CONTAMINANT BEHAVIOR AND DISTRIBUTION IN MECHANICALLY VENTILATED MULTI-ZONE BUILDINGS

BY

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Alhamdulillah. All praise is due to Allah for his mercy and endless bounties. I appreciate the support and patience from my family throughout my studies in the Kingdom of Saudi Arabia and special acknowledgement is also due to the King Fahd University of Petroleum and Minerals for supporting this research.

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GLOSSARY

Acceptable air quality: Air in which there is no known contaminants at harmful concentrations as determined by specialist authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.

Architectural Components: a term that is used (In the nomenclature of multi-zone IAQ modeling) to categorize elements such as walls, floors, doors, door frames, windows, window frames, ceiling, etc.

Air exfiltration: The uncontrolled outward leakage of indoor air through cracks, interstices and other unintentional openings of a building, caused by the pressure effects of the wind and/or stack effect

AHU: An Acronym for Air Handling Unit, which is a component of an HVAC system that includes fans, filters and coils for conditioning air.

Air leakage: The leakage of air in or out of a building or space usually driven by artificially induced pressures.

Air Pressure: The force per unit area that air exerts on any surface in contact with it. (SI units in Pascal, Pa which is equal to $1N/m^2$)

Base Case model: (Standard) computer model of a particular building. Base Case models are used to assess the relative performance of a certain (new) feature of the building by changing the model parameters associated with that feature. Comparison of the results of the Base Case model with those for the changed model will reveal the relative performance of the feature. For existing buildings, "as built" situation is often used as the Base Case.

Building Envelope: The entire area of the boundary surfaces of a building through which heat, light, air and moisture are transferred between the internal spaces and the outside environment.

Building Related Illness (BRI): Diagnosable illness whose symptoms can be identified and whose cause can be directly attributed to airborne building pollutants.

Carcinogens: An agent suspected or known to cause cancer.

Computational Fluid Dynamics (CFD): A general purpose simulation technology used to numerically model physical processes occurring within a fluid by the solution of a set of non-linear partial differential equations. These partial differential equations express the fundamental physical laws that govern the conservation of mass, momentum and energy.

Contaminant: Any unwanted airborne constituents that may reduce the acceptability of the air (quality) and may be detrimental to the health of building occupants.

Contaminant migration: The movement of indoor air pollutants throughout the building between rooms or zones. The concentration within a given portion of air of harmful or unpleasant contaminants such as noxious gases or dust particles. Concentrations are often expressed as time-weighted values over 24 hours, a working day or a working week.

Exhaust Ventilation: The mechanical removal of air from a portion of a building (e.g. piece of equipment, room or general area).

Flow equations: Equations that describe the airflow rate through a building (or component) in response to the pressure difference across the building (or component). This equation is given as $Q = KA(\Delta P)^n$ where C is the flow Coefficient, ΔP is the change in pressure over the component or envelope and n is the flow exponent. Q is the resulting volume flow rate expressed in m^3/h.

Flow network: A network of zones or cells of differing pressure connected by a series of flow paths.

Indoor Air Quality (IAQ): The characteristics of the indoor climate of a building, including the gaseous composition, temperature, relative humidity, and airborne contaminant levels.

Indoor air pollution (IAP): Pollution that occurs indoors from any sources - whether indoors or outdoors

Infiltration: Movement of air from outside (ambient) to the inside of a building through cracks in the building envelope.

Multi-zone: A building or part of a building that comprises of a number of zones or cells that are systematically distinguished for the purpose of controlling indoor parameter(s) through a single controlling device.

Nodes: Pathways through which air (and contaminants) can be migrate from one zone to another. Nodes can include general openings, exhaust openings, doors, windows, ceiling joints, cracks, electrical conduits, and plumbing networks.

Pollutant pathway: A route of entry of an airborne contaminant from a source location into the occupant breathing zone through architectural or mechanical connections or nodes (e.g. through cracks in walls, vents and open windows).

PPM: An abbreviation which stands for parts per million. It is a popular unit of expressing the concentration of gases in air. 1 ppm of a given gas signifies that 1 unit of the gas is present in every 1 million units of air. Analogically, 1 ppm corresponds to 1 minute in 2 years or 1 cent in $10,000.

Return air: Air that is removed from a space and then re-circulated or exhausted.

Return air (ceiling) plenum: The space below the flooring and above the suspended ceiling that accommodates the mechanical and electrical equipment and that is used as part of the air distribution system.

Sick Building: Any building in which the IAQ is considered to be unacceptable to a substantial majority of the occupants.

Sick Building Syndrome (SBS): A collective term that is sometimes used to describe situations in which building occupants experience acute health and/or comfort effects (such as headaches, eye/skin irritation, shortness of breath and nausea) that appear to be linked to time spent in a particular building, but where no specific illness or cause can be identified. The complaints may be localized in a particular room or zone, or may be spread throughout the building.

Supply Air: Air delivered to a conditioned space for the purpose of ventilation, heating, cooling, humidification or dehumidification.

Threshold Limit Value (TLV): The limit of an environmental condition to which any person may be exposed repeatedly without adverse effect. Typically, the air concentration of chemical substances to which healthy workers can be exposed for an 8-hour working day during a 40-hour working week without suffering an adverse effect.

Toxicity: The nature and degree of a given agent's adverse effects on living organisms.

Ventilation: The process of supplying or removing air by natural or mechanical means to and from a space. Ventilation refers to air movement between zones.

THESIS ABSTRACT

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When HVAC systems are not the source of indoor air pollution, they influence movement of contaminants within multi-zone buildings through air redistribution by ducted networks or by pressure differentials across zonal partitions. Current design, operation and maintenance procedures of HVAC systems have been unable to deal with this problem effectively and contemporary issues of weaponized contaminants emerges as a new threat to the health and lives of occupants. The objective of this research is to investigate the behavior and distribution of indoor air contaminants in mechanically ventilated multi-zone buildings. This was achieved through simulations of a theoretical multi-zone building and a Case Study. Influencing parameters such as Outdoor Air Fraction; Pressurization; Filter Efficiency; Filter Location; Local Exhaust Ventilation; Source Location and Inter-zonal Air Flow were investigated individually and collectively. Their singular effects on the migration phenomena were weighted and ranked, in order to give an insight into their quantitative impacts. Results showed that even with multiple Air Handling Units, parameters have varying degrees of influence depending on the architectural and mechanical configuration of the building, inter-zonal airflow, source location, filtration and exhausting. Guidelines in the form of recommendations were suggested to assist designers and building operators in retrofitting existing buildings or in future designs of buildings.

MATER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

DHAHRAN, SAUDI ARABIA

خلاصة الرسالة

اسم الطالب : **ذو الفقار عليو أدامو**

عنوان الرسالة : سلوك و توزيع الملوثات في المباني ذات المناطق المتعددة التي تستخدم التهوية الميكانيكية

القسم : الهندسة المعمارية

التاريخ : مايو 2006

عندما لا تشكل أنظمة التدفئة والتهوية والتكييف مصدراً لتلوث الهواء الداخلي، تؤثر هذه الأنظمة علي حركة الملوثات من خلال إعادة توزيع الهواء عبر شبكات التوزيع، أو من خلال اختلافات الضغط عبر المناطق المكيفة. تعد الطرق الحالية لتصميم، وتشغيل و صيانة أنظمة التدفئة والتهوية و التكييف غير قادرة علي التغلب بفعالية علي هذه المشكلة، و ذلك في عصر تشكل فيه الملوثات عنصر ذو تهديد لصحة و حياة ساكني أو مستخدمي المباني. يهدف هذا البحث إلي دراسة سلوك و توزيع الملوثات في المباني ذات مناطق التكييف المتعددة والتي تستخدم التهوية الميكانيكية. و قد تحقق الهدف عن طريق إجراء العديد من المحاكاة النظرية لمبني ذو مناطق متعددة مكيفة الهواء، بالإضافة إلي دراسة حالة مبنى قائم و اشتمل البحث علي دراسة مفردة و جماعية للمتغيرات المؤثرة مثل نسبة الهواء الخارجي، وضغط الهواء داخل المبنى، و كفاءة المرشح، و موقع المرشح، و التخلص من عادم الهواء، وموقع مصدر الملوثات، و مسار الهواء في المناطق المتداخلة. و اشتمل البحث أيضا علي إعطاء أوزان، و وضع ترتيب للتأثير الكمي لكل من هذه المتغيرات علي ظاهرة انسياب الهواء، و ذلك من أجل فهم متعمق لكل منهم و قد أوضحت النتائج إلى انه حتى في حالة وجود الوحدات المتعددة لتناول الهواء، يكون للمتغيرات درجات مختلفة من التأثير، و ذلك طبقا للتصميم المعماري والميكانيكي للمبني، ومسار الهواء في المناطق المتداخلة، و موقع المصدر، و ترشيح الهواء، و التخلص من عادم الهواء. وخلصت الدراسة إلي اقتراح إرشادات لمساعدة مصممي، و مشغلي المباني عند إجراء تعديلات في المباني الحالية أو تصميم المباني الجديدة.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول و المعادن

الظهران – المملكة العربية السعودية

CHAPTER ONE

INTRODUCTION

1.0 Background

There are countless indoor air pollutants in the built environment that can impinge negatively on the health of the most susceptible groups. These are the infants, the infirm (sick) and the elderly. These groups of people happen to spend most of their time indoors. Yet, even for the less vulnerable population, spending considerable time indoors could lead to exposure to an otherwise 'harmless' contaminant becoming a deadly pollutant due to time-weighted average exposure; Gamage [1996]. In other words, it is the dose that makes the poison.

Prolonged occupant exposure to indoor contamination such as radioactive emissions by building materials and surroundings has received attention from Fang and Persily [1995a and 1995b] who modeled the gradual emission and transportation of Radon in four large buildings under the influences of airflow and effective leakage areas. The presence of this radioactive material was also observed in building materials used in Saudi Arabia such as tiles Al-Jarallah *et al.* [2001] and granite, Al-Jarallah [2001]. The dangers of gradual exposure by radioactive materials are well documented in existing literature.

Contemporary indoor environments, whether residences, offices, schools and health care facilities are fraught with multiple sources of potential indoor air pollutants such as consumer products, synthetic building materials and furnishings; as well as emissions from human activities from use of equipment or habits like smoking. Brooks, [1992] showed that (as building designs keep getting tighter in order to save more energy); over 900 compounds have been clearly identified in indoor air.

Hansen and Burrough [1999] have also proclaimed that a common air pollutant like tobacco smoke is single-handedly believed to contain about 4700 chemical compounds; and a fraction of these compounds have displayed toxicity in animal test where at least 43 of them are suspected to have direct links with cancer (i.e. carcinogens). This suggests that there are about 43 possible ways of getting cancer just by inhaling environmental tobacco smoke (ETS).

Recent history has made indoor air pollution or contamination become a major issue as some contaminants can be quite fatal within a short period of exposure, unfortunately. While modeling the spread of a dangerous air borne contaminant (Anthrax) in U.S. Buildings, Sextro *et al.* [2002] acknowledged that the extent and mechanism of contaminant transportation in buildings is not well understood from the quantitative point of view. This heavily underscores the importance of this topic and need for sustained studies in the field.

HVAC systems are depended upon in some climates as the primary means of ventilating and conditioning the indoor environment in a manner that would suit human habitation. These mechanical systems are acknowledged to have the potential to affect the quality of indoor air in two basic ways: as a **transport medium** and as a **source** [Hays, 1995]. As a transport medium or pathway for contaminant migration, HVAC systems distribute pollutants through the circulation of air in occupied spaces; alternatively, contaminants could be generated from the system itself.

The relationship between contaminants and HVAC systems is hence, very dynamic. It is important to acknowledge that the design of most HVAC systems today have their roots in the temperature control period which has led to a tradition of HVAC designers concentrating on the thermal performances of these systems to the detriment of other health and comfort parameters like IAQ.

1.1 Indoor Air Pollution: Traditional Issues of Concern

The economic consequences of having an unhealthy building is too grave to be taken for granted as according to Fisk [2002], recent Figures, reveal that (a) reduced respiratory illness from unhealthy indoor environments would protect 16 to 37 million Americans from the menace common cold or influenza; (b) a reduction in allergies and asthma would bring about 8-25% decrease in symptoms within 53 million Allergy Sufferers and 16 million Asthmatics and finally, even though it is more difficult to diagnose than Building Related

Illness (BRI), Sick Building Syndrome (SBS) actually affects about 15 million working Americans. A reduction of the causal factors of SBS would lead to 20-50% reduction in its health symptoms.

Furthermore, it has been statistically shown by Kumar [2002] that whereas it would cost $80 to increase ventilation rates by 25cfm (12 L/s) per employee in the U.S.; this would result in sick leave savings to the magnitude of $480 per employee. In addition, if the 93.5 million full-time workers in the US are supplied the currently recommended ventilation rates of 9 L/s per occupant in each office, the estimated productivity that would be lost is about $23 billion. This Figure assumes an hourly compensation of $20 per employee. Doubling this ventilation rate would bring a net saving of $15 billion. Fisk [2002] put the losses due to the combined effects of BRI and SBS as at least between $17 – 48 billion.

1.2 Indoor Pollution: Emerging Issues of Concern

1.2.1 Health, Design and Performance of Multi-zone Buildings

Although research work on pollutant transportation in buildings has been going on for some time at the Lawrence Berkeley National Laboratory (LBNL), the focus had mainly been on IAQ, occupant health and the design and performance of ventilation systems. But by early 1998, a scientific group at LBNL began working on problems associated with airborne biological and chemical attacks on buildings [Price, 2002]. The susceptibility of HVAC systems were easily identified and as a result, improved building ventilation systems' design, operation and management were advocated for.

The research group developed new experimental methods and equipment for measuring the spread of tracer gas (hence the flow of air) in a large atrium; a research work that is important in the production of accurate computer models of contaminant transport. It is important to clarify that the advice given by this group of scientist applies to large commercial buildings with ordinary HVAC systems i.e. buildings that have multiple air handling units (AHU) with each supplying air to different areas of the building and designed to *draw air from the same area that they supply*. For some large buildings each AHU delivers air to different areas of the building but the return air enters a 'common return' and is a mixture of air from several of these areas. Therefore the HVAC system will simply spread contamination as if it were a single AHU serving all areas. Thus contamination generated in one area will be spread by all the AHUs that draw air from the common return. [Price, 2002].

Similarly, sequel to the discovery in late 2001 of letters containing *Bacillus anthracis* being mailed to certain locations in the US, the Department of Health and Human Services commissioned a team of engineers and scientist to assess the vulnerability of building air environments including HVAC systems to attack with chemical, biologic and radiologic (CBR) agents and fashion out a cost effective prevention and control measures. Part of the recommendations of the team addressed physical security, airflow and infiltration, maintenance administration and staff training.

Some of the new measures that were to be adopted include security for air intakes and return-air grilles. Filter efficiency were to be evaluated, HVAC system's operational controls to be assessed and preventive maintenance procedures were to be adopted. Interestingly, the recommendations do not target single family or low-occupancy buildings but were rather targeted at building owners, managers and maintenance personnel responsible for public, private and government buildings including hospitals, laboratories, offices, retail facilities, schools and public venues. [CDC, 2002]. All these are notably multi-zone buildings and this fact emphasizes the importance of contaminant distribution in multi-zone buildings and hence this study.

Additionally, it is noteworthy that Wladyslaw *et al* [2003] modeled the immunity of building systems to bio-terrorism. Their results implied that the efficiency of filtration could positively reduce the potency of weaponized contaminants only to a certain extent; after which there would be a diminishing returns effect on filter efficiency. They concluded that for lower ventilation rates, high filter efficiency would be appropriate, but not so when ventilation rates are substantially higher.

There has been a global increment in cases of tuberculosis (TB) and a significant numbers of people living with HIV (PLWH) are infected with it as stated by WHO [2000]. The fact that a third of PLWH die from TB has been emphasized by UNAIDS [2000]. In addition, the relationship between TB as an air borne disease with poor IAQ being primary risk factor for its spread was observed by Prikazsky *et al* [2003]; Not surprisingly then, when Yik and Powell [2003] reviewed and simulated the performance of a TB isolation ward, they came up with the conclusion that both negatively and positively pressurized isolation rooms (PIR) have to meet higher operational requirements than presently outlined in many national and institutional guidelines. They studied the effects of recommended ventilation rates and quality of construction on air leakage and cross contamination.

1.2.2 Innovative Ventilation Strategies and IAQ

The concept of separating ventilation and conditioning aspects of HVAC using dual-path systems was demonstrated as a novel way of achieving acceptable IAQ and desirable temperature simultaneously. Some of the cooling components advocated by Khattar [2002] to replace recirculation air subsystems include ceiling and wall panels, with circulating water used for efficient conditioning. While this concept of cooling by ceiling or wall panels may not be new, there have been other emerging philosophies and technologies aimed at ventilation, IAQ and energy efficiency. For instance, this is found in the intelligent combination of natural and mechanical ventilation- in what has now become known as hybrid ventilation systems. A clear example is provided by Heiselberg [2002] where the fundamental principles of hybrid ventilation were outlined. In this case IAQ is controlled through seasonal changeover using operation strategy not quite dissimilar to demand-controlled mechanical ventilation. This concept is based on manipulating natural, fan-assisted natural and mechanical ventilation modes.

Heinonen and Kosonen [2000] also demonstrated that hybrid ventilation systems in commercial buildings can be equipped with infrared (IR) and CO_2 sensors to ensure desirable ventilation, air quality and energy efficiency simultaneously; Consequently, through Axley *et al.* [2002], it can be perceived that natural and hybrid systems can be sized or designed using three broad kinds of techniques. Among these techniques, multi-zone coupled thermal-airflow analysis was explained as a convergence of advanced methods of building thermal, airflow and contaminant dispersal analysis. However, more research is still needed on this since compared to other techniques like the loop equation design method, the approach is not yet regarded as fully reliable for the design of natural and hybrid ventilation systems. Nevertheless, hybrid ventilation systems appear to have future promise on the aspect of satisfying ventilation requirements and energy demands.

1.3 Statement of Problem

It has been established in literature that HVAC systems that serve multi-zone buildings affect indoor air pollution (IAP) either as pathways through recirculated air and/or as inducers of inter-zonal pressure differentials. This can be illustrated as in Figure 1.1.

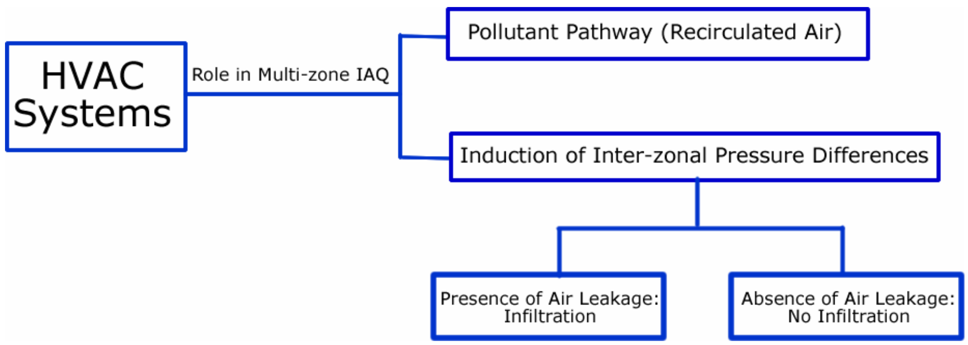


Figure 1.1: The impact of HVAC systems on IAQ via recirculated air and inter-zonal airflow

Interestingly, the problem of contamination in the area of complaint may be quite higher than the area where the pollutant (*source*) is actually located. By way of example, consider the fact that victims of toxic fumes and smoke inhalation due to fire are usually remotely located (not physically present) in the source room or zone where combustion is occurring. As a result of this phenomenon, it understandably easy then for mobility impaired, critically ill or patients undergoing surgery in a hospital, for example; to become victims of toxic fumes when there is an outbreak of fire in a remote part of the facility. This underscores the need to consider some key issues like: why contaminants get transported from one zone into the other? How and where this transportation takes place? and how the operation of HVAC system (in general); or its constituent components affect the entire process? The roles of infiltration and the rate of contaminant build-up as they spread into fresh zones are equally important. Figure 1.2 shows the graphic representation of causes, pathways and effects of contaminant problems in buildings.

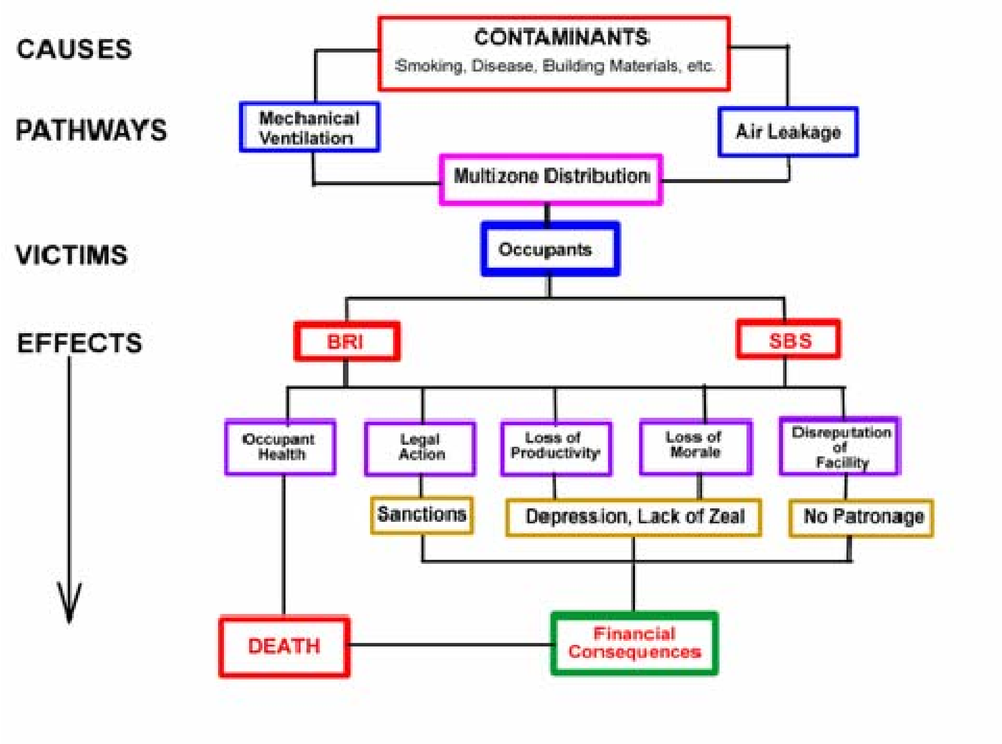


Figure 1.2: The Causes, Pathways and Effects of contaminant migration in multi-zone buildings

1.4 Research Objectives

The primary objectives of this study can be outlined as the following:

- To investigate the impact of HVAC systems on contaminant behavior in multi-zone enclosures; vis-à-vis as (1) a transport medium and (2) as an inducer of pressurization and consequent control of contaminant migration.
- To formulate design guidelines for HVAC design and operation for multi-zone buildings with IAQ as focal reference point.

1.5 Research Methodology

In aiming to achieve the objectives for this study, there are a number of methodologies that are available for use. Primarily, literature survey and review stands out as a fundamental basis upon which the techniques of achieving the research goals are built. The past and contemporary efforts on studying the behavior of contaminants in buildings would serve as a literal spring board from which to begin the research. Secondly, as far as airflow and contaminant distribution in multi-zone facilities are concerned, the parametric variables that are established (in existing literature) could be categorized as having direct or indirect impact on the flow and concentration levels of indoor air pollutants. These include the following:

- The amount of outdoor air fraction (OAF) brought in by the HVAC system.
- Pressurization i.e. ratio of Supply to Return air (S/R)
- Filter Efficiency (FE)
- Filter Location (FL)
- Local Exhaust Ventilation (LEV)
- Source Location (SL)
- Inter-zonal Air Flow across architectural components (IzF)

The expected research methodology flow process is simplified as shown by Figure 1.3.

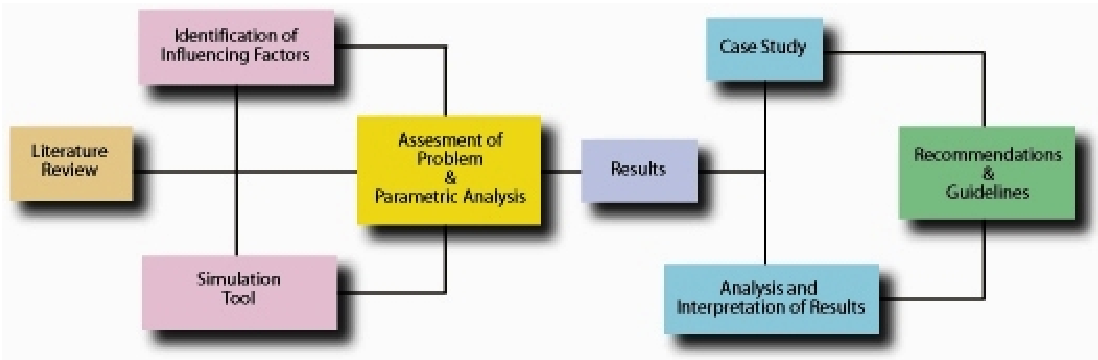


Figure 1.3: The proposed research methodology flow process.

Having identified and understood the parameters that would affect contaminant in multi-zone buildings using with the backdrop of existing literature, the research would involve running simulation according to certain criteria and strategies aiming at assessing the impact of each parameter on contaminant behavior and distribution both individually and collectively. The permutations and combinations of operation strategies as applicable to HVAC systems in multi-zone buildings can then pave the way and serve as aids that would enable a Case Study to be conducted in a meaningful way and provide input for the guidelines part of the research objective; which should emerge systematically.

1.6 Significance of Study

1. Recently, while modeling the spread of a dangerous air borne contaminant (Anthrax) in U.S. Buildings, Sextro *et al.* [2002] acknowledged that the extent and mechanism of contaminant transportation in buildings is not well understood from the quantitative point of view. This study will thus contribute to a better understanding of contaminant behavior and distribution in multi-zone buildings.

2. In harsh or extreme climates that rely on mechanical ventilation of buildings, communicable air borne diseases can easily be transmitted to healthy occupants. In addition, a 'sick' building will bring bad publicity and eventually turn an otherwise profitable property investment into a loss. An unhealthy building tends to dampen the morale of its occupants and workers may not be as productive as they could be. The economic consequences of having an unhealthy building is quite grave as observed in existing literature. The investigation of the KFUPM Press building as part of the research methodology is intended to assist in alleviating the problem of indoor air pollution which has become common knowledge within the university community.

3. The outcome research can contribute to efforts in minimizing Building Related Illnesses (BRI) and Sick Building Syndrome (SBS); through its inputs on the transfer of communicable (air-borne) diseases or other harmful indoor air contaminants which are transported through HVAC systems in hospitals, commercial and other public buildings

that draw air from multi-zone HVAC systems. Furthermore, the study should contribute to the understanding of the dynamics of contaminants thereby finding use in preventing cases of sabotage- when dangerous contaminants could intentionally be used to cause harm as described by Federspiel *et al.* [2002] and Sextro *et al.* [2002].

4. Fire protection engineers/personnel, maintenance and facility managers could use the guidelines and knowledge from this study to investigate the likely consequences and dynamics of fire-induced smoke in existing buildings or for forensic purposes. This would place them in a better position to assess the behavior of carbon monoxide, hydrogen cyanide, smoke etc, if and when there is a fire outbreak. Furthermore, the techniques and results obtainable from this study will underscore the need for fire protection and occupational safety personnel to work hand-in-hand with architects and HVAC designers right from the design stage.

1.7 Scope and Limitations

The scope and limitations of this study are as follows:

- This study is NOT going to explain the physical, chemical, biological and environmental conditions that lead to pollutant generation.

- This study intends to use specific parameters that have been identified to affect both contaminant concentration and ventilation of multi-zone buildings. This include: *percentage of outdoor air supplied; pressurization; filtration location and efficiency; source location of contaminant; local exhausting and inter-zonal airflow.*

- Only one Air Handling Unit (AHU) will be used in the theoretical model of this study. This is in order to simplify the objectives of observing the behavior of contaminants as well as the relative influence of individual parameters.

- The parametric inputs used in the models will be based on ASHRAE and other acceptable standards which would be stated accordingly. There could nevertheless be circumstances where quantitative values of ventilation strategies (e.g. amount of outdoor air supplied) will intentionally be used without following the standard recommended amounts. This is aimed at observing where and how the standard values could be manipulated with other techniques or strategies to give desired results.

- As observed in the methodology, this research will be conducted using simulation techniques/tools of multi-zone modeling. It will therefore be a key factor that readers understand the capabilities limitations of such techniques in appraising the end results.

- The impact of air leakages between the building interior and the ambient exterior is no doubt significant in ventilation and IAQ; however, this variable will be limited to fixed rates of infiltration (assumed as average) on the general building envelope.

- The strategies and approach of this study will primarily be based on ASHRAE Ventilation Rate Procedure – where acceptable IAQ is achieved by the provision of ventilation air of specified quality and quantity to the spaces. This will be done by utilizing the applicable ventilation rates needed, based on consideration for space volume, room equipment and human occupancy; in a commercially available cooling load calculation program

- The capabilities of the software as well as it limitations (e.g. over-simplification of the HVAC process and lack of control over certain operations) requires understanding as it could greatly affect the ability to model and manipulate scenarios. As such, not all situations can be represented and controlled realistically and accurately by the multi-zone modeling software.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter deals with the review of related literature that cover many aspects of IAQ issues in multi-zone buildings including factors that affect contaminant migration and distribution to ventilation systems, filtration, airtightness as well as architectural flow paths and multi-zone modeling programs. Additionally, a methodology of selecting the appropriate tool for use in this research was developed based on information and data gathered from the literature review.

2.1 Factors Affecting Contaminant Migration and Distribution

2.1.1 HVAC Systems in Multi-zone Buildings

Federspiel *et al.* [2002] reported that motion of indoor air (advection and diffusion) influences the transportation of contaminants especially in buildings that are mechanically ventilated. HVAC systems that serve multi-zone buildings affect indoor air pollution (IAP) either as pathways through recirculated air and/or as inducers of inter-zonal pressure differentials.

HVAC systems, which are central to a building's IAQ and its energy consumption, have been identified by Hansen and Burough [1999] as being notoriously responsible for 50-60% of all IAQ problems that originate within a building. Furthermore, they suggested the capacity of these systems to solve such problems as being an astonishing 80%. Within a mechanically ventilated multi-zone building, Li, et al (2004a) had investigated the bio-aerosol distribution and spatial infection behavior of SARS in a hospital ward. Their results suggested that weakness in ventilation and air conditioning design for isolation wards (flow rates in supply and exhaust grilles were unbalanced) could trigger cross-infection risks of respiratory infectious diseases such as SARS.

The relationship between declining IAQ and energy conservation measures (as precipitated by the energy crisis of the 70s) is legendary and this led to the birth of the variable air volume (VAV) systems due to the desire for any and all practical means of lowering energy cost of HVAC systems. These systems have aided the decline of a building's IAQ through their operation, maintenance or their design, with the same respective order of magnitude.

Seckar, [2002] claimed that there are two broad issues that need to be addressed when dealing with air quality in the indoor environment. These include the downstream IAQ issue- i.e. epidemiological considerations of IAQ for establishing threshold limit values (TLV) and the upstream IAQ issue - exploration of the interaction between HVAC systems and acceptable IAQ levels in the built environment. TLVs are generally set as standards developed by regulatory bodies like OSHA and professional associations like ASHRAE. Concerning the upstream issue about HVAC systems and relationship with IAQ, there are various scenarios where a HVAC system can act as a medium for contaminant transportation in buildings. Location of *outside air intake*, improper zoning of the HVAC system, poor filtration and the *presence of an emitting source* in a particular zone are common examples. [Hays, 1995]. This fact is given credence by investigations done in the wake of the SARS outbreak of 2003 in Hong Kong, Li, *et al* (2004b) utilized multi-zone modeling to show the role of prevailing winds in distributing virus-laden bio-aerosols to among some blocks of flats. By using a multi-zone program called MIX, they were able to show how the infection was minimized on the windward side flats as a result of active dilution by prevailing winds.

Meanwhile the results also provided answers to why there were high levels of infection on the leeward side flats, (which received doses of contaminated air). The research also showed the intricacies of designing ventilation systems in high-rise buildings, when natural ventilation air could play a dual role of dilution as well as transportation. While Li, *et al* (2004b) were basically modeling for natural ventilation, their investigations show the potential for outdoor air intake to be a source of pollution of mechanized ventilation system.

In related studies of airborne infections in health institutions, the relationship between tuberculosis (TB) as an air borne disease with poor IAQ being primary risk factor for its spread was observed by Prikazsky *et al* (2003); while Beggs (2003), reiterated that the causal agents of hospital infections (e.g. TB and Aspegillosis) are airborne pathogens and like Sextro *et al* (2003) he concluded that the impact of airborne transmission in this case is hazy and not well comprehended. Not surprisingly then, when Yik and Powell (2003) reviewed and simulated the performance of a TB isolation ward, they came up with the conclusion that both negatively and positively pressurized isolation rooms (PIR) have to meet higher operational requirements than presently outlined in many national and institutional guidelines. They studied the effects of recommended ventilation rates and quality of construction on air leakage and cross contamination.

2.1.2 Ventilation Air in Buildings

The interaction between contaminants and HVAC or Architectural systems cannot be appreciated in isolation to the medium of contaminant transportation i.e. the ventilation air as supplied by a ventilation system as well as the general strategies being adopted for delivery of indoor comfort. A ventilation system's performance can be evaluated by considering its efficiency, effectiveness and air change rate. However, often times in literature, there seem to be a lack of clear distinction between efficiency and effectiveness of a ventilation system. ASHRAE's ventilation standard referred to effectiveness as the 'fraction of outdoor air delivered to the space that reaches the occupied zone' [ASHRAE, 1989].

Other researchers have contributed in further explaining the ventilation efficiency to mean the efficiency with which a ventilation system conveys the quantity of fresh air to the occupied zones while the effectiveness refers to the effectiveness with which this supplied air mixes in the space to obtain good dilution; [Seckar, 2002].

The fundamental objective of delivering sufficient fresh air into enclosures is to reduce (by way of dilution) the concentration of pollutants present in the interior to acceptable levels. Other techniques that may be used to achieve the same objective include filtration and destruction of pollutants. In this regard, ASHRAE's Standard 62 [1999] extensively discussed the impact of filtration as a function of its physical placement and amount of recirculation.

There have been evidences that building energy concerns have been addressed at the expense of IAQ. This prompted Khattar [2002] to advocate that tradition needs to be broken in the sense that HVAC systems should not perform the dual functions of thermal conditioning and ventilation. Since IAQ tends to pay the price for the economic performance of HVAC systems, the aspect of delivering sufficient air steadily to meet minimum requirements would hardly be compromised if the weight of thermal conditioning can be taken off from the same system.

When the thermal loads of a multi-zone HVAC system are unequal, ASHRAE's standard 62 discusses the rationale for reducing outdoor air. The fraction of OAF can be reduced below the required level of the critical space (the space needing ventilation the most) from the total supply when some return air is recirculated and some exhaust taken from it thereof. The governing equations for this strategy can be found in ASHRAE Standard 62-1999.

In buildings, the dispersal of air borne contaminants is such that as it is produced in any ventilated room, it quickly spreads over the entire occupied zone especially in a mixing ventilation system with large rate of entrainment and a circulatory motion caused by the jet; [Awbi, 1991]. Standard 62 of ASHRAE [1999] contains a stratification model that portrays the effectiveness of delivered air based on outdoor and recirculated fractions.

Plenum-Based Air Distribution Techniques

There are basically four plenum-based air distribution methods principally. Li et al [2004] have analyzed them as first; the **Floor Supply and Ceiling Return Method,** for which they argued that it is the most popular since displacement flow pattern could improve the IAQ due to warm air rising. In addition it is possible to save energy since ceiling temperature can be maintained at higher level than comfort requirements would allow. Secondly, the **Floor Supply and Floor Return Method** during which only one plenum is used for both supply and return air. The risk involved with this system is due to thermal stratification where velocity of supply is so low as to keep a cool air reservoir at the floor level. Cool air that is supplied may also by-pass or short-circuit itself directly to the return grill when this method is used.

The third Plenum design analyzed was the **Ceiling Supply and Ceiling Return Method**, which appears to be more theoretical since the authors did not find any actual practical system that uses this method. However, it is found in a modified format as typical duct based systems usually adopt this plenum return technique. Its advantages include that lighting and sprinklers are easily co-installed with this method. Finally, the **Ceiling Supply and Floor Return Method**, which is also a theoretical possibility but there are no apparent advantages.

2.1.3 Pressurization and Filter Efficiency

For all new designs, especially for areas where there will be known sources of indoor air contamination, it is paramount for a designer to perform pressure balance analyses and provide diagrams showing airflow patterns. By applying positive air pressurization in areas adjacent to contaminated areas, effective isolation of the source and inexpensive restriction of the contaminant within its controlled boundaries is highly probable [Hays, 1995]. Of course this solution does not eliminate the presence of the contaminant in the building in anyway, but at least its spread to other parts of the building through the HVAC system will be negligibly minimal.

Pressure balance analyses are needed after determining a building's heating and cooling load and the preliminary layout of the HVAC system. At this stage also, the location of air distribution points is necessary. The pressure relationship between spaces can be indicated on building floor plans with + for positive and – for negative pressure and = for equal pressure areas while working towards corridors and lobbies that eventually lead to the building exterior openings and in the case of upper floors, work towards shafts, chutes or stairwells, which could act as relief points for each floor. The benefit of this exercise is to understand potential pathways for indoor pollutant travel (positive to negative pressure areas) and to determine that the HVAC system serving the building or particular floor not creating over- or under-pressurization problems; the HVAC system should hence be in balance. Certain areas of a building that are known to contain contaminant sources e.g. bathrooms, food preparation areas (kitchens) chemical storage areas, smoking lounges or print rooms should be maintained under negative pressures and exhausted to the outside. [Hays, 1995].

The pressurization scheme in a multi-zone building can also impact on the level of energy use as it greatly influences the level of air infiltration. Emmerich and Persily [1998] highlighted the potential energy savings of 25 tight U.S. office buildings they studied as averaging 26% for heating and 15% for cooling based on the ventilation system balance. When pressurized, the savings for heating loads averaged 32% and about 20% when the buildings were depressurized. When cooling loads were analyzed under pressurization, the savings averaged 39% and only 3% under depressurization.

Budaiwi [1998] studied the effects that pressurization has on contaminant concentrations under various air leakage characteristics and filter efficiencies. He concluded that the optimum reduction in pollutant levels for a single-zone environment would take place when equalization of indoor and positive outdoor pressures is present, a finding that is re-emphasized by Li, et al (2004a). Furthermore, he found that different levels of airtightness need varying pressurization rates for consequent reduction in contaminant concentration levels. Higher filter efficiency enhances dilution capacity of supplied air, thereby making pressurization much more effective than when unfiltered air was used.

Budaiwi [2002] also provided insights into the impact of filter location on concentration levels of steady and transient indoor contamination. Earlier, Budaiwi [1999] had worked on the combined effects of dilution and pressurization of ventilation air on indoor contaminant concentration levels and later on, he and Al-Homoud [2001] described how the rate and delivery techniques of outdoor air as well as air diluting capacity of the ventilation air can determine contaminant concentrations- and the energy needed to maintain such pollutants at acceptable levels. They considered the provision of ventilation air as a function of occupancy.

2.1.4 Airtightness and Age of Buildings

According to Persily [1998], there is may actually be no direct correlation between the tightness of building and their age. After examining data sets of 139 commercial buildings and experimenting with 90 buildings in the US, he came to the conclusion that even construction has no major bearing on envelope airtightness except that frame walls may be slightly leakier. Part of the findings of his study show that taller buildings tended to be tighter than smaller ones due to the type of construction used in them tends to lead to tighter envelopes. Smaller buildings appeared to have a wider range of tightness level from low to high. As the research was a bit generalized, the author agreed that more airtightness data would be needed in order to make more specific informed decisions about tightness of commercial buildings and the relationship between air leakage and energy savings.

2.1.5 Contaminant Migration and Architectural Flow Paths

In buildings, the dispersal of air borne contaminants is such that as it is produced in any ventilated room, it quickly spreads over the entire occupied zone especially in a mixing ventilation system with large rate of entrainment and a circulatory motion caused by the jet; [Awbi, 1991]. Airflow models for multizone buildings perceive such buildings as networks of distinct **flow elements** (doors, cracks and ductworks). These elements usually connect at **nodes** like static **zones** (e.g. rooms) or at points where two elements interact (e.g. duct junctions).

The governing equations are meant to represent (a) pressure-flow relations, (b) mass conservation and (c) hydrostatic pressure variations; in the flow elements, nodes and zones respectively [Lorenzetti, 2002]. Other than the ductwork, the return air plenum is perhaps the next most important component that aids as a contaminant pathway. *A return air plenum is fundamentally the horizontal area between the ceiling and the roof structure*. When the AHU's return system is located above the ceiling (plenum), there is little or no ductwork associated with the return air and the AHU's filter section is exposed to the plenum. In other situations, a return air grille collects air from the plenum in a central location before transporting the return air to the AHU where the supply ducts convey the air into the required environment. [Hays, 1995]

2.2 Movement of Toxic Effluents in Burning Multi-zone Buildings

Massive generation and distribution of contaminants occurs in burning buildings and hence, there is need to review and possibly integrate knowledge about smoke control with this study. When a typical building is burning, apart from the oxides of carbon, nitrogen and sulphur, there are other toxic effluents of combustion that are given off as constituents of smoke by the process of pyrolosis. These include hydrogen cyanide, ammonia, benzene, aldehydes and halogen acids. Their toxicity levels vary with concentration and exposure times but it suffices to state that two of the deadliest are carbon monoxide and hydrogen cyanide. [Butcher and Parnell, 1979].

Contamw96 has been used by Aggarwal *et al.* [2002] to verify a high-rise building's compliance with original smoke control design criteria and pressure differences under many environmental conditions. In multi-zone buildings that are designed and such that smoke zones coincide with HVAC zones, zoned smoke control applications have been utilized to maintain acceptable air quality for pre-egress occupants. Webb [1998] described HVAC systems that were activated into smoke mode by detectors such that the systems effectively checked the migration of smoke by supplying affected modules with 75% OAF; operating return fans in affected modules at 100% exhaust at specified flow rates; stopping air return in adjacent modules and operating air supply fans in adjacent modules at 100% OAF.

Klote [1995] enumerated stack effect, buoyancy, expansion, wind and HVAC systems as the major driving forces that cause smoke/gas movement in buildings though a combined effort. He listed two basic principles of smoke control as being the following:

- With the average air velocity of sufficient magnitude, airflow by itself can control gaseous effluent movement.
- With air pressure differences across barriers, gaseous effluents can be controlled.

In the second principle, (i.e. pressurization), air is made to flow through small gaps around closed doors and through construction cracks, which prevent the backflow of smoke through these same openings. This indicates that the second principle is by itself a unique case of the first principle. Furthermore, since smoke control relies on air velocities and pressure differences, smoke control is less dependent on tight barriers. Allowance needs to be made in the design for reasonable amount of leakages through barriers. But the above analysis by Klote leaves much to be desired when consideration is given to the adverse effects of barrier leakages on contaminant build up in the absence of the threshold pressure.

This technique of pressurization is even more sensitive and complex when one considers from Klote [1995] that actual leakages are products of workmanship rather than design features or construction materials. Nevertheless there are reference leakage values published by Hutcheon and Handegord [1989] and ASHRAE [1997].

In analyzing human behavior in burning buildings, Proulx [2003] concludes that if occupants of a multistory building decide to evacuate a building while there is a fire, it is quite likely that smoke (and hence other toxic effluents of combustion) will penetrate the stair shafts thereby putting the occupants above the fire floor in serious danger. Interestingly, occupants are also likely to move curiously around a building to discover 'what is happening' thereby opening doors- (which would allow smoke to travel into more areas)- or windows, (which would allow greater infiltration and hence more smoke dispersal due to induced pressurization).

2.3 Modeling Techniques for Contaminant Transportation and IAQ

Computer modeling and engineering calculations are the basic tools for predicting IAQ problems or the magnitude of most changes in the indoor environmental quality (IEQ).

Indoor temperatures can be determined from energy balances whereas humidity and pollutant concentrations are derived from mass balances. However, certain algorithms for the performances of equipment are often required and ASHRAE's handbooks (e.g. ASHRAE 1992, 1995 and 1997) are among the many reliable sources of the engineering calculations to be used in indoor air modeling. It is thus possible to perform simple steady state and transient mass balance calculations in order to estimate contaminant concentrations in well mixed zones.

Alternatively, there are many computer programs (e.g. COMIS, CONTAM and BACH) available for the purpose of predicting air infiltration rates, airflow between zones and indoor pollutant concentration levels. The difficulties in obtaining model inputs and expertise in IAQ and modeling have been identified as obstacles in modeling multi-zone buildings.

2.4 Computational Fluid Dynamics and other Techniques

Whereas Computational Fluid Dynamics (CFD) gives more accurate picture of contaminant concentration behavior, the setting up of the boundary conditions and other input parameters makes CFD prohibitively difficult. CFD solves the partial differential equations governing mass, momentum and energy transport on a fine grid. But unfortunately, CFD codes are complex, expensive and quite difficult to use. But it is still possible to perform simple steady state and transient mass balance calculations in order to estimate contaminant concentrations in well mixed zones. Lam, Yuen and Lau [1993] have described simpler (user-friendly) CFD software called EXACT3 as an alternative tool for building designers.

Research by Broderick and Chen [2000] has led to the development of SCI- (Simplified CFD Interface) specifically for the needs of architects and building engineers in getting flow information in or around buildings. Architectural and Engineering students of MIT were able to use SCI to perform air quality and thermal comfort analysis after only 2 hours of training, despite their varied differences in background. In another unique development, Sato *et al* [1999] have described the use of expert systems (ES) and artificial intelligence (AI) to diagnose indoor air quality and ventilation design for Japanese buildings. This unique approach consists of (a) a *knowledge base* (i.e. requisite knowledge for ventilation calculation stored in production rules as subroutines); (b) *an inference engine,* (c) *a user interface* and (d) *an interface for knowledge acquisition*.

2.5 Multi-zone Models

There are many simpler computer programs (e.g. COMIS, CONTAM, IAQPC and BACH) available for the purpose of predicting air infiltration rates, airflow between zones and indoor pollutant concentration levels. These programs are based on multi-zone models [Federspiel, *et al.* 2002]. Multi-zone models traditionally use a convenient approximation that large zones in building (usually whole rooms) contain well-mixed air and on this basis, calculate air flows and contaminant transportation between these zones.

Compared to Computational Fluid Dynamics (CFD) simulation, multi-zone models are set up and executed relatively easily. The primary limitation remains that the predictions are limited to room averaged values. Therefore, in a situation where concentration of a pollutant varies significantly throughout a specific zone and where this is important for design of ventilation and/or extraction equipment or for occupational exposure studies; multi-zone models may hence not be so adequate.

Airflow models for multi-zone buildings perceive multi-zone buildings as networks of distinct **flow elements** (doors, cracks and ductworks). These elements usually connect at **nodes** like static **zones** (e.g. rooms) or at points where two elements interact (e.g. duct junctions). The governing equations are meant to represent (a) pressure-flow relations, (b) mass conservation and (c) hydrostatic pressure variations; in the flow elements, nodes and zones respectively [Lorenzetti, 2002].

A typical multi-zone program operates on the presumption that the conditions in a zone are well mixed, a situation that (for all practical purposes) is not really true. Nevertheless, airflow is thus modeled through links and flow paths/elements. To run a simulation, a model is set up by identifying the zones of concern, the links between these zones and with the ambient (outside) air. The flow paths are characterized by their peculiar flow properties and flow rates are calculated based on the pressure differentials across paths. The network of links is then represented by series of flow equations that are simultaneously solved to arrive at a mass conserving solution.

If it is assumed that airflow patterns are not affected by existing contaminants, then the mass balance of pollutants in each zone at each time step can be integrated into a multi-zone model to predict the variation in concentration with time. This would give results that are adequate for certain purposes but these models may be incapable of providing detailed information about variations in air flow and pollutant concentration within a room. Also, because thermal and contaminant stratification can occur within occupied spaces, occupant exposure to contaminants can be quite higher than predicted by computer models, which assume perfect mixing. [Goodfellow, 1990].

Another difficult problem associated with multi-zone network models is that of establishing the dynamic pressure (due to wind) on the building envelope. In CONTAMW application for example, the user is required to input the values of pressure coefficient C*p* at the location of the flow path. This could be a major obstacle since C*p* values depend largely on complex environmental and architectural factors. In many case, C*p* values are derived empirically from field measurements or wind tunnel experiments. These measurements and tests are costly and time-consuming, average values of C*p* obtained from wind tunnel tests are usually applied for simulations with a price to pay in terms of predicting accuracy [Wong, 2002].

In summary, the following points stand out as prime issues affecting IAQ modeling:

- CFD techniques of IAQ simulation are accurate but require substantial human and computational resources.
- Multi-zone modeling programs have evolved into user-friendly tools capable of providing a generic overview of indoor air contamination through parametric components.
- Multi-zone packages are simplified to the extent that concentration levels in zones are average values.
- Expert systems and Artificial Intelligence (AI) hold some promise as alternative routes to diagnosing and resolving IAQ problems.

2.6 A Guide to Choosing a Modeling Program

In an attempt to use building simulation tools for IAQ and other purposes, there could be need to refer to Macdonald *et al.* [1999] who have tried to emphasize the need for simulators to introduce uncertainty considerations into their simulations. This should facilitate risk assessment, thereby improving designer confidence in simulation, as a process and in the eventual results. This is truer especially in this case where multi-zone packages would provide results that may not reflect actual concentration patterns of pollutants in given spaces, but rather a generalized output that suggests that all zones are well-mixed. It has been previously noted that thermal and contaminant stratification can occur in occupied spaces, among other oversights of multi-zone techniques. Eventually, the possible options available for multi-zone modeling should be critically overviewed, evaluated and where the application is finally chosen, there should be justification.

Provided in ASHRAE's Fundamentals [1997] is a set of general factors to be considered when choosing a computerized modeling and analysis tool. Some of the available multi-zone modeling programs are as follows:

1. BACH (Building Air Exchange) [Wong, 2003].
2. COMIS. (Conjunction of Multi-zone Infiltration Specialists); [Feustel and Raynor-Hoosen, 1999]
3. CONTAMW. Developed by the National Institute of Standards and Technology, USA [Walton 1997]
4. ESP [Clarke and Hensen, 1990]
5. IAQPC. [Owen, 1989]
6. IAQX 1.0 (Indoor air quality and inhalation exposure)
7. SPARK (Simulation Problem Analysis Research Kernel) [Buhl *et al.* 1993]

2.6.1 Alternatives Utilized in Selection Matrix

Given that some of the tools mentioned above are commercially available, it should be understandable that the quality and quantity of information obtained from the developers or their distributors would reflect the more positive aspects of the tools. However, the aim of the selection matrix includes the exposure of possible or potential flaws in either design or implementation of the software. Therefore, except for cases where an in-depth review of a particular tool already exists in literature; the tools with the most available information were those that were freely available and distributed from research-oriented government organizations. Not surprisingly, the developers of such software encourage users to report and respond to cases of bugs and other mishaps while using the products.

By appraising the capabilities of multi-zone packages, Owen *et al.* [1999] introduced IAQPC as a versatile, user-friendly, multi-zone application suitable for HVAC professionals, building occupants and scientists for investigating IAQ phenomena in the built environment. It could be combined with energy load programs to determine better designs for healthy and efficient buildings. Zhao *et al* [1998] and Pelletret *et al.* [2001] have evaluated and described the functionalities of COMIS (Conjunction of Multi-zone Infiltration Specialists) - as a modeling environment for simulation of pollutant transportation and multi-zone airflow and leakages through natural conditions.

Walton [2002] described Contamw2.0 as a multi-zone application, capable of determining airflow and pressures through flow paths, contaminant concentrations and personal exposure over time. Wong *et al.* [2003] introduced and compared the results they obtained from BACH (Building Air Change] with those from Contamw. BACH is unique in allowing for the importation of schematic design information and wire-frame representations of buildings for the purposes of generating detailed network structure of finite control volumes, computing air change rates and contaminant concentration levels.

In another development, Lorenzetti [2001] made a much more detailed analysis of perhaps two of the most popular multi-zone software available. These are COMIS and Contamw. His review showed COMIS' lack of specific models that are necessary for certain simulations. Some other major concerns about COMIS include: airflow models do not include dynamic effects; it does not provide interchangeable zone models; its licensing agreement makes the issue of ownership quite complicated and it is coded in an old programming language i.e. Fortran 77. There are some concerns and shortcomings of Contamw that were mentioned, as well. These include and may not be limited to the following: it provides only well-mixed zones; the flows across components are restricted to steady-state, monotone increasing of functions of pressure drop; it decouples the mechanical energy balance from flow equations (in a rather different way from COMIS) and low elements in Contamw have memory as well, making the result of a simulation to influence the next.

Nevertheless, a comparative matrix of some selected multi-zone packages is shown in the Table 2.1. This would most likely be beneficial to new as well as experienced researchers looking for appropriate simulation tools. This Table would also serve as a quick overview of the performances and capabilities of the selected applications.

Table 2.1: Comparative Matrix of selected Multi-zone Software

	Feature	COMIS (with IISiBat)	CONTAM	IAQPC	IAQX
A. Software inputs and simulation technicalities	*Design zones or choose layout option*	Design by representing building elements	Design your layout	Choose from existing layouts	Design
	Maximum number of zones	Unlimited	Unlimited	2 - 20 rooms	1- 10 zones
	Multi-Level Options (floors)	Saves a floor as macros for repetition	Multiple floors	One floor (can have more floors but without stack effect)	Single storey
	Maximum number of simulated days or hours	Unknown*	Unlimited	62 days	User-specified hours
	Airflow and contaminant simulation types [Transient, Cyclic, Steady State]	Unknown*	Combinations of Steady state, Transient and Cyclic	Unknown*	Depends on ventilation modes
	Maximum number of sources and sinks	Unknown*	Unlimited	6 sources, 4 sinks	26 sources, 5 sinks
	Inflow of contaminants from exterior	Yes	Yes	Unknown*	Unknown
	Stop, evaluate then continue simulation	Unknown*	Can restart transient and cyclic simulation files	yes	Unknown*
	Ventilation modes	Unknown*	Steady state, cyclic and transient	Unknown	Constant, cyclic, time-varying
	Maximum number of HVAC Systems	Unknown*	Multiple	Unknown*	No HVAC system. Uses air exchange flow rates to ventilate zones
	Sizing HVAC components	Yes	Yes	Unknown*	No
	Number/location of filters	Unknown*	Outdoor Air, Return Air, supply and return point filters	Room air cleaners and 2 HVAC filters	2 filters
	Automatic control elements and models (modifiers, actuators, links, sensors etc)	Needs some amount of coding (programming)	Event-based controls available	Unknown*	No
	Library of Utilities [component leakages etc]	Standard library of components can also save items as macros for future use.	Library of ASHRAE and commercial components	Not available	Not available
	Code/programming language	Fortran 77	C	Unknown*	Delphi
B. Reliability and Results	*Verification of software results*	Available	Available	Unknown*	Accuracy of 0.01% insured as long as inputs are reasonable
	Results at Nodes	Unknown*	Yes (airflow)	No	No
	Export/Output and Result Types	Concentration; airflow; output file available with text editor and as graphs, (3D) bar charts	Graphs of Airflow, concentration; exposure, flow at nodes Can use ContamPP and ContamRV (free) for air	Graph of current concentrations; flow rates, input data	Graph of concentration, inhalation exposure and adequate ventilation rate

			and contaminant results		
	Export formats	IISiBat spreadsheet/ plotting program available.	Tab-delimited results exported for spreadsheets; can generate TRYNSYS data for TYPE96	Unknown*	Copy to windows clipboard or save as ASCII file
	Availability of summarized inputs	Input files can be made by IISiBat	No summary of inputs except for external weather and contaminant files	Input can be viewed summarily	None
C. Integration	*Collaboration with other software or files*	TRYNSYS	TRYNSYS	Unknown*	None
	Hybrid capabilities with CFD	Unknown*	None	None	None
	Import and CAD options	Unknown*	None	None	None
	Weather Files	Weather simulated from within program	Steady State weather within program and external (transient) Weather program also available (free)	Unknown*	None
D. Operating System & User Interface	*User Interface*	Available in IISiBat graphic environment or standalone Fortran and DOS applications	Windows	Menu driven/DOS-based	Windows
E. Availability	*Cost*	Available at a certain cost	Freeware	Available at a certain cost	Freeware
	Licensing Issues and Upgradeability	Code modification may be a problem from v. 3.1. Upgraded regularly by developers	Freely modifiable with due credits given, regularly upgraded by NIST	Commercially available; should contact developers/marketers	Permission *may* be given upon request for code modification

Notes:

*Unknown** indicates that despite sustained efforts, the author was unable to get the required information from available literature or software developers.

2.6.2 Criteria Utilized in Selection Matrix

The selection matrix utilized in Table 2.1 was developed based on certain criteria. Firstly and most importantly, the review of simulation tools as used in many technical papers provided a valuable insight into the motivation, objectives, end-results and validation studies that many researchers obtained. In addition, ASHRAE's Fundamentals also provided a brief guidance into what a simulation tool should be capable of. Much of the criteria that were collated were then streamlined and fused into categories that would serve as quick visual references for wide range of users; based on the experience and engineering judgment of the authors. Eventually, the following criteria were adopted. They are listed not necessarily in any predetermined order of priority, since user-requirements could be relative.

A. ***Software inputs and simulation technicalities*** : This refers and covers many areas that typical a multi-zone software would posses in terms of schematic diagrams/building idealization, representation of mechanical systems an their characteristics, sources, sinks, duration and types/combinations of simulations etc.

B. ***Reliability and Results****:* This group of criteria covers verification of results from recognized institutions/users, import and export options as well as formats of end-results.

C. ***Integration*****:** The capability of a multi-zone package to be integrated with other CAD or CFD, spreadsheet and weather files are covered in this section.

D. ***Operating System & User Interface***: The graphic user interface and the system requirements for installation and running simulation are mentioned here.

E. ***Availability****:* This covers aspects of cost and ownership, Licensing Issues as well as Upgradeability

2.6.3 Analytical Hierarchy Process (AHP)

To select the most suitable software based on the alternatives and criteria shown in Table 2.1, the techniques of pairwise comparison are applied by using an existing program called Expert Choice. This program uses Analytical Hierarchy Process (AHP) and is ideal in the sense that it can handle multiple criteria and alternatives in an automated manner. As long as the inconsistency level of every comparison is not beyond 0.1, then the software would provide a quick way of choosing a multi-zone modeling program. The major advantages of AHP can be outlined as follows:

1. It adapts to the decision-making style of individuals or teams
2. It facilitates the identification of objectives
3. It facilitates the identification of alternative solutions
4. It assists in evaluating key trade-offs among objectives and alternatives

5. It enables individuals or teams appreciate the decision by understanding how it was reached objectively. [Expert Choice, 2000]

The main characteristic of the AHP-based Expert Choice is that it uses pairwise comparisons to deduce accurate ratio scale priorities, rather than using traditional approaches of ‘assigning’ weights. The process operates by relatively comparing the importance, performance or likelihood of two elements with respect to another element in the level above. An assessment or decision is then made as to which is more important and by what magnitude.

2.6.4 The Weighting of Criteria and Alternatives in Expert Choice

Assigning weights in expert choice is done through pairwise comparison of relative importance of any item X and another item Y. The weighting factors come from the needs and preferences which the user has identified in this case under the **Variables, Features** and **Criteria** Columns of Figure 2.1. What this implies is that there are three levels of input: These are (a) the variables or minimum level (b) the features or medium level and (c) the criteria or maximum level as can be inferred from the figure. *The variables are thus the yardsticks with which a feature is judged and the features are yardsticks of measuring a criterion.* Eventually, the entire procedure involves ranking the relative importance of each criterion, upon which every alternative (software) will be judged and also ranked.

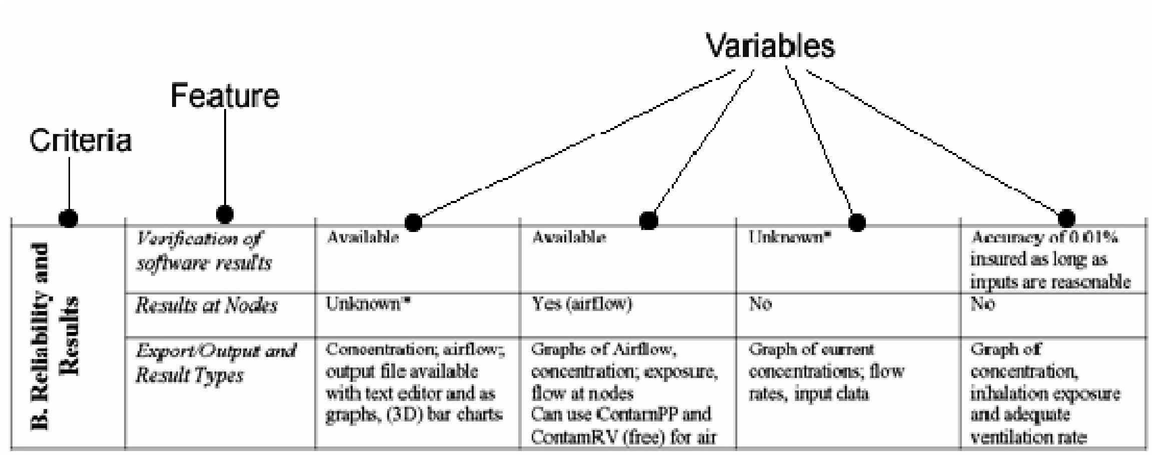


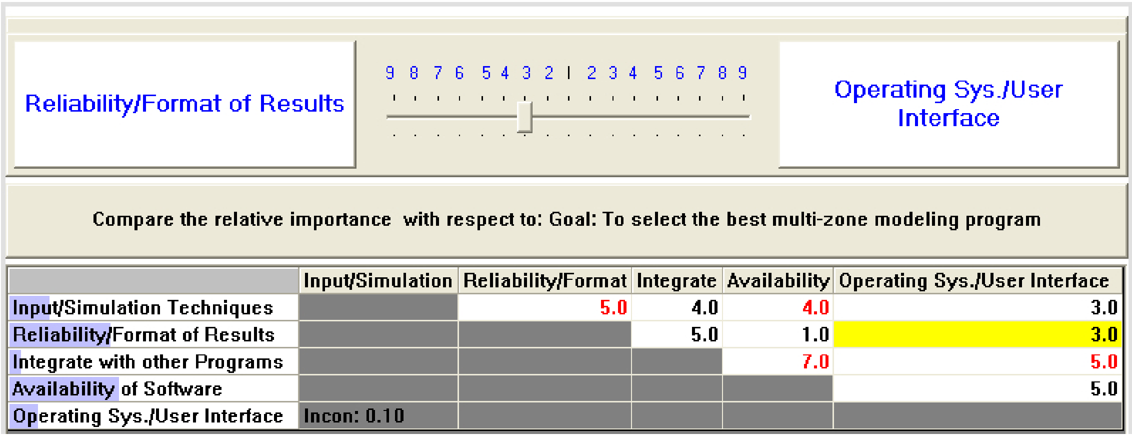
Figure 2.1: Variables, Features and Criteria of the Selection Matrix

The ranking begins at the feature level. Firstly, features (at the medium level) would be judged amongst themselves to see which matters the most to the user and ranked accordingly. When the **feature** versus **feature** comparison is done, (e.g *Verification of Software Results* versus *Export/Output and Result Types*) by comparing them in terms of user's preference (i.e. variables) they will give constituent results that define a criterion. Each of the listed criterion (refer to Table 2.1) is then weighted and ranked based on how its constituent features have performed.

Secondly, pairs of software e.g. IAQPC and Contamw would be compared by analyzing user preference with respect to each feature. Inputs for this user analysis come from the user's preferences or variables. This way IAQPC as a tool would be compared to Contamw with respect to e.g. *Results at Nodes;* and the favored tool would get the higher mark and on this basis, weighting would be done to show the global performance of each software.

The procedure in Expert Choice 2000 (EC 2000) gives users the option of making these pairwise comparisons through three different ways of making decisions between any two items, X and Y. These comparative methods are: Numerical Comparisons, Verbal Comparisons and Graphic Comparisons. A user has the choice of using any method (and switching between methods) that best suits a given circumstance. Further explanations of these methods are explained below. Figures 2.2a, 2.2b and 2.2c, are screenshots from the EC 2000 interface showing pairwise comparisons of the criteria used in selecting a multi-zone modeling program.

1. **Numerical Comparison**: In which case a user assigns numbers (range 0 – 9) to competing items by sliding to his preferred item at the expense of the other. The magnitude of preference would be reflected by the number where the slide rests finally. An indecisive (or neutral) choice would mean that the slide remains in the exact middle. Figure 2.2a illustrates the numerical comparative process and how the decisions made are recorded for every paired comparison done for the entire criteria. From the figure, it can be seen (as an example) that for the given multi-zone modeling program (e.g COMIS) *Reliability and Format of Results* is much more important (and thus preferred) by the author than the *Operating System and User Interface* of COMIS Also, the magnitude of preference is giving as 3 in favor of *Reliability and Format of Results.* Numerical comparison would be appropriate in situations where a user is best able to assign preference quantitatively by numbers.



	Input/Simulation	Reliability/Format	Integrate	Availability	Operating Sys./User Interface
Input/Simulation Techniques		5.0	4.0	4.0	3.0
Reliability/Format of Results			5.0	1.0	3.0
Integrate with other Programs				7.0	5.0
Availability of Software					5.0
Operating Sys./User Interface	Incon: 0.10				

Figure 2.2a: Numerical comparison in EC 2000

2. **Verbal comparison:** where the user chooses the preferred of any two items from verbal description of preferences; ranging from extreme, very strong, strong and moderate or equal; as shown in Figure 2.2b. Both items compared will have all the above verbal values allocated to them but they share the *equal* mark. From the Figure, it can easily be deduced that *Availability of Software* is **Very Strongly** preferred to *Integration with other Programs*. Verbal comparison method would suit a situation where a user is better able to assign preference by using words.

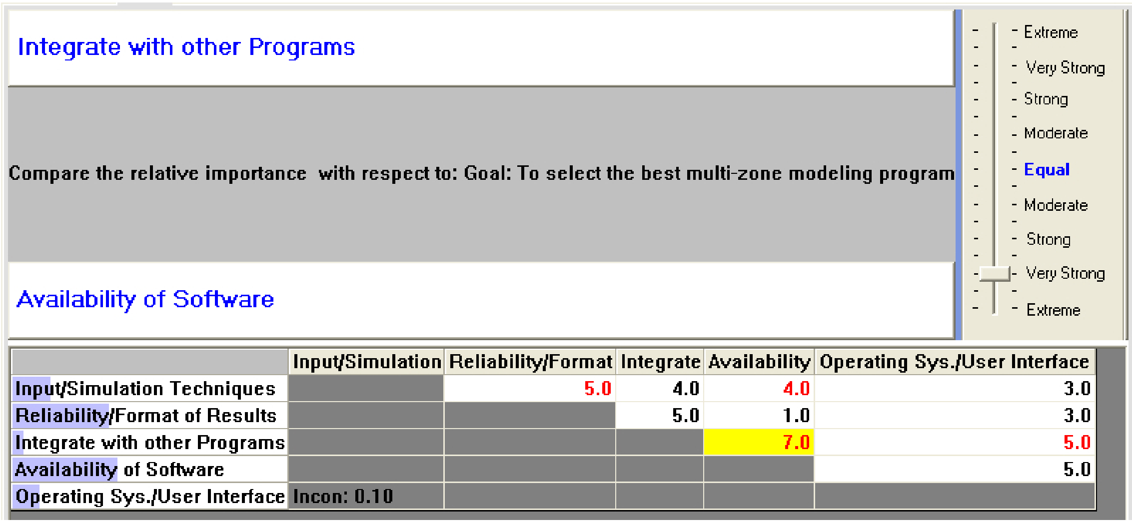
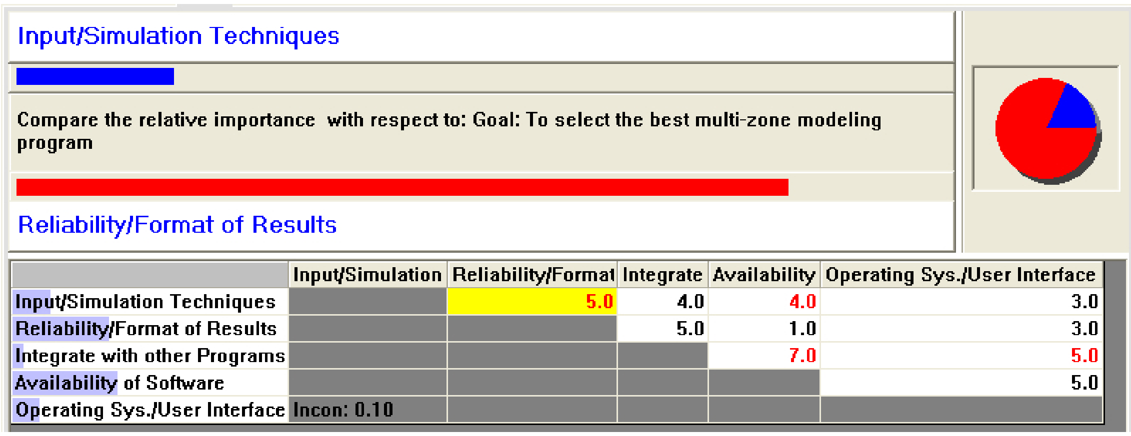


Figure 2.2b: Verbal comparison in EC 2000

3. **Graphical comparison:** where the user chooses the preferred of the two items from a graphical display where two slides are available for each option and preference is made by dragging the slide of the favored option to the desired length at the expense of the less-preferred item. This option is most useful for users who for one reason or the other are unable to assign numeric or verbal preferences between any two items. Figure 2.2c reveals that Reliability and Format of results is favored by the user over Input/Simulation Techniques; and the magnitude of this favoritism is expressed by the graphical length of the **black** slide *(Reliability and Format Slide)* which is much longer than the **grey** *(Input/Simulation Technique)* slide.



	Input/Simulation	Reliability/Format	Integrate	Availability	Operating Sys./User Interface
Input/Simulation Techniques		5.0	4.0	4.0	3.0
Reliability/Format of Results			5.0	1.0	3.0
Integrate with other Programs				7.0	5.0
Availability of Software					5.0
Operating Sys./User Interface	Incon: 0.10				

Figure 2.2c: Graphic comparison in EC 2000

2.6.5 Recording and Consistency of Result

During the decision making process of each pair of items (e.g. criterion) EC 2000 records every paired comparison and checks to ensure that consistency of decision is maintained all the time. A user is thus kept in check if (for example) Decision 1 is made such as "B is preferred to A" then Decision 2 is made such that "C is preferred to B". If then Decision 3 attempts to say "A is preferred to C", such a decision would not be allowed because it is contradictory to the previous decisions. When all decisions are made successfully, the program computes all the inputs made and assigns weights based on user preferences and the bias shown in ranking the deciding factors. The weights assigned to each individual item are then used to rank all the items (e.g. the total items that make the criteria) and the output will show which item ranks first and by what magnitude compared to the rest of the items. The results shown by Figure 2.3 imply that for the user (author) *Availability* is the most critical issue in adopting any software for this study. This (availability) has a weighting of 0.375 followed closely by *Reliability and Format of Results* which ranks 2nd with a weight of 0.349 and so on.

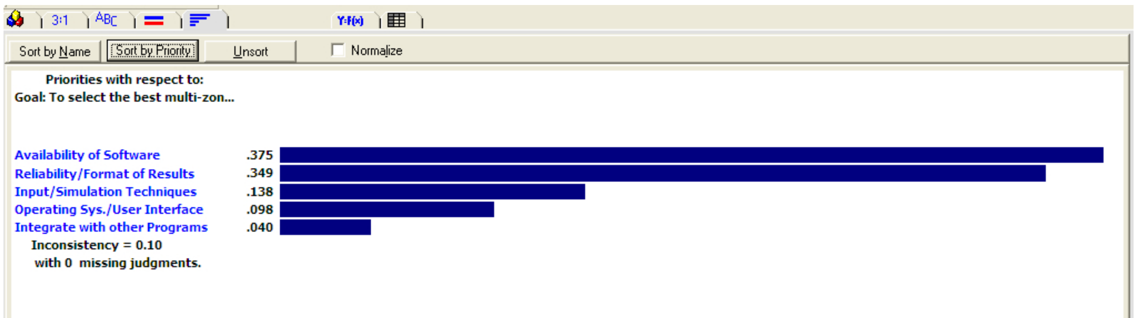


Figure 2.3: Criteria of Software Prioritized

2.6.6 The Selection of Multi-Zone Program

The final aspect of using Expert Choice requires further pairwise comparison to be made. This time around, all the alternatives (i.e. the available software that are competing) would be paired against each other. Every pair will be subjected to all the items in the criteria. For example, IAQPC would be compared with Contamw with respect to the criteria *Software Inputs and Simulation Techniques*. The user then decides which among the two is better with respect to the Features (sub criteria) of both software as documented in Table 2.1 For example in sketching a multi-zone building for simulation, if IAQPC program offers users the choice of existing (fixed number and style of) layouts, whereas Contamw allows users to design their own layouts, then the user may prefer Contamw to IAQPC in this regard. And the user would express this preference by certain magnitude based on the research needs or personal preference. All recorded decisions are given their respective weights based on the importance attached to the deciding factor (criteria). A software may thus perform well in *Inputs and Simulation Techniques* (due to its flexible tools for **layout modeling**), but it would perform awfully in terms of *Availability* (due to **licensing issues**).

The procedure of pairwise comparison is similar to the previous exercise (criteria), except that decisions made in comparing software are now based on previous weighting and ranking of criteria. This would ensure that the best possible decision is made eventually, as consistency in decisions would be ensured as well. It is important to note also that apart from decision making in the broader sense, another major strength of EC 2000 lies in its individuality or customizability. For example, a user in an institution in Saudi Arabia may (for all sorts of reasons) be subjected to different technological, economic and personal factors than another similar user in a different country. As such, each user would have to work with his strengths and constrains in order to come up with the **Alternatives** (programs) and **Criteria** (needs). An important criterion for a particular researcher may therefore appear to be trivial for a different researcher, due to different constraints or opportunities faced by individuals.

After running EC 2000 successfully, Figure 2.4 below shows the ranking of the alternatives (software) from the selection matrix in a prioritized manner. As is evident from the Figure, CONTAMW has the highest score with a weighted value of 0.42, followed by IAQX with 0.258 and COMIS with 0.217. The least is IAQPC with a weighted value of 0.105. This selection process considered the criteria and criteria-ranking as shown previously in Figure 2.3.

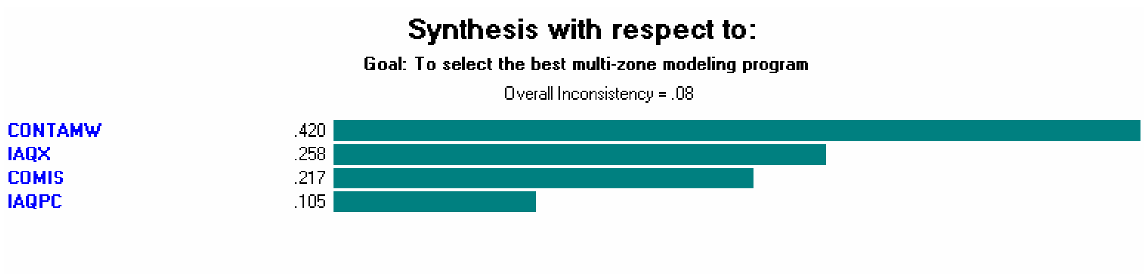


Figure 2.4: The choice of software

2.7 Overview of Contamw

CONTAMW is a Windows application used for multi-zone IAQ modeling which originated from a late 80's predecessor called AIRNET. AIRNET was conceived and developed as an airflow modeling application, with possible applications in contaminant movement and distribution patterns. Modeling airflow in a building typically requires (a) determination of the location and mathematical characterization of the airflow paths (b) determination of the boundary conditions (c) calculation of the resulting airflows and (d) user-friendly framework in which to carry out the analysis. AIRNET and Contamw utilize the network flow model technique as the mathematical background. Walton [1989].

By the late 90's Contamw had developed into a full-fledged Airflow and Multi-zone Modeling package with a simple graphic user interface. The basic functions of CONTAM are to assist in simulating the following:

1. Contaminant Concentrations: Contamw is able to simulate the transportation of dispersed airborne contaminants through airflows, with the added chemical and radio-chemical transformation, adsorption and desorption to surrounding materials and filtration;

2. Airflows: Contamw is designed to calculate infiltration, exfiltration and room-to-room airflows that are due to wind on building envelope or mechanical forces within the building, as well as buoyancy effects brought about by internal/external temperature differentials.

3. Personal Exposure: Contamw can assist in the prediction of exposure to a building's occupants for assessing risks from airborne contaminants.

Some of the practical applications of Contamw include its use in assessing the ventilation rates in building for the purpose of determining variation in such rates with time, and how such ventilation is distribute across the building. In addition, by predicting contaminant concentrations, Contamw is beneficial for determining the quality of indoor air in a building even before construction and occupation. This prediction of personal exposure to occupants can be used in conjunction with various ventilation rates in order to optimize the performance of ventilation systems proposed for the building. Furthermore, it is a used in designing and assessing smoke management systems by applying the same principles of airflow and contaminant movement which occurs during smoke dispersal. Walton [2002].

2.7.1 Features and Resources Available in Contamw

The main features of Contamw include: Building Envelope Components (walls), Flow Paths, Supply and Return Points, Air Handling Units, Ducts, Controls, Sources, Sinks, and Occupants/Exposure Agents. In addition, peculiar building characteristics like stairwells, atriums and plenums can be represented easily. A library of resources is available as well. These resources which include characteristics of typical building components and Pollutants are obtained from ASHRAE standards; NIST/Contamw developed and tested items as well as building components developed by independent researchers for commercial buildings.

2.7.2 Validations of Contamw Results

Validation of Contamw was been done several times, notably experiments that were performed in occupied 3-story building in Reston, VA. In this experiment, tracer gas, (sulfur hexaflouride SF6), was manually delivered into one of the zones in the building. Afterwards, the concentration of SF6 was measured in all zones. This procedure was then simulated in CONTAMW. The predictions that resulted from Contamw were then compared statistically to the measured values. Between May 2000 and June 2001, 10 experiments were conducted and simulated using ASTM D5157 (ASTM 1997) for all the tested and simulated cases. Finally, comparisons were then made for general zonal average concentrations and individual zonal transient concentrations. The results obtained for the zonal average concentrations were very good and in many cases the results met most or all criteria of the D5157. Emmerich, et al [2003]. Contamw is regularly updated to fix expected bugs and program errors. As of March 2006, the latest version is now generally referred to as Contamx 2.4, which is also freely available for download.

2.8 Summary of Findings

The benefit of this literature review goes beyond the immediate purposes of this thesis as it would serve as a background to researchers new to IAQ whereas established researchers could utilize its scope to reassess the pace and progress made in this field. This review of literature is a literal profile of the traditional and contemporary challenges of IAQ, including mechanical and architectural factors responsible for pollutant distribution, weaponization of airborne contaminants, the relationship between smoke control techniques/considerations and general contaminant transportation problems. In addition, the types, strength and weaknesses of multi-zone modeling software/techniques available to researchers were extensively covered. A comparative matrix of modeling programs has been provided as a Table to aid the selection and utilization of multi-zone software by IAQ investigators and researchers. The entire process has actually contributed by exposing the popular programs for IAQ as well as the strengths and weakness of such multi-zone packages.

CHAPTER THREE

IAQ SIMULATIONS OF MULTI-ZONE BUILDINGS

3.0 Introduction

As a technique, multi-zone simulation of IAQ performances of building has been available for over 25 years but it is the improvements in personal computing power that has contributed to its recent progress and reliability. In addition, this type of indoor environmental simulation is currently much applied by the general public and is no longer an exclusive reserve of researchers. [Emmerich, 2001]. Historically, HVAC systems have been designed to supply conditioned ventilation air from outdoor air either through constant volume or by considering thermal loads. However, since ventilation and IAQ needs may not necessarily coincide with thermal conditioning, HVAC systems have more recently began to consider both aspects as critical to well-being of occupants. After all, both aspects are inter-related, Musser [2000]. Furthermore, Beattie and Ward [1999] discussed the advantages of using such simulation by building engineers to assess a HVAC system's ability to provide indoor comfort. Among the advantages they listed of such simulation include better plant selection. This implies that a selected and installed HVAC system could be the result of a simulation exercise, and the desired system could be designed to consider IAQ as an integral component space conditioning.

This study is aimed at understanding how HVAC systems contribute to the distribution of contaminants throughout a building's enclosure either directly or indirectly. In addition, part of the objective of this study is to come up with guidelines for HVAC design and operation for multi-zone buildings with IAQ as focal reference point. To achieve these goals, the study takes a two-prong approach viz: A theoretical study of independent and combinatorial effects of HVAC parameters and an applied study in the form of a Case Study. This section shows the underlying principles through which the goals would be achieved, from the study of a theoretical building to the eventual applications. As such this chapter would also cover IAQ investigations, simulation strategy and matrices and weighting of parameters, multi-zone characteristics, assumptions and inputs for the Base Case simulation.

3.1 Conducting an IAQ Investigation

An investigation into IAQ of a building typically stems from complaints by occupants. While some complaints may be dealt with easily, in certain cases, the complaints can only be resolved only after an extensive investigation and testing by qualified individuals. The flowchart in Figure 3.1 below should serve as a guide into the manner which such investigation should follow.

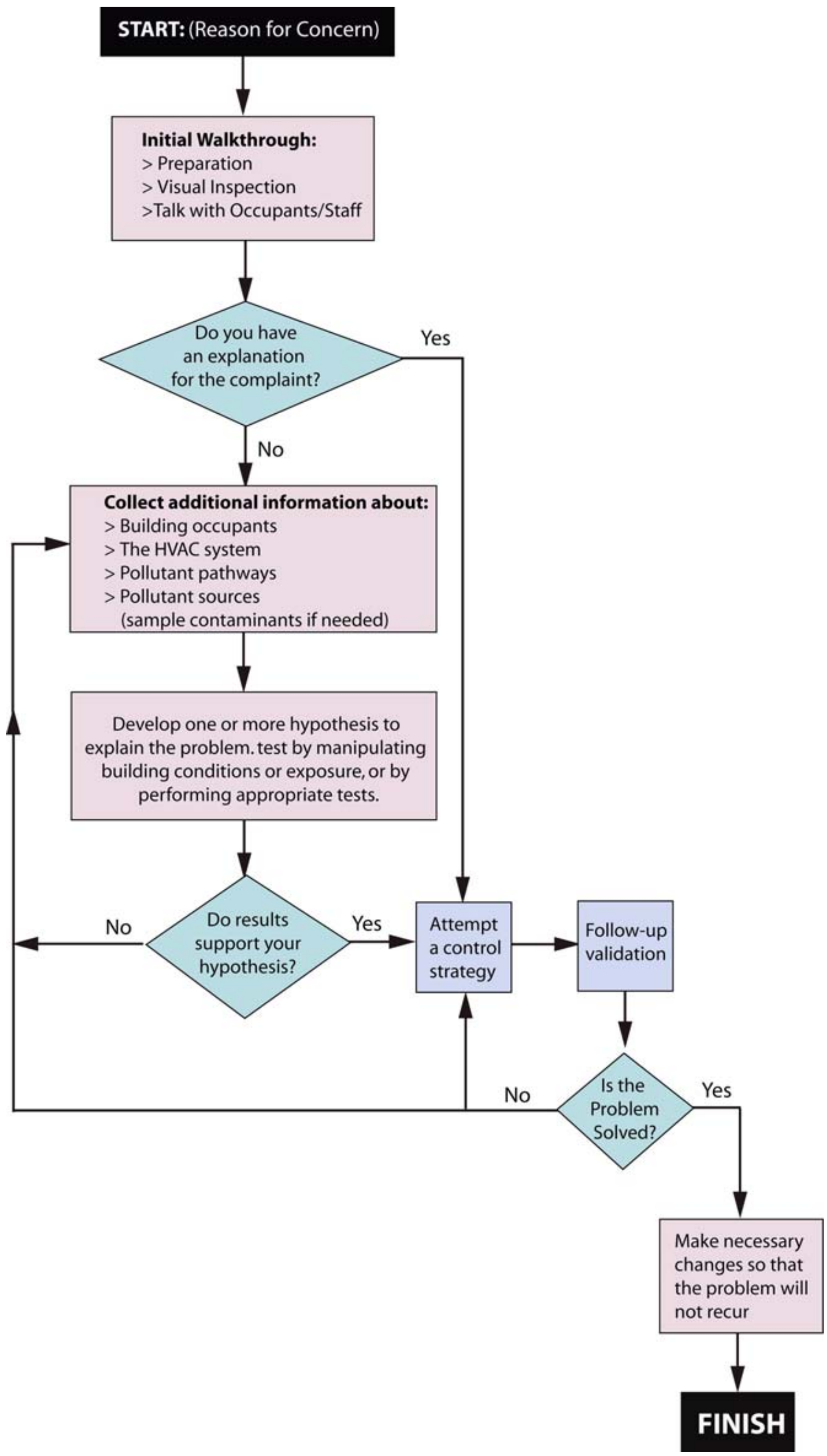


Figure 3.1: Steps for conducting an IAQ investigation. Source: EPA/NIOSH

The primary difference between the case study and a typical investigation and a simulation/case study as outlined in the research methodology is that computerized method of analysis is used for the iterative process, whereas a typical investigation may end up with measurements and other forms of data collection and experimentation. Indeed it can be rightly stated here that the simulation is part of the techniques of an investigation even if it does not involve a physical building. This has been justified by Beattie and Ward [1999] as they discussed the importance of simulation in HVAC plant selection and installation. Therefore the iterations of the flowchart would be valid in providing a general concept into what an IAQ investigation entails.

Pre-Simulation Investigation

In comparison with the procedures laid out in Figure 3.1, the pre-simulation investigation has certain things in common with the initial walk-through investigation process such as:

a. There has to be a reason for concern: i.e. established by common knowledge about the environment, as well as by short discussions with workers in the building
b. A walkthrough to be conducted in order to streamline the architectural drawings with recent modifications and to also have a visual appreciation and inspection of equipment, processes and the general environment.
c. An explanation for the possible causes may or may not be available.

d. Additional information from maintenance staff to be collected about the HVAC system, its operational procedures; and types of possible pollutants should be identified from the procedures used in the daily activities in the building as well as occupant behavior. In addition, potential pollutant pathways can be identified.
e. A general **hypothesis** should be developed to explain the causes of IAQ problem.
f. The simulation would confirm if the hypothesis is correct or not.
g. If there is an element of accuracy in the hypothesis, then manipulation of the building and mechanical parameters would commence as part of the problem-solving aspect of the simulation.
h. If the problem is mitigated, then recommendations would be made so that there is no recurrence.

As can be observed from Figure 3.1, an IAQ investigation could entail cycles of information-gathering, hypothesis-formation and hypothesis-testing. For the goal of solving the IAQ problem (and to avoid going through an endless cycle) it is pertinent that the investigator understands the nature of the problem and that his hypothesis is logically related to solving that problem. The vital aspects of any IAQ investigation include:

1. Initial walk-through
2. Developing of hypotheses
3. Collecting Additional Information.

It is based on the findings of such an investigation that further detailed analysis (e.g. measurements) can be made if warranted. This is because IAQ-related complaints by occupants can be highly subjective and only a thorough first-hand investigation can reveal whether there is indeed a problem; and whether this problem is pollution-related or caused by other important components of IEQ such as thermal, visual or acoustic discomfort. If on the other hand, a process of investigation using computer simulation has already been factored into the methodology of research as in this study, then another flow chart is necessary. Figure 3.2 below shows juxtaposition of traditional IAQ investigation, with multi-zone modeling as a refinement of the research methodology. The procedure derived in this chart is applicable to multi-zone modeling of theoretical buildings or case studies.

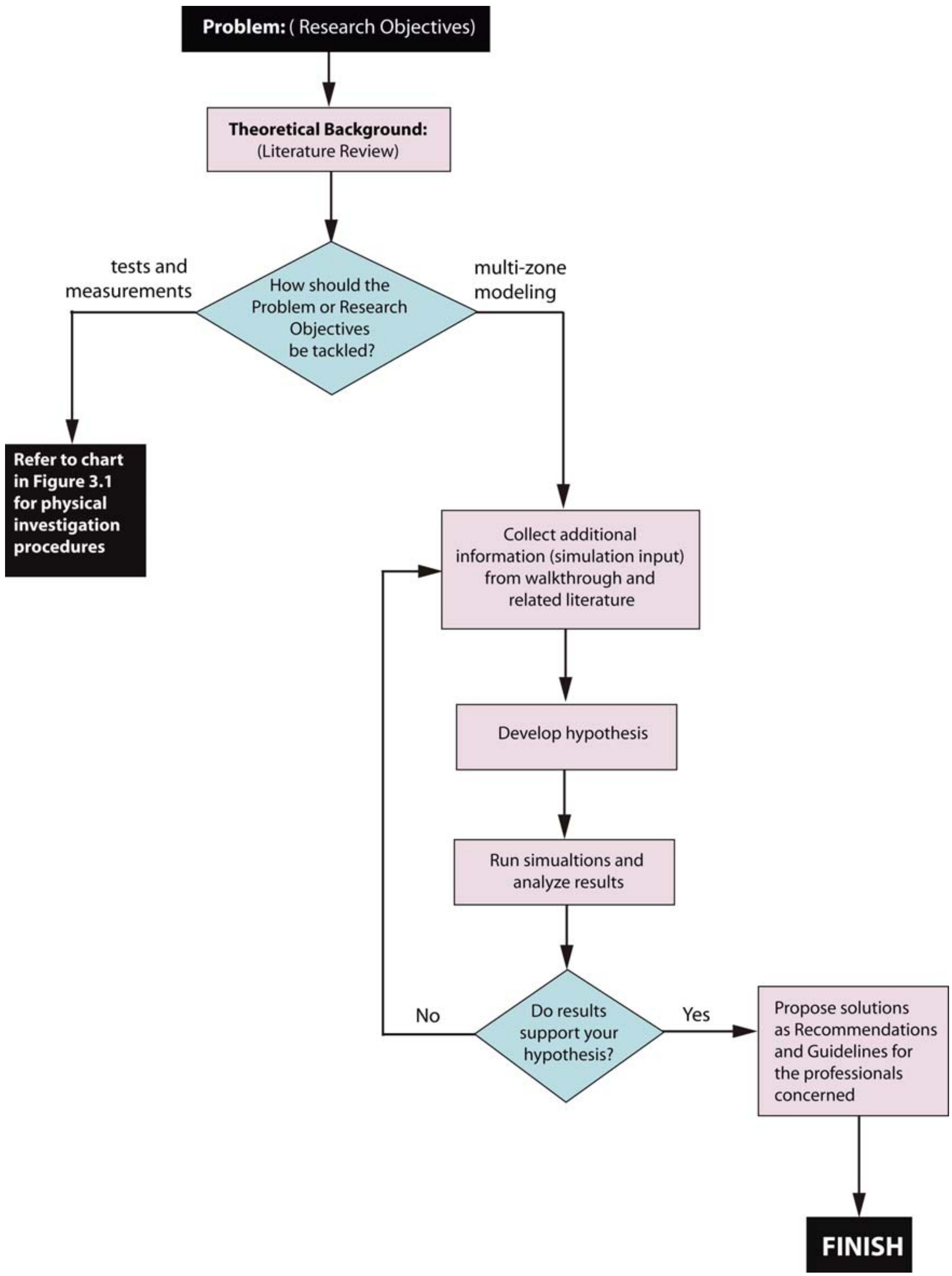


Figure 3.2: Steps for conducting an IAQ multi-zone simulation

3.2 The Simulation Strategy

In order to provide a clear picture of what is to be done in the simulation for the theoretical model, a strategy for running the test simulation was formulated. The strategy involves a systematic arrangement of the primary IAQ parameters and their value ranges. This is a pre-requisite requirement for the formulation and understanding of the simulation matrix. The matrix is a step by step guide on the objectives and components of each simulation case. It is from the knowledge obtained here that the Case Study is expected to benefit. This strategy is best understood from Figure 3.3 below. The Figure reveals a grand overview of the possible combination or paths towards achieving the objective, i.e. to ascertain the behavior and distribution of contaminants under the influence of HVAC sub-systems within an architectural system.

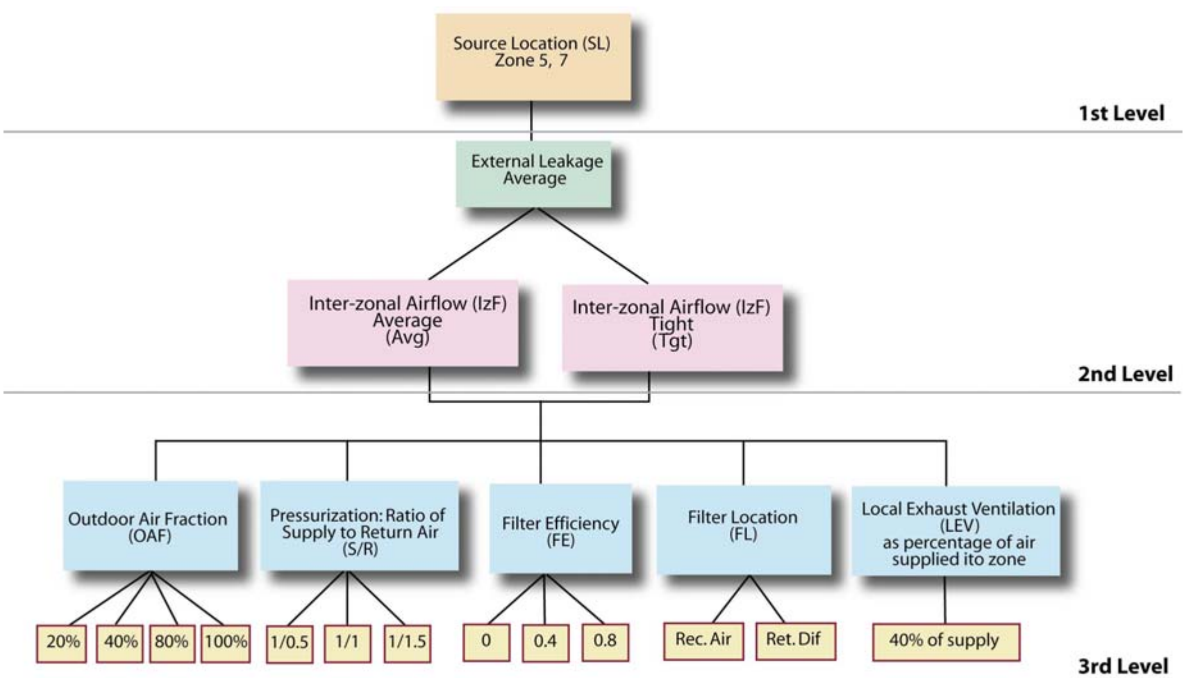


Figure 3.3: The IAQ parameters and value ranges

The strategy shown by Figure 3.3 also identifies the seven (7) parameters under study and their hierarchical relationship in levels. The 1st level parameter deals with the source location (SL) of contaminant. On the part of the theoretical contaminant to be modeled, one dispersal scenarios was considered for the purpose of the study i.e. in internal release as would occur in a particular zone. The 2nd level parameters are concerned with the building fabric such as external leakage and inter-zonal airflow (IzF). However, unlike other parameters, external leakage has a fixed value and is not regarded as a primary parameter for investigation. The 3rd level parameters include OAF, S/R, FE, FL, and LEV. All the above parameters and their variables are listed below as follows:

1. Outdoor Air Fraction (OAF): variables = 20,40,80, or 100%
2. Pressurization (S/R): variables = 1/1, 1/0.5 or 1/1.5
3. Filter Efficiency (FE): variables = 0.4 or 0.8
4. Filter Location (FL): variables = Recirculated Air or Return Diffusers
5. Local Exhaust Ventilation (LEV): variables = 40% of supply; Location = z4, z5, or z7
6. Source Location (SL): variables = z5 or z7
7. Inter-zonal Air Flow (IzF): variables = Average or Tight

The variables (range of values) chosen for these parameters are based on knowledge obtained from literature about HVAC system operation and the leakage characteristics of architectural components; (e.g. flow paths such as cracks).

3.3 The Simulation Matrix

Despite the possession of a strategy that portrays the general picture of *what* is to be done, the question of *how* to do it is vital because of the many possible combinations of parameters. The application of these parameters is better understood by referring to the Table 3.1, which shows a Matrix of the Simulation Strategies. In other words, this Table reveals the pattern that is followed in running each case of the simulation. The Table assists in interpreting the order of steps followed from the simulation strategy earlier shown in Figure 3.3. It is important to observe that one of the primary functions of the Table of matrix is its ability to show that in detailing the simulation (i.e. moving from case to case), two kinds of movement are possible: i.e. Vertical and Horizontal Movements along columns and rows respectively.

3.4 Cases within Simulation Matrix: Columns and Rows

A. Vertical (Inter-Parametric) Movement along Columns

In vertical movements, the simulation options move from one parameter to the next parameter along the respective columns, e.g. from Case A to Case B down to Case U or from Filter Efficiency (FE) to Local Exhaust Ventilation (LEV), then to Source Re-location etc. From Case to case, each individual, pair or groups of parameters are treated as entitled to being a major subgroup with enough characteristic change in their variables to distinguish them from the option directly above or below them. Vertical nomenclature would therefore be in the form of CaseA, CaseB …CaseN,

Table 3.1: Matrix of Simulation Strategies

S/N	PARAMETER / CASE	Outdoor Air Fraction (in %) * 20 * 40 * 80 * 100	Pressure Ratio (S/R) * 1/0.5 * 1:1 * 1:/1.5	Filter Efficiency (FE) * 0.4 * 0.8	Filter Location (FL) 1. Rec. Air 2. Ret. Diff	Local Exhaust Ventilation LEV 40% of Supply in zone)	Source Location (SL) 1. Z5 2. Z7	Inter-Zonal Flow IzF *Average (Avg.) *Tight (Tgt)	Prime parameters under investigation
1.	No HVAC -1	-	-	-	-	-	Z5	Avg.	Inf, IzF
2	No HVAC -2	-	-	-	-	-	**Z7**	Avg.	SL, IzF
3	**Base Case**	**20**	**1/1**	**-**	**-**	**-**	**Z5**	**Avg.**	**Base Case: OAF, S/R, SL, IzF**
4	Case A	20	**1/0.5**	-	-	-	Z5	Avg.	S/R
5	Case B1/B2	20	1/1	**0.4/0.8**	Rec. Air	-	Z5	Avg.	FE, FL
6	Case C	-	-	0.8	**Ret. Diff**	-	Z5	Avg.	FL
7	Case D1/D2	20	1/1	-	-	**Z4/Z5**	Z5	Avg.	LEV
8	Case E	20	1/1	-	-	-	**Z7**	Avg.	SL
9	Case F	20	1/1	-	-	-	Z5	**Tgt.**	IzF
10	Case G	20	1/1.5	-	-	-	Z5	Avg.	S/R
11	Case H	40	1/1	-	-	-	Z5	Avg.	OAF
12	Case I	40	1/0.5	-	-	-	Z5	Avg.	OAF, S/R
13	Case J1/J2	40	1/0.5	0.4	Rec./Ret	-	Z5	Avg.	OAF, S/R, FE
14	Case K	40	1/0.5	0.4	Rec. Air	Z4	Z5	Avg.	OAF, FE, FL, LEV
15	Case L	40	1/0.5	0.8	Rec. Air	-	Z5	**Tgt**	OAF, S/R, FE, FL, IzF
16	Case M	40	1/0.5	0.8	Rec. Air	Z7	**Z7**	Avg.	S/R, FE, FL, SL, IzF
17	Case N1/N2	40	1/1.5	0.8	Rec./Ret	-	Z5	Avg.	FE, LEV
18	Case P	80	1/1	Nil/0.4	Nil/Rec.Air	Z4	Z5	Avg.	OAF, S/R, FE, FL, SL,
19	Case Q	80	1/0.5	0.8	Ret. Diff	-	Z5	Avg.	OAF, S/R, F, FL
20	Case R	80	1/1.5	0.8	Rec. Air	Z5	**Z7**	**Tgt.**	LEV, SL
21	Case S1/S2	100	1:1	-	-	Nil/Z4	Z5	Avg.	OAF, FL
22	Case T	100	1/0.5	-	-	Z5	Z5	Avg.	OAF, S/R, LEV
23	Case U	100	1/0.5	-	-	Z5	Z5	**Tgt**	OAF, FL, IzF

B. Horizontal (Intra-parametric) Movement along Rows

In horizontal movement, more options within a single parameter would be available, e.g. within FL, efficiencies could be varied to give sub-simulations. This is necessary because some parameters have variables within possible values that can significantly alter the impact of the parameter. For example, consider a parameter such as Filter Efficiency, which could have possible values of 0.4 or 0.8. Each of these values is capable of providing significantly different results depending on its combination with other parameters. Therefore, it is necessary to investigate these options (0.4 and 0.8) all within the same level or row (of Filter Efficiency). The Table also shows that alphabetic nomenclature was used both vertically and horizontally to distinguish the simulation options. Horizontal nomenclature would therefore be in the form of CaseB1, CaseB2, CaseBn etc.

3.5 The Multi-zone Model Characteristics and Inputs

3.5.1 The Model Characteristics

A single-storey, multi-zone institutional building with seven well-mixed zones having a total floor area of 5,440m^2 and volume of 18900m^3 was idealized in CONTAM. The building components with leakage values that characterized exterior elements and interior divisions were obtained from readily available library of ASHRAE's building elements. Across the building envelope, the infiltration air change per hour (ACH) was calculated to be 0.1; assuming unwanted flow of air to occur across doors, windows and conduit penetrations only.

An external file of ambient weather (wind speed and direction) was also developed for Dhahran using WEATHER, a sister program of CONTAM. The desired supply rates of ventilation air were obtained from a commercial cooling load design application whereas the required fraction of outdoor air (OAF) was derived from ASHRAE Standard 62 of 1999. A simple constant air volume air handling unit was deployed to work with various modes/schedule ranging from 20 – 100% outdoor air schedule with intermediate values of the order of 20. The choice of one single AHU is simply based on the need to simplify the multiple scenarios of contaminant and air movement into and out of the building. The simplified AHU system provided by CONTAM makes it easy to deploy a mechanism that supplies, returns and re-circulate specific volumes of air, which is the basic necessity required for this study.

Modeling of the building in CONTAMW could not account for all possible building elements and flow characteristics that would exists in practical situations, partly because there is no sufficient literature that covers certain aspect of institutional buildings. Nevertheless, Fang [1995], Fang and Persily [1994] and Walton [2002] were among the numerous sources of valuable inputs for the study.

3.5.2 Modeling the Multi-zone Building in Contamw

The building design is such that there are a total of 7 zones. Four of the zones (1, 2, 6 and 7) have a direct relationship with the ambient environment. These are the zones that are expected to be affected by infiltration. The remaining three zones are all internal. Zone 4 is a contiguous zone, much like a corridor, that shares boundaries with all the 4 external zones. Zones 3 and 5 are isolated 'island' zones which share a partition amongst themselves. Figure 3.4a and 3.4b below show the schematic layout of the building and its representation in the CONTAMW graphic user interface.

Considering the above multi-zone building in Contamw, a total of 34 major components were used to describe external leakage routes while 41 flow paths were used to characterize major pathways generated across internal architectural components. With the exception of the highly equipped zone 5, with a large internally generated heat and which had 8.88 ACH^{-1}, all other zones had ACH^{-1} values ranging from 3.1 to 4.0. One AHU was identified as well as numerous supply and return outlets in each zone. The reason for using a single AHU for this building is based on the need to keep the objectives as simple as possible. Using multiple AHU may seem more practical, but it will also complicate the process of manipulating all the possible HVAC parameters. A single AHU would keep the permutations and combinations straightforward and tidy.

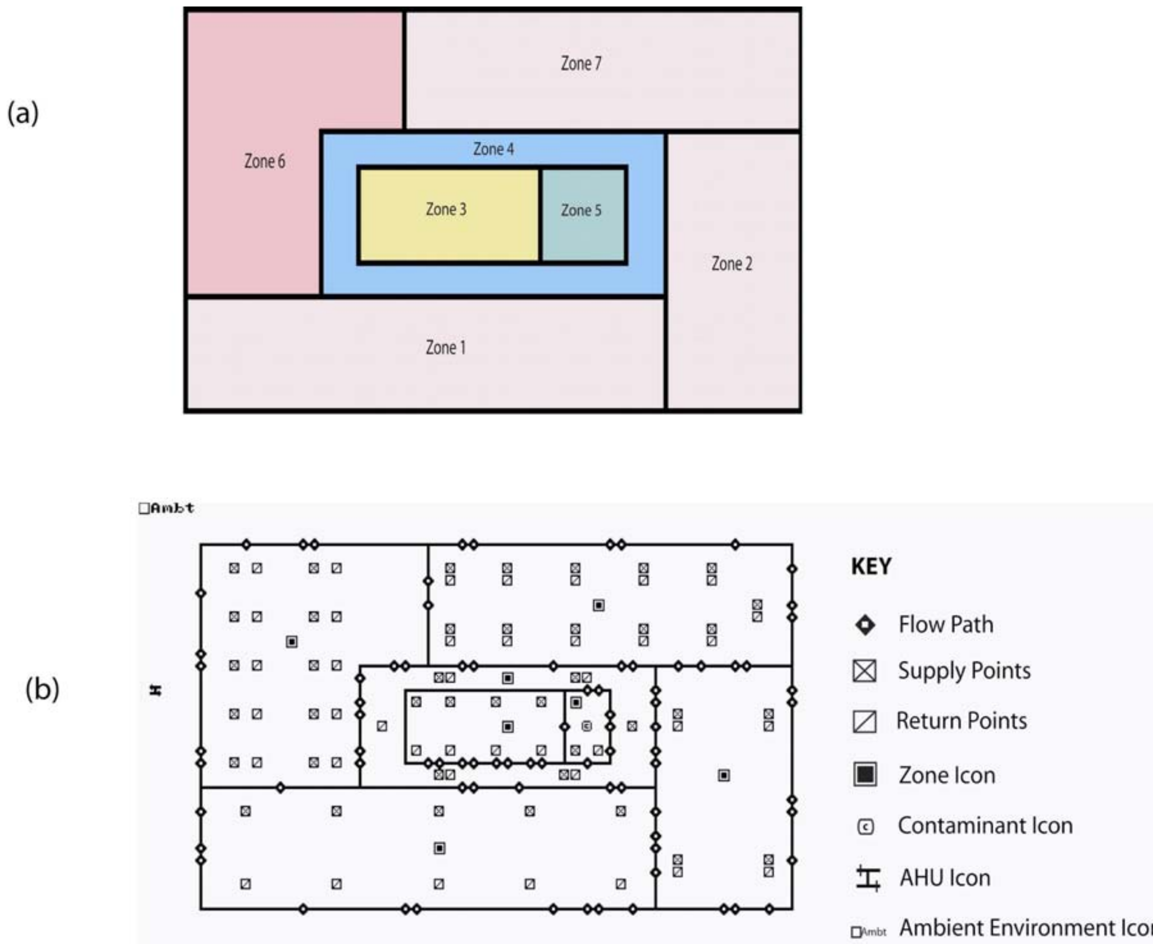


Figure 3.4 Layout of multi-zone building as (a) schematic and (b) modeled in Contamw

Contaminant source was also located in zone 5, with the possibility of relocating it to zone 7. Further qualitative and quantitative description of the building can be inferred from Figure 3.5 and Table 3.2 below.

Due to the need to simplify the results obtained from the simulations, three zones were selected to be representative for the entire building. These include an external zone (zone 6) a contiguous zone/corridor (zone 4) and zone 3, which is isolated in the middle as shown by the sketch of the building in Figure 3.3. It is believed that in terms of physical location, volume, computed air supply and occupancy, these zones are representative of the variety of spaces available in the building for the following reasons:

- Zone 6 has a connection to the ambient environment.
- Zone 4 is contiguous and is physically connected (via flow paths) to all other zones
- Zone 3 is an isolated zone but also has a direct relationship (zonal partition) with the source zone.

3.5.3 HVAC and IAQ-Related Calculations, Assumptions and Estimations used in the Simulations

Carrier, a commercial cooling load calculation program was used to determine the required designed air flow rate for the building. Table 3.2 and Figure 3.3 below summarize the calculated flow rates for each zone with its component occupancy and area.

Table 3.2: Occupancy, OAF Requirements and Computed Design Air Supply

Zone Name	**Area (m^2)**	**Occupancy (people)**	**Minimum OAF (L/s x Persons)**	**Computed Design Air Flow Rate (L/s)**
1	1473	60	8 x 60 = 480 L/s	5500
2	828	25	13 x 25 = 325	3300
3	370	15	7 x 15 = 105	1150
4	430	20(corridor)	108	1410
5	40	0	30	550
6	1043	30	15 x 30 = 450	15,300
7	1258	60	13 x 60 = 780	4400
Total	**5400**	**200**	**2278 L/s**	**31610**

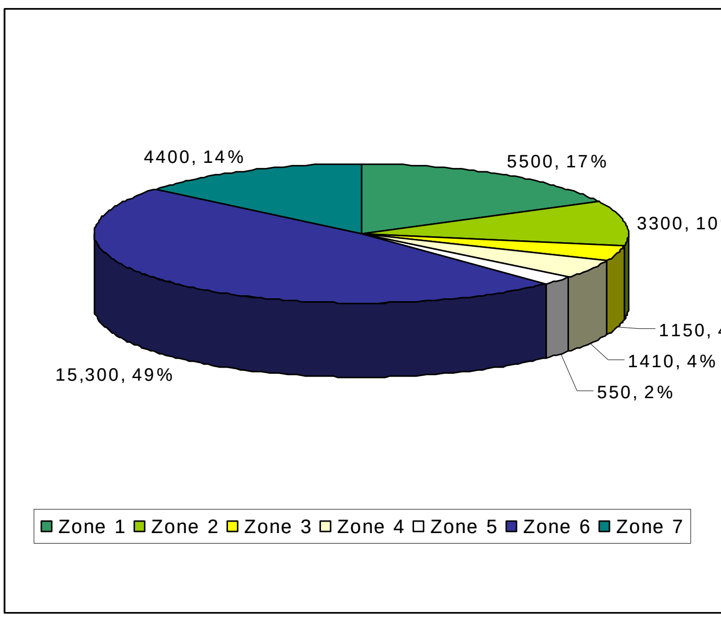


Figure 3.5: Percentage representation of Computed Design Air Flow Rate for all zones

A number of estimations and assumptions were necessarily made, preparatory to running the simulations. These assumptions and estimations are either directly related to HVAC systems and their characteristic input or indirectly as in the architectural pathways that would aid pressurization. These four groups of assumptions and estimations are listed below.

1. **The Source:** Contaminant source is in zone 5, an assumed VOC spill generated through Constant Coefficient Model @ 0.005kg/s. The choice of zone 5 as the initial source zone is based on assumption that the spill occurs in a storage-like room that goes unnoticed for some hours. The rate of generation is sufficient enough to provide a measurable/significant quantity of contaminant that would mix with clean air; and the value has no special mathematical importance.
2. **Outdoor Air Fraction**: For a single AHU serving a multi-zone environment, only a single fraction of outdoor air (OAF) can be applied, even though the spaces have different fractional requirements. The required fraction used in order to avoid over-ventilating or under-ventilating the multiple spaces is obtained from equation 1 below as provided by ASHRAE's standard 62:

$$Y = \frac{X}{[1 + X - Z]}.$$

$$X = 2278/31610 = 0.072$$

Z = 780/4400 = 0.177

$$Y \text{ is then } = \frac{0.072}{[1 + 0.072 - 0.177]}$$

Where:

Y = Fraction of the supply system's air to originate from outdoor air

X = Ratio of total minimum outdoor air required to total design air flow rate

Z = Ratio of largest zonal outdoor air required to zonal design air flow rate

(Refer to Table 3.2 for all input values used in the equation above)

Y = 0.072/0.895 = 0.08 i.e. meaning that this is the fraction of the supply system air that must originate from OAF. *Note: This ratio may not necessarily hold true during pressurization but rather, serves as a guide into what the Standards specify.*

Therefore required OAF = 0.08 x 31610 (L/s) = **2, 529 L/s** (minimum). In other words, Y gives 2529/31610 x 100 or 8 % of OAF as part of supply air. Accordingly, from ASHRAE's Fundamentals, the ratio X/Y can be described as the efficiency of the ventilation system. In this case, that would be 0.072/0.08 = 0.9.

3. **Leakage Values used**: Assuming overall average external rate of leakage, see Table 3.3 below. These leakage values are derived from Contamw Library of

leakage values derived from ASHRAE and other commercial/independent data. The leakage values represent the typical results obtained from tests and experiments conducted on various building components categorized under minimum, average and maximum leakage per item or per unit length. The leakage values describe the rate at which each building component allows air or contaminants to penetrate across it from one zone to another.

Table 3.3: Assumed Leakage Values

S#	Leakage Items used	Average Leakage Value (from ASHRAE/Contam Library)	Placement and quantity
1.	Door, single, weather-stripped, best estimate (exterior)	12 cm^2 per item	Fire escape and Side doors
2.	General door frame - best estimate (including main entrance door frame)	12 cm^2 per item	All doors
3.	Door, sliding, exterior glass patio, per area, best estimate (Main entrance door)	5.5 cm^2 /m^2	Main entrance
4.	Piping/Plumbing/Wiring penetrations, caulked - best estimate (all zones, assuming 8 outlets per external zone) i.e. 8 x 4 penetrations	2 cm^2 per item	All zones
5.	Inoperable window, Building AA, typical (zone 7)	0.58 cm^2 /m	One zone
6.	….Window framing, masonry, caulked, best estimate	1.3 cm^2 /m	

7.	Window: Double horizontal slider, aluminum w/weather - strip-best estimate	0.72 cm^2 /m	Four zones
8.	….Window framing, masonry, caulked, best estimate	1.3 cm^2 /m	Four zones
	Calculated Total Building A*L*		

4. **Inter-zonal airflow items**: Assumed inter-zonal flow items as shown below in Table 3.4. These values are similar in origin and purpose as those obtained in the previous table 3.1, but they relate to internal building components.

Table 3.4: Assumed inter-zonal flow components

S#	Leakage Items used	Average Leakage Value (from ASHRAE/ Contamw Library)	Placement and quantity
1.	Door, general, best estimate (interiors)	0.31 cm^2 /m	All inter-zonal doors, (8 in number)
2.	Ceiling-wall joint - best estimate (all internal walls, with total length of 78m))	1.5 cm^2 /m	All zones
3.	Piping/Plumbing/Wiring penetrations, caulked - best estimate (all zones, assuming 4 outlets per zone) i.e. 28 penetrations	2 cm^2 per item	All zones
4.	Internal walls	0.35 cm^2 /m^2**	

5. **Base Case Parametric Inputs:** Average leakage values of major components were used to characterize the building envelope. Given that Wladyslaw *et al*

[2003] have shown the needlessness of increasing efficiency of filters beyond a certain point, the Base Case and hence maximum efficiency of filters for this study was fixed (using best engineering judgment) at 80% (i.e. 0.8). Based on ASHRAE's algorithms for fractional OAF, a schedule of delivering 20% OAF was initiated. Note that ASHRAE [2001] approximated OAF fractions for institutional buildings to fall within 10 to 40%.

6. **Weather:** A weather file was created using data collected through a test reference year for Dhahran, Saudi Arabia. For a 24-hour time frame, the weather file would account for transient factors like wind speed, wind direction, temperature, pressure and humidity ratio.

7. **Interior Temperature**: For the building interior, Indoor temperature was maintained for all zones at 24^{o}C; and S/R for all zones were maintained or manipulated for pressurization purposes.

CHAPTER FOUR

CONTAMINANT BEHAVIOR AND DISTRIBUTION IN MULTI-ZONE BUILDINGS

4.0 Introduction

This chapter is the backbone of the research. It covers the primary objective of this study which is to investigate the behavior and distribution of contaminants in mechanically ventilated multi-zone buildings. The study is carried out via a multi-zone contaminant simulation program. Architectural and HVAC parameters that affect the behavior and distribution of contaminants are investigated individually and collectively through a systematic procedure. The multi-zone building described in chapter 3, was first modeled architecturally and mechanically in Contamw, during the major HVAC and architectural components are represented as realistically as possible.

The simulations begin with a Pre-HVAC scenario, where the objective is to assess the consequence of natural forces (e.g. infiltration) in the behavior of contaminants. This would be done by having two different source zones. Afterwards, the Base Case simulation would be done with the purpose of establishing a benchmark upon which all consequent and previous cases will be compared and analyzed. Furthermore, there would be simulations of individual parameters (S/R, FE, LEV etc), followed by combinations of different parameters as outlined in the matrix of simulation strategies in Table 3.1.

4.1 Pre-HVAC Simulations: Providing a background for Future Simulations

Despite the fact that the study is basically concerned with the behavior of contaminants in multi-zone buildings under the influence of HVAC systems; it may be worthwhile to observe the behavior of the contaminant in the same building without any mechanical ventilation. This would aid us in the final assessment of the role, which the HVAC system may play as an influencing medium.

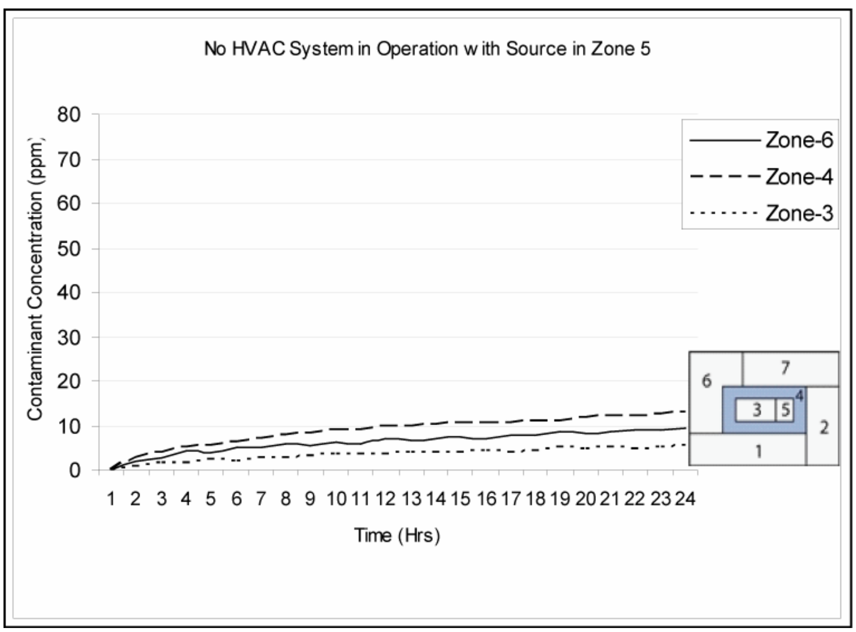


Figure 4.1: Contaminant concentration levels in selected zones when no HVAC system is in operation: (source zone 5)

Given the 24-hour period as the simulation period, it is observed from Figure 4.1 that concentrations in all zones would be constantly on the rise. The outdoor air is assumed to be uncontaminated (fresh). This general rise is attributable to the fact that the contaminant being modeled is constantly generated without any sink or removal mechanisms. Zone 6 displays an undulating curve that reflects ambient/windy conditions through infiltration. The contaminant concentration level for this zone at the 24-hour mark is 9 ppm.

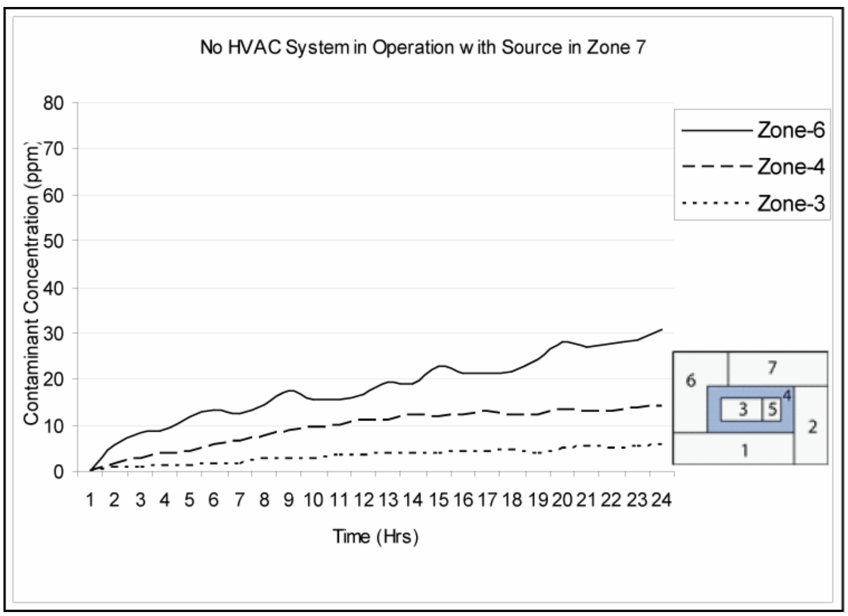


Figure 4.2: Contaminant Concentration levels in selected zones when no HVAC system Is in operation: (source zone 7)

The trend of contaminant concentration levels appears to increase proportionally for the three zones under consideration. As at the 24-hour mark, the difference in contaminant concentration levels is approximately 20 ppm between all zones. This may be indicative of the effect of natural air flow and pressurization, which acts as a stabilizing force by ensuring proportional flow of contaminants into and out of each zone. In addition to this, the ambient air is acting as a sink as it is responsible for the dilution which must be occurring as a result of infiltration.

A different perspective to the pre-HVAC simulation is obtained when (from Figure 4.1), the source is moved from the internal zone (#5) to zone 7. As in the previous Figure, concentrations in all zones continue to rise throughout the simulation time-frame. However, zone 6 shows a higher concentration than previously owing to its close proximity to zone 7, where the source has been relocated to. The contaminants are no doubt finding their way into zone 6 through the architectural components that characterize the building's inter-zonal movement, especially under the added influence of infiltration; which is providing more air to serve as vehicle for the movement of contaminants from the source to other zones. The effect of wind speed and direction is also noticeable in the rising concentration levels of zone 6. At the final hour, the concentration is 30 ppm, representing a 70% increment over the level recorded when the source was in zone 5.

4.2 The Base Case Simulation

The Base Case is the focal point of origin and reference for the other simulations, i.e. from where there would be a datum or point of reference to compare all results with. The fundamental component of the Base Case is that there is a 20% delivery of outdoor air without any additional parameter being actively deployed. The results of the base (and subsequent) case would focus on showing the situations in only three zones as explained earlier. The parameters that are utilized in the base case can be identified in Table 4.1.

Table 4.1 Base Case Parametric Inputs

BASE CASE PARAMETERS	**MAGNITUDE**
OAF	20%
S/R	1/1
FE	Nil
FL	Nil
LEV	Nil
SL	Zone 5
IzF	Average

From the Base Case result in Figure 4.3 below, it can be seen that the concentration levels for zones 6, 4 and 3 are averaged as 58 ppm, 75 ppm and 62 ppm respectively. These levels were reached after about 12 hours, without pressurization and an outdoor air fraction fixed at 20%. Compared with the previous situations were no HVAC system was delivering air to the zones, it can be observed that there is a sharp rise in the concentration of contaminants in all zones within the first 3-5 hours. Afterwards, a steady state level was generally achieved (by the 9th hour on the average). This phenomenon can be attributed to the speed and spread of mechanically delivered air, which aids in the distribution of contaminants in all zones at a faster rate than when there is no mechanical system of supply. The observed trend is thus evidence that the mechanical systems are responsible for the distribution and rate of spread of contaminated air across the building. Subsequent investigations (cases) would reveal the influence of other parameters (e.g. pressurization, increased OAF or IzF) are able to alter this phenomenon. Thus there is now a basis for which comparisons with other simulation parameters can be made.

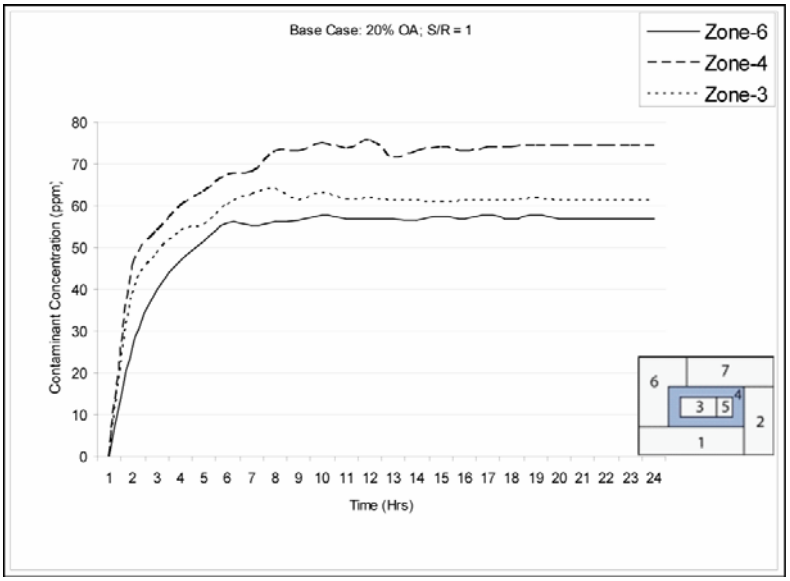


Figure 4.3: Variation in contaminant concentration levels under base case conditions

4.3 Simulating for Individual Parameters

Each of the seven parameters that listed earlier (OAF, S/R, FE, FL, LEV, SL and IzF) needs to be introduced individually into the simulation before a collective assessment can be done much later to obtain multiple impacts. Figures 4.4 – 4.9 below reveal the way in which each parameter affects the concentration level in the selected zones. Sequentially, the parameters were simulated as follows: S/R, FE, FL, LEV, SL and IzF. This implies that the first individual parameter to be introduced is in Case A, where impact of Pressurization was studied. This is followed by Case B1 and B2 (Impact of Filter

Efficiency of 0.4 and 0.8 respectively); Case C (Impact of Filter Location); Case D1 and D2 (Impact of Local Exhaust Ventilation in Zone 4 and Zone 5 respectively); Case E (Impact of Source Location –relocation of source to Zone 7). As can be observed, there were horizontal variations (changes along the rows of the simulation matrix) in Filter Efficiency (FE), which had variables of 0.4 and 0.8 as well as Local Exhaust Ventilation (LEV) with variables in terms of locating exhaust in zone 4 and zone 5.

4.3.1 Case A: Impact of Pressurization

In Case A, the objective is to ascertain the impact of pressurization alone. To do so, an S/R (Supply/Return) ratio of 1/0.5 was used. The pressurization was done in Zone 4, which is the zone with direct architectural and mechanical relationship with all other zones. It is observed that the concentration levels in zones 6, 4 and 3 are reduced by 13%, 16% and 8% respectively after steady state conditions are attained in about the 12th hour. This is evident from Figure 4.4 below, where the concentration values of 50 ppm for zone 6, 65 ppm for zone 4 and 57 ppm for zone 3. Note: It should be mentioned that by this pressurization procedure, the inter-zonal airflow into the pressurized zone 4 is reduced; simultaneously however, the removal capacity of this zone is also hampered due to lesser volume of air being returned via ventilation system. Alternatively, tackling this problem could entail increasing the supply air by the same fraction that was meant to be reduced instead; i.e. the S/R would be 1.5/1.0. This approach could also counter the possible thermal effects of having a reduced return ratio in the affected zone. Nevertheless, this would mean that the AHU is going to increase its supply capacity over the original design rates. In addition, the 20% OAF used for this Case means that substantial amount of air (that is part of the 80% recirculated air), would find its way back into the supply system.

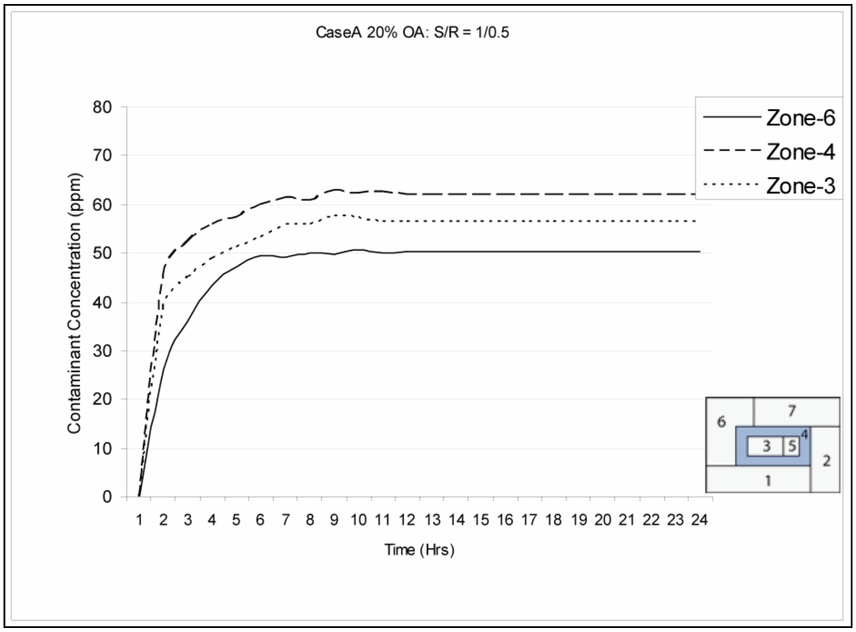
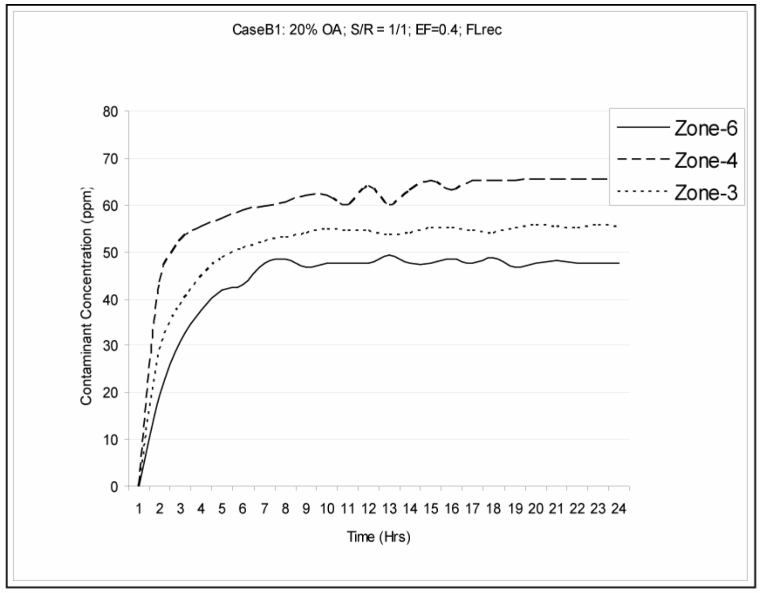


Figure 4.4: Contaminant concentration in selected zones at 20% OAF; S/R of 1/0.5

4.3.2 Case B1 and B2: Impact of Filtration (FL = Recirculated Air)

The second parameter to be investigated is filtration of recirculated air. The impact that filtration exerts on the concentration levels of the zone is studied under two sub-conditions, which are efficiencies of 0.4 and 0.8. From Figures 4.5a and 4.5b below, it can be observed that Filter Efficiency of 0.4 produces a reduction in concentration levels in the order of 17%, 13% and 11% for zones 6, 4 and 3 respectively.

(a)



(b)

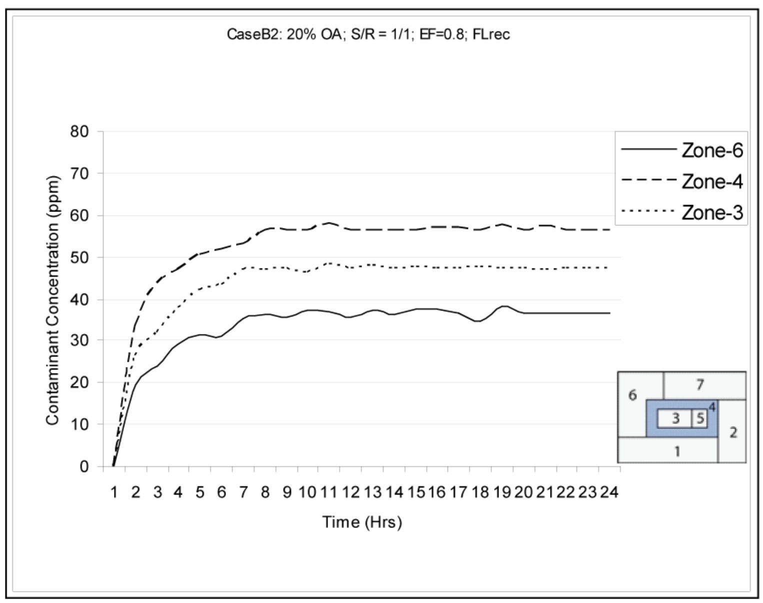


Figure 4.5: Contaminant concentration in selected zones with (a) FE=0.4 and (b) FE=0.8

However, by increasing efficiency to 0.8, there is a reduction in concentration to be 37%, 22% and 23% for the respective zones as deduced from above.

4.3.3 Case C: Impact of Filter Location: (FL = Return Diffusers)

Having observed the quantitative effect of filtering recirculated air, the next investigation is targeting the differences in performance when filters are located at the point of recirculated air and at return diffusers.

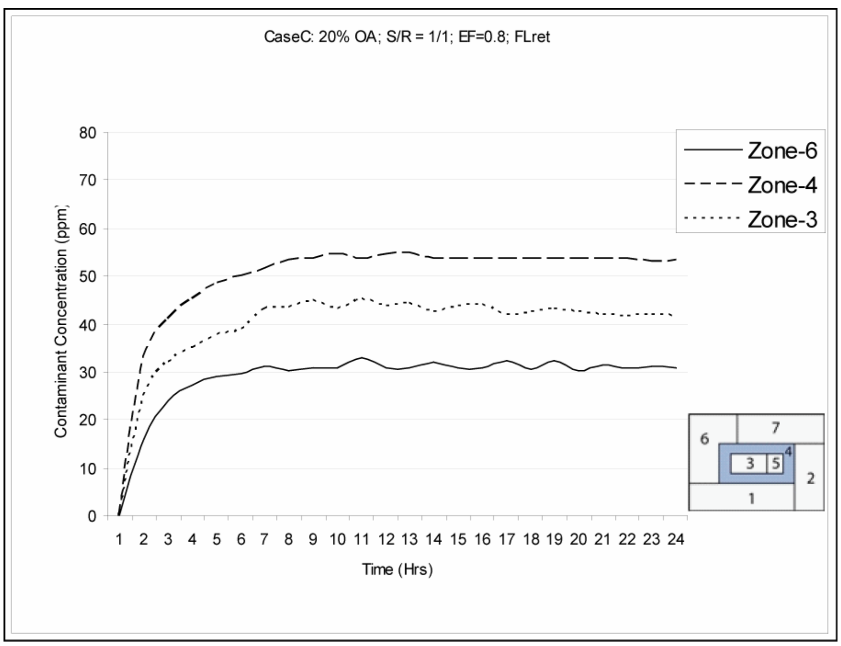


Figure 4.6: Contaminant concentration in selected zones; filter (E = 0.8) at return diffusers

Evidently, it is observed from Figure 4.6 that zones 6, 4 and 3 record steady state contaminant levels of 31 ppm, 56 ppm and 42 ppm representing a drop of 46%, 25% and 32% respectively when compared to the Base Case. As in all cases so far, there is no additional parameter that is assisting Filter Location. Perhaps, that could explain why zone 3 (which shares direct inter-zonal flow paths with source zone) records only an additional 3% reduction in contaminant levels when compared to Case B2. It should be remembered that Case B2 has FE of 0.8 and FL was recirculated air. The situation in Case C provides us with a better result than in Case B2. This issue would probably be clarified when further combinations of parameters is done in subsequent stages.

4.3.4 Case D1 and Case D2: Impact of Local Exhaust Ventilation in Zones 4 and Zone 5

From the simulation strategy that with respect to local exhausting using fans, a flow rate calculated at 40% of zonal air supply is to be used. The reason for this decision is that there are multiple values of fan flow rate useable in this sort of investigation. But if the objective is simply to appreciate the impact of local exhaust ventilation (with the fan locatable in as many zones as possible) then, there should be a common reference factor. This is because the zones have different areas/volumes, different design air flow supply rate and different physical relationship to the source zone. The common denominator is chosen as 40% of whatever the designed air flow rate is meant to be. In addition, two locations of LEV were chosen. The contiguous zone 4 (corridor) and the source zone (5). Figures 4.7a and 4.7b are the outputs obtained from the simulation of these two individual sub-parameters.

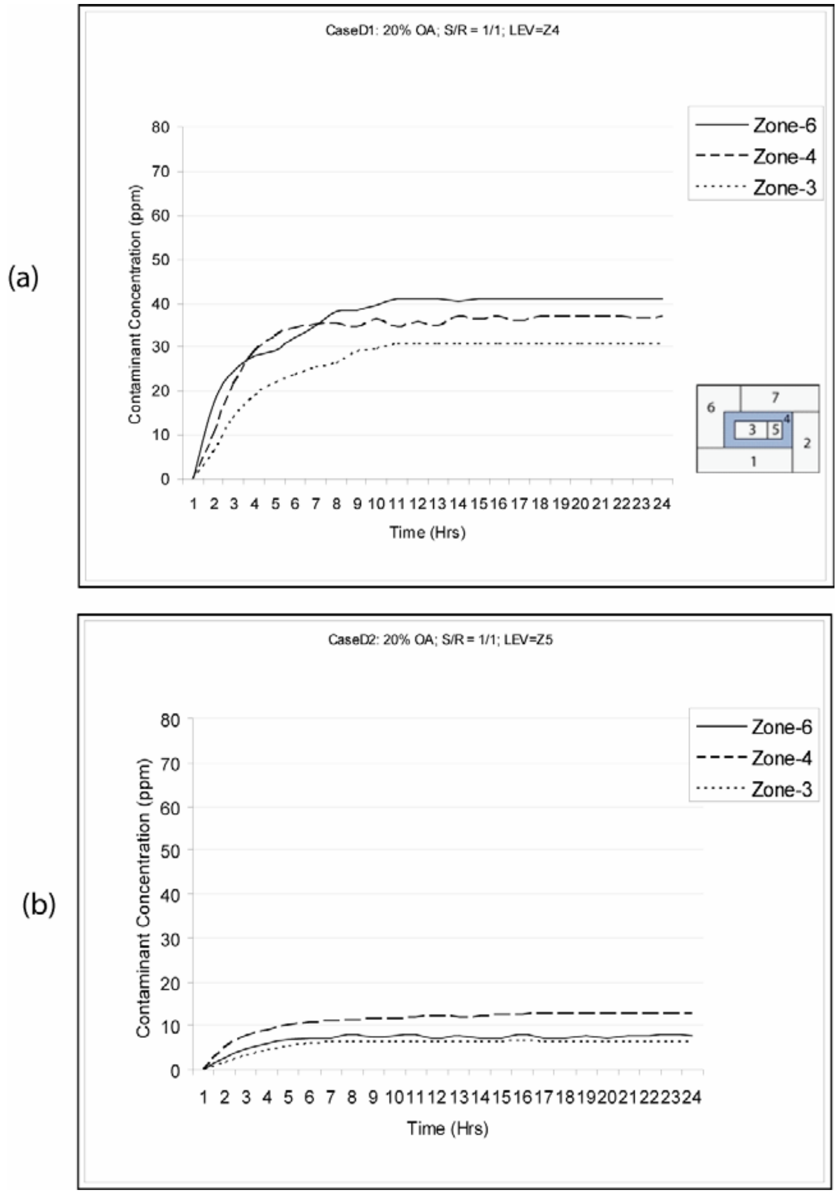


Figure 4.7: Contaminant concentration in selected zones with LEV in (a) zone 4 and (b) zone 5

From Figure 4.7a, it is noticed that at steady state, when the exhaust is located in zone 4 with the flow rate of 0.564 m^3/s the average concentration for zones 6, 4 and 3 are 41 ppm, 36 ppm and 31 ppm, representing a percentage reduction in concentration levels in the order of 29%, 52% and 50% respectively. However, from Figure 4.7b where the exhaust fan is located in zone 5 (with flow rate = 0.22 m^3/s) there is an 87% reduction in concentration level for zone 6 at 7.5 ppm. Similarly, zones 4 and 3 record significant drops in contaminant level; as seen by the 13 ppm and 6 ppm average levels of steady state concentration. This represents 82 and 90% drops in contaminant levels. The significance of locating an exhaust fan at the source zone is quite obvious, especially as the exhaust fans are working at 20% OAF, without filtration or pressurization.

4.3.5 Case E: Impact of Source Location

The next parameter to be studied is location or relocating of the source within the building. Figure 4.8 below depicts the results obtained from a simulation that seeks the impact of relocating the source from the original zone 5 to a new zone (#7). This new zone location is interesting for the following reasons. Firstly, it is a much larger zone (about 30 times larger in both floor area and design air flow rate) and at the same time, zone 7 is connected to the ambient conditions directly unlike the isolated zone 5. However, both zones have similar bounding conditions due to their contiguity with zone 4.

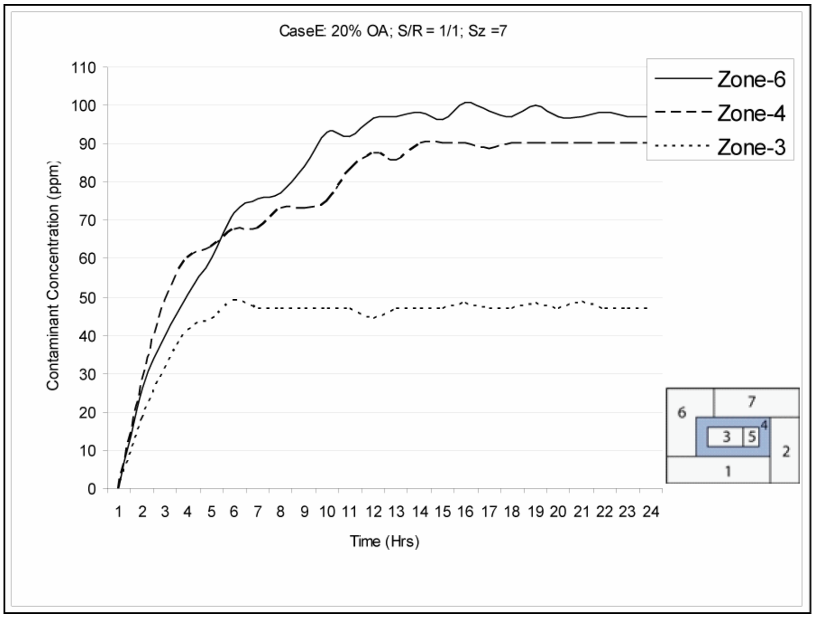


Figure 4.8: Contaminant concentration in selected zones when source is re-located to zone 7

When the source was in zone 5 (i.e. Base Case), the lowest concentration was recorded in zone 6 with 58 ppm and the highest was in zone 4 with 75 ppm. With the relocation of source to zone 7, zone 6 happens to be influenced by the close proximity to zone 7. So much that it records an *increase* (40%) in concentration level for the first time by attaining an average steady state level of 98 ppm. Likewise, the contiguous zone 4 records a 16% increment in concentration level, bringing its steady state level to an average of 90 ppm. *Only zone 3 records a reduction* of 22% in average steady state concentration of 48 ppm.

The situation in zones 6 and 4 is attributable to the relocation of the source to a new zone which (a) is directly sharing a unique architectural flow paths with zone 6 as well as typical flow relationship with zone 4 and (b) the new source zone accounts for 14% of design air supply rate, while the original source zone # 5 accounted for 2% of design air supply rate. This is indicative of the fact that the percentage of supply (and thus return) air which a zone shares with respect to other zones can affect its ability to distribute contaminants accordingly into the system; due to its proportionate share of the ventilation air. The applicability of this result shows that for practical design purposes, it would be desirable to have possible sources located in zones which consume the least proportion of design air supply in the entire system, as this would affect their ability to contaminate other zones in the recirculation process.

4.3.6 Case F: Impact of Inter-zonal Air Flow (Tightness of Partitions)

The final individual parameter to be investigated is how the tightness of the building's architectural components affects the behavior of contaminants and their distribution from zone to zone. The tightness of the zonal partitions was achieved by substituting the flow components in the Contamw library with similar components which have a tighter leakage value. This is done within the predefined components which have been selected in groups of three; via maximum, average and minimum to represent loose, average and tight construction items. Figure 4.9 below is indicative of the effect of tightening the flow paths relative to the average amount of air flow that has being used from the Base Case to all other cases so far.

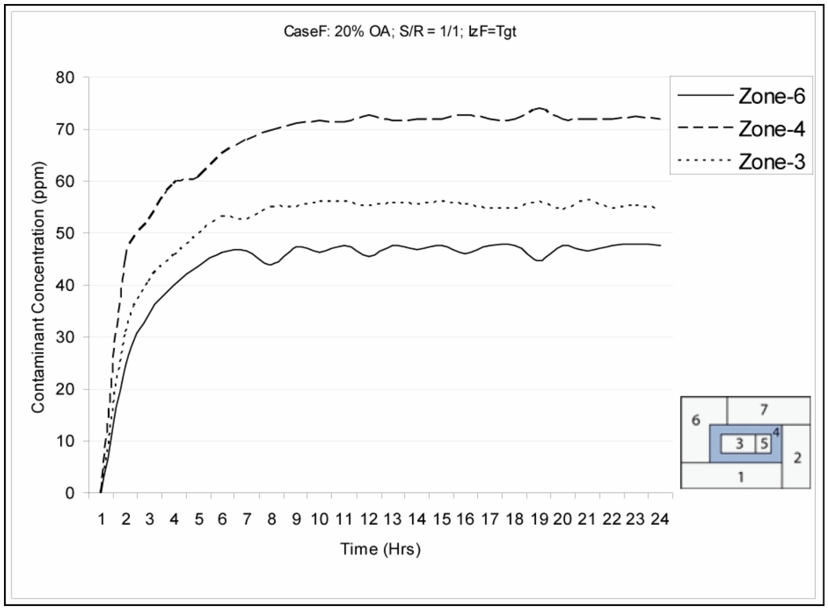


Figure 4.9: Contaminant concentration in selected zones when Inter-zonal Air Flow is tight

It is observed that this parameter (i.e. tightness of inter-zonal components) produces the least singular effect in terms of reduction of concentration levels. This is obvious from the average steady state percentage reduction in concentration levels. Zones 6 levels drop by just 17% and zone 4 by only 4%, while zone 3 levels drop by 11%. Considering the different parameters under investigation and especially those parameters that produce a reducing effect on concentration levels when used, Inter-zonal Flow (when tight components are used) has the least effect of reducing contaminant flow from one zone to another.

4.3.7 Summary of the Impacts of Individual Parameters

Table 4.2 summarizes the average changes in concentration levels for Figures 4.4 – 4.9, while Figure 4.10 shows a graphic representation of the contaminant levels of the parameters compared to the Base Case as well.

Table 4.2: A summary of the impacts on concentration levels by individual parameters

	Zone 6	Zone 4	Zone 3	Unique Parameter
Base Case	**58 ppm**	**75 ppm**	**62 ppm**	
Case A	50 ppm (-13%)	65 ppm (-16%)	57 ppm (-8%)	OAF = 20%, ditto below
Case B1	48 ppm (-17%)	65 ppm (-13%)	55 ppm (-11%)	FE = 0.4 Rec. Air
Case B2	36 ppm (-37%)	58 ppm (-22%)	48 ppm (-23%)	FE = 0.8 Rec. Air
Case C	31 ppm (-46%)	56 ppm (-25%)	42 ppm (-32%)	FE = 0.8, Return Diff
Case D1	41 ppm (-29%)	36 ppm (-52%)	31 ppm (-50%)	LEV = z4
Case D2	7.5 ppm (-87%)	13 ppm (-82%)	6 ppm (-90%)	LEV in Source Zone (5)
Case E	98 ppm (+40%)	90 ppm (+16%)	48 ppm (-22%)	Source Location = z7
Case F	48 ppm (-17%)	72 ppm (-4%)	55 ppm (-11%)	IzF = Tight

Summarily it can be deduced that all the parameters have various ways of affecting the behavior and distribution of contaminants in the building under study. The effect of having air filters with higher efficiencies can be appreciated as shown by Cases B1 and B2 where filters with 0.4 and 0.8 efficiencies were studied under 20% OAF. The impact of local exhaust ventilation in the source zone surpasses the result obtained when LEV is in the contiguous zone 4 as should be expected, but the magnitude is significant as well.

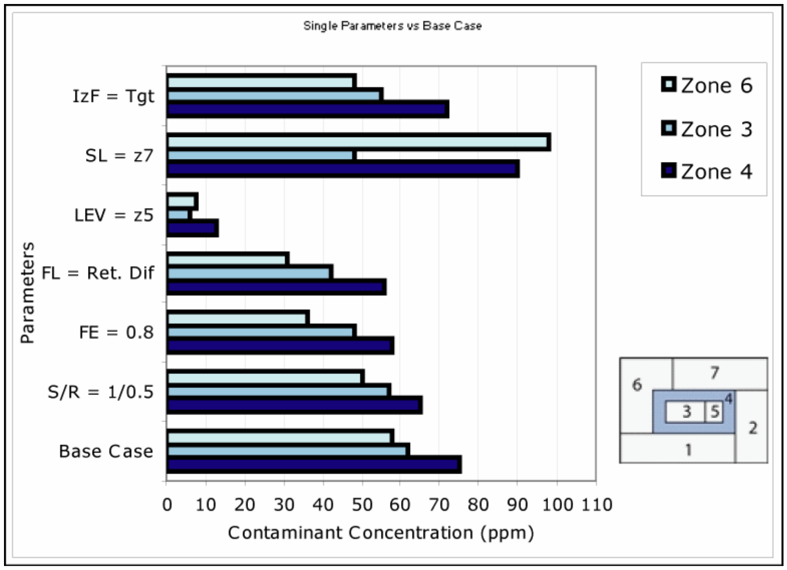


Figure 4.10: The 24-hour average concentration levels of individual parameters and the Base Case

Between Case D1 and D2 where LEV was done in zone 4 and 5 respectively, it can be observed that there is a 58% difference in the reduction obtained with LEV in source zone 5. Meanwhile, relocating the source as was done in Case E tends to affect the distribution of contaminants due to the high proportion of ventilation air which the new source zone accounts for.

4.4 Simulation of the OAF and S/R Group

The next three cases (i.e. cases G, H and I) can be called the Outdoor Air (OAF) and Pressurization (S/R) group. This is because the basic parameters they have in common are the change in OAF and S/R ratio. Consider the Figure 4.11 – 4.12 below:

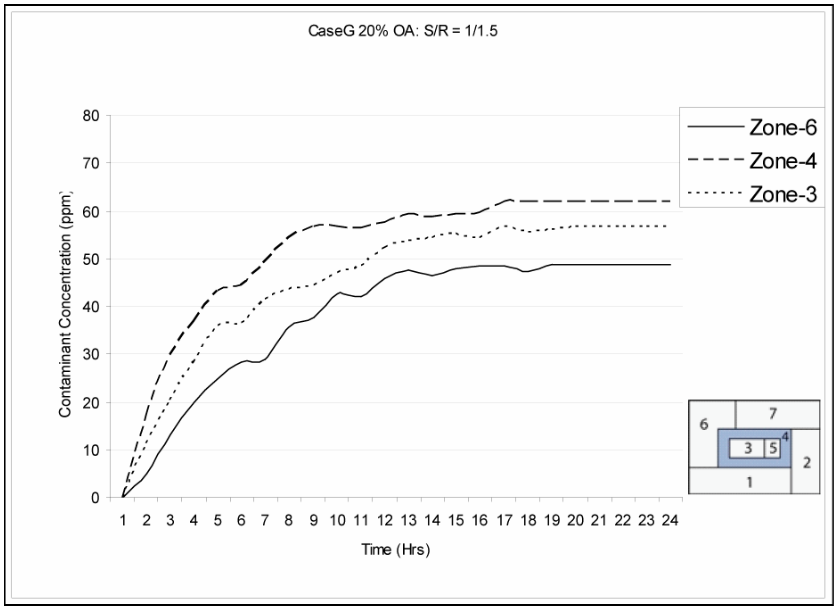


Figure 4.11: Contaminant concentration in selected zones with depressurization of zone 4 and 5

4.4.1 Case G: Impact of Depressurization of Zone 4 and Source Zone

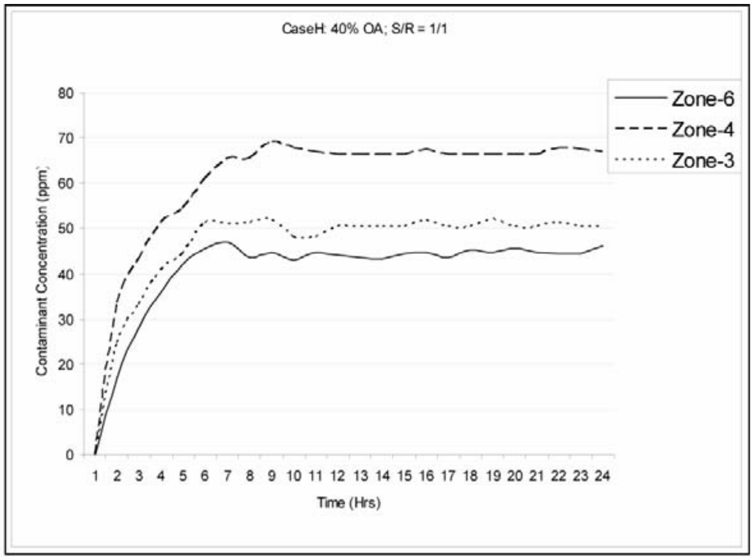
The first set of combination in this group of cases is OAF and depressurization of certain zones. In this Case G (Figure 4.11), (de)pressurization takes place in zone 4 and 5. The OAF is 20% and the S/R ratio is 1/1.5, indicating that the volumetric ratio of return is 50% more than the expected (normal) amount. What this does to the system is that from affected zones, 50% more contaminated air is taken back to the AHU, where it again mixes with 20% OAF and the normal 80% returned air from all other zones. Despite the fact that more contaminated air is returned, the 20% OAF is barely sufficient to make any meaningful dilution in the affected zones.

Eventually then, much of the removed air finds its way back into the supply, where it is re-distributed among the zones, using the criteria of the design air supply rate. As such, it is not surprising that there is only 15% reduction in concentration levels for zone 6, with 17% and 8% reductions for zone 4 and 3 respectively. Of great interest is the fact that this average percentage reductions has remarkable resemblance to the Figures obtained in Case A, when pressurization ratio of 1/0.5 was used.

4.4.2 Case H: Impact of 40% Outdoor Air without Pressurization

This case actually represents a major vertical movement along the matrix of simulation simply because of the doubling of outdoor air fraction from 20 to 40%. From Figure 4.12a, it is seen that although no pressurization is taking place, i.e. S/R = 1; yet the average steady state contaminant levels are reduced by 22%, 9% and 17% (relative to the Base Case) for the respective zones 6, 4 and 3. Of interest, is the seemingly low reduction in levels for zone 4. However, the 9% recorded could be attributed to the fact that there is no pressurization. The value of pressurization as a technique is further underscored when it is realized that in Case A, with S/R of 1/0.5 but an OAF of just 20%, this particular zone records 16% reduction in average contaminant levels.

(a)



(b)

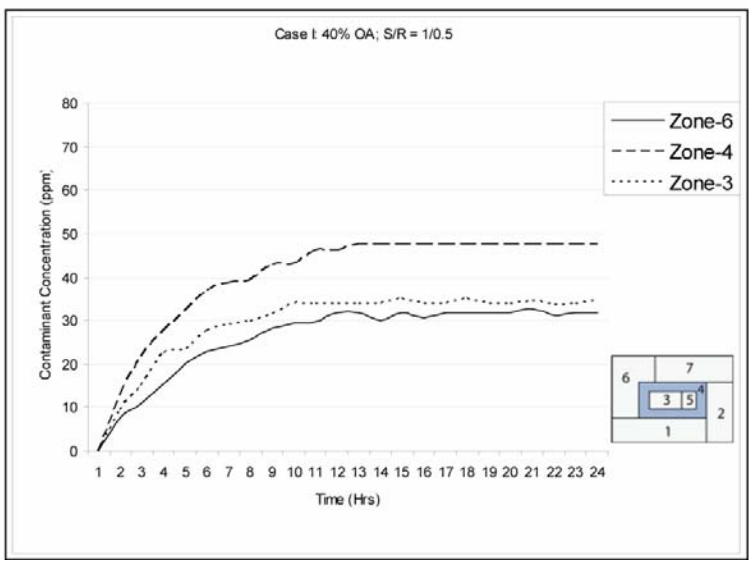


Figure 4.12: Contaminant concentration in selected zones at 40% OAF (a) without Pressurization and (b) with S/R = 1/0.5

4.4.3 Case I: Impact of 40% Outdoor Air with Pressurization

The next logical step is to simulate the conditions of Case H with the additional parameter of pressurization with an S/R value of 1/0.5. As revealed by Figure 4.12b, the reduction in concentration levels after steady state roughly attained in the 14th hour is significant for zones 6 and 4. For these zones, the reduction by 48% and 36% respectively is comparable to the result obtained when 20% OAF is used with S/R of 1/0.5 as well as filtration of recirculated air with efficiency of 0.8 without pressurization. This means the present Case I is a rough equivalent of *combining* the parametric effects of Case A and Case B2. As such, of interest would be a future scenario where 40% OAF with pressurization is accompanied by filtration.

For zone 3, whose average concentration level is reduced by 44%, (33 ppm) the effect of this combination (40% OAF and S/R of 1/0.5) can be roughly equated to Case D1 when the singular parameter LEV was used in zone 4. This also provides an opportunity to contemplate trade-offs in choosing appropriate techniques to reduce contamination in such a zone; i.e. should LEV be used (if an exhaust fan is in place) or should 40% OAF and pressurization be applied? Given that existing literature [ASHRAE, 2001] suggests that many institutional buildings typically work with OAF of 10 - 40%, then the trade-off could actually be between LEV and pressurization, assuming that OAF is maximized.

4.4.4 Summary of the OAF and S/R Group

Table 4.1 below summarizes the average changes in concentration levels for Figures 4.11 - 4.12, while Figure 4.13 shows a graphic representation of the contaminant levels of OAF and S/R groups of parameters.

Table 4.3: A summary of the impacts of the OAF and S/R group of parameters

	Zone 6	Zone 4	Zone 3	Unique Parameters
Base Case	**58 ppm**	**75 ppm**	**62 ppm**	
Case G	49 ppm (-15%)	62 ppm (-17%)	57 ppm (-8%)	OAF and S/R (DP* Z4 + Z5)
Case H	45 ppm (-22%)	68 ppm (-9%)	51 ppm (-17%)	OAF = 40%
Case I	30 ppm (-48%)	48 ppm (-36%)	33 ppm (-44%)	OAF = 40%, S/R (1/0.5)

*DP = Depressurization

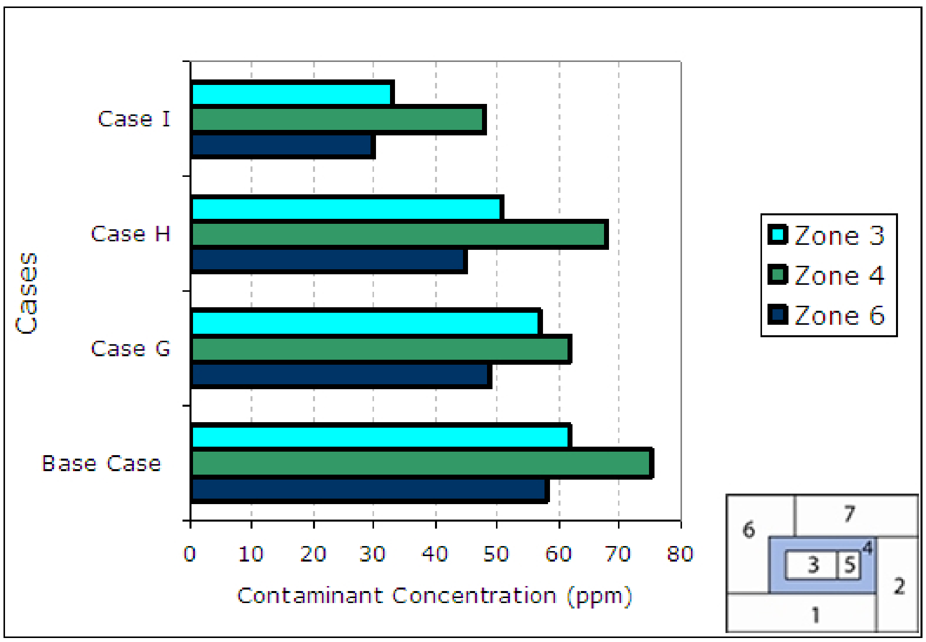


Figure 4.13: Summary of the OAF and S/R Group of Cases

4.5 Simulating for Combinations: The OAF, S/R, FE, FL and LEV Group

The subsequent group of simulations has the greatest number of possible combinations. These group members are each made of at least four out of five possible parameters which are: Outdoor Air, Supply/Return ratio, Efficiency of Filter, Location of Filter and Local Exhaust Ventilation. The combinations made for the various possible values of each parameter are represented by the results shown in Case J1 to Case R.

4.5.1 Case J1 and J2: Impact of 40% OAF, Pressurization and Filter Location

Consider Figures 4.14a and 4.14b, where Filtration (efficiency of 0.4) is introduced to the previous case. But in order to fully appreciate filtration effect, it is best to have two similar simulations with the differences being in locating filters in recirculated air (as in Case J1) or at the return diffusers as in J2. The average reductions in contaminant levels for the three zones (6, 4 and 3) are as follows respectively:

J1: 26 ppm (55%), 45 ppm (40%) and 30 ppm (51%)

J2: 25 ppm (57%), 38 ppm (49%) and 27 ppm (56%)

Zone 6, which does not benefit much from locating filters by its return diffusers. One explanation could be the fact that volumetrically it constitutes 23% of the total building volume and by designated air supply; this zone requires 49% of the total design air supply rate. In addition, it has the largest amount of nodal connections (pathways) to zone 4 which in turn, is the only zone directly connected to all other zones. Further discussion and analysis of the contaminant behavior in these two cases will be appreciated in the subsequent Cases N1 and N2, where filter efficiency would be increased to 0.8 and depressurization of zone 4 and source zone (5) is done instead of pressurization of zone 4 alone as in the present case.

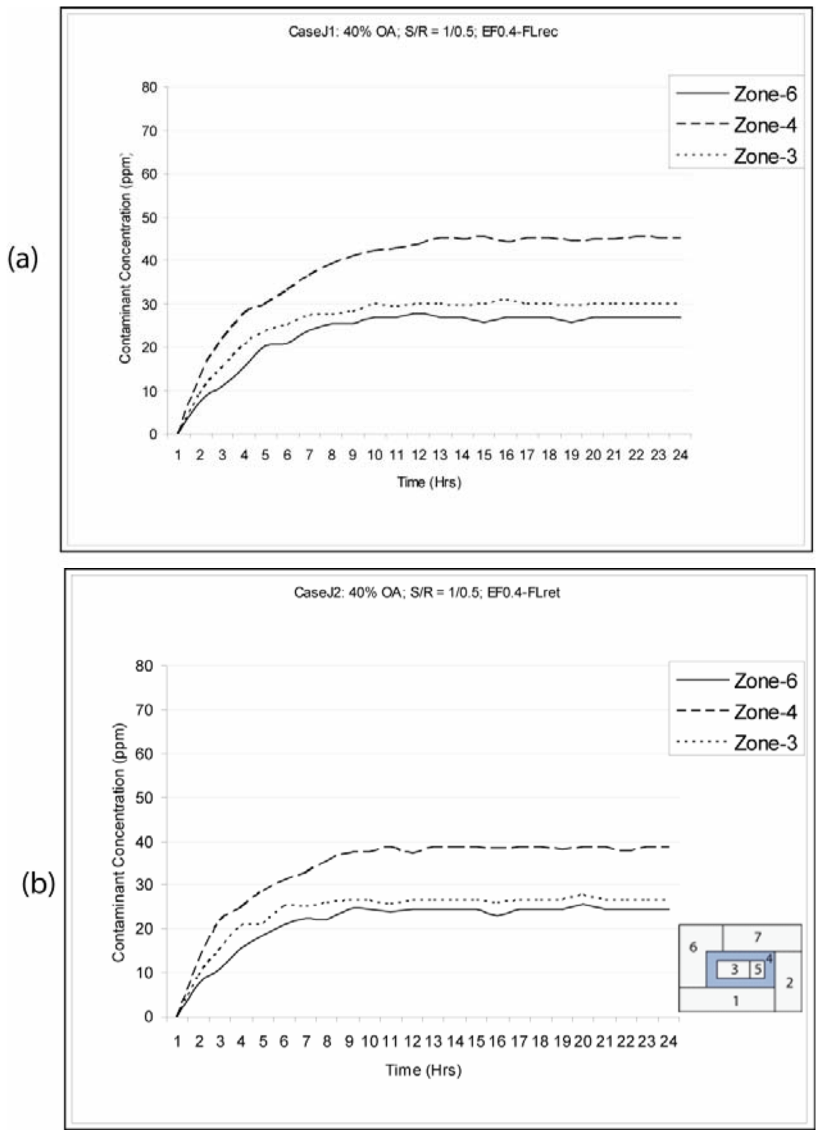


Figure 4.14: Contaminant concentration in selected zones at 40% OAF, S/R=1/0.5, FE=0.4, with (a) FL=Rec and (b) FL=Ret.

4.5.2 Case K: Impact of 40% OAF, Pressurization, Filter Location and Exhausting

An additional parameter (local exhaust ventilation, LEV) is now introduced into the previous scenario, to give a new combination of parameters. Figure 4.15 is as a result of simulating for local exhausting (Q = 0.56 m^3/s) in the contiguous zone 4. The resulting reduction in average contaminant level after steady state is evident from the fact that 63% was recorded for zone 6 and 3, while 76% reduction is achieved for the exhausted zone 4.

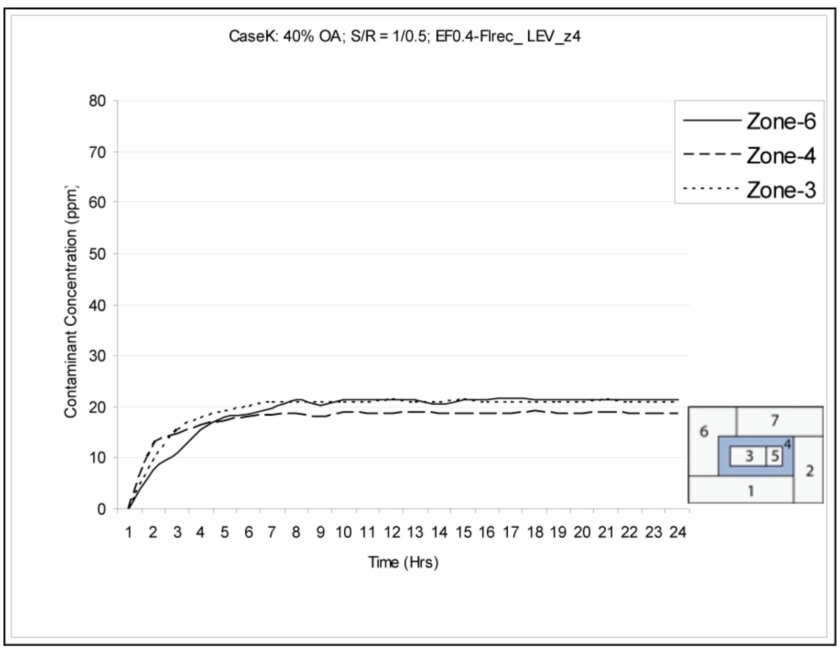


Figure 4.15: Contaminant concentration in selected zones at 40% OAF, S/R=1.0.5, FE=0.4, FL= Rec. LEV=Zone 4

4.5.3 Case L: Impact of 40% OAF, Pressurization, Filter Location and Tight Inter-zonal Flow (IzF)

At this stage, an interesting question would be in the form "what if LEV was substituted for tight inter-zonal components?" Previously in Case F, it is observed that individually, tightness of flow components accounts for 17%, 4% and 11% for zones 6, 4 and 3 respectively. Figure 4.16 provides us with an answer to the impact of tightness in combination with 40% outdoor air, pressurization and filtration of recirculated air.

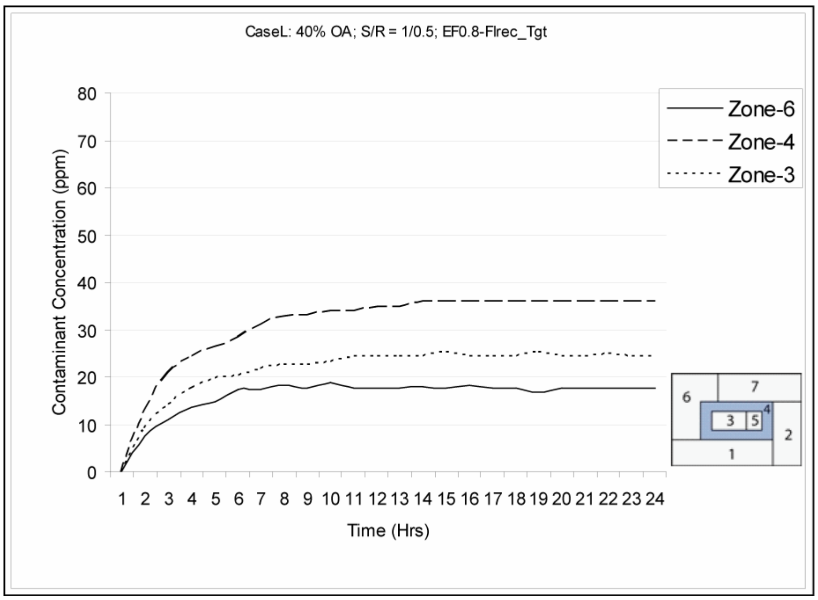


Figure 4.16: Contaminant concentration in selected zones at 40% OAF, S/R=1/0.5, FE=0.8, FL=Rec. IzF=Tgt

There would be a 69% average reduction (from Base Case) in contaminant level for zone 6 representing only 3 % change from levels obtained from the use of LEV in zone 4 as in the previous Case K. Zone 3 also displays an additional 3% difference between level in this Case and the levels of former Cases since new levels are now averaging at 60% less than the Base Case. Zone 4 on the other hand records 53% total reduction (from Base

Case) in average levels of contamination, which is 20% **less** in contaminant levels compared to the Base Case after steady state conditions are attained. It is arguable that compared to the previous Case (K), zone 6 is does not experience any noticeable increment in average concentration levels due to the expected infiltration of air into the zone from the exterior; which accounts for some level of dilution.

4.5.4 Case M: Impact of 40% OAF, Pressurization, Increased Filter Efficiency, Exhausting and Source Location

When the parameters LEV and Inter-zonal Airflow (Tight) are substituted with increased filter efficiency of 0.8 and source relocation to zone 7, the resulting simulation produces Figure 4.17 below.

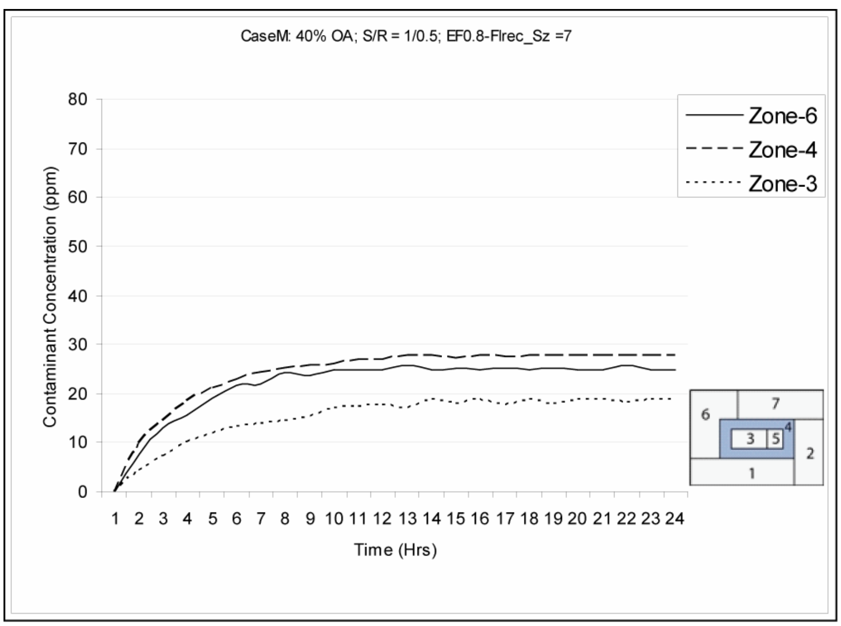


Figure 4.17: Contaminant concentration in selected zones at 40% OAF, S/R=1/0.5, FE=0.8, FL=Rec, SL=Zone 7

The most outstanding issue here is that although source is located in zone 7 which happens to be exhausted with its own fan designed to remove air with a Q value (flow rate) of 1.76 m^3/s, the reduction in zone 6 from Base Case level is 57% (25 ppm); similar to the effect obtained in Case J2, where filter efficiency was only 0.4 located at return diffusers. The reason for this is the proximity to source and inter-zonal movement of contaminated air through architectural flow paths. The other zones (i.e. 4 and 3) record 64% and 71% average reduction in contaminant levels at steady state. They happen to be better beneficiaries of this combination than zone 6.

4.5.5 Case N1 and N2: Impact of 40% OAF, Depressurization and Increased Filter Efficiency at different Locations

When the permutations of parameters is modified such that pressurization gives way for depressurization of zone 4 and the source Zone (5), coupled with recirculated air filtered with an efficiency of 0.8, the resulting simulation provides the result as seen in Figure 4.18a. This time around, the average steady state concentration levels of zone 6, 4 and 3 are 22 ppm, 21 ppm and 18 ppm, representing a drop from Base Case concentration levels of 62%, 72% and 71% respectively. For zone 6 in particular, this reduction is similar to what was obtained in Case K, where 40% OAF was pressurized and combined with 0.4 filtration efficiency of recirculated air and exhausting of zone 4.

In a similar simulation of Case N1, Figure 4.18b is the result of substituting the location of filter from recirculated air to return diffusers with same efficiency level of 0.8. This time around, the average contaminant levels of steady state conditions is 20 ppm, for both zone 6 and 4, but representing 65% reduction for zone 6 and 73% reduction for zone 4. As for zone 3, 17 ppm is representative of a 72% drop in average contaminant level.

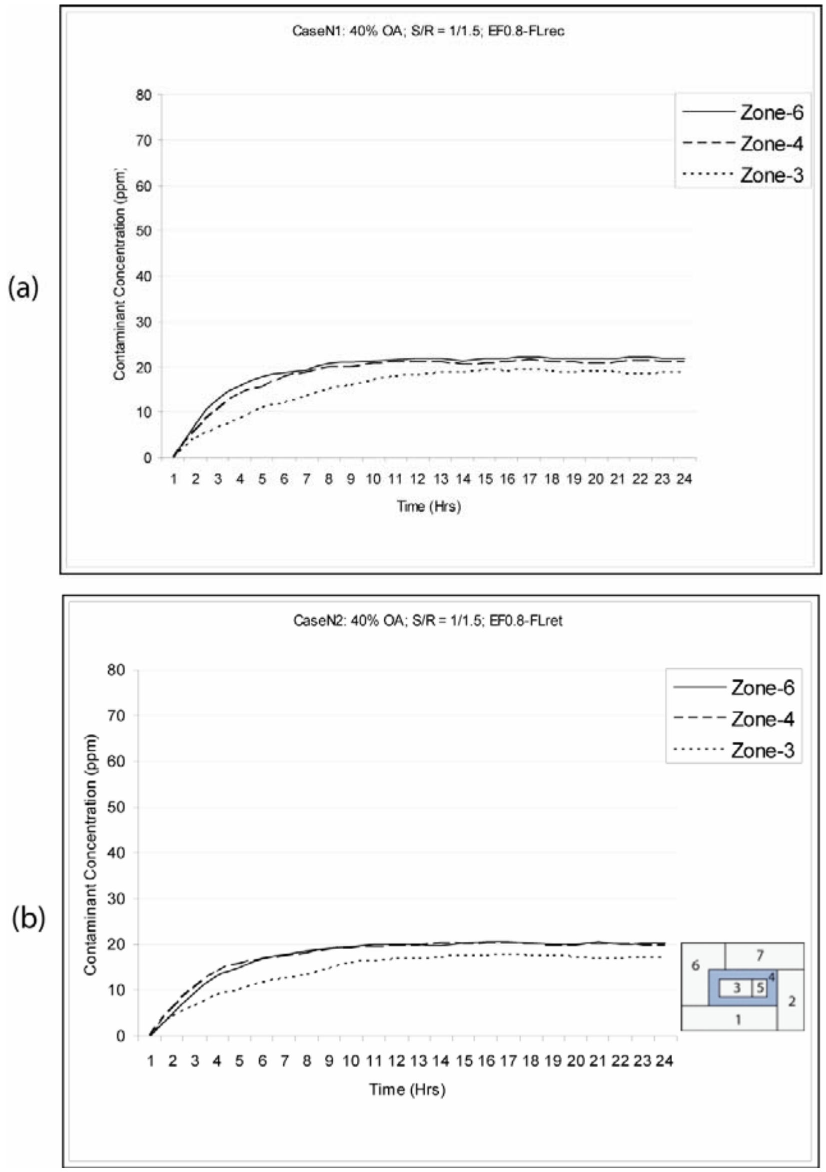


Figure 4.18: Contaminant concentration in selected zones at 40% OAF, S/R=1/1.5, FE=0.8, with (a) FL=Rec. and (b) FL=Ret

It can be noticed here that the location of filters has barely impacted on the behavior of the contaminants (as observed from the patterns of the concentration levels of Cases N1 and

N2). However, this appears to contradict the behavior noticed in Case J1 and J2 where more significant changes are noticeable in the concentration behaviors. The answer to the obvious question may lie in the following facts:

a. In Case J1 and J2, Pressurization of zone 4 was carried out whereas in Cases N1 and N2, depressurization of zone 4 and the source zone was conducted simultaneously.

b. As the source zone is itself subjected to depressurization forces, it appears to have a marked effect in the overall behavior of concentration levels of Cases N1 and N2, where concentration levels are barely changed.

c. The efficiency of filtration in Case J1 and J2 was 0.4, whereas in Cases N1 and N2, the filters were operated at 0.8 efficiencies.

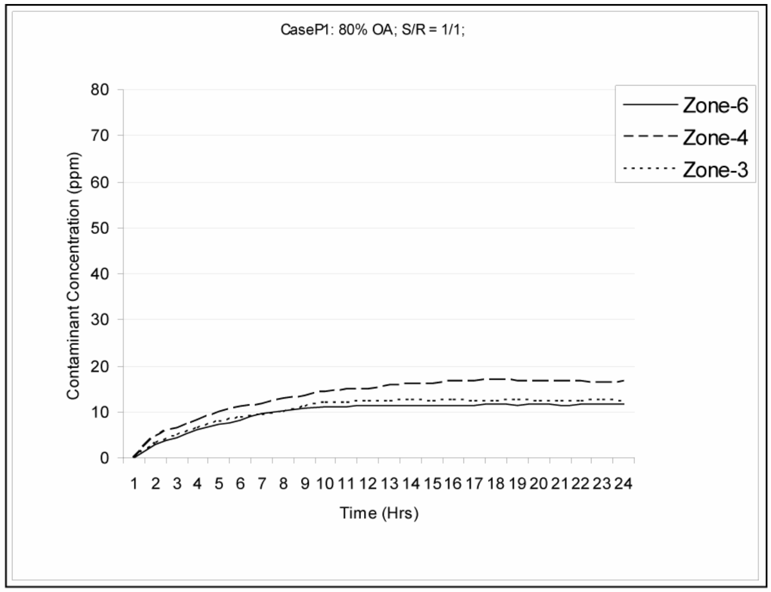
4.5.6 Case P1 and P2: Impact of 80% OAF with Local Exhausting or Filtration

This simulation represents another milestone in the vertical movement of the Simulation Matrix by the increment of OAF fraction to 80%. From the patterns emerging so far, it is becoming clear that dilution works positively in alleviating the contamination of indoor air. Thus, even without filtration, it should be interesting to discover to what extent the delivery of 80% fresh air, mixed with 20% return air as well as local exhausting of zone 4 would have in – especially without pressurization. Indeed these two parameters (dilution and exhausting) have appeared to be influential as was observed during individual assessment of parameters.

Figure 4.19a shows the resulting contaminant concentration behavior where there is an 80% drop in average levels for zone 6 and 3 each; similarly, zone 4 records a 78% reduction in average concentration levels, producing 11.5, 16.5 and 12.5 ppm for zones 6, zone 4 and zone 3 respectively.

If on the other hand, filtration with 0.4 efficiency is introduced into the previous case, the resulting simulation produces results which show that zone 6 and zone 3 would benefit by having 87% reduced levels of average steady state contaminant concentration. Zone 4, on the other hand experiences an 84% drop from its Base Case value. This is shown by Figure 4.19b where the average concentration levels for the zones are: 7.5 ppm, 11.5 ppm and 8 ppm for zones 6, zone 4 and zone 3 respectively.

(a)



(b)

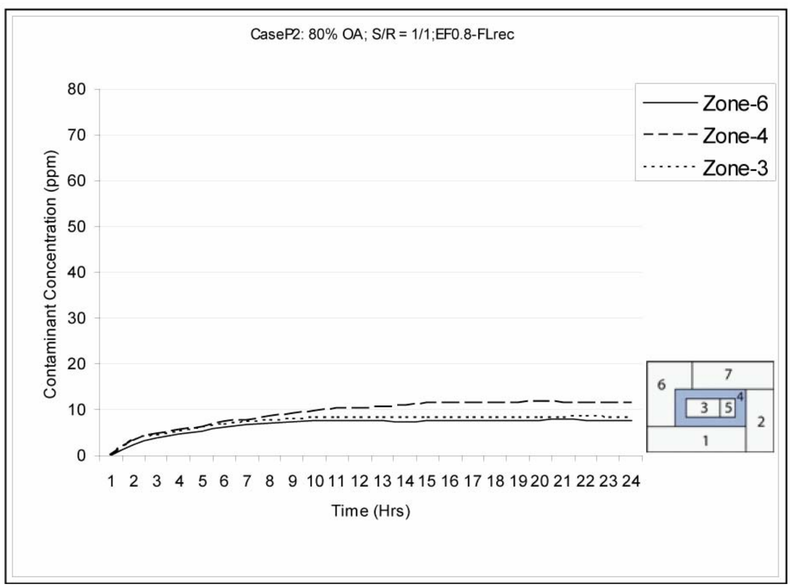


Figure 4.19: Contaminant concentration in selected zones at (a) 80% OAF, S/R=1 and with (b) FE=0.8, FL=Rec.

4.5.7 Case Q: Impact of 80% OAF, Pressurization and Increased Filter Efficiency at Return Diffusers

To further investigate the impact that 80% OAF would have, the balance of return air (at 20%) is filtered at the return diffusers with efficiency of 0.8 while pressurization of zone 4 is introduced simultaneously. From Figure 4.20, the decrease in average contaminant level is of the order of 91% (at 5.5 ppm) for zone 6 and 88% (at 9 ppm) for zone 4, while zone 3 has a reduction by 90% at 6 ppm.

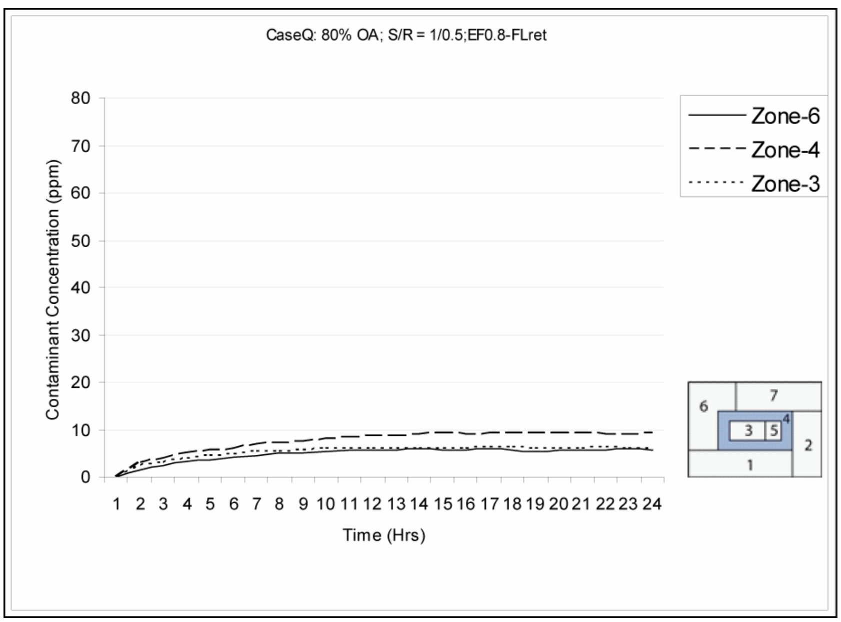


Figure 4.20: Contaminant concentration in selected zones at 80% OAF, S/R=1/0.5, FE=0.8, FL=Ret.

4.5.8 Case R: Impact of 80% OAF, Depressurization, Increased Filter Efficiency of Recirculated Air, Source Location, Exhausting and Tightness of Inter-zonal Components

In what is apparently the longest combination of parameters but with a 'reversal' of technique, given the same OAF as in Case Q, there is a simulation where depressurization and filtration of recirculated air are used instead of pressurization and filtration at return diffusers. In addition, the source is relocated to zone 7 which is also subjected to the effects of local exhausting. The result is evident from Figure 4.21.

It may be difficult at this stage to begin to ascribe positive or negative effects to each individual parameter used in this Case. However, as has been noticed in earlier Cases, a parameter may behave differently depending on its synergy with other parameters. Therefore, the exercise of this Case is intended to study the lump sum effect of having all the previously mentioned parameters of this Case, working together at specific values and in total combination. Furthermore, the location of filters at return air was substituted for locating at the lesser performing recirculated air in order to ascertain if concentration behavior of contaminants would change as a result of parametric recombination.

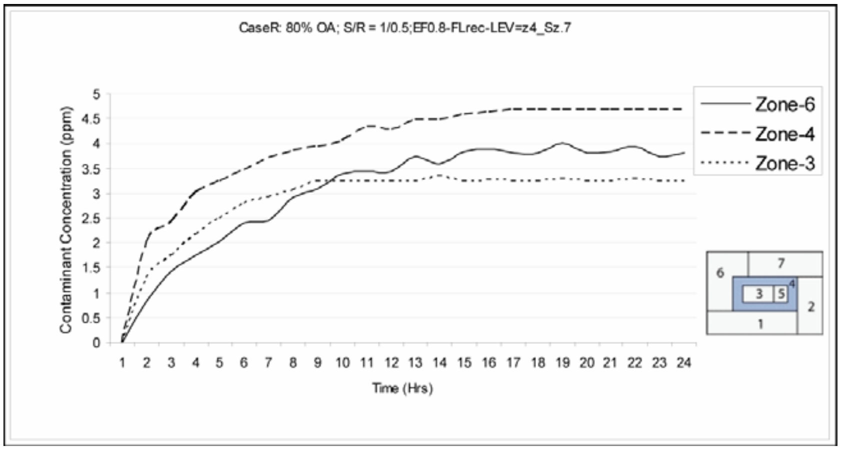


Figure 4.21: Contaminant concentration in selected zones at 80% OAF, S/R=1/0.5, FE=0.8, FL=Rec; LEV=Zone 4, SL=Zone 7

It is arguable from the past simulations that depressurization of zone 7 and 4 would not have had as much effect in this case, without the additional parameters such as LEV and high filter efficiency. Consequently, as a result of this multiple combinations, there is a percentage drop in for all zones standing at approximately 94%, even though the actual average concentration levels are different numerically viz: 3.7 ppm, 4.7 ppm and 3.2 ppm for zones 6, 4 and 3 respectively.

4.5.9 Summary of the OAF, S/R, FE, FL and LEV Group

Table 4.4 and Figure 4.22 are summaries of the results obtained in tabular and graphic formats respectively. One of the main observations deduced from this group of simulations is that increase in OAF and Pressurization works as means of diluting contaminated air and in checking inter-zonal air flow respectively; but these techniques are more effective when the air is much cleaner. This underscores the importance of filtration. As for filtration itself, the location of filters can have more much significance when return diffusers (at least in specific zones) are fitted with filters. In practical terms, cost would be one of the factors that may work against this, but it is not hard to conclude so far, that not all the zones need to be fitted with filters at the return diffusers. This is because some zones may have local exhausting (contaminant removal) or be highly pressurized (contaminant blockage) that their net intake/output of contaminated air is greatly reduced.

Table 4.4: Summary of the OAF, S/R, FE, FL and LEV Group

	Zone 6	Zone 4	Zone 3	Unique Parameters
Base Case	**58 ppm**	**75 ppm**	**62 ppm**	
Case J1	26 ppm (-55%)	45 ppm (-40%)	30 ppm (-51%)	OAF (40%), S/R, FE, FL
Case J2	25 ppm (-57%)	38 ppm (-49%)	27 ppm (-56%)	OAF, S/R, FE, FL
Case K	21 ppm (-63%)	18 ppm (-76%)	21 ppm (-63%)	OAF, S/R, FE, FL, LEV=z4
Case L	18 ppm (-69%)	35 ppm (-53%)	25 ppm (-60%)	OAF, S/R, FE, FL, IzF
Case M	25 ppm (-57%)	27 ppm (-64%)	18 ppm (-71%)	OAF, S/R, FE, FL, Sz=7
Case N1	22 ppm (-62%)	21 ppm (-72%)	18 ppm (-71%)	OAF, S/R, FE, FL
Case N2	20 ppm (-65%)	20 ppm (-73%)	17 ppm (-72%)	OAF, S/R, FE, FL
Case P1	11.5 ppm (-80%)	16.5 ppm (-78%)	12.5 ppm (-80%)	OAF (80%) S/R =1/1
Case P2	7.5 ppm (-87%)	11.5 ppm (-84%)	8 ppm (-87%)	OAF, S/R, FE, FL
Case Q	5.5 ppm (-91%)	9 ppm (-88%)	6 ppm (-90%)	OAF, S/R, FE, FL
Case R	3.7 ppm (-94%)	4.7 ppm (-94%)	3.2 ppm (-95%)	OAF, S/R, FE, FL, LEV, Sz

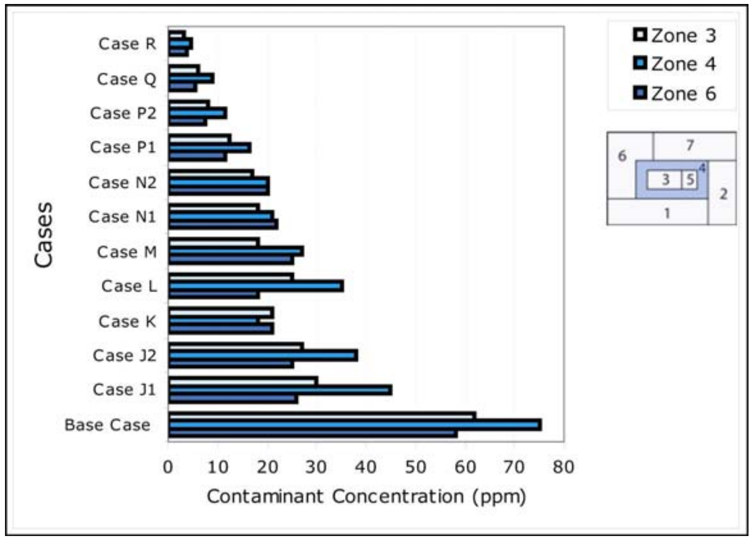


Figure 4.22: Summary of the OAF, S/R, FE, FL and LEV Group

A close look at the summary of the groups of simulations conducted so far (from Base Case to Case R) points towards a graduated effect of contaminant reduction. However, in practical terms, this cannot be immediately interpreted to mean that Case R is the best alternative. It could be, if certain conditions (finance, health implications) warrant it. Nevertheless, the objective of this study is to investigate the behavior of contaminants under different ventilation strategies and not to present the best operating strategy. Rather, as part of the contribution of this research, the impact or magnitude of using individual or groups of parameters will be highlighted and presented to operators and designers in the built environment. Actual application of any results obtained here should be guided by the resources or objectives or concerns of all who use such multi-zone buildings.

4.6 Simulation of Combinations: The Fresh Air and Exhaust Group

The final group of simulations is called the Fresh Air and Local Exhaust Ventilation group simply because the group is made of simulations that utilize 100% outdoor air, with or without pressurization/depressurization and local exhausting of air. Consider the Figures 4.23 – 4.25 below.

4.6.1 Case S1 and S2: Impact of 100% OAF with and without Exhausting of Zone 4

If the air delivered into the multi-zone spaces is brought completely fresh at 100% OAF without pressurization (S/R = 1) then it would be interesting to experiment with and without local exhaust ventilation in zone 4. While Figure 4.23a below represents the scenario without LEV, Figure 4.23b is the opposite. Case S1 has zone 6, 4 and 3 having average levels of concentration hovering at 2.7 ppm, 3.2 ppm and 1.8 ppm. This indicates 95% reduction for zone 6 and 4, while zone 3 has a 97% drop in average steady state contaminant level.

As for Case S2, with LEV in the contiguous zone 4, it is noteworthy that zone 3 does not show any change whatsoever in its percentage drop (remaining at 97%) while zone 6 and 4 have their levels dropping to 97%. The numeric value of the contaminant levels in zones 6, 4 and 3 are: 1.7, 1.6 and 1.3 ppm respectively.

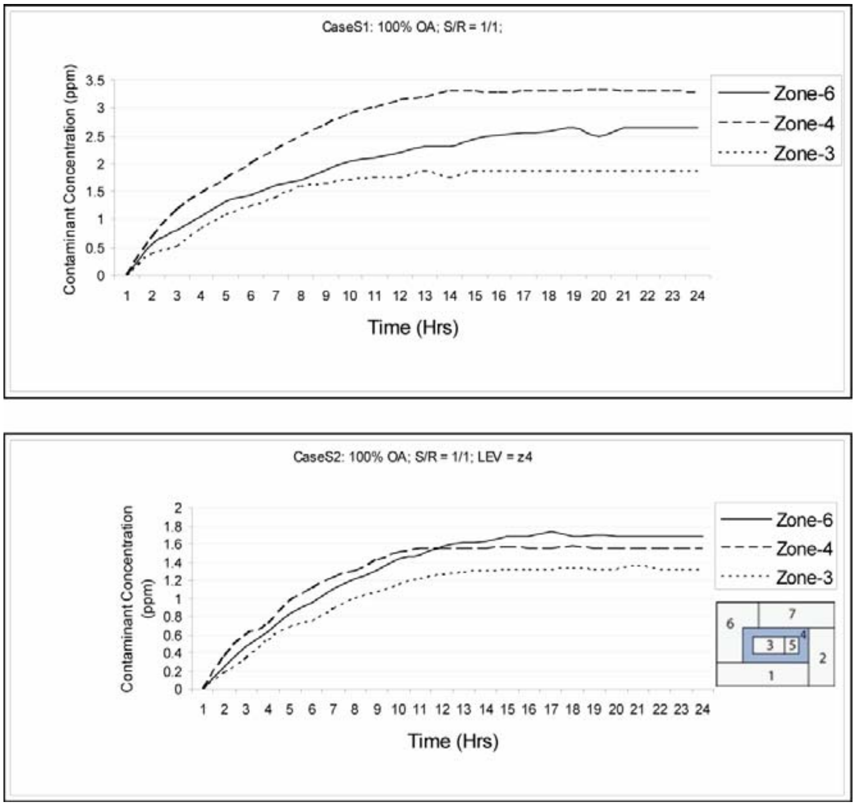


Figure 4.23: Contaminant concentration in selected zones at (a) 100% OAF and with (b) LEV=Zone 4

4.6.2 Case T: Impact of 100% OAF, Pressurization and Exhausting of Source Zone (Zone #5)

When total fresh air delivery is accompanied by pressurization of zone 4 and local exhausting in the source zone (5), the result is not significantly improved even if the flow components between the zones are tighter. In the former case, Figure 4.24 reveals 97-98% average reduction in contaminant levels. Even though (from the Figure) the concentration levels appear to be on the rise, it is doubtful they could rise any further than 1.14 ppm, 1.25 ppm and 0.9 ppm for zone 6, zone 4 and zone 3 respectively. For the latter case, when the components are tight, refer to Case U, which is the final case.

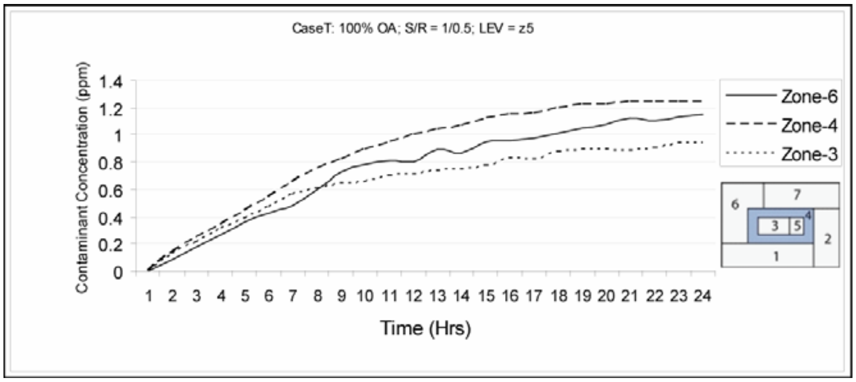


Figure 4.24: Contaminant concentration in selected zones at 100% OAF, LEV=Zone 5

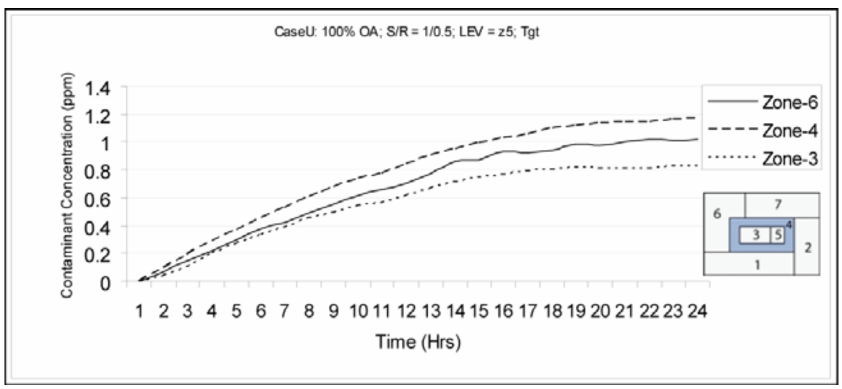


Figure 4.25: Contaminant concentration in selected zones at 100% OAF, S/R=1/0.5, LEV=Zone 5, IzF=Tgt

4.6.3 Case U: Impact of 100% OAF, Pressurization and Exhausting of Source Zone (#5) and Tightness of Inter-zonal Components

Having a tighter construction in terms of inter-zonal air flow components does not have any significance from the results of the simulation in this case. Even though numerically, the values of concentration level at the 24th hour are 1.0 ppm, 1.18 ppm and 0.82 ppm for zones 6, 4 and 3 respectively, they all share a 98% drop in concentration levels as shown by Figure 4.25. At this stage, it is only a removal of the constantly generating source or a very high flow rate of exhaust fan in the source zone would completely eliminate any trace of contamination in the multi-zone building, at least theoretically.

4.6.4 Summary of the Fresh Air and Exhaust Group

Table 4.5 summarizes the drop in concentration level for the Fresh Air and Exhaust Group. However, it can be deduced from the Figures 4.23 to 4.25 that when fresh air is brought in at 100%, the pattern of contaminant build-up (although very small); is similar to the pattern obtained when the building was simulated without any mechanical means of air delivery- i.e. the pre-HVAC simulation graphs.

Table 4.5: Summary of the Fresh Air and Exhaust Group

	Zone 6	Zone 4	Zone 3	Unique Parameters
Base Case	**58 ppm**	**75ppm**	**62ppm**	
Case S1	2.7 ppm (-95%)	3.2 ppm (-95%)	1.8 ppm (-97%)	OAF
Case S2	1.7 ppm (-97%)	1.6 ppm (-97%)	1.3 ppm (-97%)	OAF, LEV
Case T	1.14 ppm (-97%)	1.25 ppm (-98%)	0.9 ppm (-98%)	OAF, S/R, LEV
Case U	1.0 ppm (-98%)	1.18 ppm (-98%)	0.82 ppm (-99%)	OAF, S/R, LEV, IzF

4.7 Summary of Overall Findings and Discussion

The Table 4.6 below is simply a summary of all the cases simulated. It also shows the parameters which are unique in all cases, meaning that these parameters are either under direct study in that case or they have a bearing to the particular and subsequent cases.

Table 4.6: Summary of Concentrations with respect to cases

	Zone 6	Zone 4	Zone 3	Unique Parameters
Base Case	**58 ppm**	**75 ppm**	**62 ppm**	
Case A	50 ppm (-13%)	65 ppm (-16%)	57 ppm (-8%)	OAF = 20%, ditto below
Case B1	48 ppm (-17%)	65 ppm (-13%)	55 ppm (-11%)	FE = 0.4 Rec. Air
Case B2	36 ppm (-37%)	58 ppm (-22%)	48 ppm (-23%)	FE= 0.8 Rec. Air
Case C	31 ppm (-46%)	56 ppm (-25%)	42 ppm (-32%)	FE = 0.8, Return Diff
Case D1	41 ppm (-29%)	36 ppm (-52%)	31 ppm (-50%)	LEV = z4
Case D2	7.5 ppm (-87%)	13 ppm (-82%)	6 ppm (-90%)	LEV in Source Zone (5)
Case E	98 ppm (+40%)	90 ppm (+16%)	48 ppm (-22%)	Source Location = z7
Case F	48 ppm (-17%)	72 ppm (-4%)	55 ppm (-11%)	IzF = Tight
Case G	49 ppm (-15%)	62 ppm (-17%)	57 ppm (-8%)	OAF and S/R (DP* Z4+ Z5)
Case H	45 ppm(-22%)	68 ppm (-9%)	51 ppm (-17%)	OAF = 40%
Case I	30 ppm (-48%)	48 ppm (-36%)	33 ppm (-44%)	OAF = 40%, S/R (1/0.5)
Case J1	26 ppm (-55%)	45 ppm (-40%)	30 ppm (-51%)	OAF (40%), S/R, FE, FL
Case J2	25 ppm (-57%)	38 ppm (-49%)	27 ppm (-56%)	OAF, S/R, FE, FL
Case K	21 ppm (-63%)	18 ppm (-76%)	21 ppm (-63%)	OAF, S/R, FE, FL, LEV=z4
Case L	18 ppm(-69%)	35 ppm (-53%)	25 ppm (-60%)	OAF, S/R, FE, FL, IzF
Case M	25 ppm (-57%)	27 ppm (-64%)	18 ppm (-71%)	OAF, S/R, FE, FL, Sz=7
Case N1	22 ppm (-62%)	21 ppm (-72%)	18 ppm (-71%)	OAF, S/R, FE FL
Case N2	20 ppm (-65%)	20 ppm (-73%)	17 ppm (-72%)	OAF, S/R, FE, FL
Case P1	11.5 ppm (-80%)	16.5 ppm (-78%)	12.5 ppm (-80%)	OAF (80%) S/R =1/1
Case P2	7.5 ppm (-87%)	11.5 ppm (-84%)	8 ppm (-87%)	OAF, S/R, FE, FL
Case Q	5.5 ppm (-91%)	9 ppm (-88%)	6 ppm (-90%)	OAF, S/R, FE, FL
Case R	3.7 ppm (-94%)	4.7 ppm (-94%)	3.2 ppm (-95%)	OAF, S/R, FE, FL, LEV, Sz
Case S1	2.7 ppm (-95%)	3.2 ppm (-95%)	1.8 ppm (-97%)	OAF

Case S2	1.7 ppm (-97%)	1.6 ppm (-97%)	1.3 ppm (-97%)	OAF, LEV
Case T	1.14 ppm (-97%)	1.25 ppm (-98%)	0.9 ppm (-98%)	OAF, S/R, LEV
Case U	1.0 ppm (-98%)	1.18 ppm (-98%)	0.82 ppm (-99%)	OAF, S/R, LEV, IzF

The table above is a grand summary of the results obtained from the multiple simulation Cases. It shows the parameters that were applied in each Case and the effects on concentration levels for the selected zones 6, 4 and 3.

4.7.1 Concentration Levels in the two Source Zone (#5 and # 7) at Different OAF

This study would be incomplete without proving a glimpse of what has been occurring in the source zones which are zone 5 and zone 7. Figure 4.26 is a graph that shows how different OAF fractions and pressurization has affected the contaminant levels in the source zone.

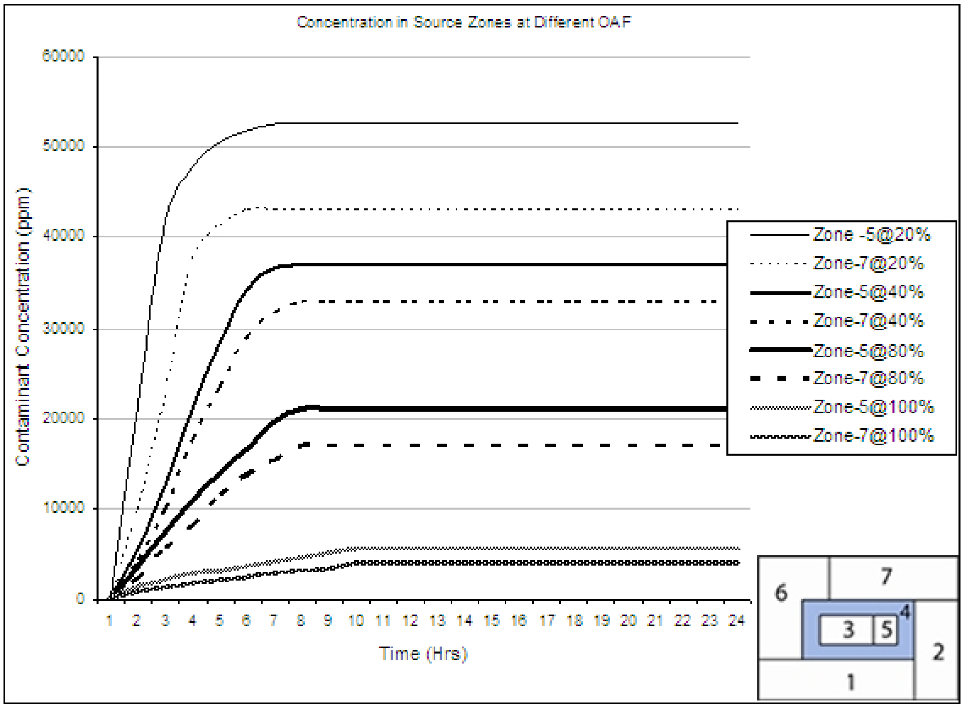


Figure 4.26: Concentration level at zone 5 and zone 7 at different OAF

From Figure 4.26 it appears that a pattern is emerging suggesting that as OAF fractions in the source zones increases from 20% to 100%. This pattern reveals that the more OAF increases, the longer it takes for the concentration levels to get to steady state. When OAF was 20%, steady state was reached after the 6th hour, while at 100% OAF; it appears to be reached after 12 hours. In addition, the figure also reveals major and proportional reduction in contaminant concentration levels in both zone 5 and 7 at different OAF.

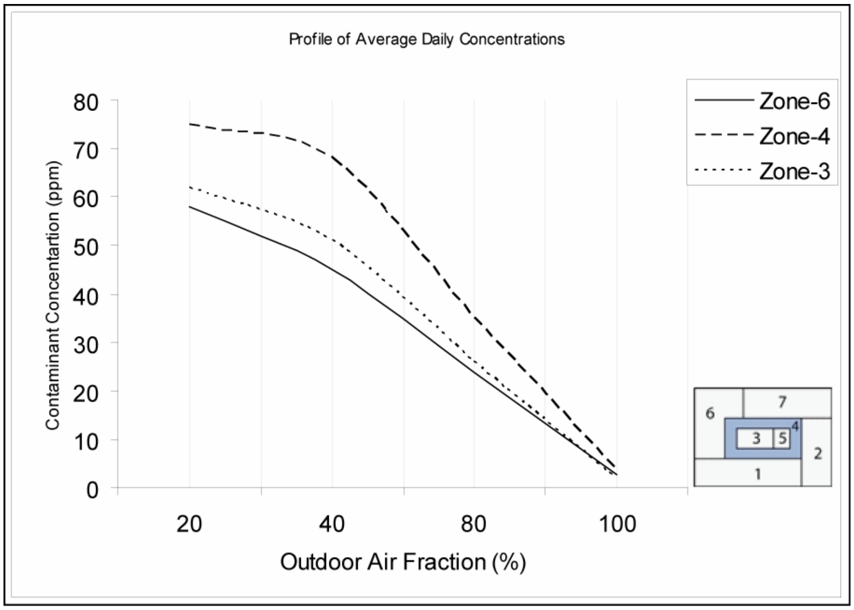


Figure 4.27: Profile of Average Daily Concentration at Different OAF

4.7.2 Profile of Average Daily Concentrations

In Figure 4.27, what is seen is profile of the average contaminant concentration in the three zones of interest as they are reviewed according to their responses to different OAF fractions. It is obvious from the nature of the slope that all the zones have almost the same response to outdoor air percentages, which is a statement that indicates the significant role of HVAC systems in the contaminant dispersal scheme. However, it is noteworthy that major changes/decrease in average concentration level occurs between 40 to 100% OAF fractions. The least noticeable change occurs between 20 and 40% OAF fractions.

4.7.3 Profile of Filter Locations

The Figure 4.28 below reveals a profile of filter locations. In essence, this is simply an overview of how the locations of filters in two separate locations have affected the concentrations when comparing their efficiencies. In other words, this gives us a glimpse at the performance of filters when located in either Return Diffusers or Recirculated air.

Figure 4.28: Profile of filter performance in Return Diffusers and Recirculated Air

From the Figure 4.28, it is observed that Return Diffusers have generally kept concentrations at lower levels than at Recirculated Air point with respect to two selected zones (i.e. zone 6 and zone 4). However, the least location in terms of 'effectiveness' happens to be filtration of recirculated air in zone 4. This is not unconnected to the fact that this zone is contiguous and thus gets a lot of inter-zonal flow from every zone in the building. Meanwhile from the slope it is noticed that zone 6 benefits the most when filters are in return diffusers. This may not be unconnected to the fact that since zone 6 contributes 49% (the largest fraction) of the total design air supply in the ventilation system and it can be assumed that short-circuiting of contaminants (inefficiency of ventilation system allowing contaminants to flow back into a zone) occurs between the point of return and the point of recirculation.

4.8 Interpretation of Results and Guide to its Applications

It may be acceptable to review the changes occurring in each zone as shown by percentage increments or reduction with respect to individual parameters, at this stage. This is because ideally or for practical purposes, there would be an interest in eliminating or reducing the menace of a contaminant in the multi-zone building, and to do so would require studying the parameters as has been done, in order to assess their individual and collective importance.

Nevertheless, it would provide additional value to the study if weights could be assigned to the changes in concentration levels with respect to each parameter. The idea of weighting is that it would assist in making some rankings which could prove useful in assessing the impact of each parameter. Furthermore, as was mentioned earlier in the significance of this research, understanding the phenomenon of contaminant migration is still in its infancy from the quantitative point of view as Sextro *et al.* [2002] have revealed. So in addition to showing percentage changes in individual and collective parameters, weighting of these parameters would assist in giving ‘quantitative values’ and rankings of each parameter with respect to its peers.

As a result of the previous experience (Literature Review, section 2.6.3 and 2.6.6) where Expert Choice was utilized to select the most appropriate multi-zone package for this study, it is feasible to make another Pairwise Comparative analysis of HVAC parameters.

The advantage of this endeavor is summarized by the following points:

a. It would allow for the reviewing of how each zone is affected by a parameter with respect to others; i.e. each zone would be able to choose the parameter that works best for it.

b. The collective impact of the parameters on ALL zones at the same time can be appraised.

c. The result would contribute to the quantitative understanding of the impacts that these parameters have on IAQ and contaminant distribution in multi-zone buildings.

4.8.1 Explanation of Weighting and Ranking in Expert Choice

The Pairwise Comparison was done in Expert Choice (EC) 2000 by comparing two single investigated parameters at a time in terms of their percentage reductions or increment in average contaminant levels. The individual parameters are those used in Case A – F. A Table of ranges was developed to aid in providing numerical values to one parameter over the other or in other words; equating them and evaluating which one has the greater impact. For example given two parameters X and Y, if parameter X has 40% reduction compared to the Base Case and parameter Y has 63% reduction, then the difference is 23% which falls under the 21-30 reduction range as in the Table 4.7 below.

Table 4.7: The Table of percentage reduction ranges developed for EC 2000 input

Percentage Reduction Range	**Numerical Value for input in EC 2000**
0 – 10	1
11 – 20	2
21 – 30	3
31 – 40	4
41 – 50	5
51 – 60	6
61 – 70	7
71 – 80	8
81 – 90	9
91 - 100	9*
9* EC 2000 has a maximum of 9 Numerical Values	

The Figure 4.29 below shows the Graphic User Interface of EC 2000 in which Efficiency of Filter (0.8) being compared with Local Exhaust ventilation in zone 5. Due to the difference between them (LEV has more magnitude within the range of 41-50% as in the table 4.7) there is a numerical slide resting at point 5.

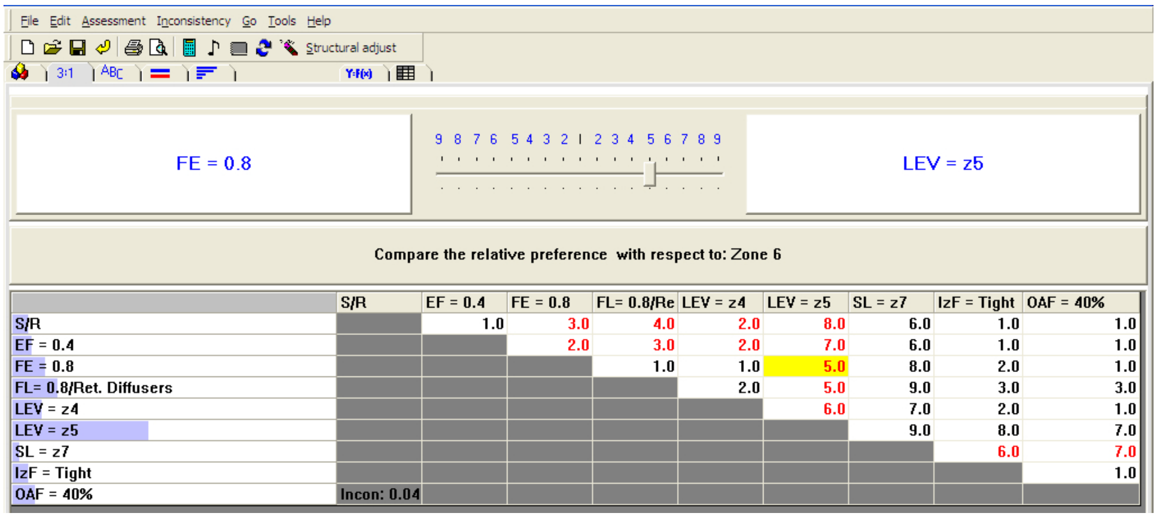


Figure 4.29: The EC 2000 interface showing Numerical Pairwise Comparison

4.8.2 Ranking of Individual Parameters

The objective of this study may appear to be better served by considering the second and third points above, but the benefit of the first point is that it would assist in appreciating how each zone reacts to the manipulation of individual HVAC parameters investigated.

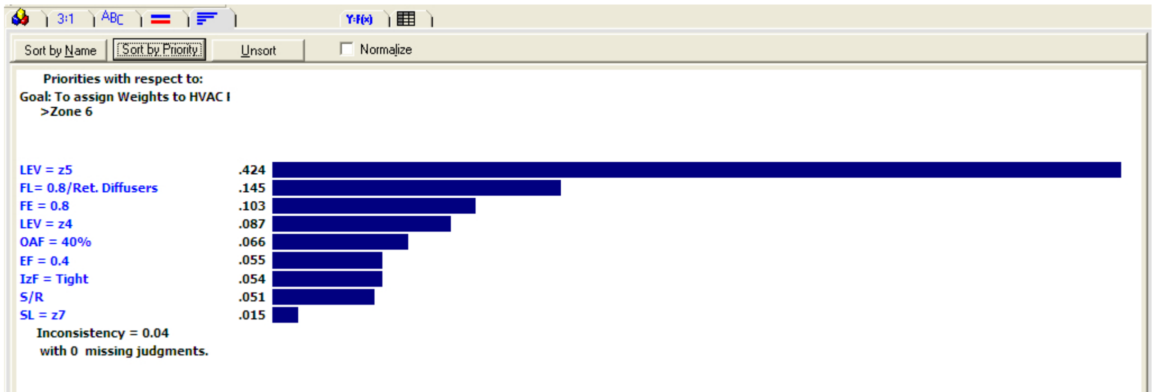


Figure 4.30: Parameters as Prioritized and Weighted with respect to zone 6

As is evident from Figure 4.30 which shows prioritization of the parameters with respect to Zone 6, it is seen that the subject zone # 6 would benefit the most when LEV is utilized in zone 5 (source zone), followed by Filter Location at the Return Diffusers. To appreciate this fact, consider the Figure 4.31 below which shows a similar prioritization but with respect to zone 4.

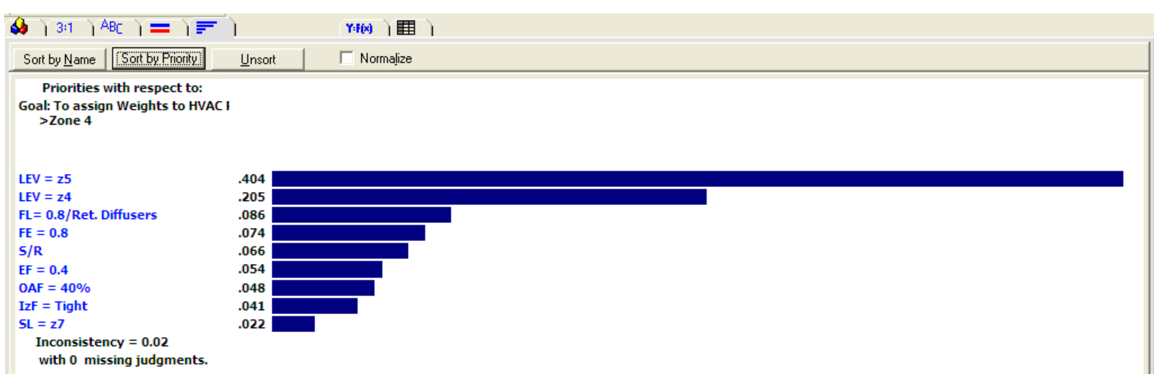


Figure 4.31: Parameters as Prioritized and Weighted with respect to zone 4

In this case, Zone 4 would prefer to have LEV in zone 5, followed by LEV in its own zone before Filter Location at Return Diffusers and then Efficiency of Filters of 0.8 and so on. However, the magnitude of preference between these two prioritization exercises can be further appreciated by observing the following:

- Zone 6 prefers LEV in zone 5 (0.424) to FL at Return Diffusers (0.145) with a difference of 0.279;
- Zone 4 prefers LEV in zone 5(0.404) to LEV in its own zone (0.204) with a difference of 0.199

If this exercise is continued, it would be seen that it is not only the choice or prioritization of the individual parameters that counts but also by what magnitude. The value of this exercise would appear when it is time for us to proffer guidelines for HVAC design and operations at the concluding segment of this study. Figures 4.32 below show the prioritization for zone 3 as well.

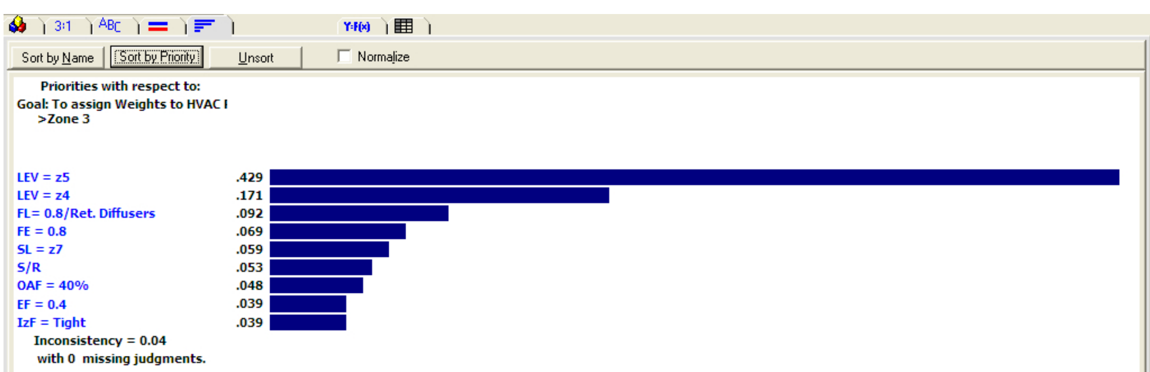


Figure 4.32: Parameters as Prioritized and Weighted with respect to zone 3

A look at the overall synthesis with respect to the goal of assigning weights to the individual parameters can be appreciated graphically by the Figure 4.33 below and by the Table 4.8 below as well. Although, summarily, this overall weighting may be attractive, the individual result of priorities with respect to each zone shows that the zones appreciate the parameters differently. So care must be taken in the interpretation of the results.

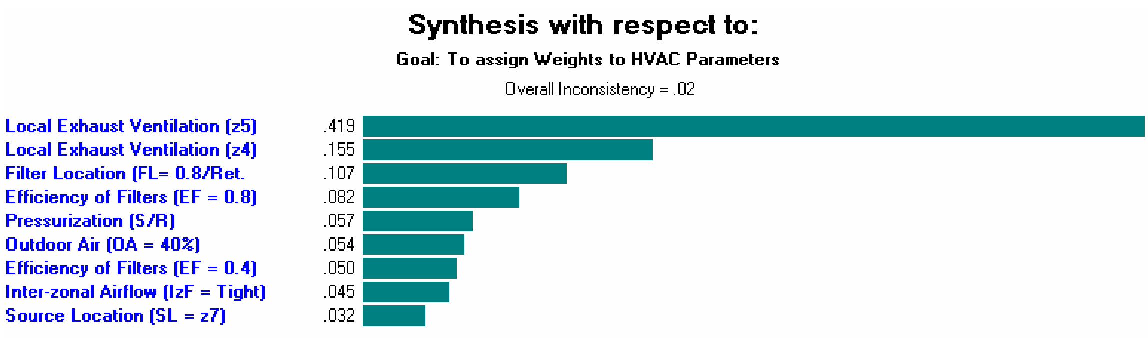


Figure 4.33: Parameters as Prioritized and Weighted for all zones

Table 4.8: Final Ranking of Individual Parameters

Individual Parameters	**Overall Weighting**	**Rank**
Local Exhaust Ventilation (z5)	0.419	1
Local Exhaust Ventilation (z4)	0.155	2
Filter Location (FL= 0.8/Ret. Diffusers)	0.107	3
Filter Efficiency (FE = 0.8)	0.082	4
Pressurization (S/R)	0.057	5
Outdoor Air Fraction (OAF = 40%)	0.054	6
Filter Efficiency (FE = 0.4)	0.050	7
Inter-zonal Airflow (IzF = Tight)	0.045	8
Source Location (SL = z7)	0.032	9

CHAPTER FIVE

A CASE STUDY: INVESTIGATION OF KFUPM PRESS BUILDING

5.0 Introduction

A Case Study is an extensive exploration of one particular case (situation or subject) for the benefit of gaining deeper understanding into the issues being investigated. The primary advantages of conducting a Case Study for this research include is the ability to apply previous theoretical knowledge gained for practical purposes and it is an ingredient of the research methodology. The purpose of the Case Study is to apply the acquired knowledge from the techniques developed during the simulation of the theoretical multi-zone building in order to solve a real life IAQ problem.

5.1 An Overview of KFUPM Press Building

To start with, an overview of the design of the KFUPM press building would enable an appreciation of the building from many perspectives such as its architecture, the mechanical air conditioning (HVAC) systems and an overview of the operation strategies.

5.1.1 The Architecture of KFUPM Press Building

Designed in the early eighties, the KFUPM Press Building is a single floor structure that is roughly 'T" shaped in plan. Its design comprises of four major segments or zones. The Largest zone is the Production Hall, a 1,081 m^2 floor area which houses the actual printing Press and related equipment. Partitioned spaces within the hall include the solvent room, chemical storage, mechanical room #1, supervisor's room as well as the finish material store.

Adjacent to this hall and separated by a corridor are two intermediate zones (Design zone and Process zone) which is also intercepted by a corridor. The Design zone is a 244 m^2 space that includes art designers' layout, type composer room, artwork storage, dark room, multi-purpose room, janitor's office and toilets. The Design zone is flanked by the Processing zone, which is a 286 m^2 zone that is partitioned into 4 dark rooms, stripping room, process camera room, film storage, artwork storage electrical room and mechanical room #2. The remaining zone is the Offices section that has a waiting room, secretary's office and reception, director's office, conference room, multi-use space, staff room and staff toilets; (a floor plan of this building is shown in Figure 5.1). The primary materials of construction are concrete, glass, steel and wood.

Figure 5.1: The KFUPM Press Building Floor Plan

5.1.2 HVAC Systems of KFUPM Press Building

Ventilation of the building is mechanically achieved. Three Air Handling Units (AHUs) are deployed to service the building with conditioned air. AHU #1 is located in Mechanical Room 1 and it services the Production Hall. It has a supply capacity of 13,630 cfm. In Mechanical Room 2, there are two AHUs (AHU #2 and AHU #3). AHU #2 has a design supply capacity of 8045 cfm and its area of jurisdiction is the Design and Processing Zones. AHU #3, with a supply capacity for 3230 cfm services the Offices area. The required air from all the AHUs are supplied through a duct network made of various rectangular cross-sections, while the ceilings are used as plenums for the return air. Each AHU has filters at its recirculation point with the estimated efficiency of the filters being about 0.65 [Younus, 2006]. The thermal set point for supplying air is at 22^{o}C.

5.1.3 The Outdoor Air, Supply and Return Systems

In supplying fresh air to the building, two operational strategies are applied within the two basic weather extremes of each year: winter and summer. In summer, 5% of the required air comes as fresh outdoor air, while the remaining fraction is from recirculated air. However in winter, the fraction of OAF is up to 20% of total air supplied into the spaces. [Younus, 2006].

The supply points are typically ceiling diffusers and side-wall supply registers with individual air supply rates ranging from a minimum of 150cfm to a maximum of 750cfm.

The return systems are designed so that ceiling return diffusers and exhaust registers (as shown previously in Figure 5.1 work in collaboration with side-wall return and exhaust registers, which all take air to the plenum, from where it makes its way to its appropriate AHU. The Design and Process zones which share AHU #2 are therefore compelled to share the same plenum.

5.1.4 Exhaust Fans and Air Cleaners

In the Processing section, there are 3 exhaust fans with an estimated flow rate of 0.5 m^3/s, while the Design area is also equipped with the same number and type of exhaust fans. Other locations of exhaust fans in the building are the solvent room and chemical storage spaces of the Production Hall as well as in the toilets. The production hall is also equipped with 8 industrial air cleaners/ionizers. A typical air cleaner and ionizer has 3 types of filters and 4 speed air flow to be able to clean $960m^3/h$. Each air cleaner has an effective area range of $278m^2$ with a filter size of $0.9m^2$. The filter life is fixed at 4 months.

5.1.5 Pressurization and Air Changes

The operation strategy of the HVAC system of the press building is such that pressurization is maintained at all times in every season. This is achieved through a regulation of the supply and return ratios of ventilation air. Depending on the amount of OAF being delivered, the system is configured so that there is no exhausting of unwanted return air. The S/R ratio works in such a way that (for all AHUs) if 20% OAF is used in winter, for example, then 80% return air is added to it to make a total supply of 100%. This means the S/R ratio is 1/0.8. Since no exhausting is done at the AHU, then the 20% air that is not returned for recirculation is forced to exfiltrate out of the building. This concept is part of the reason why the building's corridors have no supply outlets and as such; rely heavily on the pressure differentials across openings in order to receive air. All zones are confirmed to operate under relative pressurization at all times including the Production Hall. Based on the supply system of the AHU to the individual zones, the Air changes that take place in each zone (and sub-zone) can be summarized as shown in Table 5.1 below.

Table 5.1: The Ventilation Parameters of the Zones in KFUPM Press Building

<table>
<tr><th>Zone/
Sub-zone</th><th>Volume (m^3)</th><th colspan="2">Designed Air Flow rate, cfm (m^3s^{-1})</th><th>Air Change per Hour</th><th>Exhaust Fans</th></tr>
<tr><td>Production Hall</td><td>5139</td><td colspan="2">13,630 (6.43)</td><td>4.5</td><td>-</td></tr>
<tr><td>Design Area</td><td>600</td><td>3855 (1.8)</td><td rowspan="2">8045cfm (3.8)</td><td>8.85</td><td>3 x 0.5 m^3s^{-1}</td></tr>
<tr><td>Process Area</td><td>732</td><td>4190 (1.62)</td><td>9.72</td><td>3 x 0.5 m^3s^{-1}</td></tr>
<tr><td>Offices</td><td>570</td><td colspan="2">3230 (1.52)</td><td>9.6</td><td>-</td></tr>
<tr><td>Corridor</td><td>203</td><td colspan="2">Nil</td><td>-</td><td>-</td></tr>
</table>

5.2 Key Components of the IAQ Pre-simulation Investigation

As mentioned earlier in Chapter 3, the success of this (and all) IAQ investigation depends on many factors. In this case, since the actual investigation would be done through simulation, then the following pre-simulation issues must be dealt with because they have a direct bearing on how the problem is tackled and what solutions are proposed. These issues/components are:

1. Initial walk-through
2. Collecting additional information
3. Developing of hypotheses

The next subsection shall discuss the initial walkthrough and the information collected in general terms and greater detail. As for the developing of the hypothesis, it is important to state here that the critical aspect that could lead to an early and successful hypothesis is the knowledge of how the building functions everyday, the location and sources of pollutants and how they are likely moving from one part of the building to the others.

Established much earlier in the review of literature is the fact that if HVAC systems are not responsible for the direct transfer of contaminants from one zone to another, then they are responsible due to their role in inducing pressure differentials. The early knowledge that the building works with three HVAC systems was beginning to point to two issues:

a) The operational strategy of mechanical ventilation in place (especially amount of fresh air)
b) The particular zones that each AHU is serving.

The first issue is answered by the fact that this building is not the only one using the 5% and 20% OAF strategy in the campus; [Younus, 2006]. Furthermore, the complaints are not fuzzy in the manner of general lethargy, dizziness or other forms of SBS, but rather, it is clear to all who experienced discomfort that the (sometimes pungent) odor emitted from the entire printing process. This printing process is all encompassing of the pre-production, actual production and post-production activities.

As for the second issue, the zones which are being served by individual AHUs have been identified, but only through a very thorough investigation through simulation can an informed opinion be made about the effectiveness of the ventilation systems. It has been established earlier that a ventilation system can be efficient (in bringing in required amount of clean air) but not very effective (in removing the contaminated air from the problematic zones).

5.2.1 The Initial Walk-Through

The initial walk-through has already assisted in providing most of the information outlined in the preceding sub-sections of this chapter such as, the building's mechanical and architectural information.

The main activity of the Press Building is the Design, Processing and Production of Graphic-Oriented material for the publication needs of the university. As such, most of the work done is either to design, process or to produce some poster, pamphlet or brochure, as well as books, calendars etc.

The discomfort/irritation experienced by staff of the KFUPM Press is described as odor in the press coming from numerous chemicals/solvents as well commonly used materials like kerosene, glue and ink. Other staff in the Design, Process and even Office sections also complain of similar discomfort.

5.2.2 Collecting Information: Contaminant Pathways, Leakages and Air Flow Paths

The IAQ walk-through audit that was done in order to assist in the diagnosis suggests that generated contaminants are moving into unintended spaces due to the following possible factors:

1. The building's architectural components (doors, windows, ceiling connections, and other leakage paths) cannot be expected and categorized as tight. Considering that the building is at least 20 years old, some components are less than averagely loose; this provides air flow path and hence contaminant pathways as well.

2. The use of the building as a semi-industrial structure, where automated (e.g. use of machinery) and other process (e.g. film development) have to take place along with offices; this would increase the chances of contaminant migration.

3. Behavioral aspects of occupants such that doors leading to the Production Hall and Process Areas are left open by busy workers at the same time. Office doors are also typically open.

4. The design of the building, which though has considered the need to separate sensitive zones with their own AHU, yet has left the vital corridor without its own supply. This suggests that the corridor is under negative pressure with respect to all other zones.

5. The design of the building using the plenum method of return is also critical. If due to age of building the ceiling's architectural components (i.e. the ceiling panels and their present condition of fixture to each other and to the sidewalls) across zones become lose, then there could be a problem.

In modeling the KFUPM Press building for the simulation, the ASHRAE and Contamw Building Components Library have been used to represent existing airflow paths and leakage items.

5.2.3 Developing of Hypotheses

The hypothesis that has been developed is based on the initial walkthrough, which provided clues as well as discussions with the Press staff and maintenance personnel.

The hypothesis is basically outlined as follows:

1. Even though the Production Hall (which has many effluents used as part of the production process e.g. mixing, oiling, printing etc) has its own independent HVAC system, i.e. AHU #1, it is still directly related to the other parts of the building through the corridor. The plenum of the hall is isolated from the other plenums but a minimal amount of leakage may be allowed across cracks. It should be noted that because the corridor is not having its own supply outlets (in fact relies on pressure from all other zones); then the flow of contaminated air through architectural components under pressurization should not come as a surprise. In fact, this was meant to be a technique of supply the corridor with air; unfortunately the fact is that contaminants also use the same air to migrate.

2. The Building's HVAC systems are designed with plenums as the return air sub-systems. If there is any leakage or inter-flow of returned (and contaminated) air in the ceiling due to age-old cracks, lack of maintenance e.t.c, then contaminants would easily move from the plenum of e.g. the Process/Design zone into the Office zone.

5.3 Modeling the KFUPM Press Building: Summary of Theoretical Case vs. Case Study

Before a simulation of the Press Building is carried out, it is proper to make some comparisons about their features in a summarized order. At least, it would enable firstly, for a fair overview of the mechanical and architectural systems (i.e. what they share in common and how they differ) as well as an appreciation of the way the HVAC parameters of both buildings are operated.

5.3.1 The Theoretical Case Building

The theoretical model was designed with multiple (7) zones; with 4 zones having direct nodes (environmental connections) with the exterior and these zones form an enclosure for the corridor zone which also encloses two island (physically isolated) zones. In the theoretical model, the corridor zone is equipped with its own Supply and Return systems and is subjected to some of the individual parameters used in the investigation, namely Pressurization and Local Exhaust Ventilation. Similarly, all other zones have individual Supply and Return points which are capable of being manipulated to produce either a Pressurization or Depressurization regime. Filtration was achieved at the return diffusers and at the recirculated air points. In addition, the building's HVAC system was designed to work with a single AHU (located outside the building) for the sake of simplicity in studying the effects of all parameters. Furthermore, the source of contamination in the source zones of the theoretical study was designed to emit a constant amount of contaminants into the air.

5.3.2 The Case Study (Press) Building

In the Case Study (Press) Building, a fairly similar layout of zones exist, i.e. there are zones enclosing a central corridor, with the exception that there are fewer (3) zones and that the corridor has direct nodal connections to the ambient environment. However, in the Press building, there are no supply outlets in the corridor as all ventilation air come from the pressured air in the adjacent zones, while the return air goes through a plenum system. The return air (of all zones) goes to any one of the three AHUs located within the Press Building itself. However, AHU #1 located separately from AHU #2 and #3. The identified sources of contamination for the Press building are also located in 2 zones, but unlike the theoretical building, these sources emit contaminants simultaneously under the working hour schedule. However, local exhausting exists as well in all zones of this building while filtration occurs only for recirculated air. Figure 5.2 below shows the KFUPM Press building as modeled in Contamw.

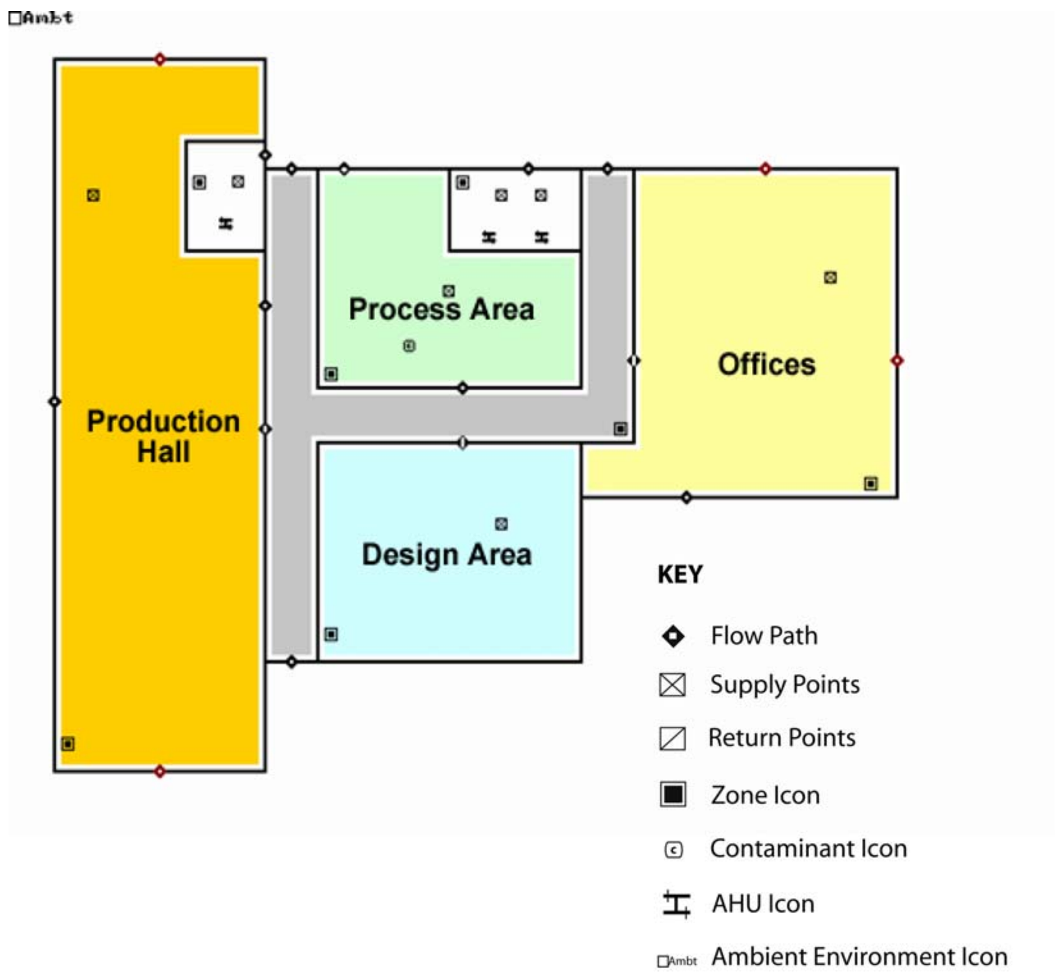


Figure 5.2: Modeling of KFUPM Press Building in Contamw

5.4 Simulation of KFUPM Press Building

5.4.1 Winter and Summer HVAC Operations of the Press Building

Two basic operation strategies are used in the extreme (winter and summer) periods of every year. In winter, the amount of OAF delivered is 20% and 80% is recirculated, whereas in summer, just 5% outdoor air is utilized with 95% recirculated. There is an apparent attempt to conserve cooling energy in these OAF delivery fractions since the cooler winter fresh air is used in larger quantities than the hot summer air. The next series of figures illustrated are the results of simulations carried out to see the typical behavior of the contaminants during these two periods. However, the results show the distribution pattern of contaminants for three scenarios. These are:

1. When the source is located only in Production Area
2. When the source is located in Process Area
3. When the source is located in both Production and Process Areas.

The source that was used to represent the multiple indoor air pollutants is simply called Fume, which has a generation rate of 0.0005kg/s. This rate is deemed sufficient to represent the generation of a generic contaminant across the buildings sub-systems.

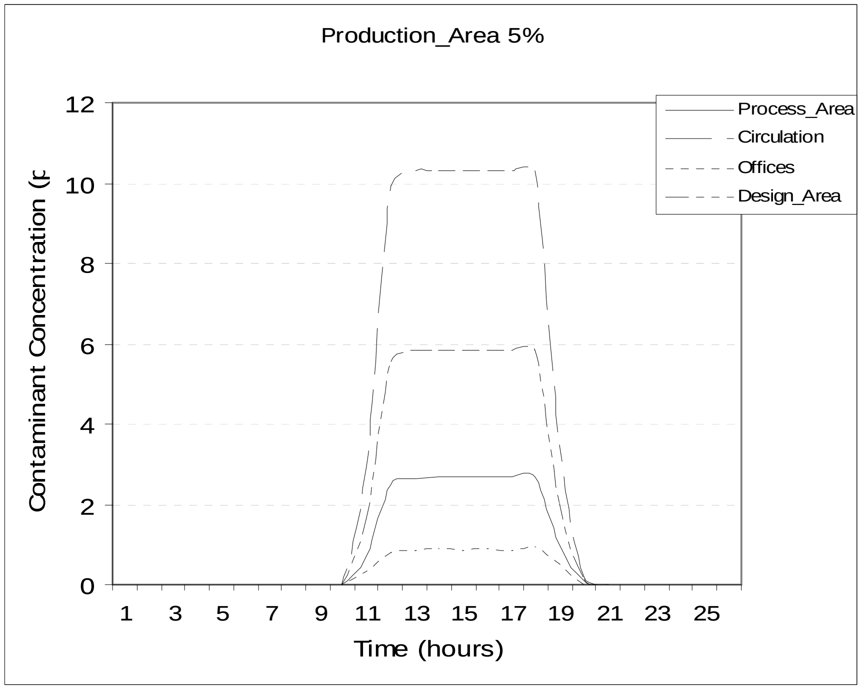


Figure 5.3: Contaminant behavior for summer schedule with source in Production Hall

5.4.2 Source Location: Production Area

From Figure 5.3, it is apparent that should the source be located only in the Production Hall during summer with 5% outdoor air, the Circulation area has an average steady state concentration value of about 10 ppm. The Design Area, Process Area and Offices come next with levels of 6 ppm, 3 ppm and 1 ppm respectively. This should serve as a simple Base Case upon which other scenarios can be compared. In winter, when the OAF of the AHUs are 20%, the concentration in the zones are as follows (see Figure 5.4): the circulation area has an average steady state concentration of 9 ppm, Design area is 5 ppm, while Process and Office Areas have 1.8 ppm and 0.3 ppm respectively. These reductions represent roughly 10% reduction in concentration levels for all zones.

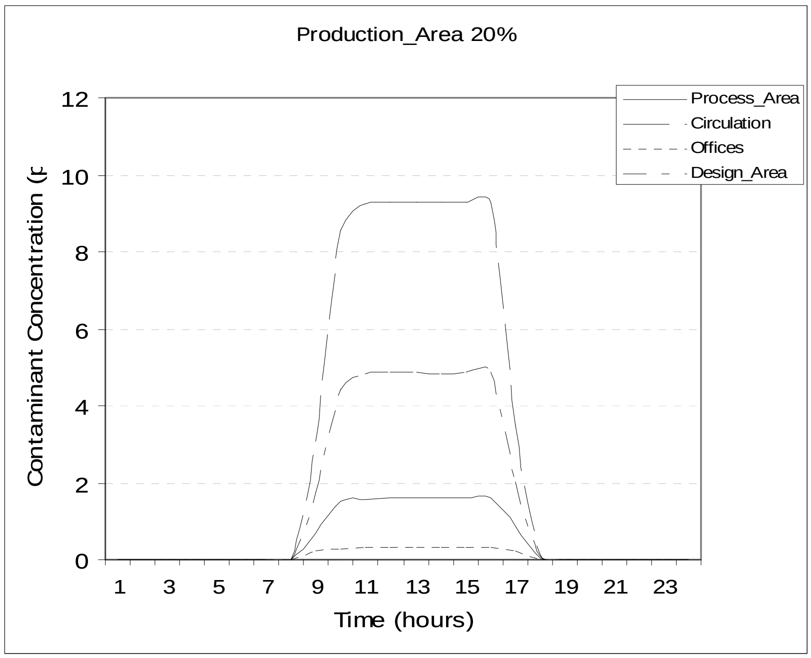


Figure 5.4: Contaminant behavior for winter schedule with Source in Production Hall at 20% OAF

Although not part of the current options of HVAC operations, if the OAF supplied to each zone where to be increased to 40%, then from Figure 5.5, it can be seen that this dilution process is enough to eliminate traces of contaminants in the office zone. However, other zones such as the Circulation zone would have 6.6 ppm (34%average reduction); Design Area would have 3.6 ppm (40% average reduction) and 0.64 ppm for the Process area which represents an average of about 44% total reduction in steady state concentration for that zone as well.

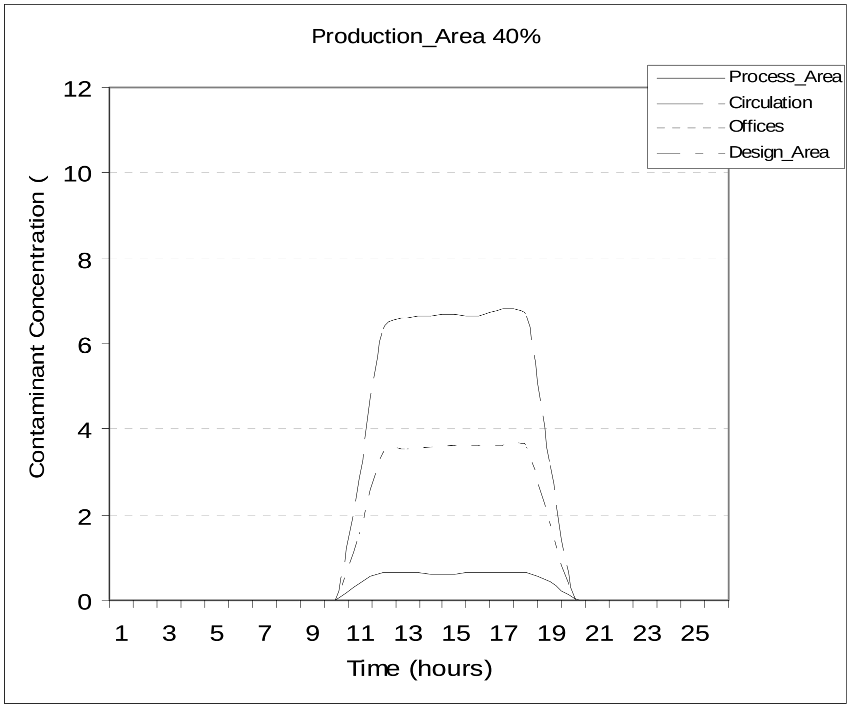


Figure 5.5: Contaminant behavior for the scenario if 40% OAF is used with source in Production Hall

5.4.3 Source Location: Process Area

When the source is located in the Process Area of the Press building, the behavior and distribution of the contaminants are better appreciated by referring to Figures 5.6 and 5.7.

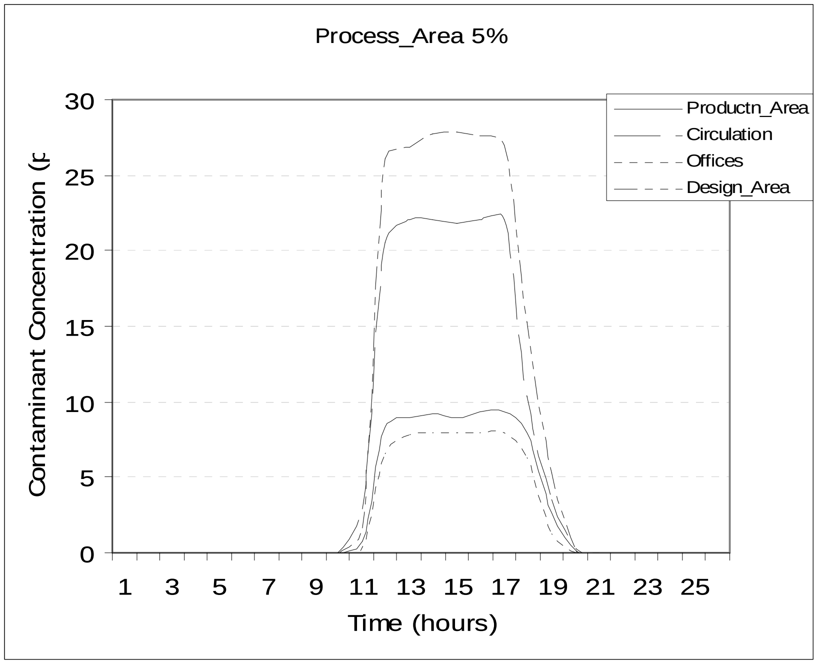


Figure 5.6: Contaminant behavior for summer schedule with Source in Process Area

Evidently, from Figure 5.6, during summer operations when OAF is just 5%, the highest concentration is in the Design Area with a steady state value of 27 ppm. This is not surprising since it shares the same AHU with the Process Area. The circulation area on the other hand has an average concentration of 22 ppm. This is almost four times the concentration level when source was in Production Hall. The explanation for this is simple. The corridor is served by the same AHU as the Process and Production Hall. In fact, the only reason why the average value in the Circulation is not as high as the Design Area is most likely due to inter-zonal flow of cleaner air (dilution) from the Office Zone as Well as Production Hall (which is assumed not to have a source in this case).

In winter, when the source is in the Processing Area and OAF is 20% it is seen that the average concentration level of the Design Area falls to 19 ppm, while that of Circulation, Production and Office Zones to fall to 13 ppm, 5.65 ppm and 2.72 ppm on the average respectively. This would represent a percentage reduction of the magnitude of 29%, 40%, 37% and 66% respectively; as compared to the summer operations as shown by Figure 5.7.

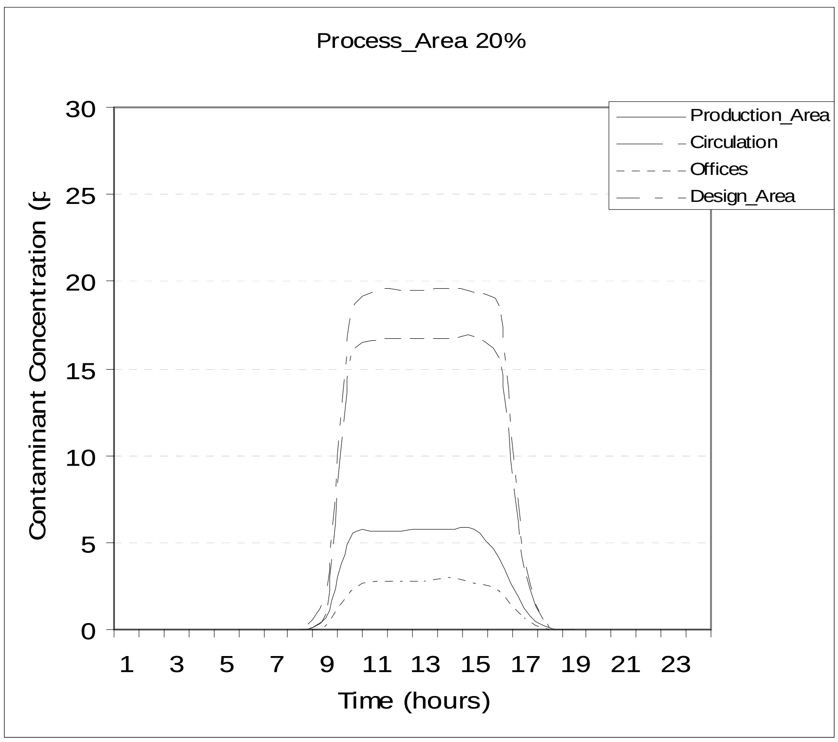


Figure 5.7: Contaminant behavior for winter schedule with Source in Process Area

Again, should the OAF fraction be increased to 40%, there would be a further decrease in average concentration levels as shown by Figure 5.8.

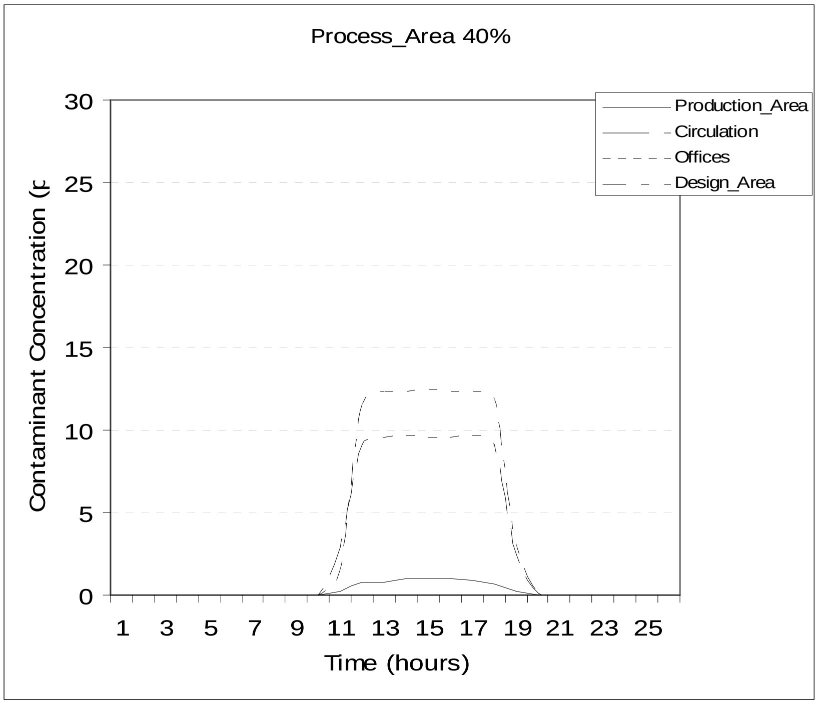


Figure 5.8: Contaminant behavior for the scenario if 40% OAF is used with source in Production Hall

The Office zone would surely be largely free from any contaminants but the Circulation area would still have an average concentration level of 9.6 ppm. This means it has been reduced by 56%. The Design Area would also record a reduction by 54% due to its new average level of 12.2 ppm.

5.4.4 Source Location: Production Hall and Process Area

The stage is now set for investigating the combinational effect of having the source in two locations as is most likely the case in reality. In order to simplify the process of evaluating the impacts of the HVAC parameters, the source strengths of the contaminants in both Production and Process Area has being made equal; Figures 5.9 - 5.12 below represent the current 5% and 20% and the possible 40% scenarios. The concentration levels averaged in each case for particular zones are shown subsequently in Table 5.2.

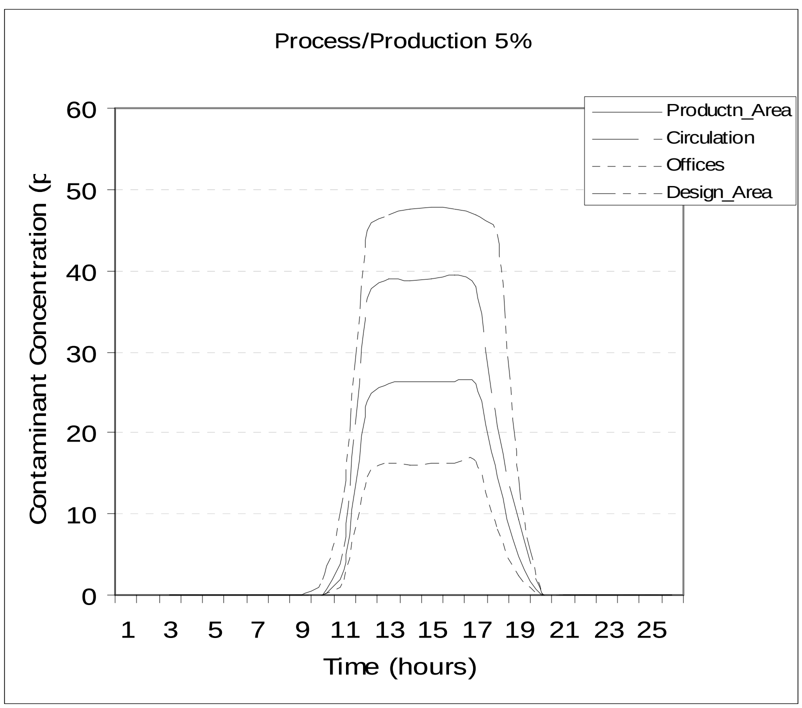


Figure 5.9: Contaminant behavior for actual scenario in summer with source in Production/Process Zones

In the initial (summer) case when 5% OAF is used, the average steady state levels are 47 ppm, 39 ppm, 26 ppm and 16 ppm for Design, Circulation, Production and Office Zones respectively as shown by Figure 5.9. The percentage reductions in average concentration levels for the zones when winter OAF (20%) is used is 34%, 28%, 23% and 31% respectively.

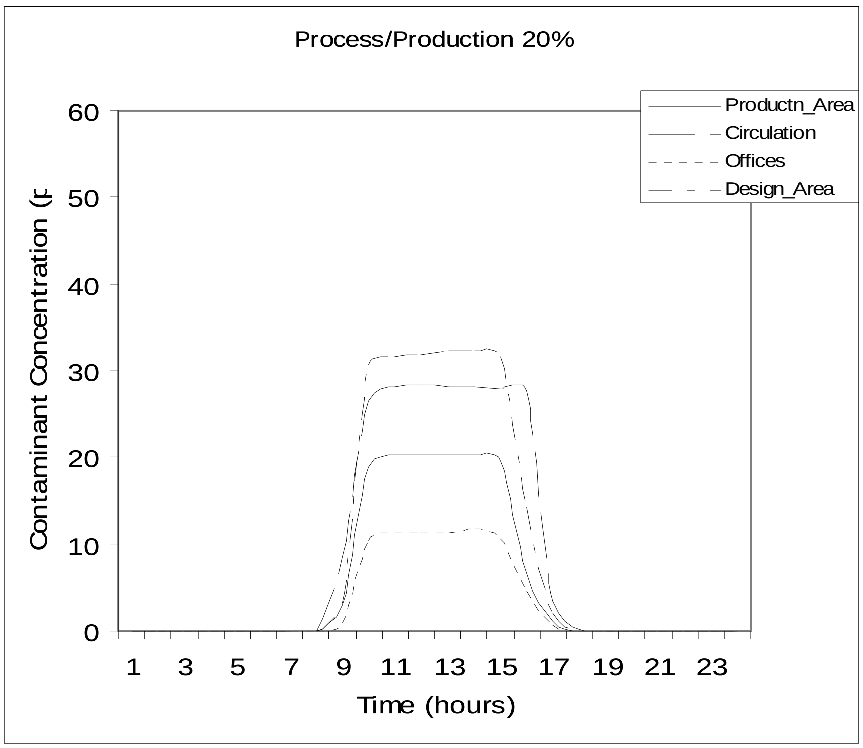


Figure 5.10: Contaminant behavior for actual scenario in winter with source in Production/Process Zones

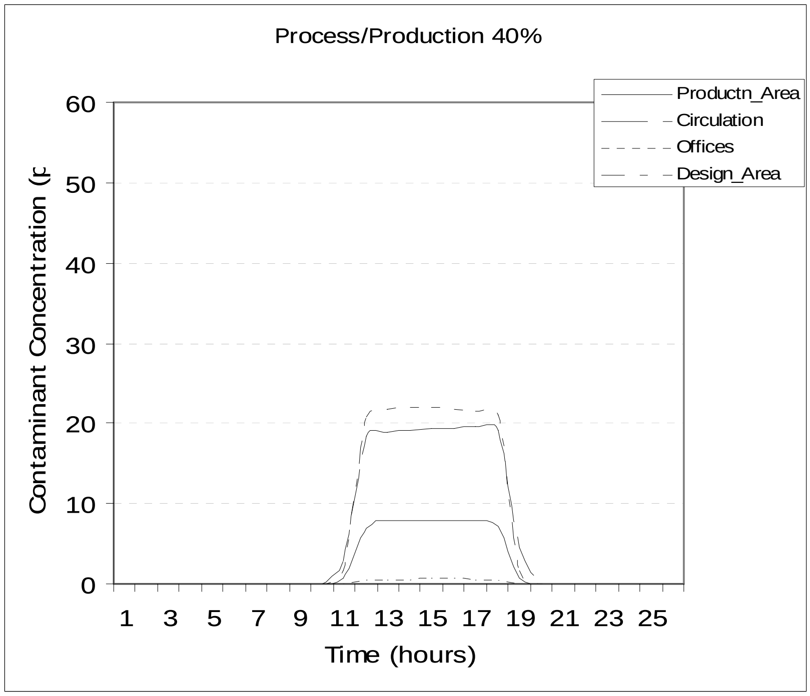


Figure 5.11: Contaminant behavior for the possible scenario if 40% OAF is used with source in Production/Process Zones

If it were possible for the OAF to be increased to 40% then there would be average reductions of 57%, 51%, 42% and 96% for the same Design, Circulation, Production and Office Zones respectively.

Table 5.2: The changes in average concentrations levels of the zones summarized

Zones	5% OAF	20% OAF	40% OAF	Source
Design Area	47 ppm	31 ppm	20.3 ppm	Process and Production Area
Circulation	39 ppm	28 ppm	19 ppm	Process and Production Area
Production Hall	26 ppm	20 ppm	8 ppm	Process and Production Area
Offices	16 ppm	11 ppm	0.56 ppm	Process and Production Area

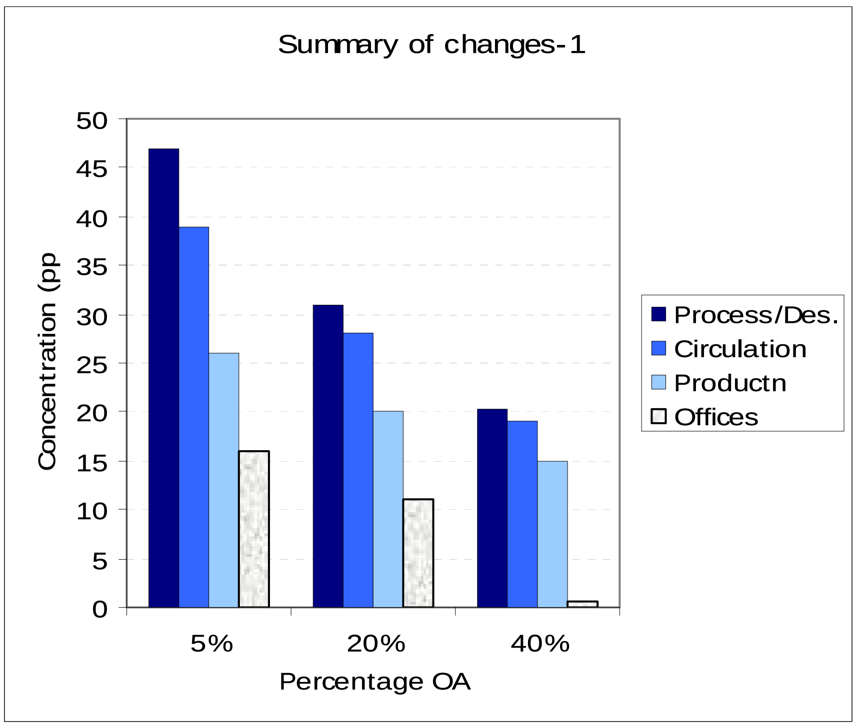


Figure 5.12: Summary of changes in concentration levels for KFUPM Press zones at different OAF

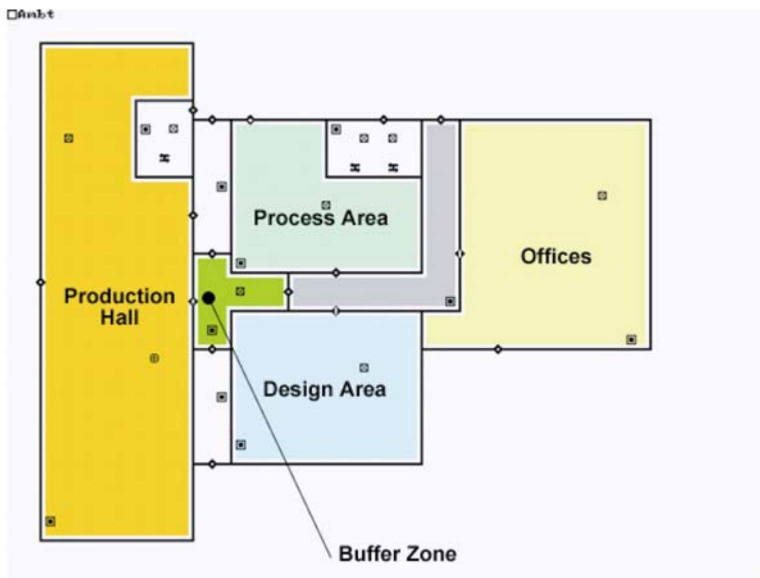
5.4.5 Creating and Pressurizing a Buffer Zone

From the mere fact that three AHUs are put in place to serve the three basic zones already points to the sensitivity of the designers to IAQ. However, what may have been the greatest undoing of the Press Building Design is that the Corridor was left without any independent supply of clean air.

The buildings as was modeled in Contamw had to take cognizance of the fact that the many of the doors especially the ones in the Offices areas and Production and Design Areas tend to be left open due to heavy traffic. In other words, from the simulation of the building, irrespective of the amount of fresh air brought into the supply, the circulation area would always be under pressure from all other surrounding zones. Consequently, there would be a transfer of contaminants towards it.

The logical thing to do in this case would be to encourage air to move *out of* the corridor and not *into* the corridor. To do this would require enclosing critical parts of the corridor to form a buffer zone and then creating air supply points, which would give the new buffer zone its own relative pressurization. This was done as shown by Figures 13a and 13b below. But two possible scenarios were also considered. In the first case, the buffer zone would not include the doors of the Design and Process Area. *(Note: doors are represented by flow path icons in the Figures 5.13a and 5.13b)*

(a)



(b)

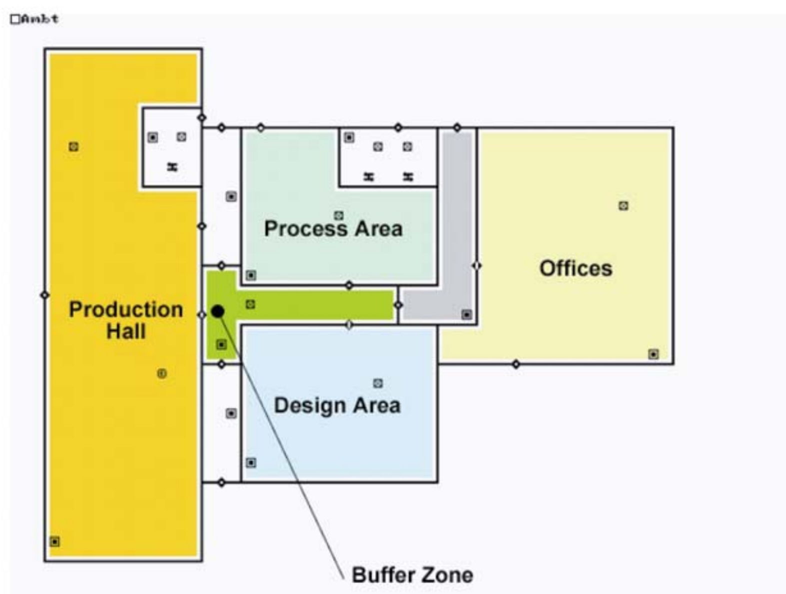
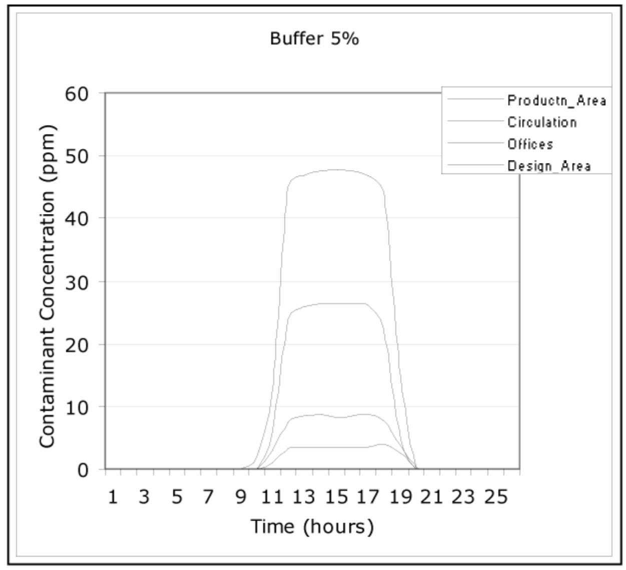


Figure 5.13: The buffer zone enclosing doors of (a) one zone and (b) three zones

In the second case, the buffer zone would enclose the doors leading to the Design and Process Areas. The second choice was found to provide a better result. This is because from a visual perspective, it is clear that the doors of these two areas are still capable of allowing contaminants (location in Process Area which also shares AHU with Design Area) to move into the un-buffered part of the corridor. This would enable contaminants to move into the corridor as well as the office area where they would be of nuisance to occupants.

As can be observed from the next two Figures (5.14a and 5.14b), the current winter (20% OAF) and summer (5% OAF) HVAC operational strategies of the Press Building are retained, but the buffer is introduced zone. The reduction in the Circulation area and Office zone are respectively, 8.4 ppm and 3.4 ppm when OAF is 5%. There would also be 4.3 pm and 0.4 ppm for Circulation and Office areas respectively when OAF is 20%. This is assuming that there is source in both Production Hall and Process Area.

(a)



(b)

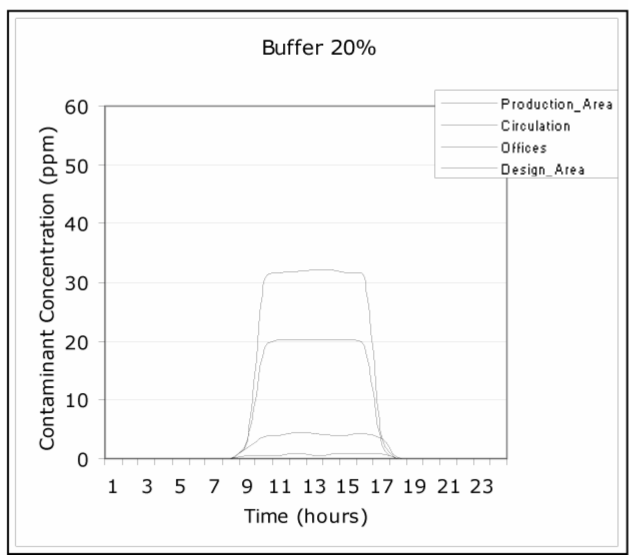


Figure 5.14: The concentration levels with buffer zone in (a) summer and (b) winter

5.4.6 Delivering Constant Fresh Air into the Production Hall

The production hall could be subjected to a constant supply of fresh air i.e. by using 100% OAF. This could happen as a result of the need to try other alternative solutions other than the buffer zone. As evident from Figure 5.15, (where 100% OAF was used in production and 40% OAF was used in other zones); the buffer zone was ignored.

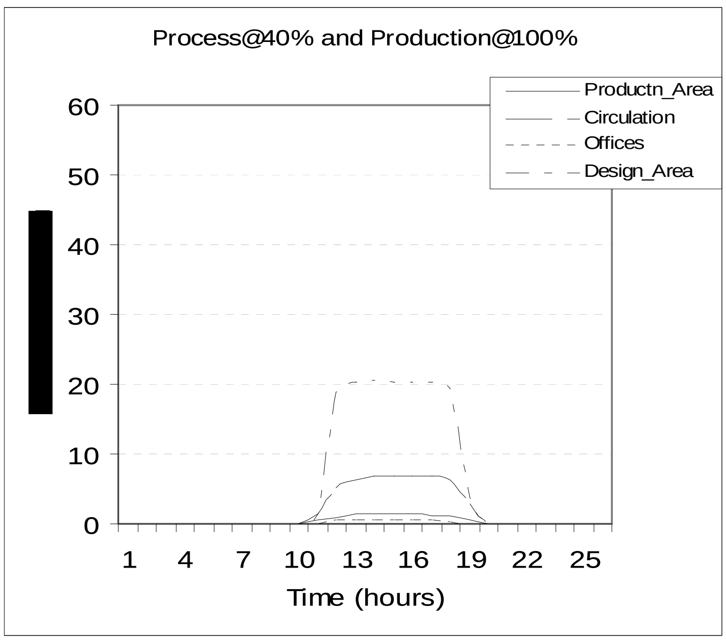


Figure 5.15: The concentration levels with 100% OAF in Production Hall and 40% OAF in other zones

The result shows that the average contaminant concentration level in the production hall would be about 1.3 ppm; representing an 83% reduction from the average concentration levels when 40% OAF was utilized. Meanwhile, under the same 100% OAF in production hall regime, the average concentration levels in the critical Circulation area drops to an average of 6.5 ppm, which also represents a significant 65% reduction from the 40% OAF levels. However, the offices do not record any meaningful reduction in average levels but the Process/Design Area records a very slight decrease to 19 ppm from the previous 20.3 ppm. In Figure 5.16, we have a final summary of the changes to be expected as the OAF is increased from the 5% winter schedule to 100% production hall schedule of constant fresh air. These results are indicative of the measures which can be adopted in the Press Building to alleviate the problem of contaminant generation and distribution.

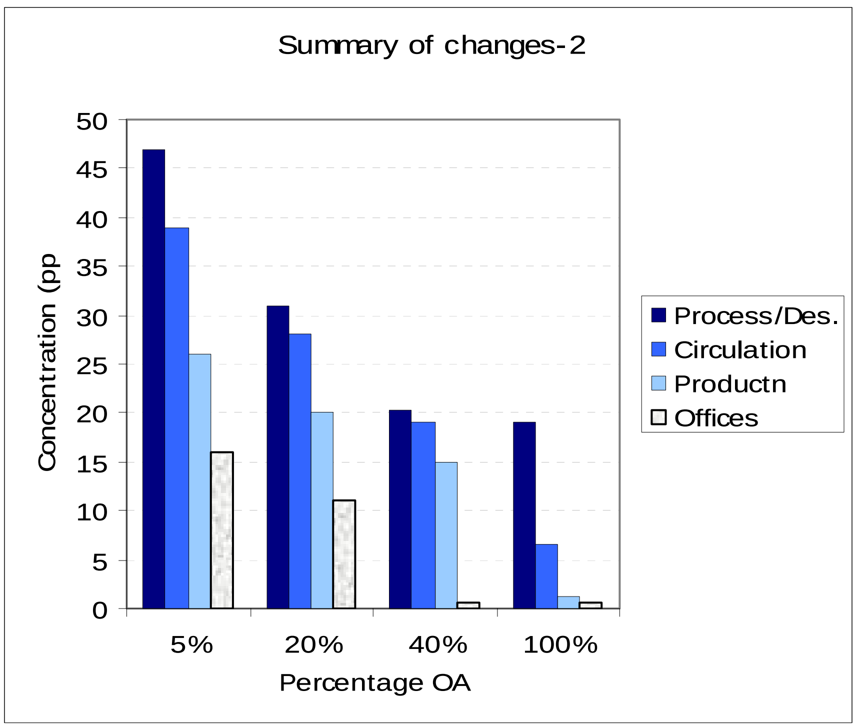


Figure 5.16: Summary of changes in concentration levels for KFUPM Press zones between 5% - 100% OAF

5.4.7 Using More Powerful Exhaust Fans in Process Area

The process Area, which incidentally shares its AHU with the design area has been observed in Figure 5.16 to still retain relatively high levels of average concentration; as much as 19 ppm. This problem can be alleviated by installing more exhaust fans which are more powerful than the current fans which extract air at 0.5 m^3/s. In Figure 5.17, the results show another summary of expected changes; and what could be obtained if the current exhaust fans are increased in number from 3 to 6, and their flow rates increased also from 0.5 m^3/s to 0.75 m^3/s.

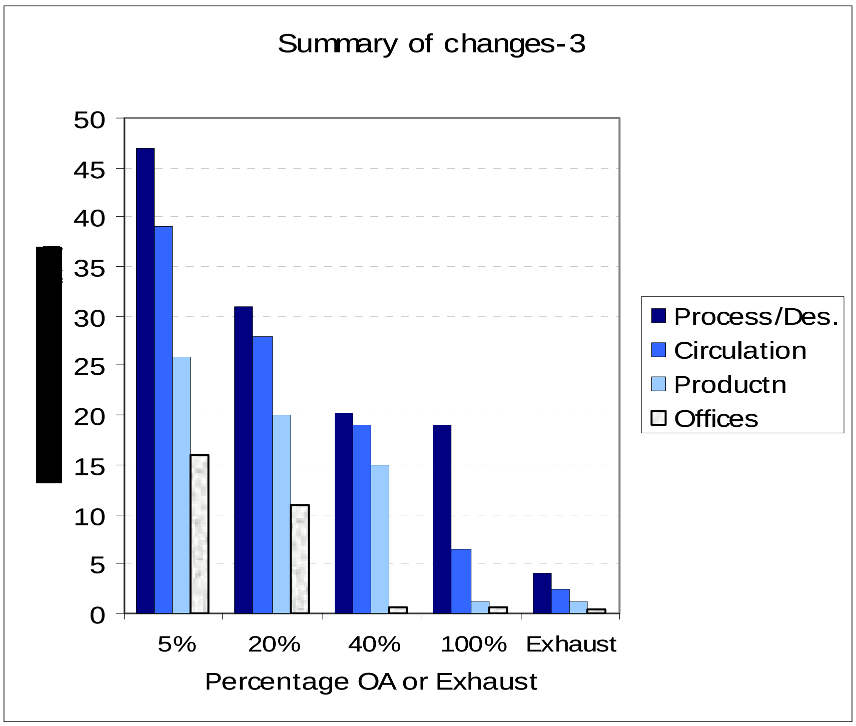


Figure 5.17: Summary of changes in concentration levels for KFUPM Press zones using OAF and Exhausting

The results show that the Process Areas would have an average concentration level of about 4 ppm, a 78% total reduction from the case when only 3 less powerful exhaust fans were used. Consequently, the Circulation space would also experience a drop in its average levels of contaminant concentration as does the Production Hall and Offices. The new concentration levels for the adjoining zones would be 2.4 ppm, 1.2 ppm and 0.33 ppm.

5.5 Findings of the KFUPM Press Building Simulations

1. For the buffer zone, it is estimated that if it could be designed to enclose an area of about $20m^2$ out of the current 67 m^2 of corridor floor space and supplied with air at the rate of 1000cfm, then there should be the kind of results as shown in the Figures and findings summarized above; which show that the buffer zone reduces concentration in the circulation area to 4.3 ppm (from 28 ppm) at 20% OAF. This is an 83% reduction rate from the un-buffered situation. If however, the OAF is increased to 40%, the circulation area would have its concentration down to 19 ppm (32% reduction) without a buffer zone.

2. Furthermore, results obtained from increasing the OAF in production hall to 100% show that the average concentration level in the production hall would be reduced by 83% from the average concentration levels when 40% OAF was utilized; and the average concentration levels in the critical Circulation area drops by 65%. The use of more exhaust fans with greater flow rates in the Process Area would lead to 80%, 87% 92% and 41% reduction in concentration levels for the Process Area, Circulation Area, Production and Office Areas respectively.

3. The concentration levels of the Production Hall and Process Areas can therefore be further reduced as well if more exhaust fans (with higher flow rates of 0.75 m^3/s) are used in the Process Area. Additionally, for the benefit for providing acceptable air quality in the Press Building, it is recommended that the Production Hall should be subjected to a 100% OAF schedule and be kept at relatively lower/negative pressure with respect to the buffer zone.

The issue of using higher efficiency filters may appear as a worthy idea, but this would not achieve any significant effect on the level of *contaminant transportation* in the building. This is because all three major zones have **independen**t Air Handling Units and cross contamination of ventilation air is not occurring **through** these separate HVAC systems, but rather as a result of *pressure differentials* across architectural flow paths/nodes cause by the HVAC systems operating independently.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.0 General Summary and Conclusions

An extensive literature review into contaminants and indoor air pollution in general as well as the characteristic behavior and distribution tendencies of pollutants in multi-zone buildings was conducted. The review covered many aspects of mechanical ventilation as well as the architectural components that play separate and collective roles in indoor air pollution. Certain HVAC and Architectural parameters were selected for detailed study using multi-zone modeling software Contamw. Furthermore, a selection matrix for choosing a multi-zone modeling program was developed using a Table of alternatives and user-defined criteria needed for successful simulations.

A theoretical model was made which considers many multi-zone layout possibilities. For instance, there were zones that were isolated (in form of an island) within the enclosure, zones with direct connection to the external (ambient) environment and there was also a zone that was contiguous (i.e. it adjoined all isolated and external zones) in the form of a corridor.

To carry out the simulations in an organized and logical order, a simulation strategy was developed which was used in conjunction with a matrix. The strategy and matrix are very vital in interpreting the steps used throughout the study.

In the simulations, the various parameters that relate to both HVAC and Architectural systems have been analyzed with respect to their individual and collective impact in the propagation of contaminants within multi-zone enclosures. The results that have been obtained from the many simulations done on the theoretical model of a multi-zone building suggests that the parameters have the capacity to affect the behavior and distribution of contaminants within a multi-zone building with varying levels of influence.

The initial parameters were studied by running transient simulations in Contamw, while the results were synthesized and ranked by using Expert Choice, an AHP and Pairwise comparison software. By making Pairwise comparisons, the parameters were ranked in order of how they affect the entire multi-zone building by the value of their respective weights. However, this does not suggest that these parameters would always have the same effect in all multi-zone buildings. As a matter of fact, even in the theoretical building, the different zones have their own unique ranking of parameters which differ in magnitude as well as priorities. Weighting and Ranking of the parameters was done primarily as a means of providing a quantitative glimpse into the impact that the selected parameters have in aiding or alleviating the movement contaminants within the given multi-zone building. This study has shown that ranking the performances of such parameters can give an insight into expected behavior of contaminants in similar architectural configurations. Studies of other building layouts are strongly recommended.

To further study the multi-zone behavior of contaminants, a case study of an existing building was conducted. The building chosen (KFUPM Press Building) is simple, but interesting as well. It has a similar contiguous zone, (corridor) and the building is served by three Air Handling Units but the operations of the HVAC as well as the architectural layout have given opportunities for contaminants to travel freely. The simulation of this building showed that the present winter and summer strategies of OAF delivery are inadequate in solving the IAQ problem on their own. However, when these strategies are used in a modified layout of the building, some improvement can be seen whether 5% or 20% OAF is used for summer or winter respectively.

6.1 General Recommendations

Listed below are generalized recommendations for all professionals involved in the design, operation or maintenance of buildings and their mechanical ventilation systems.

- Among the important lessons derived from this study, one of the vital issues is that a building must not only be designed from the Architectural or HVAC point of view alone. In architectural considerations, the functionality of human occupants is paramount, complimented by the thermal comfort which

HVAC systems are designed to achieve. However, this study has shown that *contaminant-based designs* are necessary today. In addition, this study (especially the case study part) has reinforced the notion that it is not only HVAC systems that are responsible for contaminant migration. The architectural design can be a willing or unwilling accomplice in transportation of contaminants in multi-zone buildings.

- Care has to be taken when pressurizing corridors because in some designs (e.g. isolation wards in certain hospitals) it may be necessary to depressurize corridors. So a trade-off must be done which may involve a compromise between the architect and HVAC designer. Since the architect may be forced to reconsider some 'traditional' aspects of functional design due to IAQ concerns, then it means the client would also be indirectly involved in making early decisions and compromise. What this implies is that public knowledge about IAQ in multi-zone buildings has to be made more widespread, for only then would a client see reason to accept what may appear as a radical departure from his expectations.

As a result of the findings of this research, the following guidelines are being suggested for future designs of multi-zone buildings as well as for retrofitting existing buildings with peculiar IAP problems.

6.2 Guidelines for Operating HVAC Systems

The guidelines developed from the results of this study are listed below and categorized according to professional relevance i.e. for the Architect, HVAC Designer, HVAC Operator and the Facility Manager. Some of the guidelines have over-lapping implications and relevance and this has been reflected as well.

Architect:

1. The Architecture of the building must reflect the pressure relationship between individual zones. These relationships could be studied by using simple multi-zone modeling programs like Contamw, which has recently (in version 2.4) included Building Pressurization as part of its simulation options.

2. Sensitive zones (i.e. they are potential sources of contaminants or they are potentially going to be seriously affected by inter-zonal air flow from contaminated zones) must be identified early at the design stage by analyzing the expected and possible uses for which the building is designed. If there are many such zones, then it is crucial to group them (i.e. similar zones should

be together) and have a buffer zone in between source zones and destination zones. These buffer zones could be a highly pressurized corridor. However, the architectural and mechanical configuration of this buffer zone must be determined via pressurization tests. Since experimental pressurization tends to be expensive, time consuming or complex; simulation of airflow through multi-zone programs (e.g. Contamw) can be done in order to give the zones the most appropriate flow relationship with each other.

Architect/HVAC Designers:

1. When potential sources of contaminants are identified at the design stage, it would be better if they are located in zones with minimal amount of overall design air supply or smaller volumes. A source in a zone with larger share of designed air supply will contribute much more pollution into the re-circulated air than if the same source was in a smaller zone.

2. The behavioral aspect of occupants should also be considered in designing HVAC and architectural systems. It is easy to design a door and calculate the supply/return ratio in a zone as either pressurized or otherwise. What is not easy or cannot be guaranteed is that such openings would remain closed as seen in the KFUPM Press building, where busy staff in both Office and Production Zones typically leave the door open or use it so often that the

doors are rather considered open than closed. A retrofitted buffer zone could alleviate this problem in existing buildings. A simple way of achieving this buffer zone is by using Security Portal type of doorways, which can ensure closure without compromising functional movement of occupants. Rather than using a simple door, these **doorways** (about $2m^2$ in floor area) are typically designed as small enclosures connecting two zones. Two doors (usually sliding doors) are used to connect the two zones with the enclosed space kept under positive pressure relative to both connecting zones.

HVAC Designer:

1. At the design stage, the ranking techniques developed here show the order in which parameter options could be chosen comparatively by assessing their relative ranking and performances. This ranking technique should be used as inputs in the configuration and design of HVAC systems. For example, different zones that are expected to be susceptible to inflow of contaminants can be designed to automatically pressurize, exhaust or depressurize; depending on the unique relationship which each zone has been observed to have with the rest of the building.
2. The use of exhaust ventilation in source zones is critical, but it has been observed to be most effective only when the exhaust is directly situated

over the source. In this study, although each zone is assumed to be well-mixed, in reality, it is not the case. Also, it has been observed that exhausting would only lower the amount of contaminant in the source zone. As long as the source is continuously generated, e.g. and undisclosed chemical spill, combustion, off-gassing etc, then the long-term effect of exhausting should not be relied upon. Rather, the synergy of exhausting and other techniques like pressurization should be pre-determined through multi-zone modeling procedures.

3. As much as is practically possible, filtration in source zones and other polluted zones should be done at the return diffusers. Or somewhere along the return ducting system. This may however be impossible especially if it is a plenum-return building that needs retrofitting. In that case, at the earliest possible location before the air is recirculated, it should be filtered. The logic behind this is: If heavily polluted air is filtered before mixing with OAF, then the chances of delivering cleaner air is much better than when the air is only filtered at the mixing point. This is because in case of the former, short-circuiting of contaminated would be minimized because all air leaving each zone would be certified as treated, whereas in the latter case, contaminated air could leave a zone and re-enter another zone (through various flow paths). In addition, if the efficiency of the recirculated Air filter is not very good, then other zones which share AHU

with the contaminated zones would suffer even if they have no direct architectural relationship/pathway with the source zone. Both Return Diffuser and Recirculated Air filtering should be done if possible.

HVAC Operators/Facility Managers:

1. In an era where certain contaminants can be weaponized through chemical, biological or radiologic agents, it is of utmost security concerns for the managers of public buildings to review their current designs, (and for future designs to consider this possibility as well). It may be possible to harmonize contaminant-based designs with existing smoke-control practices. This can be done by subjecting as-built designs to simulated tests of airflow patterns in multi-zone modeling programs. Design shortcomings observed or occupant practices that may be deemed unacceptable (after to risk assessment) should be discouraged passively by design modifications or actively by authoritative instructions and enlightenment. Note: *It is expected that smoke control practices could be one of the main beneficiaries of this study because smoke itself could be the contaminant that one has to design against. Consider that Carbon monoxide and Cyanide gases are given off in combustions.*

6.3 Potential Investigative Areas of Research

The obvious lack of extensive and in-depth knowledge about contaminant dispersal in multi-zone buildings points to the urgent need for continuous research into the medium and modes of this phenomenon. Especially with the grim fact that many toxicants could be aerated, weaponized, and ushered with relative ease throughout multi-zone building envelopes. As such many of the subject areas covered in the literature review of study would qualify as prime candidates for further research.

- Primarily, the tools for conducting quick analysis of the performance of multi-zone buildings under multiple scenarios may be simple enough, but they need to be simplified further, to the level of the common consultant or HVAC operator. Sohn et al [2003] have identified the need for first-responders to be equipped with Personal Digital Assistants (PDAs) that could be utilized in this regard. However, it is imperative to realize that the operators in particular, would be required to respond to sudden releases, where in such cases; there could be no time to run simulations. The application of artificial intelligence (AI) through sensors and fuzzy controllers may provide on-field guidance for semi-automatic response to a toxicant adjudged to be of harmful or questionable quality or quantity.

- With suggestions and efforts towards building security, the question of outdoor air intake as an easier point of contaminant source/release would have a dramatic effect on the concentration levels. This unique scenario needs to be considered too.

- Sometimes, it has been observed in existing literature that wherever gains are made in IAQ of a building, aspects of thermal comfort tend to suffer. Evidence of this tendency comes from the design of majority of present day HVAC systems, which date back to the energy crisis period of the 70's, where economy of thermal comfort was given priority over IAQ. Furthermore, recent calls for the separation of thermal conditioning from ventilation aspects in buildings indicate that these two aspects (IAQ and thermal comfort) have not co-existed easily. In this study, the use of pressurization required that supply volumes/rates remained constant while the return was increased above its designed value. This manipulation is expected to produce a change in the level of thermal comfort. When more air is returned than supplied, there could be a rise or drop in temperature of the affected zone. Although, multi-zone modeling programs like Contamw are designed to make up for sudden shortfalls and excesses of air within the AHU, further studies into the thermal impact of pressurization would be needed.

- Given the accuracy of CFD models, and the fact that processors and other computing hardware are getting cheaper, yet the relative ease of utilizing multi-zone model inputs and parameters may continue to tilt the balance of simulation tools in their favor.

However, for large spaces, (e.g. auditorium and gymnasium, which could be choice targets for malicious release of contaminants); Mora et al [2003] have shown how zonal models are (by themselves) insufficient in providing acceptable results for simulating airflow and contaminant dispersion. There is need then for the development of special algorithms and models that could tackle such large spaces. These models could (if possible) work within the environments of existing multi-zone applications to present some sort of Hybrid Software.

REFERENCES

1. Aggarwal S., Gagnon B.D. and Reed M.D. (2002). 'Smoke control analysis of a high-rise building using a network air flow model.' Fire Protection Engineering Magazine. Spring Issue. Vol. 14, pp.42-45

2. Al-Jarallah MI. (2001). "Radon Exhalation from Granites Used in Saudi Arabia." Journal of Environment and Radioactivity.; Vol. 53, pp.91-98.

3. Al-Jarallah MI, Abu-Jarad F. and Fazal-ur-Rehman. (2001). "Determination of Radon Exhalation from Tiles using Active and Passive Techniques." Radiation Measurements. Vol. 34, No. 1-6, pp 491-495.

4. ANSI/ASHRAE: ASHRAE Standard 62-1989. (1989). Ventilation for Acceptable Indoor Air Quality. American Society of Heating Refrigeration and Air Conditioning Engineers, inc., Atlanta Georgia,

5. ANSI/ASHRAE: ASHRAE Standard 62-1999. (1999). Ventilation for Acceptable Indoor Air Quality. American Society of Heating Refrigeration and Air Conditioning Engineers, inc., Atlanta Georgia,

6. ASHRAE Handbook: Fundamentals. (1997). The American Society of Heating Refrigeration and Air Conditioning Engineers, inc., Atlanta Georgia,

7. Awbi, HB. (1991). Ventilation of Buildings. Chapman and Hall. 1st edition.

8. Axley J, Emmerich S, Dols S and Walton G. (2000)“An Approach to the Design of Natural and Hybrid Ventilation Systems for Cooling Buildings”. Proceedings of Indoor Air 2000.

9. Beattie, KH and Ward IC. (1999) ‘The Advantages of Building Simulation for Building Design Engineers’ Proceedings of Building Simulation ’99, Vol II

10. Beggs, C.B. (2003) ‘The airborne transmission of infection in hospital buildings: fact or fiction?’ Indoor Built Environment, Vol. 12, 9–18

11. Broderick III, CR and Qingyan, C. (2000). 'A Simpler Interface to Computational Fluid Dynamics Programs for Building Environment Simulations.' Indoor Built Environment; Vol. 9, pp.317 – 324.

12. Brooks, BO and Davis, WF. (1992). Understanding Indoor Air Quality. CRC Press Inc. Boca Raton, Florida.

13. Budaiwi, Ismail M. (2002). "The Impact of Filter Placement in Air-Conditioning Systems on the Behavior of Indoor Contaminant Concentration". Proceedings of the 6th Saudi Engineering Conference, Vol. 1. Architecture and Construction, Engineering Education.

14. Budaiwi, Ismail M. (1998). "Impact of Combined Dilution and Pressurization Effects of Ventilation Air on Indoor Contaminant Concentration". Indoor Built Environment; Vol. 7, pp 289-299.

15. Budaiwi, IM. and Al-Homoud, MS. (2001). 'Effect of ventilation strategies on air contaminant concentrations and energy consumption in buildings.' International Journal of Energy Research. June Issue, pp.1073 – 1089.

16. Butcher, EG and Parnell, AC. (1979). Smoke Control in Fire Safety Design. E & F.N. Spon Ltd. London.

17. Buhl, W, Erdem, A, Winkelmann, F. and Sowell, E. (1993). 'Recent Improvements in SPARK: Strong component decomposition, multi-valued objects and graphical interface.' Proceeding of Building Simulation 1993. Third International IBPSA Conference, Adelaide (August '93).

18. Center for Disease Control, CDC. (2002). 'Protecting Building Environments from Airborne Chemical, Biologic or Radiologic Attacks.' Morbidity and Mortality Weekly Report. <www.cdc.gov/mmwr/preview/mmwrhtml/ mm5135a4.htm>. (3 June 2002).

19. Clarke, JA and Hensen, JLM. (1990). "An approach to the simulation of coupled heat and mass flows in buildings." Proceedings of the 11th AIVC Conference, Vol. 2. Air Infiltration and Ventilation Center, Belgirate Italy.

20. Emmerich, SJ. and Persily AK. (1998). 'Energy Impacts of Infiltration and Ventilation in U.S. Office Buildings Using Multi-zone Airflow Simulation.' Proceedings of IAQ and Energy '98 Conference; pp.191 – 203.

21. Emmerich, SJ. (2001) 'Validation of Multi-zone IAQ Modeling of Residential-Scale Buildings-A Review' Proceedings of ASHRAE Transactions 200; Vol 107, Pt2.

22. Emmerich, S. J.; Nabinger, S. J.; Gupte, A.; Howard-Reed, C. (2003) 'Validation of CONTAMW Predictions for Tracer Gas in a Townhouse'. Building Simulation 2003, 8th International Building Performance Simulation Association (IBPSA) Conference. Proceedings. August 11-14, 2003, Eindhoven, Netherlands, 299-306 pp, 2003.

23. Fang, JB and Persily, AK. (1995a) "Airflow and Radon Transport Modeling in Four Large Buildings." National Institute of Standards and Technology, Gaithersburg, MD. Environmental Protection Agency, Washington DC. ASHRAE Transactions, Vol. 101. No. 1. CH. 95-16-3.

24. Fang, JB and Persily, AK. (1995b) "Computer Simulations of Airflow and Radon Transport in Four Large Buildings." National Institute of Standards and Technology, Gaithersburg, MD. Environmental Protection Agency, Washington DC. NISTIR 5611; 46p. April. PB95-220422.

25. Federspiel, CC, Li H, Auslander DM, Lorenzetti D, and Gadgil AJ. (2002). "Modeling Transient Contaminant Transport in HVAC Systems in Buildings." Proceedings of Indoor Air 2002.

26. Feustel, H. E., and Raynor-Hoosen (eds). (1990). "Fundamentals of the Multi-zone Airflow Model- COMIS". Tech. Note TN29, Air Infiltration and Ventilation Center, Coventry, England.

27. Fisk, William J., (2002). 'How IEQ Affects Health, Productivity.' ASHRAE Journal. May Issue. pp.56 – 58.

28. Gamage, RB and Berven, BA. [eds]. (1996). Indoor Air and Human Health. Lewis Publishers, CRC Press Inc. 2nd Edition.

29. Giovanni, Andrea Cornia (ed). Aids, Public Policy and Child Well Being www.unicef-icdc.org/research/ESP/aids/chapter9.pdf

30. Goodfellow, H. (1990). Indoor Air Quality Simulation. Fairmont Press Inc.

31. Hansen, S. J and Burrough, H.E. (1999). Managing Indoor Air Quality. Fairmont Press Inc., 2nd Edition.

32. Hays, SM, Gobell, RV and Gannick, N.R. (1995). Indoor Air Quality: Solutions and Strategies. McGraw-Hill Inc. New York.

33. Heinonen Jarno and Kosonen Risto. (2000). “Hybrid Ventilation Concepts in Commercial Buildings-Indoor Air Quality and Energy Economy Perspective”. Proceedings of Healthy Buildings 2000. Vol. 2. pp 517-522.

34. Heiselberg, Per. (2002). (ed.) Principles of Hybrid Ventilation. Hybrid Ventilation Center, Aalborg University, Aalborg, Denmark.

35. Hutcheon, NB. and Handegord, GOP. (1989). Building Science for a Cold Climate. Construction Technology Centre, Atlantic Inc.

36. Khattar, Mukesh K. (2002). “Separating the V in HVAC: A Dual-Path Approach”. ASHRAE Journal., May Issue. pp 37 – 43.

37. Klote, J. (1995). ‘Smoke Control.’ SFPE Handbook of Fire Protection Engineering, 2nd Ed. P.J. DiNenno (ed.), NFPA, Quincy, MA.

38. Kumar, S. (2002). ‘IEQ and the Impact on Employee Sick Leave.’ ASHRAE Journal., July Issue. pp 97 – 98.

39. Lam, JC, Yuen, RKK and Lau TM. (1993) 'Improvements to User-friendliness of a Computational Fluid Dynamics (CFD) Code for Simulation of Air Movement in Buildings. Proceedings of Building Simulation '93: pp.77-83.

40. Li, Yuguo; Sandberg Mats and Hui, Sam. [2004]. Robustness of Air distribution in Plenum-Based Ductless Ventilation Systems. International Journal of Ventilation. Vol. 3 No. 2 pp-105 -118.

41. Li, Y, Huang, X, Yu, ITS, Wong TW and Qian, H. (2004a) 'Role of air distribution in SARS transmission during the largest nosocomial outbreal in Hong Kong' Indoor Air. Vol. 15: 83 -95.

42. Li, Y, Duan, S, Yu, ITS. and Wong, TW. (2004b) 'Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens'. Indoor Air. Vol. 15 pp 96 -111

43. Lorenzetti, DM. (2001). 'Assessing Multi-zone Airflow Software.' LBNL-47653. Lawrence Berkely National Laboratory. Berkely CA, USA.

44. Lorenzetti, DM. (2002). 'Computational aspects of nodal multi-zone airflow systems' Building and Environment. Vol. 37, pp. 1083-1090

45. Macdonald, IA, Clarke, JA and Strachan, P.A. (1999). 'Assessing Uncertainty in Building Simulation.' Proceedings of Building Simulation '99.

46. Mora, L.; Gadgil, AJ and Wurtz E. (2003). "Comparing Zonal and CFD Model Predictions of Isothermal Indoor Airflows to Experimental Data" Indoor Air 2003; vol. 13, pp 77-85.

47. Musser, Amy. (2000). 'Multi-zone Model as Indoor Air Quality Design Tool' Proceedings of Healthy Buildings 2000; Vol.2. pp 455-460.

48. Owen, MK, Lawless, PA and Ensor, DS. (1999). 'Indoor Air Quality Simulation: IAQPC.' Proceedings of Building Simulation '99.

49. Pelletret, RY and Keilholz Werner. (2001). 'COMIS 3.0: A new simulation environment for multi-zone air flow and pollutant transport modeling.' Proceedings of Building Simulation '01.

50. Persily, Andrew K. [1998]. 'Airtightness of Commercial and Institutional Buildings: Blowing Holes in the Myth of Tight Buildingss'. Thermal Envelopes VII Conference. Dec. 6-10. 1998. Clearwater, FL.

51. Price, P. N., Sohn, MD., Gadgil AJ., Delp WW., Lorenzetti, DM., Finlayson, EU., Thatcher, TL., Sextro, RG., Derby EA and Jarvis, SA. (2002). Protecting Buildings from a Biological or chemical Attack: Actionsto take before or during a release." <www.securebuildings.lbl.gov/images/BldgAdvice.pdf>.

52. Prikazsky, V; Havelkova, M and Bencko,V. (2003) "Indoor Air as a Risk Factor for Tuberculosis" Indoor and Built Environment. 2003 Vol. 12; pp 47-53

53. Proulx, Guylene. (2003). 'Playing with Fire - Understanding Human Behavior in Burining Buildings.' ASHRAE Journal. July Issue. pp.33 – 35.

54. Sato, S, Kobayashi, H and Utsumi, Y. (1999). 'Diagnosis of Indoor Air Quality and Ventilation Design Utilizing Expert Systems.' Proceedings of the 6th International IBPSA Conference. Kyoto, Japan.

55. Seckar, SC, Tham, KW and Cheong David. (2002). 'Ventilation Characteristics of an Air-conditioned Office Building in Singapore' Building and Environment. Vol. 37. pp. 241-255.

56. Sextro, RG, Lorenzetti, DM, Sohn, MD and Thatcher, TL. (2002). 'Modeling the Spread of Anthrax in Buildings.' Proceedings of Indoor Air '02.

57. Sohn, Michael D; Reynolds Pamela; Singh, Navtej and Gadgil, Ashok J. [2002]. "Rapidly Locating and Characterizing Pollutant Releases in Buildings". Journal of Air and Waste Management. Vol. 52. Dec. 2002.

58. Walton, GN. (1989). Airnet- A Computer Program for Building Airflow Network Modeling. NISTIR 89-4072, National Institute of Standards and Technology. USA

59. Walton, GN. (2002). "Contamw2.0 Users Manual'. NISTIR 6921, National Institute of Standards and Technology. USA

60. Webb, William A (1998). "Zoned Smoke Control Applications." ASHRAE Journal. Dec. Issue. pp. 36 - 40.

61. Wladyslaw, K; Bahnfleth, W and Musser A. (2003). "Modeling Immune Building Systems for Bioterrorism Defense". Journal of Architectural Engineering. June 2003. Vol. 9 No. 2. pp 86-96

62. World Health Organization, WHO. (2002). "Strategic Framework to Decrease the Burden of TB/HIV." WHO/CDS/TB/2002. <www.who.org.>

63. Wong, NH, Mahdavi, A, Boonyakiat J and Lam Khee P. (2002). 'Detailed Multi-zone Airflow Analysis in the Early Building Design Phase'. Building and Environment. Vol. 38, No. 3. pp. 1-10.

64. Yik, Francis WH and Powell Greg. (2003). "Review of Isolation Ward Ventilation Design and Evaluation by Simulation." Indoor and Built Environment. 2003 Vol. 12; pp 73-79.

65. Younus, A. (2006) "Interview with HVAC Maintenance Engineer on 29th March 2006". KFUPM Dhahran, Saudi Arabia by Zulfikar Aliyu Adamu

66. Zhao, Y, Yoshino, H and Okuyama, H. (1998). 'Evaluation of the COMIS Model by Comparing Simulation and Measurement of Airflow and Pollutant Concentration.' Indoor Air. Vol. 8, pp.123 – 130.

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