from start to finish."
- "It's a solid way to get professionals resolving IAQ building / design / systems problems and issues."
- "It is an excellent and comprehensive document. Excellent detail within the interiors section, which provides a good overview for the designer."

The section augments the Decision Support Tool for designers in a manner that enables designers to cover ALL the critical issues for a healthy office building.

Incorporation of an educational component to support long-term decision-making was another objective of the research. Reviewers were asked if the section under review would help educate a designer who was not an expert in indoor air quality, in indoor air quality issues. Responses to this question ranged from 4 – 5 out of 5 with and average of 4.4.

Although the reviewers were not prompted to comment on the IAQ cycle and problem-solving approach, several offered comments that suggested this met with their approval. Positive comments on the approach included:

- " I believe your concept and approach are excellent."
- "Very simple but effective approach – the IAQ cycle is a very useful approach to a complex problem."
- "An appropriate and insightful use of ventilation. ASHRAE 62-1999 revision committee should welcome this."

No negative comments on the solution approach were made. The reviewers graded the consistency between the question database and the IAQ model with scores between 4 – 5 and an average of 4.4 out of 5.

Reviewer C had suggested that air pressure relationships should be used to prevent the spread of pollutants between stairwells, toilets, lifts and other occupied areas. He considered that the use of vestibules carried a space penalty and had implications on fire evacuation routes. While it is acknowledged that vestibules do take up more space than single doorways, they were considered important in certain situations as they provide a permanent and effective means of preventing migration of contaminants and are more reliable than air pressure relationships (refer to previous discussion in Section 6.3.2.2 Contaminant Pathways).

The use of stairwells for either the supply naturally semi-tempered air or air extraction, was also raised by Reviewer C, however, this function would not be altered by the installation of vestibules as fire regulations already require protected smoke stop doorways or vestibules between fire compartments and stairwells.

Locating kitchens/food areas on the top floor of the building was also recommended by Reviewer C to reduce the need for isolating the air pathway between the kitchen and the stairwells with vestibules. This suggestion could work in some building developments, however, the top floor of many office buildings commands higher rentals than other floors due to superior views and perceived status. Using the top floor for kitchen and food areas may cause an economic penalty for the building developer and owner.

Reviewer C also mentioned the importance of cleaning of duct interiors, and the need to place priority on the control of contamination in the HVAC system, rather than the plant room. He also queried if re-entrainment of contaminants exhausted from the building was covered in other sections. These topics are all covered in detail in the Ventilation section of HEAD-Start.

Reviewer C identified four additional topics that could be included within HEAD-Start. These were: adding a weighting to the level of vehicle activity in carparks and loading docks; inclusion of the IAQ impact of recycling and re-use storage areas; insulation of infrequently used cold pipes in warm areas; and inclusion of multiple cleaners cupboards.

These are very useful suggestions and will be included in computer-based version of HEAD-Start.

Reviewer C asked whether, or not, the designer would have control of the use of storerooms, the specification of printing equipment, the operation of the ventilation and filtration systems, and cleaning of interior surfaces. While it is probable that the building designer will not control the usage of these items, it is prudent to design a building to optimise every opportunity to achieve good IAQ. This includes installation of sufficient well ventilated storage areas to avoid clutter that could restrict building hygiene practices, and discourage storage in the occupied areas of goods, such as printed materials or building maintenance chemicals, that can off gas VOCs. Printing equipment is a special case in that printing processes can release very large quantities of VOCs and particulate matter, and all efforts to influence the reduction of these at source should be made. Further, while the building designer may have no direct influence over the cleaning process used in a building, they do exercise indirect control to the extent that, installation of fleecy surfaces suggests that vacuum cleaning will be necessary, while resilient flooring will require VOC emitting floor polishes.

6.4.2 The Validation Process

The validation phase achieved the objectives of the validation methodology. It also identified several areas for development in subsequent stages of the research. There are, however, several lessons that have been learnt from the process.

Six months were originally allocated to the review process. However, it was actually found that more than double this time was required. It is difficult to identify further opportunities to accelerate this process other than providing financial incentives to the reviewers. Individuals who had achieved a reputation for expertise, by being actively involved in research projects, professional societies, editorial boards of IAQ journals and conferences and so forth, were sought for the review process. However, this same group of people were also in demand for other tasks, and this impacted on the amount of time and priority that could be assigned to "voluntary work", such as reviewing HEAD-Start.

The success of the review process relied heavily on the goodwill, commitment and intellectual curiosity of the reviewers. It appeared that reviewers who had a close professional relationship with the developer of the DSS made more comments on the hardcopy or in other forms of communication, compared to reviewers who were less well known to the developer. However, the scores given by the reviewers were very homogenous and a similar effect between strength of professional relationship and scores awarded did not appear to exist. The sample size was too small to test the statistical significance of this observation.

The reviewers consistently scored the closed questions, between four and five on a five-point scale. Reviewer E, commented, in a meeting following the return of his review report, that it was against his principles to give five out of five for anything, but he found he had to for the questions on "provides correct assistance to the designer; educates designer on IAQ issues and logical sequence of questions". The reviewers might have found greater flexibility if a seven-point, rather than five-point scale had been used. This is contrary to the findings by Sprague and Carlston (1989) who had found five-point scales suitable for the validation of DSS and had even successfully used three-point scales.

7 CONCLUSIONS

The knowledge acquisition phase of the research showed that there was sufficient good quality literature to lend scientific rigour to a decision support system to assist building designers design healthy office buildings. While there were a few areas in the literature where further research would be beneficial, or would clarify the knowledge for New Zealand conditions, this was not considered a barrier to the development of a Healthy Office Building DSS.

It was apparent from the literature that there is no simple solution for a healthy office building. Indeed, there are many building and environmental factors that interact on many levels, and affect how healthy the IAQ is for the occupants.

Few comprehensive strategies for achieving good IAQ, that simultaneously address more than one pollutant, are reported in the literature. The general occupational health and hygiene approach to controlling pollutants uses a hierarchy starting with eliminating pollutants, through to dilution ventilation and personal protection. With the exception of personal protective equipment, this structured approach is applicable to IAQ in the office environment, and was used to derive the IAQ cycle and formulate the philosophy of HEAD-Start.

Liddament (1999) also proposed a hierarchical approach, which prioritised source control and isolation of contaminants ahead of dilution ventilation and pollutant removal. The IAQ cycle described in this research is essentially the same as the strategy for achieving optimum IAQ presented by Liddament.

The three pollutants control strategies noted above are fundamentally different from the Ventilation Rate Procedure in ASHRAE 62 –1989 (ASHRAE, 1989) and New Zealand Standard 4303:1990 (Standards Association of New Zealand, 1990), which both rely on dilution ventilation as the primary, if not only, method of indoor pollutant control.

The Ventilation Rate Procedures given in ASHRAE 62-1989 and NZS 4303:1990 have evolved from the premise of providing thermal comfort. However, ventilation plays very different roles in achieving acceptable thermal comfort and IAQ. Numerous case studies cited in the literature have found that thermal comfort alone does not guarantee that the indoor air will be healthy for the occupants (Baechler, et al., 1991; Hanssen, 1993).

The pollutant control strategies of the IAQ cycle and Liddament's strategy for achieving optimum IAQ require a philosophical shift in the role of ventilation. This provided the opportunity to generate a fresh paradigm on methods to achieve acceptable IAQ in office buildings.

Addressing the problem from the perspective of the IAQ research included an analysis of the sources and dynamics of pollutants found in the office environment, the interactions between different building factors and pollutants. The research literature strongly supported the concept that a building designed to eliminate contaminants at the point of origin can generate many opportunities to improve the IAQ. It also follows that the reduction of pathways and driving forces for the communication of contaminants to the occupied areas will further reduce the indoor concentrations of pollutants. This contributed to the rationale for drawing conclusions and justifying the recommendation of alternative building features.

Characterising the pollutants' properties, such as their temporal and spatial attributes, provided further useful distinctions. By evaluating the attributes of the contaminants, mitigation techniques could be recommended which were complementary to the pollutants properties and this could reduce the wholesale reliance on dilution ventilation.

Analysing the problem from the building designers' perspective highlighted some situations where the selection of an appropriate building detail could, theoretically, produce healthy IAQ. Dividing the building and environmental factors into their simplest elements allowed the identification of many potential opportunities to control at source and reduce the distribution of indoor pollutants.

Quantifying which building features will yield the greatest IAQ benefits, is not yet possible due to the current state of knowledge on the additive and synergistic effects between the different IAQ factors on human health. Further research in this area will increase the quantitative ability of IAQ design tools, such as the importance factors within HEAD-Start. However, there is currently sufficient IAQ knowledge to support building designers generate building solutions with improved IAQ, even if the assessment of the decisions is of a qualitative nature.

Seven independent experts completed a review of sections of HEAD-Start. The comprehensiveness of the system was considered the strongest point. The reviewers identified a few minor omissions and these were addressed. The system was also considered correct and complete. The weakest point was seen as the repetitive nature of the text-based version, however this was necessary to provide full transparency of the system's logic and will be resolved once the system is programmed into a software application.

The reviewers considered that HEAD-Start would assist a building designer who was not an expert in IAQ issues, make decisions which would lead to an office building with good IAQ. It was confirmed that the system was able to support the non-expert building designer identify opportunities to reduce the sources of gaseous pollutants, VOCs, microbial contaminants and particulate matter, as well as the pathways which would allow these contaminants to migrate to the occupied areas.

The reviewers verified that the current IAQ knowledge was correctly interpreted in HEAD-Start. They also considered that the system was educational for non-IAQ expert users, which will support longer-term decision-making. A further outcome of the review process was the confirmation that the structure of HEAD-Start was sound and logical which will facilitate further development.

8 REFERENCES

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