DECISION MODEL TO OPTIMIZE INDOOR AIR QUALITY IN COMMERCIAL BUILDINGS IN FLORIDA

By

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This dissertation is dedicated to my dear parents, Kemal and Nukhet Celik. This endeavor would not have been possible without their unwavering patience, support, and love.

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Sustainable design and construction practices have been developing rapidly. Many building experts apply sustainable building strategies to their practices. One of the crucial aspects of designing a sustainable building is creating a healthy and comfortable indoor air quality (IAQ). Specific levels of indoor air pollutants may affect the health and comfort of the occupants of a building. The problem starts with the lack of a decision system for choosing a specific IAQ management option. The building industry is not thoroughly aware of the consequences of different IAQ management methods and decisions, and it lacks the resources to identify the "best" solutions to IAQ problems. These consequences may result in added soft costs such as lost productivity, as well as added hard costs such as the conditioning of the incoming outdoor air. This research combines these two types of costs into a true cost and introduces a modeling methodology of linear mathematical programming for optimizing IAQ in commercial buildings. These analyses also explore the conflicts between IAQ and energy efficiency.

This research explores alternative IAQ control options in terms of improved ventilation and air cleaning and presents an objective function and a set of decision variables, as well as the technical, financial, and legal constraints. The significance of the research derives from introducing the idea of applying operations research to construction management and providing the conceptual background for formulating the optimization of IAQ in commercial buildings. Defining a decision model for commercial buildings will help decision makers such as designers, contractors, or building owners and managers in making more sophisticated decisions regarding indoor air control technologies and strategies.

CHAPTER 1
INTRODUCTION

Introduction

The Massachusetts Environmentally Preferable Products Program (MAEPP) defines sustainability as the process of conducting business in a resource conservative and efficient manner so that operations do not compromise the ability of future generations to meet their own needs (MAEPP 2006). Sustainability concerns have been emerging in many different areas. The building industry is one of these areas that have been integrating the concepts of sustainability into industry practices. Sustainable design and construction of buildings deals with many different issues in buildings. One of these is Indoor Environmental Quality (IEQ). The IEQ concept includes factors such as noise, indoor air quality (IAQ), lighting, and acoustics. All of these factors affect the quality of a building's interior space. Consequently different levels of IEQ affect the comfort and health of occupants differently. On the other hand, IAQ focuses specifically on the control of indoor air pollutants.

Most people are more aware that not only outdoor air pollution but also indoor air pollution can be damaging to their health. A public opinion survey of 1,000 full-time workers reported that 95 percent of those interviewed ranked the quality of air at work as very or somewhat important, and only 3 percent believed it was not important (Chelsea 2000). The United States (US) Environmental Protection Agency (EPA) studies of human exposure to air pollutants indicate that indoor air levels of many pollutants may be 2 to 5 times, and occasionally more than 100 times, higher than outdoor levels (USEPA 1993).

These levels of indoor air pollutants are of particular concern because it is estimated that most people spend as much as 90% of their time indoors. In contrary to outdoor air, indoor air can be recycled constantly causing the air to trap and build up contaminants. Common contaminants include smoke, dust, mold and spores, pollen, and odors. The indoor air pollutants can be caused by several different reasons such as various equipments, heating ventilation and air conditioning (HVAC) systems, human activities, and building materials. Controlling these systems and many other sources of air pollution involves measures to be taken at many stages of a building's lifecycle. Design, construction, and occupancy phases are all crucial stages that can include activities and decisions to affect IAQ.

One of the interesting contradictions of sustainable construction practices is between IAQ and energy efficiency measures. Energy efficiency has become one of the most important issues for many industries since the oil crisis took place in 1970s. This trend has become stronger with the development of "green" building strategies, environmentalism, and other movements that promote tighter building envelopes to maximize the energy savings. However this trend unintentionally decreased the indoor air quality of the buildings. Tighter building envelopes decrease the amount of outdoor air (OA) supplied into the building, thus creating buildings that are mostly dependant on mechanical systems. In several cases this approach created the Sick Building Syndrome (SBS), which describes

> situations in which building occupants experience acute health and/or comfort effects that appear to be linked to time spent in a particular building, but where no specific illness or cause can be identified; complaints may be localized in a particular room or zone, or may be spread throughout the building. (BIOTECH 2005, p. 6)

The effects of poor indoor air quality are not limited to health problems. Buildings with higher indoor air contaminant levels can possibly cause loss of productivity, legal liabilities, and remediation costs. The problems associated with poor indoor air quality are examined and explained in more detail in Chapter 2.

Statement of the Problem

The building itself generates many indoor air pollutants mainly due to poor choices of building materials or furniture, and poor maintenance of HVAC systems. The main objective for improving air quality is to determine the required levels of ventilation, air filtering, and contaminant source management. The problem that the building industry is facing is that there are no decision support tools other than the local and national standards that can guide the decision makers with their choice of indoor air management options in a more precise and cost-effective manner.

A common experience is that building regulations do not in themselves guarantee a good indoor climate in specific cases. Mendell et al. (2002) explain that current building codes are also based primarily on practical experience within the building sector and not on health-related criteria. The major IAQ problems derive from frequent design, construction, and operation defects. These defects usually create indoor environmental problems deriving from indoor air contaminants such as mold, fungi, various bacteria, and viruses. The environmental technology that is used in a building can either be a contributor or a solution to the IAQ of a building.

Mendell et al. (2002) argue that science is not the limiting factor but rather economic and institutional barriers are the primary barriers. Decisions affecting IAQ are often made on lowest hard costs and this approach usually discourages spending more on improving IAQ. The cost of poor IAQ commonly falls on occupants rather than on building decision makers who may ignore the soft costs of IAQ measures.

Soft costs in the building industry are architectural, engineering, and legal fees as distinguished from land and construction costs (Corporate Real Estate Solutions [CRES] 2005). Soft costs generally represent any costs that are not related to the actual land and construction costs. Consequently the soft costs associated with IAQ may include but not be limited to costs associated with productivity, health, insurance fees, litigation, etc. One of the most important issues in regard to improving IAQ of a building thus reducing the soft costs may be found in the relationship between occupant comfort and productivity. Worker salaries constitute the major cost of operating a commercial building, generally estimated at over 90% of the total operating cost, so that even a small increase in employee productivity can considerably decrease a company's operating costs (American Institute of Architects San Francisco Chapter [AIASF] 2001).

Purpose of the Study

The purpose of this research is to develop a decision model for optimizing the control of indoor air pollutants in commercial buildings in Florida. The goal of the research is to help decision makers determine the optimal indoor air management options to maximize the benefits of a better indoor air quality.

Research Questions

The major research question to be investigated in this research is given below:

- Can an optimization model be developed to select effectively the optimal IAQ measures in commercial buildings in Florida to meet or exceed the standards required by code?

This study also explores the answers to the following question:

- What are the decision criteria for building owners and managers when choosing a specific indoor air management option?

Significance of the Study

Decision-making processes for IAQ issues in the building industry have been determined by the local and national regulations that may not always guarantee the optimum decision. Building owners and managers or their representatives are not completely aware of the consequences of different indoor air quality management methods and decisions, and they may lack the means to identify the "best" solutions to IAQ problems. The significance of this study derives from the determination of the optimum IAQ options for commercial buildings in Florida. However the outcome model of this study and its methodology would also be used as a basis of similar building-related decisions such as different locations, different types of buildings, or even different management problems.

From a wider perspective, this research contributes to current sustainable building research in terms of quantifying the benefits of better IAQ in buildings, which would eventually help promote sustainable buildings. The research also aims to contribute to the clarification of arguments regarding the conflicts between IAQ and energy efficiency issues from a quantitative point of view. In conclusion, defining a decision model for commercial buildings will help decision makers such as designers, contractors, or building owners and managers in making more sophisticated decisions regarding indoor air control technologies and strategies. The model developed in this research may potentially help commercial building owners and managers build long-term savings by increasing the productivity of the workers and decreasing the losses due to worker health and performance problems.

Assumptions and Limitations

Indoor air problems in buildings can appear in many different types of buildings. However these problems are more common in commercial and institutional buildings due to their dense population. This study only focuses on IAQ management in new commercial buildings, where significant savings can be generated by increased worker productivity and performance.

There are several types of IAQ management options in commercial buildings. These options may include different technologies with various initial and lifecycle costs. In order to limit the number of options, this study concentrates on the following two categories:

- Improved Ventilation
- Air Cleaning

There are various situation and considerations under which one or more options may be included, or excluded, as a candidate for IAQ control in a particular building. Although in some cases one of these approaches might be the only logical candidate, this research limits the research to buildings that would have the two above options as IAQ control techniques. More detailed descriptions of these and some other options are given in Chapter 2.

In order to control the different fixed costs, the study limits the analysis to research on marginal costs. Marginal cost may be defined as the "change in cost per exposure" where exposure would be (concentration) x (number of occupants) x (time) (Henschel 1999). This research only focuses on buildings that are not located in regions or zones where the outside air is a source of contamination such as industrial sites. It is also assumed that the number of occupants inside a building will not exceed the limits that are mentioned in ASHRAE Standard 62.1-2001 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] 2001).

The assumptions adapted while configuring the optimization model are given below. Many of these assumptions aim to clarify the optimization model and set clear boundaries on the potential applications of the model.

- The cost data regarding the proposed energy cost calculations are based on equipment that runs on electricity. Simple modifications that are also mentioned in this study would provide calculation methods for other sources of energy as well.
- The cleaners considered are only the particulate air cleaners with an average removal efficiency of 65% or greater as measured in ASHRAE standard 52.1-1992 (Henschel 1999).
- The model assumes that the total outdoor air (OA) ventilation will not go over 140 cfm assuming that above this value there would be additional fixed costs due to equipment replacement and/or upgrade.
- As default the overall Energy Efficiency Ratio (EER) for the cooling system is assumed to be 10 Btu/h/W.
- Overall efficiency of the heating system is assumed to be 1.0 Btu/h per Btu/h. (Users may use 0.7 for systems that work with gas)
- The assumption is that in Florida, on average over the cooling and heating seasons, all of the heat added to the air stream by the fan must be removed by the cooling system (Henschel 1999).
- The assumption is that the productivity curves for air cleaning and the amount of OA ventilation are independent from each other. However studies such as Wargocki et al. (2000) state that the amount of pollution and the amount of ventilation are in fact correlated when calculating the performance index. Yet there is not enough data to actually quantify this dependency. In the case of generation of these new data the model would become nonlinear.
- The assumption for the proposed cost calculation methods is that the heating capacity range of the HVAC system is between 11 and 40 kW.
- The assumption is that the systems used in buildings have economizers where the required OA increase can be achieved without enlarging the OA intake duct and without increasing the dimensions of the central exhaust ducting compared to initial design (Henschel 1999).

- The assumption is that if a dedicated-OA unit is to be installed in a new building, it will be designed to condition all of the OA entering the building.

Organization of the Study

The major outline of the research is explained in more detail in the following chapters. Chapter 1 introduces the problems regarding IAQ in commercial buildings, as well as lists the research questions, purpose, limitations, and assumptions. Chapter 2 reviews the current literature that is relevant to IAQ issues in sustainable buildings. Different techniques to control IAQ in commercial buildings, and the consequences of change in indoor air quality are also investigated in Chapter 2. There are many studies that demonstrate the importance of IAQ in commercial buildings and its effects on the occupants of a building. Chapter 2 covers some of these important studies in terms of their approach and results.

Chapter 3, which includes the design of the research as well as the tools and methods used in the study, briefly explores the methodology of the research. Chapter 3 also introduces the research questions and the research population. Chapter 4 covers the details of the methodologies for calculating the required parameters and introduces the developed IAQ decision model. The solution to the model and the sensitivity analyses along with the discussions of the solutions are presented in Chapter 5. Finally Chapter 6 presents an overall conclusion and the possible recommendations for future work.

CHAPTER 2
REVIEW OF THE LITERATURE

Introduction

This chapter explores the existing literature relevant to sustainable buildings and specifically IAQ issues in commercial buildings. Buildings have significant impacts on the environment and their occupants during construction, throughout their operation, and during end-of-life (decommissioning). The US Green Building Council (USGBC) defines "green" or "sustainable" building as a term that refers to design and construction practices that significantly reduce or eliminate the negative impact of buildings on the environment and its occupants through all life cycle phases of the building (USGBC 2003). This concept can be applied to design, construction, and operation of new buildings or renovations of existing buildings.

The building industry is ever more focused on making its buildings more sustainable, which includes using healthier, less contaminating, and more resource-efficient practices. Indoor environmental quality (IEQ) deals with the quality of the air and environment inside buildings, based on many different conditions that can affect the health, comfort, and performance of occupants. These conditions may include contaminant concentration, temperature, relative humidity, light, sound, and other factors (USEPA 2005a). It is important to note that a good IEQ is a vital element of sustainable buildings. Building owners, managers, occupants, architects and builders can all benefit from the increased IEQ in terms of minimizing the negative health effects, legal liability, and possible remediation cases.

IAQ is a crucial segment of IEQ and has major impacts on the overall IEQ of a building. Improving IAQ involves to design, construct, commission, operate, and maintain buildings in ways that decrease contaminant sources and remove contaminants while ensuring that fresh outdoor air is persistently supplied.

Sustainability and the Built Environment

The problem of sustainability should first be explored in order to provide a strong basis for the concept of sustainable buildings. The subject of a sustainable future is taking place at the center of gravity of the triangle of environment, sociology, and economy. Environmental problems, the magnitude and frequency of which are continuously increasing, keep their place at the agenda of many countries rather than being just a local concern. In order to find an answer to all of these worries, many different ideologies and hypothesis are being discussed in today's world. One of these different proposals to determine the relation between nature, human, and the built environment is sustainability or sustainable development.

Many definitions of sustainable development have been offered, some general and some more precise. The following definitions are some examples.

> Development, which meets the needs of the present without compromising the ability of future generation to meet their own needs. (World Commission on Environment and Development [WCED] 1987, p. 43)

> Using natural renewable resources in a manner that does not eliminate or degrade them or otherwise diminish their renewable usefulness for future generations while maintaining effectively constant or nondeclining stocks of natural resources such as soil, groundwater, and biomass. (World Resource Institute [WRI] 1992, p. 2)

> The net benefits of economic development, subject to maintaining the services and quality of natural resources. (Goodland & Ledec 1987, p. 36)

To generalize and simplify various definitions, the definition of sustainability can be summarized as a system that delivers services without exhausting resources over time. It uses all resources efficiently in an environmental, social and economic sense.

In past years, sustainability has become a catchword capable of capturing the attention not only of environmental scientists and activists but also of some mainstream economists, social scientists, and policymakers. The reason for that is the sustainability of the human activity in the biggest sense depends on technological, economic, political, and cultural factors, as well as on environmental ones (Holdren et al. 1995). According to this context, economists explain different ideas about sustainability. According to Lehner et al. (1999), a sustainable economy is one that is capable of continuously securing and reproducing the basis of its operation. This economy includes both the natural system from which the economy extracts all the resources that it needs, and a variety of economic and social factors. These factors may include knowledge and skills, technology, social standards, and political standards and regulations, which determine the capacity of an economy to generate wealth and living standards in society.

At this point instead of explaining all the definitions of various disciplines about sustainability a more convenient approach may be to refer to the ideas of McHarg (Kibert et al. 2002). He states that geologists, meteorologists, hydrologists, and soil scientists were informed in physical science but not in real life; on the other hand, ecology and the biological sciences were only aware of physical processes. He determined this problem as the lack of integration within the environmental sciences.

Now one has to answer the question: How are all these discussions related to the built environment? That is the question various disciplines try to answer and come finally to the word of “Sustainable Construction”. Sustainable construction can be defined as the creation and maintenance of a healthy built environment using ecologically sound principles (Kibert et al. 2002). Many different concepts are involved in creating the healthy built environment. Energy, water, waste, materials, and IEQ are some of the concepts to focus on when creating and maintaining a healthy built environment. Since this study concentrates on the IEQ issues in buildings the following sections will be exploring the relations between sustainability and IEQ in more detail.

Humans and Their Environment

Human beings have always had a mental and physical relationship with their environment. Human beings themselves can be called a microenvironment and the environment around them a macro environment (Fitch & Bobenhausen 1999). The problem has always been to understand and balance the relations between these two environments. There were times throughout history that had extreme environmental conditions. There are currently regions in the world where sustaining a direct relationship with the natural environment is almost impossible. In fact there are only few regions in the world where people can survive without developing an “interface” between themselves and nature (Fitch & Bobenhausen 1999). Fitch and Bobenhausen (1999) in their “The American Building” rename the term “interface” as the third environment.

So what are the interfaces that people need in order to interact with the environment around them? The simplest answer to this question would be “clothing”. However, wearing clothes has not always satisfied people, so they also have created spaces such as buildings to live in. Controlling the environment of these spaces rather than controlling the natural environment, has always been much easier. These comfort conditions for humans depend on the essential requirements of their microenvironment. Several conditions that are listed below determine the metabolic level of relationship between humans and their environment (Fitch & Bobenhausen 1999).

- Thermal
- Aqueous
- Sonic
- Spatio-gravitational forces
- Atmospheric
- Luminous
- World of objects

Adjusting these conditions according to the specific individual needs forms the basics of the configuration of IEQ. This is one of the means used to create the essential conditions in the third environment and many issues have affected the use of this tool. These issues and their solutions that concerned humans have been constantly changing throughout the history. The discussion on controlling the third environment is related to some other issues such as the use of science, technology and its integration in buildings. These issues are discussed in the following sections.

Humans and Technology

According to Heidegger (1976) the purpose held by human beings has always been to conquer the physical world in order to establish and extend the power and domain of the human race itself over the universe. However, human freedom and victory over nature has depended on the degree of knowledge about the laws of nature. The pure knowledge of humans can be called “science” whereas the application of science is known as “technology”. Often the terms, technology and science, are confused. Science deals with the natural world. Technology is the application of natural laws, which govern the universe. This is not to say science and technology are unrelated. Science deals with "understanding" while technology deals with "doing"(Heidegger 1976).

Technology is a human activity. It is an activity in which human beings form and change natural reality for practical reasons with the help of means and methods. In his "A Question Concerning Technology", Heidegger (1976) states that the manufacture and utilization of equipment, tools, and machines, the manufactured and used things themselves, and the needs and ends that they serve, all belong to what technology is.

Modern science and technology have been intentionally and methodically applied to every side of human existence. Heidegger (1976) states that modern technology is something incomparably different than all earlier technologies because it is based on modern physics as an exact science. He concludes that modern science represents nature as a calculable coherence of forces. Nature at any case seems to have the most crucial significance when dealing with technology. McCleary (1983) in his "An Interpretation of Technology" clearly defines the relations between technology, human, and nature. He explains a person's fundamental activity as one of productive interchange with nature. This productive interchange that we may call "technology" is defined as the communication between societies and their natural environments in the production of the built environment.

According to McCleary (1983), construction of a new nature, which is interposed between societies and original nature, is called "supernature". Supernature is definitely a product of technology. A higher level of supernatural existence is "super-supernature", which is the concern of high technology. McCleary (1983) divides technology, which is an interconnection between the original nature and human, into three levels:

- High technology
- Middle technology
- Low technology

McCleary (1983) explains the product of “super-supernature” as the concern of high technology. Low technology on the other hand is explained as a concern of those who wish to return to that earlier relation that existed between societies and their natural environments preferably in a technologically underdeveloped region. McCleary (1983) claims that current practice of our professions is in the bondage of middle level technology to the exclusion of both high and low technologies. Heidegger (1976) states that more questioning of technology means that the mystery of it reveals itself. Yet because of the more questioning of the technology’s essence, the more mysterious the essence of art becomes. Heidegger (1976) shows the contradictions of human nature by stating that the feeling of danger helps human being become more questioning. Finally, Heidegger (1976) wants to emphasize whether the kind of revealing of ‘Being’ that shows itself in the fine arts can rescue man from danger of enframing, which he defines as the essence of technology. So man has to rethink the meaning of modern science and technology.

Humans and Buildings

The relation of humans with buildings is related to the essence of architecture and building construction. It is essential at this point to remember the purpose of buildings. Fitch and Bobenhausen (1999) define the ultimate task of architecture as activity in favor of human beings. They state that the purpose of architecture is to maximize our capacities by permitting us to focus our limited energies upon those tasks and activities that are the essence of the human experience.

To be able to understand the relation between the buildings and the occupying people we should also remember the essential needs of humans so that we will be able to understand the expected fundamental requirements about the buildings and the third environment they create. The relation of the human with the environment can be reviewed at two different levels, which are perceptual and metabolic (Fitch & Bobenhausen 1999). The conditions that determine the metabolic level of relation are already given in the "Human and Their Environment" section. The perceptual level on the other hand, comes into play only after the metabolic level requirements are met (Fitch & Bobenhausen 1999).

IEQ deals with controlling and adjusting the third environment in a metabolic level. According to Fitch and Bobenhausen (1999) there are four stages of optimizing metabolic fit between building and its environment:

- Mechanical systems
- Enclosing membranes
- Building's exterior surfaces
- Site

Banham (1969) in his "Architecture of the Well-Tempered Environment" discusses the environmental management in three different modes:

- Conservative mode
- Selective mode
- Regenerative mode

Thick walls of a house in a hot climate hold the radiation heat as a thermal mass during the day, and then, after sunset, the radiation of the heat into the house helps to control the sudden chill of evening. This whole technique can be termed as "Conservative" mode of environmental management. The "Selective" mode, on the other hand, employs structure not just to retain desirable environmental conditions but also to admit desirable conditions from outside (Banham 1969). However traditional construction has always had to mix these two modes, even without recognizing their existence, just as it has always had to incorporate the “Regenerative” mode of applied power without fully acknowledging its presence (Banham 1969).

The Eskimo igloo displayed in Figure 2-1 is a good example for the conservative mode of environmental management. The shape and material used to build the igloo signifies high-level environmental recognition and responsibility. The rounded shape provides maximum resistance and minimum exposed surface to cold winds while enclosing the most volume with the least material. With no mechanical systems and no source of heat other than a small stove, interior air temperatures can be hold at a tolerable range.

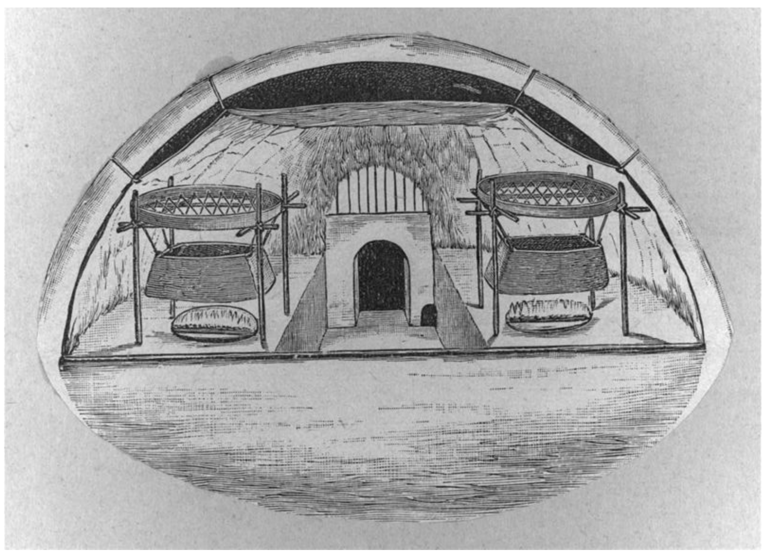


Figure 2-1. Historical design for the Eskimo igloo, Baffin Island, Canada. (Wikipedia 2006a).

Another pre-industrial age example for the conservative mode of environmental management is the mud masonry Indian House (Fig.2-2). The high heat capacity of mud masonry, well suited to the great environmental fluctuations of the desert, is cleverly used in primitive housing. Although the air may be dry, when it becomes very hot ventilation may not be desirable. Native Americans build freestanding brush-covered arbors for daytime shade, using houses for storage and cold weather sleeping while they used the rooftops for summer sleeping (Fitch & Bobenhausen 1999).

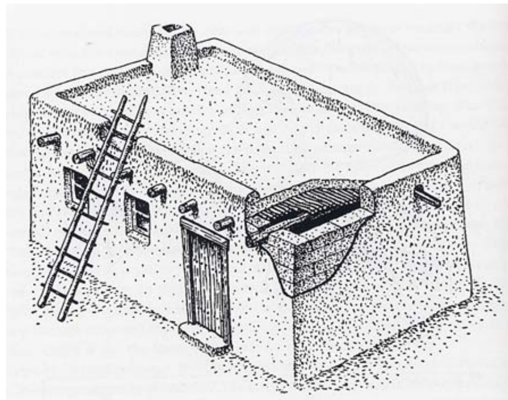
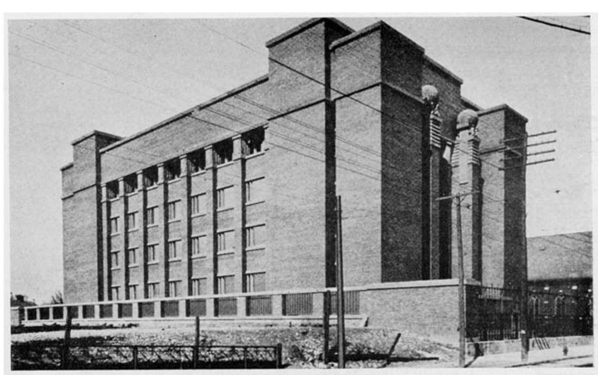


Figure 2-2. Mud masonry Indian House (Fitch & Bobenhausen 1999).

The Larkin Administration Building by Frank Lloyd Wright is the first entirely air-conditioned building on record (Banham 1969). It was built in 1904 and demolished in 1950 and was one of the early masterpieces of pioneer, modern architecture (Banham 1969). The Larkin Building is one of the good examples, which employ both selective and regenerative modes of environmental management. The mechanical and architectural aspect of the whole environmental concept is illustrated in Figure 2-3.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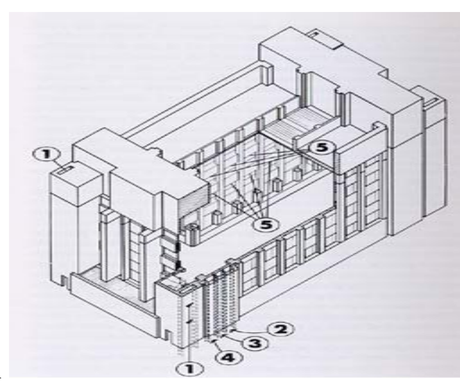
B

Figure 2-3. Larkin Administration Building, Buffalo, NY, 1906 by F. L. Wright A)Exterior photo, B)Isometric drawing (Banham 1969).

In the late 80s, while the application of computer technology into buildings was the main theme of the building practice, Norman Foster Associates designed an innovative building in Hong Kong that is dominated by several environmental management ideas. In 1986, Hong Kong and Shanghai Banking Corporation Headquarters was built in Hong Kong by Norman Associates (Fig. 2-4). Flexible layout and systems such as raised floor system provide space for the distribution of services and also help to cope with the issue of flexible functional design. Computer technology is used in the building in order to control the sun scoops that are used to track the sun location, together with mirrors positioned outside and on top of the building atrium to diffuse sunlight to different floors through the atrium and down to the plaza floor (Dobney 1997). The concept of energy efficiency in the Hong Kong Bank resulted in the sunshades on the external facades to avoid direct sun light into the building and to reduce the heat gain (Dobney 1997).

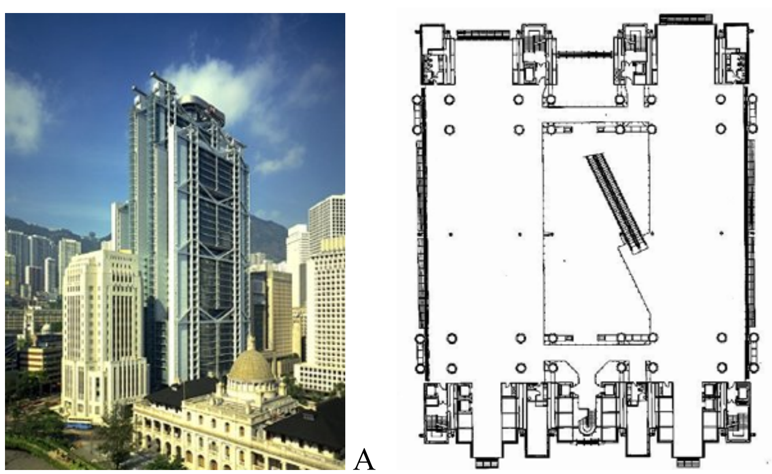
A B

Figure 2-4. Hong Kong and Shanghai Banking Headquarters, Hong Kong. A) Exterior photo, B) Floor plan (Dobney 1997).

In 1997, Norman Associates built another innovative design for Commerzbank in Frankfurt, Germany (Fig. 2-5). Commerzbank Headquarters is termed as the “world’s first ecological tower” (Fischer & Grüneis 1997). Commerzbank Headquarters’ ventilation is provided by mechanical ventilation and air extraction that is used only on days with extreme conditions, and the outer offices are naturally ventilated directly from the outside. The offices on the atrium side receive air from outside indirectly through ventilation flaps designed on the high glass walls of the garden facades. Just like the Hong Kong Bank, Commerzbank also integrated complex computer technology that controls the quantity of air pumped in, cut of supply to unoccupied spaces, sun shading, the opening angle of windows, and the release or lock of controls and regulators. Cooling on hot days is provided by a water-filled cooling system and the cold water needed for cooling is produced by environmentally friendly refrigerating machines (Fischer & Grüneis 1997). High heat insulation quality on the facades and glazing also has a positive influence on the energy efficiency of the building. Fluorescent tubes with daylight-dependent regulation light the offices, and movement detectors automatically switch continuous lighting in the corridors and offices (Fischer & Grüneis 1997).

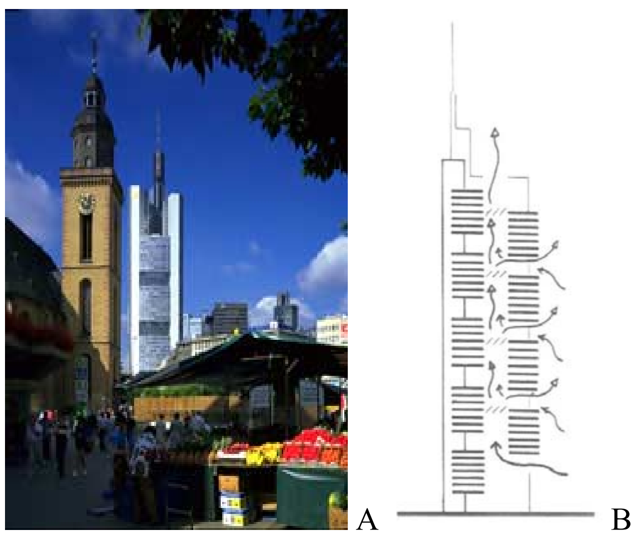

Figure 2-5. Commerzbank Headquarters, Frankfurt, Germany. A) Exterior photo, B) Natural ventilation diagram (Fischer & Grüneis 1997).

Similar to what Banham (1969) proposed earlier, Baker and Steemers (2000) categorized the modes of environmental management in contemporary buildings. They state that there are two modes of environmental management. The Selective mode includes designs that work with a combination of form and fabric operating in a calculated relationship with mechanical systems such as Hong Kong Bank or Commerzbank Headquarters. On the other hand, exclusive mode of environmental management separates the exterior and interior environments and employs mechanical services as the main controllers of the interior environment.

The environmental management concepts, techniques and their influence on building design, construction, and themes have always been changing since humans created their third environment. Table 2-1 summarizes all these different approaches in the context of major issues and the building concepts in the world of buildings since the 1960s.

Table 2-1.Historical progress of building issues and concepts.

Decade	Issues	Building concept
1960s	Sense of coolness, heating, ventilation, insulation, shading	Mechanical systems
1970s	Energy crisis	Energy-efficient buildings
1980s	Application of computer and high technology in buildings	Intelligent and smart buildings
1990s	Sick building syndrome	Healthy, green buildings
Twenty-first century	Globalization towards sustainable development	Sustainable buildings

Indoor Air Quality (IAQ) in Commercial Buildings

Commercial buildings can include office buildings, retail establishments, light manufacturing and assembly, restaurants, bars, etc. Commercial buildings, just like other types of buildings use HVAC systems in order to provide a well-conditioned interior environment for the occupants. Unlike residential buildings, these buildings have a higher density of population and equipment. Consequently, managing a good IAQ in commercial building may be more challenging than residential buildings.

The major IAQ problems in commercial buildings include airborne particles, moisture, insufficient ventilation, and odors and gases from materials, etc. It is more likely in commercial buildings that more moisture will be present due to the lack of fresh air and the inconsistency in humidity and temperature control. Therefore commercial buildings have higher risks associated with mold and bacteria problems. Many office spaces have a number of toxic gas generating equipments such as computers, fax machines, copiers, and printers. This can significantly impact the quality of air in commercial buildings and the employees would be exposed to a variety and high concentration of contaminants for at least 8 hours per day in these buildings. Levels of carbon dioxide inside commercial buildings may also be higher due to lack of fresh outdoor air ventilation. This can possibly cause headaches and other health related problems among the workers. These effects and their details will be discussed in the IAQ and Health section of this study.

Air quality in a space is determined by the quantity of air intake and also by other factors such as air conditioning, room function, etc. Intake air in general is provided by outdoor air (OA) and in some cases by re-circulating the existing air. However, re-circulated air should be controlled in a manner, which would minimize energy use but also protect occupant health thus maintain acceptable levels for worker performance and productivity. The IAQ systems should be designed by fresh OA intake strategies whenever it is possible. The reason fresh air intake should be used is that in many cases increasing OA should ensure a sufficient amount of dilution to reduce the concentration of pollutants. Natural ventilation is one of the possible ways to bring more OA into the building as long as the energy consumption of the building is still kept at an acceptable range.

The amount of indoor air pollutants is correlated with different conditions that create the building such as the site, building materials, construction techniques, building type and use, occupant density, HVAC system, and etc. The following four elements are involved in the development of IAQ problems (USEPA 2005b):

- Source: source of contamination or discomfort indoors, outdoors, or within the mechanical systems of the building.
- HVAC: the HVAC system that is not able to control existing air contaminants, not able to control conditions that help build up contaminants.
- Pathways: one or more pollutant pathways that connect the source of contamination to the occupants of the building and a driving force to move pollutants along the pathway(s).
- Occupants: building occupants who are present in the building.

It is important to understand the role that each of the above factors may play in order to identify, prevent, and resolve IAQ problems.

Standards, Regulations and Guidelines

Currently, the Federal government in the USA does not regulate IAQ in nonindustrial settings. However, many state and local governments regulate ventilation system capacity through their building codes. Building codes have been developed in different states in order to promote healthy and safe construction practices. There also professional associations, international health associations, industry organizations, state governments, and private programs that develop recommendations or guidelines for appropriate building and equipment design and installation. These recommendations may play a mandatory role when state or local regulations integrate them in to their code and regulation policies (USEPA 2005c). There is generally a time delay between the change in new standards by professional organizations such as ASHRAE and the integration of those new standards as code requirements (USEPA 2005c).

Below are some of the major tools, standards, and regulations towards regulating IAQ in commercial buildings.

Occupational Safety and Health Administration (OSHA). The agency proposed guidelines in 1994 towards regulating IAQ in non-industrial buildings. However on December 17, 2001 OSHA withdrew its IAQ proposal and terminated the rulemaking proceedings (OSHA 1994). The proposed IAQ regulations would have help (OSHA 1994):

- Ban smoking in the workplace or required employers to provide separately ventilated smoking areas.
- Develop IAQ compliance plans in non-industrial work sites to protect workers from certain indoor air contaminants, inadequate ventilation, and sick building syndrome.
- Have periodic inspections and air testing.
- Maintain written records including documentation of reported IAQ problems.
- Control for specific contaminants such as restricting the use of chemicals and pesticides.
- Have a good maintenance program.
- Conduct employee-training programs about IAQ.

OSHA stated that integrating these regulations would have required an initial cost of $1.4 billion along with an annual cost of $8.1 billion to employers. These costs would have occurred due to increased and proper maintenance of building IAQ systems as well as the increased operating costs. OSHA also estimated an annual $15 billion savings for employers due to increased employee productivity and reduced absenteeism (OSHA 1994). Although these proposed regulations cannot yet be enforced, they at least provide guidelines for those companies, which are willing to start a high-quality IAQ management program.

The General Duty Clause of the Occupational Safety and Health Act requires employers to provide a safe and healthy working environment regardless of the proposed IAQ guidelines being in effect. It is also important to know that all workers are covered under federal OSHA. These regulations are enforced also at the state level in the 23 states including Florida.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). ASHRAE has noncompulsory ventilation standards for commercial and industrial buildings. However ASHRAE standards become mandatory when local governments adopt the standards into their local building codes. ASHRAE first published its Ventilation for Acceptable Indoor Air Quality 62.1 in 1973. ASHRAE Standard 62.1-1989 defined acceptable IAQ as the air in which there are no known contaminants at harmful concentrations as determined by authorities and with which a substantial majority of the people exposed do not express dissatisfaction (ASHRAE 1989). However, this statement could not guarantee that no unpleasant health effects would occur. ASHRAE Standard 62.1-2001 aimed to minimize the probability of adverse heath effects among building occupants. It became applicable to all occupied spaces except where other standards exist. ASHRAE Standard 62.1-2001, depending on the building function, recommended that 15 to 20 cubic feet per minute (cfm) of outdoor air should be supplied for each building occupant (ASHRAE 2001). Recently the 2001 standard has been replaced by ASHRAE 62.1-2004, which specifies outdoor air requirement for an office as 5 cfm per person plus 0.06 cfm/ft^2 (ASHRAE 2004). In this latest version of ASHRAE Standard 62.1, requirements for the office may still remain the same in cases where the occupant density varies, or is indefinite at the time of the system design. However this recent ASHRAE revision as the first major revision to the ventilation rates since 1989 appears to result in slightly lower outdoor air requirements for the office spaces (17 cfm/person). The reason for this reduction in ventilation rates should be further researched to explore whether the motive towards this change derived from the effort towards reducing equipment capacities as well as the energy usage over the life of each mechanical system.

New construction design and building operation plans should ensure that at least the minimum OA amounts recommended by ASHRAE Standard 62.1 are being followed to minimize IAQ concerns and associated discomfort and illness. Authorities may also consider writing these specifications into the construction and building operation codes.

Environmental Protection Agency (EPA). The EPA does not have any constitutional role in the enforcement of IAQ, other than issues regarding asbestos and radon. However, there has been a legislation proposal presented in Congress that requires the EPA to create a voluntary program to certify indoor air contractors, but this legislation has never passed (Conlin & Carey 2000)

The EPA has established a set of specifications for use in its own facilities to regulate the emissions from office furniture, equipment and other products. The specifications include regulations such as workstations cannot add more than 0.5 mg/m^3

of total volatile organic compounds (VOC), 0.05 ppm of formaldehyde, and 0.1 ppm total aldehydes within one week of receiving and unpacking the furniture.

Other guidelines. The American Conference of Governmental Industrial Hygienists (ACGIH) has created a manual called "Guidelines for the Assessment of Bioaerosols in the Indoor Environment". The manual provides the most important basic data on IAQ however it does not go into much detail. ACGIH also presents exposure limits for chemicals in the workplace, in a document called "Threshold Limit Values". This document is widely used in assessing whether excessive chemical exposure has occurred (ACGIH 1989). National Institute for Occupational Safety and Health (NIOSH) and National Ambient Air Quality Standards (NAAQS) also published standards to regulate specific IAQ levels.

The Air-Conditioning and Refrigeration Institute (ARI), which is an industry trade group for air-conditioning system manufacturers, has created guidelines for design, installation, and maintenance of A/C systems. These guidelines provide some of the basic information one should know on these issues.

Building codes. Building codes vary from place to place. These codes generally regulate IAQ by specifying the amount of OA that is to be supplied by the ventilation system for commercial buildings. Additionally, these codes are often very specific on construction means and methods, which may affect IAQ of a building such as carbon monoxide problems, moisture entry into the building, and re-entry of exhaust fumes. As a general rule, building codes are only enforceable during the construction and renovation processes. Code requirements may change over time as code organizations adapt to new technologies and information. However the buildings are usually not obligated to make modifications in their structure or the way they operate in order to conform to the new codes. It also a well known fact that many buildings do not operate in standards parallel with current building codes, or even with the codes they had to meet at the time of their construction (USEPA 2005c).

State laws and regulations. In the absence of any action at the national level, several states took steps on their own to improve IAQ in buildings. At least 37 out of 53 states and territories have designated an IAQ contact person due to the increase in the number of complaints about SBS, also called building-related symptoms (Slap 1995). 45 states have laws prohibiting smoking in public buildings. Also 19 states limit or restrict smoking in private workplaces acknowledging that tobacco smoke is a major indoor air pollutant (OSHA 1994). The Florida Building Code (FBC) regulates IAQ in commercial buildings in Florida. FBC is based on the 2003 editions of the International Building Code (IBC), International Mechanical Code (IMC), and International Plumbing Code (IPC). FBC mandates that:

- Ventilation units shall distribute tempered heated or cooled air to all spaces and shall supply outside air in the quantity of either the sum of all exhausts or 20 cfm per person whichever is greater.
- The quantity of all exhaust air must match the intake volume of all outside air. Supply, exhaust, and return fans shall run continuously while the building is occupied.
- Areas in which smoking is permitted shall be well vented by at least 35 cfm per person to the outside in order to minimize smoke diffusion throughout the unit.

The International Mechanical Code that is the base of ventilation regulations in FBC has the following statements regarding ventilation in section 403.3:

- No less than 15 cfm of outside air per occupant is required for waiting room areas, based on the estimated maximum occupant load of 60 per 1,000 square feet.

- No less than 20 cfm of outside air per occupant is required for office areas, based on the estimated maximum occupant load of 7 per 1000 square feet.

Although ASHRAE 62.1-2004 has changed the requirements for minimum ventilation rates in office spaces, the rates in IMC and FBC still remain to be parallel to ASHRAE 62.1-2001. However IMC is giving strong consideration for a change in the code towards synchronization with the new ASHRAE 62.1-2004 standards.

Sources of Indoor Air Pollutants

Indoor air contaminants can start building up within the building itself. Although this study assumes that OA is not a source of contamination, pollutants can be brought from outdoors as well. If the pollution sources are not controlled, IAQ problems can begin, even if the HVAC system is accurately configured and well maintained. The USEPA categorizes the sources of indoor air pollutants as given below. The examples given for each category are not intended to be a complete list (USEPA 1991).

- Sources Outside Building
    - Contaminated outdoor air
        - Pollen, dust, fungal spores
        - Industrial pollutants
        - General vehicle exhaust
    - Emissions from nearby sources
        - Exhaust from vehicles
        - Loading docks
        - Odors from dumpsters
        - Re-entrained (drawn back into the building)
    - Soil gas
        - Radon
        - Leakage from underground fuel tanks
        - Pesticides
- Equipment
    - HVAC system
        - Dust or dirt in ductwork or other components
        - Microbiological growth in drip pans,
        - Humidifiers, ductwork, coils
        - Improper use of biocides, sealants, and/or cleaning compounds
        - Improper venting of combustion
        - Refrigerant leakage

  - Non-HVAC equipment
    - Emissions from office equipment (VOCs, ozone)
    - Supplies (solvents, toners, ammonia)
    - Emissions from shops, labs, cleaning processes
    - Elevator motors and other mechanical systems
- Human Activities
  - Personal activities
    - Smoking
    - Cooking
    - Body odor
    - Cosmetic odors
  - Housekeeping activities
    - Cleaning materials and procedures
    - Emissions from stored supplies or trash
    - Use of deodorizers and fragrances
    - Airborne dust or dirt (e.g., circulated by sweeping and vacuuming)
  - Maintenance activities
    - Microorganisms in mist from improperly maintained cooling towers
    - Airborne dust or dirt
    - Pesticides from pest control activities
    - Emissions from stored supplies
- Building Components and Furnishings
  - Locations that produce or collect dust or fibers
    - Textured surfaces such as carpeting, curtains, and other textiles
    - Open shelving
    - Old or deteriorated furnishings
    - Materials containing damaged asbestos
  - Unsanitary conditions and water damage
    - Microbiological growth on soiled or water-damaged furnishings
    - Microbiological growth in areas of surface condensation
    - Standing water from clogged or poorly designed drains
    - Dry traps that allow the passage of sewer gas
  - Chemicals released from building components or furnishings
    - Volatile organic compounds or inorganic compounds
- Other Sources
  - Accidental events
    - Spills of water or other liquids
    - Microbiological growth due to flooding or to leaks
    - Fire damage (soot, PCBs from electrical equipment, odors)
  - Special use areas and mixed use buildings
    - Laboratories
    - Print shops, art rooms
    - Exercise rooms
    - Beauty salons
    - Food preparation areas

- Redecorating/remodeling/repair activities
  - Emissions from new furnishings
  - Dust and fibers from demolition
  - Odors and volatile organic and inorganic compounds.

Depending on building location and characteristics, several different types of contaminants can pollute the indoor air from the processing of organic and inorganic elements. Daniels (1998) categorizes these pollutants as:

- Gases and vapors (CO, CO_2, SO_2, O_3, radon, formaldehyde, carbon-hydrogen)
- Odors
- Aerosols (inorganic or organic particulates such as heavy metals and pollen)
- Viruses
- Bacteria and bacterial spores
- Fungi and fungal spores

ASHRAE 62.1-2004 provides a table that compares the acceptable levels of indoor air contaminants by different agencies (Table 2-2).

Table 2-2. Comparison of regulations and guidelines for acceptable contaminant levels

	Enforceable & regulatory levels		Non-enforced guidelines	
	NAAQS/EPA	OSHA	NIOSH	ACGIH
Carbon dioxide		5,000 ppm	5,000 ppm 30,000 ppm [15m]	5,000 ppm 30,000 ppm [15m]
Carbon monoxide	9 ppm 35 ppm [1 h]	50 ppm	35 ppm 200 ppm [Ceiling]	25 ppm
Formaldehyde		0.75 ppm 2 ppm [15 m]	0.016 ppm 0.1 ppm [15 min]	0.3 ppm [Ceiling]
Lead	1.5 µg/m³ [3 months]	0.05 mg/m³	0.1 mg/m³ [10 h]	0.05 mg/m³
Nitrogen dioxide	0.05 ppm [1 yr]	5 ppm [Ceiling]	1 ppm [15 m]	3 ppm 5 ppm [15 m]
Ozone	0.12 ppm [1 h] 0.08 ppm	0.01 ppm	0.1 ppm [ceiling]	0.02 ppm
Particles <2.5µm MMAD	15 µg/m³ [1 yr] 65 µg/m³ [24 h]	5 mg/m³		3 mg/m³
Particles <10µm MMAD	50 µg/m³ [1 yr] 150 µg/m³ [24 h]			10 mg/m³
Sulfur dioxide	0.03 ppm [1 h] 0.14 ppm [24 h]	5 ppm	2 ppm 5 ppm [15 m]	2 ppm 5 ppm [15 m]
Total particles		15 mg/m³		

(ASHRAE 2004).

Many of the indoor pollutants can be avoided by increased OA ventilation as long as the outdoor air is not polluted. However the building materials inside the building can be the source of contamination as well. Daniels (1998) lists the sources of the worst contaminants as follows:

- Insulating paints
- Adhesives of all kinds
- Floor coverings
- Suspended ceilings
- Jointing compounds
- Insulating materials
- Pre-fabricated materials
- Wood preservatives
- Raised floors

IAQ Control Techniques

Efforts towards improving IAQ may include different strategies depending on the nature of the problem. Henschel (1999) approaches the control techniques in three categories for reducing the concentrations of indoor air pollutants:

- Improved ventilation: Increases in the quantity of outdoor air (OA) supplied to a building, and/or improvement in the distribution and mixing of the supply air throughout the various zones in the building.

- Air cleaning: Devices mounted in the central HVAC ducting, or self-contained devices mounted in the occupied zones, to remove contaminants from the air.

- Source management: Removal of all or part of the source, replacement of the source by a lower-emitting alternative, treatment of the source to reduce emissions, relocation of the source or relocation of the occupants.

In some situations it may be difficult for the decision-makers to choose which one(s) of these options to use. When there is a localized source of contaminant Henschel (1999) suggests using a logic diagram presented in Figure 2-6 that may help select a specific IAQ control option. Henschel (1999) helps users by asking yes or no questions regarding the source of contamination and directs the users towards one of the options.

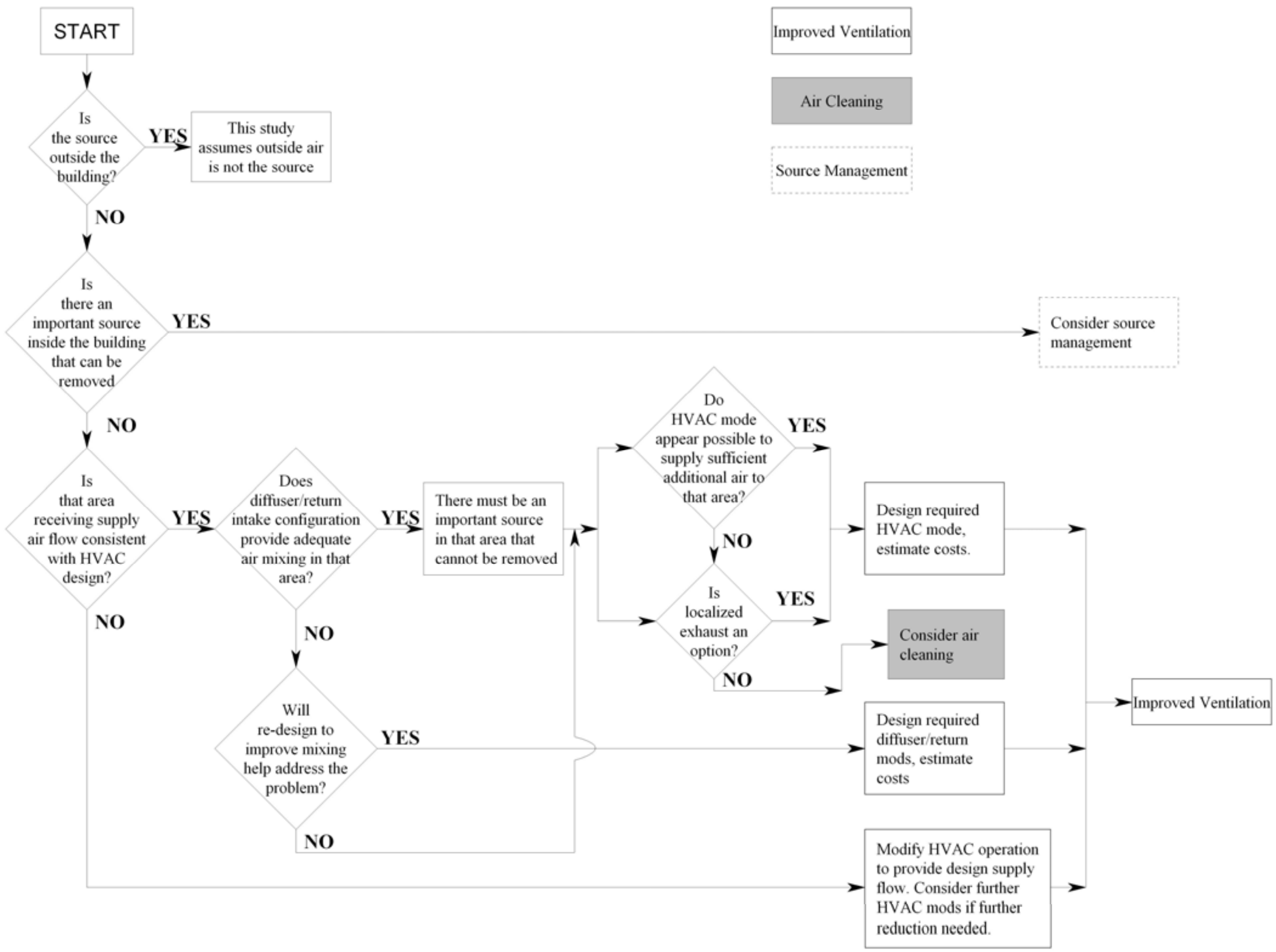

Figure 2-6. Logic diagram for selecting an IAQ control approach (Localized problem resulting from sources inside the building) (Adapted from Henschel 1999).

According to a 1987 NIOSH survey, 52 out of 100 buildings with IAQ problems suffered from mainly inadequate ventilation (Seitz 1989). According to the same study, 16% of the buildings suffered from indoor contaminants where 10% suffered from outdoor contaminants (Seitz 1989). These numbers clearly indicate that many IAQ problems derive from within the building and its indoor air management systems. Manufacturers have been working on generating more advanced products for a better ventilation technology. One example is a ventilator manufactured by Honeywell called Perfect Window ®. This ventilator is a heat recovery ventilator, which is structured as a pair of insulated ducts run to an outside wall. This ventilator recovers the moisture and heat from the outgoing air in winter times, and removes it from in-coming air in the summer[1]. Another important issue in controlling the IAQ in a commercial building is to be able to monitor IAQ constantly (Bas 1993). For this reason, manufacturers like Honeywell and some other companies have introduced more efficient and easy to use handheld CO_2 monitoring devices. Monitoring CO_2 levels is vital since studies show that at levels beyond 1,000 ppm occupants can experience health problems and general discomfort, making it more difficult for them to think and work (Bas 1993). The health effects of IAQ problems are discussed in more detail in the "IAQ and Health" section.

Ventilation: All buildings require a certain amount of OA. The outdoor air may need to be conditioned (heated or cooled) before it is distributed into the occupied space depending on the specific climate. Bringing OA into the building allows the indoor air to be exhausted or to escape by passive relief, which aids to remove indoor air contaminants. The types HVAC systems range from independent units that serve

[1] More information available online at http://www.honeywell.com/sites/acs/.

individual spaces to large central systems serving multiple zones in a building (USEPA 1991). The components of a typical HVAC system are given in Figure 2-7, which illustrates the general relationship between many components of an HVAC system. However it is important to note that many variations can be possible.

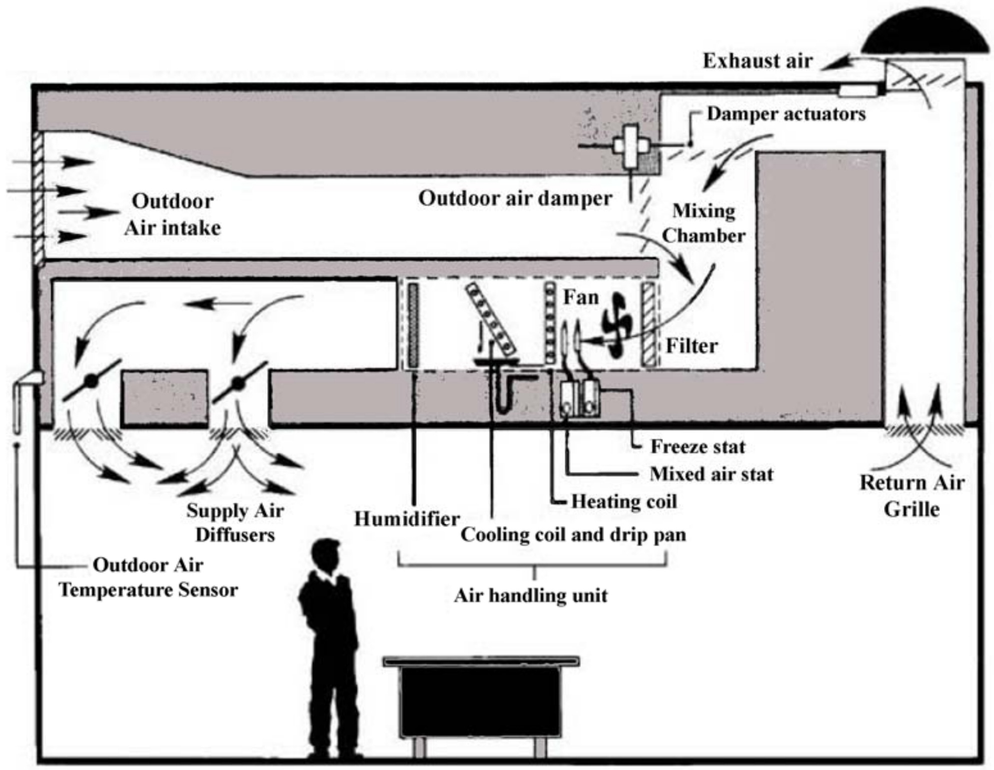

Figure 2-7. Typical HVAC system components (USEPA 1991).

The EPA categorizes different HVAC systems as follows (USEPA 1991):

- Single zone systems
- Multiple zone systems

According to the EPA, a single air-handling unit can serve more than one building area if the areas served have similar HVAC requirements. This would also be possible if the control system can compensate for differences in HVAC needs among the served spaces. Areas regulated by a common control are referred to as zones (USEPA 1991).

Multiple zone systems can provide each zone with air at different temperatures by heating or cooling the air stream in each zone. Alternative design strategies involve delivering air at a constant temperature while varying the volume of airflow, or modulating room temperature with a supplementary system (USEPA 1991). Constant volume systems, on the other hand, generally deliver constant amounts of air to each space. These systems often operate with a fixed minimum percentage of OA or with an “air economizer” feature (USEPA 1991).

Rather than by changing the air temperature variable air volume (VAV) systems maintain thermal comfort by changing the amount of heated or cooled air delivered to each space. However, many VAV systems also have requirements depending on the characteristics of the weather, such as resetting the temperature of the delivery air on a seasonal basis. Underventilation often happens if the system is not arranged to introduce at least a minimum quantity of OA as the VAV system throttles back from full airflow, or if the supply air temperature is set too low for the loads in the zone (USEPA 1991). Overcooling or overheating can also occur in a zone if the system is not adjusted to according to the cooling or heating load (USEPA 1991).

Most commercial buildings use VAV systems for ventilation (Public Interest Energy Program [PIER] 2005). However the main reasons VAV systems are used in commercial buildings derive from the financial constraints. In 1970s before the energy crisis, a different system was used in order to bring constant air volume into the building spaces however the air was at variable temperatures. This system brought substantial quantities of OA to the building. However while energy efficiency has become a more important concept, this system became less popular due to its expensive operating (energy) costs. The VAV system on the other hand brings in only the amount of air that is necessary and re-circulates a building's already conditioned air at various quantities. Although a VAV system saves energy, re-circulating air thus increasing the amount of air contaminants is the price that it pays for those savings. This is one of the good examples of the contradiction between IAQ and energy efficiency. The true costs of IAQ issues are discussed in more detail in the "IAQ and True Costs" section.

Air cleaning: Air cleaning is one of the IAQ control techniques. The air filter is a product that has been around for many years and still is one of the most crucial parts of a building's IAQ management system. There are currently many different types of air filters in the market that provide different protections and methods for different types of contaminants. Many buildings use poor performance of 89% filters, which are used to protect the HVAC system but not the occupants of the buildings. According to ASHRAE (1999), the performance of these filters on filtering dust and similar contaminants is only 7 to 12% effective. Burgess et al. (2004) categorize the filters into three categories:

- Fibrous and Granular (Media) Filters: Remove large particles before a second stage collector of greater efficiency and filters the dusts that cannot be easily collected by other collectors.
- High Efficiency Particle Air (HEPA) Filters: These filters are used extremely high particle collection is required such as in hospital operating rooms. This type of cleaners are not cleanable and have low dust capacity which limits their use to gas streams with low dust loading.
- Fabric Filters: These are the most common type of filters in the industrial environments. They must be eventually cleaned.

Another method for cleaning air is electrostatic precipitators. This type of cleaner collects particles by electromagnetic action. These cleaners have the advantage of less maintenance but can pose a different threat due to ozone production (Stein & Reynolds 1992).

The most challenging part of the air-cleaning problem is the selection of the type of filter or the cleaning device to be used. Different contaminants may require different types of air-cleaning devices. Thus the selection of the device demands the knowledge of the type of contaminants to be removed. Burgess et al. (2004) summarizes the basic information about the collection device in Table 2-3.

Table 2-3. Collection device characteristics.

Collection Device Type	**Types of Contaminants**	**Initial Cost**	**Operating Cost**	**Durability**
Filters				
Industrial	All dry powder	Moderate	Moderate	Good
HEPA	Pre-cleaned air	Moderate	High	Fair to Poor
Electrostatic Precipitators				
Single Stage	Flyash, H_2SO_4	High	Low	Fair
Two Stage	Welding Fume	Moderate	Low	Good
Wet Scrubbers				
Venturi Scrubber	Chemical Fumes	Low	High	Good
Wetted Cyclone	Crushing, grinding	Moderate	Moderate	Good

(Burgess et al. 2004).

Contaminant source management: One of the control techniques when dealing with air contaminants is to manage the contaminant source. This may involve several approaches (USEPA 1993):

- Source removal: This strategy involves identifying a source of contamination and relocating it therefore it will not affect the IAQ. Examples include not keeping garbage in spaces with HVAC equipment, and replacing moldy materials.
- Source substitution: This strategy involves identifying a material likely to impact the IAQ of the building and selecting a similar but less toxic substitute. For example choosing latex paint instead of oil based paint.
- Source encapsulation: Encapsulation involves creating a barrier around the source and isolating it from other areas of the building so that there is no recirculation of air from the contaminated area into occupied spaces. This may include isolating a division of the building with polyethylene sheeting as well as isolating the space from the general ventilation system by blocking return air grilles.

IAQ and Health

Following the energy efficiency trend in 1970s, many concerns about the occupants' health in buildings started to arise due to low indoor air quality of commercial buildings in 1980s. Government agencies, university groups, and private consulting firms started to receive an increasing number of requests to investigate health complaints specifically in office spaces. This led to a whole new syndrome, which is called Sick Building Syndrome (SBS). SBS is defined as a group of symptoms that are two- to three-fold more common in those who work in large, energy-efficient buildings, associated with an increased frequency of headaches, lethargy, and dry skin. Clinical manifestations include hypersensitivity pneumonitis (alveolitis, extrinsic allergic), allergic rhinitis (rhinitis, allergic, perennial), asthma, infections, skin eruptions, and mucous membrane irritation syndromes (Segen 1992). A 1984 World Health Organization Committee report suggested that up to 30 percent of new and remodeled buildings worldwide may be the subject of excessive complaints related to poor indoor air quality (IAQ) (American Lung Association [ALA] 2000). Although the most common site of injury by airborne pollutants is the lung, acute effects may also include non-respiratory signs and symptoms, which may depend on the toxicological characteristics of the contaminant substances (ALA et al. 1994).

Although many studies prove that indoor air contaminants can have various health affects on the occupants, there is still an on-going argument on the validity of several studies such as the health affects of mold. Along with many studies indicating a relationship between the several symptoms of occupants and allergic pollutants such as mold, there are also some studies claiming that this has not been scientifically proven. However it is already acknowledged by the scientific community that there are many other indoor air pollutants that can cause low to severe health problems. According to Gamble et al. (1986), buildings where allergies are suspected present a difficult diagnostic challenge. Gamble et al (1986) believe that only a few people may be affected, and an allergic diagnosis may be overlooked when building occupants have complaints about insufficient outdoor air supply, thermal discomfort, or cigarette smoke. Allergic symptoms can be relatively mild and nonspecific, and may have disappeared by the time a worker visits a physician's office. Some of the findings of Gamble et al. (1986) in a study where they evaluated a 9-story office building and compared the results to the outside air provided per person are given in Table 2-4. According to Table 2-4, the SBS symptoms as well as the thermal discomfort reaches to the highest rates, on the 2nd and 3rd floors where no outside air (OA) was provided for 175 workers.

Table 2-4. Complaints on floors with outside air provided per person.

n=Number of occupants	Floors 8-9 n=56	Floors B-1 N=42	Floors 6-7 n=155	Floors 4-5 n=131	Floors 2-3 n=175
Chronic Bronchitis Symptoms	12%	5%	6%	6%	7%
3 or more SBS symptoms	26%	26%	15%	20%	36%
Sinus Symptoms	40%	36%	25%	31%	46%
Thermal Discomfort	76%	84%	73%	67%	89%
OA (cfm/person)	**126**	**72**	**28**	**14**	**0**

(Gamble et al. 1986)

IAQ and True Costs

Indoor air quality has financial consequences as well as its health affects. The cost of an IAQ management option is associated with two different types of costs. These costs can be categorized as hard and soft costs.

"Hard costs" in the building industry is a term for the amount that includes total land and construction costs (Environmental Law Institute [ELI] 2005). In addition hard costs associated with indoor air quality would be the life cycle costs (LCC) of managing the indoor air quality in a building. LCC of a specific system should include the owning and the operating costs. Owning costs of a system include (Rizzi 1980):

- Initial cost of the system
- Capital recovery
- Interest and return on the investment
- Property taxes
- Insurance

Operating costs of a system include the following costs:

- Fuel and energy
- Maintenance allowances
- Labor for operation
- Water costs
- Water treatment cost

Rizzi (1980) explains how LCC analysis should be conducted for any heating, cooling, and/or ventilating systems. Rizzi (1980) states that when studying owning and operating costs of a system, the period covering the lifetime of the system should be 20 years. Rizzi (1980) also provides a methodology to calculate the owning and operating costs of an HVAC system.

Soft costs in the building industry are known as architectural, engineering, and legal fees as differentiated from land or construction costs. However soft costs in general represent any costs that are not related to the actual land and construction costs. Consequently soft costs of a specific IAQ management option include costs associated with productivity, health, insurance fees, litigation, etc. Unfortunately many investors or building owners usually do not see major incentives in considering the soft costs associated with poor or good IAQ.

One of the most important soft costs of IAQ is productivity. Productivity and its financial consequences become a more important issue in commercial buildings. Worker salaries constitute the major cost of operating a commercial building, generally estimated at over 90% of the total operating cost, so that even a small increase in employee productivity can substantially increase a company's financial return (AIASF 2001). According to the study conducted by the US Department of Energy (USDOE) and Lawrence Berkeley National Labs in 1997, the costs of lower productivity for the US economy ranged from $12 to $125 billion per year (Damiano 2005).

Another survey conducted by Reel Grobman & Associates (2005) among interior design and facility planning decision-makers indicates that the respondents feel that overcrowding, followed by IEQ complaints have the greatest negative impact on employee productivity (Damiano 2001). According to the report, 40% of the respondents said that overcrowding had the greatest negative effect, while 31% cited noise. Poor indoor air quality (19%) and poor lighting (10%) were among other factors cited by those surveyed. 74% of the respondents said they felt that workplace environmental conditions were critical to employee productivity, while the rest said those conditions had some impact (Reel Grobman & Associates 2005).

Very often, building owners or managers propose cost-saving measures without considering the added costs due to lowered performance and productivity. An example of this occurred when the Building Owners and Managers Association (BOMA) presented to members about its success in beating back two provisions in ASHRAE Standard 62.1.

The article was published in BOMA's member newsletter “SkyLines” (Bas 1993). The two provisions that were discussed by BOMA would have required renovation areas to be secluded from the rest of the building by using negative pressure and mandated a 48-hour period for purging contaminants from those areas following construction (Bas 1993). BOMA stated that these requirements were hard to implement and also would have cost building owners about \$0.10 per ft² for the first provision and \$0.01 per ft² for the second. According to the BOMA analysis, rejecting those provisions would save a building owner approximately \$11,000 for a 100,000-ft² building[2]. However, BOMA's analysis did not take the loss of productivity (soft cost) into consideration. This soft cost would increase if pollutants from construction activities were drawn into the occupied space of the building. This has been a factor in numerous IEQ cases and was the principal cause of the problems 10 years ago at the headquarters of the EPA (Bas 1993). This type of situation may also result in people being injured and thus may result in multiple lawsuits. But according to Bas (1993) just a small positive effect on productivity in a typical 100,000 ft² commercial building could save more than significant amounts of money. If we consider a building with an occupant density of 5 persons per 1,000 ft² this would result in a total of 500 people in the building. If an average annual salary of \$30,000 were assumed for each person in that building, this would be a total biweekly salary of \$576,923. If construction activities cause IEQ degradation thus the productivity decreases by 0.5%, this would be result in a loss of \$2,884 every two weeks that the situation existed.

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[2] More information can be found online at http://www.boma.org/.

Wargocki et al. (2000) conducted a study in order to evaluate the correlation between IAQ and productivity in an office space. In order to define the performance index Wargocki et al. (2000) defined four major tasks for the subjects of the study. The subjects throughout different exposures of IAQ, were asked to perform simulated office work consisting of four different tasks: text typing, addition, proofreading and creative thinking.

Wargocki et al. (2000) calculated and normalized the average number of characters typed per minute, average number of correctly completed arithmetical calculations (units) per hour, and average number of lines that were correctly proof-read per minute. Performance was measured in three independent studies with different subjects and could have been influenced by group differences in the subjects' experience, intellectual skills, and level of practice. The normalization factors were the ratios between the mean of performance at all air quality levels in all three studies to the means of performance at all air quality levels in each individual study.

To estimate the overall performance of simulated office work, the Wargocki (2000) calculated a performance index by dividing normalized performance at a specific level of air quality by the mean of normalized performance of a specific task at all air quality levels.

The findings of Wargocki's study clearly display the importance of IAQ in office buildings. Figure 2-8 shows an overall summary of the results of the study and displays how productivity index increases when the ventilation rate increases and the pollution load decreases.

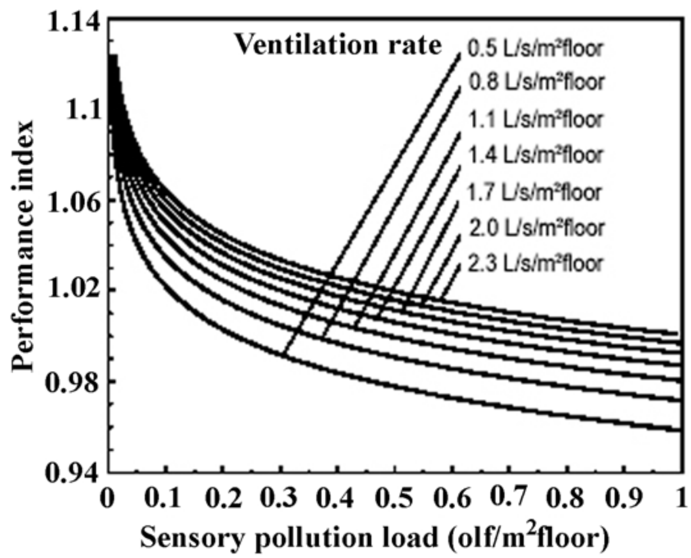

Figure 2-8.Overall performance of simulated office work as a function of sensory pollution load and ventilation rate (outdoor air) (Wargocki 2000).

One of the other soft costs associated with IAQ is the economic loss created by health problems. In OSHA's effort to establish ventilation rules for nonindustrial workers, they used the following justifications, in part[3]:

> The Agency estimates that the excess risk of developing the type of non-migraine headache, which may need medical attention or restrict activity, which has been associated with poor indoor air quality, is 57 per 1,000 exposed employees. In addition the excess risk of developing upper respiratory symptoms, which are severe enough to require medical attention or restrict activity, is estimated to be 85 per 1,000 exposed employees. These numbers are extrapolated from actual field studies and therefore show the magnitude of the problem at present (OSHA 1994, p. 63).

This amounts to an estimated average excess risk of lost work-time or diminished productivity for approximately 6% of workforce, on any given day, in any facility that exhibits poor indoor air quality (Damiano 2001). Additionally, approximately 9% are estimated to be at excess risk and would probably incur lost time due to upper respiratory sickness (Damiano 2001). In the same Lawrence Berkley/USDOE study mentioned

[3] On December 17, 2001 OSHA withdrew its indoor air quality proposal and terminated the rulemaking proceedings, see Federal Register 66:64946.

earlier, it is estimated that the direct cost to the U.S. economy due to increased allergies, asthma and SBS symptoms were $7 to $23 billion per year (Damiano 2005). Damiano (2001) claims that a large portion of these costs are estimated to be in the form of workmen's compensation claims, health care insurance premiums and direct health care costs mostly borne by the claimants' employers.

Milton et al. (2000) conducted one of the studies that focus on how employers need to strike a balance between the energy costs of providing higher ventilation rates and the health benefits from higher ventilation rates. The researchers of this study analyzed the sick leave records of 3720 hourly workers for the calendar year of 1994. They used a statistical technique called Poisson regression to analyze the relationship of sick leave with ventilation rate category. The results generated by this study, when the ventilation rate is increased by 25-cfm per person, are given in Table 2-5. The results indicate that by increasing the ventilation rate by 25-cfm up to 50-cfm/person employers can save up to $400 per employee assuming $40 hourly compensation rate.

Table 2-5. Potential economic costs and benefits of increasing ventilation rate by 25 cfm per Person.

Criteria	Annual savings per employee
Energy Costs 25 cfm/ workers x $3.22/cfm/year	$80
Sick Leave Costs Sick Leave avoided (1.50 days per workers)	-$480
Total Savings	-$400

(Kumar & Fisk 2002)

IAQ related litigation cases are increasing along with the awareness of the effects of poor IAQ in buildings. One of the buildings that exhibited the classic symptoms of SBS was the DuPage County Courthouse in Wheaton, IL (Bas 1993). Bas (1993) reports that one day in 1992, 25 employees were rushed to the hospital, suffering from shortness of breath, headaches, and nausea. The four-story, $50 million building was closed temporarily, affecting some 700 employees. The main problem with the courthouse as it is with many other buildings with SBS, was inadequate ventilation. The county in this case sought $3 million in damages for the design, engineering, and construction of the building (Bas 1993). Another sick building was the Polk County Courthouse in Central Florida. The building was opened in the summer of 1987 at a cost of $37 million. Due to IAQ problems, the building was shut down, and the remediation of the building realized at a cost of $26 million (Bas 1993).

Public attention and the litigation cases about IAQ issues have been continuously increasing. The major reason for this increase is due to the growing belief among employees that the employers owe them a safe and healthy working environment. Many of the employees believe there is a higher possibility of winning this type of litigation cases when there is a third responsible party involved. This may include anybody that is involved in the design, construction or operation of the building. This list may include HVAC engineers, contractors, subcontractors, property managers, building owners, and designers as the major targets in IAQ related liability cases.

Optimization of IAQ

The continuous demand for sustainable and higher performance buildings has resulted in the development of more sophisticated and efficient technologies. The main goal of this development is to create “better” buildings that would satisfy many different performance criteria. Papamichael (1998) describes the decision-making process in relation to performance prediction and evaluation for design options in high performance buildings in Figure 2-9. According to Figure 2-9 building design is the iterative generation of alternative courses of actions in the form of technological combinations and the prediction and evaluation of their performance. According to Papamichael (1998), building performance is considered and communicated through the use of performance indices, or parameters, based on the values of which designers judge appropriateness. Some of these might include measures such as aesthetics, economics, and comfort.

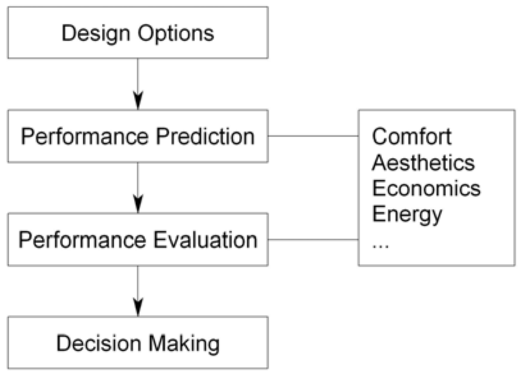

Figure 2-9. Building design decisions require performance prediction and evaluation with respect to multiple performance considerations (Papamichael 1998).

Atthajariyakul and Leephakpreeda (2004) conducted a study that presents another example of parameter generation to measure Indoor Environmental Quality. They use well-known parameter indices to quantify the degree of thermal comfort and air quality for human and energy usage in an HVAC system. These parameter indices are directly or indirectly defined in terms of time-dependent variables of the indoor-air condition in building. An example of parameter generation by the use of Predicted Mean Vote (PMV) and its indication as a thermal sensation index is given in Figure 2-10.

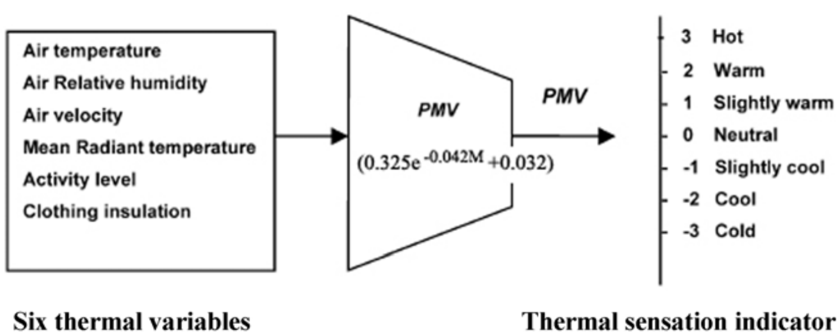

Figure 2-10. PMV and thermal sensation (Atthajariyakul & Leephakpreeda 2004).

There are several studies that concentrated on optimizing IEQ. Some of these studies have concentrated on multi-criteria optimization by taking many concepts of IEQ into consideration. The most studied items in the optimization studies are building shape, thermal comfort, IAQ, and aesthetics. Al-Homoud (1997) used the direct search optimization technique in order to optimize the building envelope. His study consisted 14 variables and used an external simulation program to perform the optimization. Nielsen (2002) developed an optimization system by using Matlab to find the optimum combination of the geometry and mix of building components to maximize building performance. Caldas and Norford (2002) used a genetic algorithm (GA)[4] as response generator in optimal sizing of windows for optimal heating, cooling and lighting performance. Additional examples of building envelope optimization for thermal comfort and energy savings can be reached at Marks (1997). Bouchlaghem (2000) also presents examples for optimization studies developed for environmental technology in buildings. Wright (2002) presents an example for HVAC system optimization by using GA to examine the trade-offs between HVAC system costs and thermal discomfort. Gustafsson (2000) also studied optimization of HVAC systems, by mixed integer linear programming. Linear programming (LP) has been used to solve optimization problems in industries as diverse as banking, education, forestry, and construction scheduling and planning. LP has been used as a tool to determine the optimal allocation of limited resources in linear and deterministic problems. In a survey of Fortune 500 firms, 85% of those responded said that they had used linear programming (Winston 1993). Kumar et

[4] A genetic algorithm is a search technique used in computer science to find approximate solutions to optimization and search problems. Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology (Wikipedia 2006b).

al. (2003) have also studied various successful applications of the use of linear programming in construction projects.

One of the most challenging issues in IAQ modeling derives from energy efficiency constraints. One of the reasons for this is because the HVAC systems are subject to time varying boundary conditions, and that the system operation must be optimized at each boundary condition. Wright et al. (2002) in their work on optimizing HVAC system design, optimized the model for 9 boundary conditions that represent a period during the early morning, midday, and afternoon, in each of three seasons: winter, fall/spring, and summer. Wright et al. (2002) in their study seeks to minimize the annual energy use of the system. However they take the “annual energy use” as a weighted average of the system capacity at each of the 9 operating conditions, the weights being applied in accordance with the relative proportion of the prevailing climatic conditions. Wright et al. (2002) configure the decision variables in a way to investigate the pay-off between the HVAC system energy cost and the occupant thermal comfort. Wright et al. (2002) also gives interesting examples for different pay-off situations such as the one between capital cost of a system and the operating cost of a system. Figure 2-11 is an illustration of the function between these different costs.

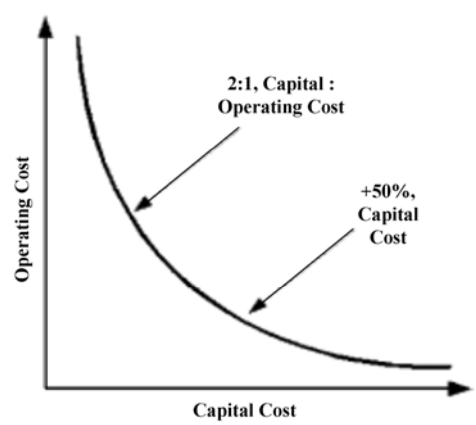

Figure 2-11. Example pay-off characteristic (Wright et al.2002).

Wright et al. (2002) group the decision variables under two categories: system operation and size of the HVAC system. Wright et al. (2002) specify three optimization criteria:

- The operating cost of the HVAC system for the design days
- The maximum thermal discomfort during occupancy on each design day
- The infeasibility objective

The constraints in the study can be summarized as follows:

- Restriction on design of the coils
- Performance of the supply fan
- Requirements to ensure that the system has sufficient capacity
- Air velocity to limit noise
- Water velocity limit to prevent excessive pipe erosion
- Fan speed
- Volume flow rate through the fan
- HVAC capacity to meet required supply air temperature and flow rate

Although there are some successful examples of optimization for different aspects of indoor air quality, none of these studies look at the problem from the building owner and manager point of view. Thus these studies generally ignore the soft costs associated with the various values of decision variables. Many of the previous studies are constructed for optimization of system component design thus they rely on mostly technical engineering variables and constraints. This research approaches the problem as a prescreening of the sustainable management problem and simplifies the engineering calculations since the goal is not to find the optimum component design but to find the optimum comparison of alternative values in relation to their performance change and associated cost per change in air quality.

Review of Literature Summary

The body of knowledge for IAQ has been expanding tremendously since the1980s. Many studies have been conducted. However there are still gaps in our knowledge of

IAQ in buildings. European Commission (1996) listed a comprehensive list of recommendations for the researchers and the industry in order to improve indoor quality and energy efficiency of buildings. Some of the areas that require further research could be listed as follows:

- Contaminants and sources: Identify contaminants and occurring occupant exposure, safe and acceptable emissions, safe and acceptable levels of contaminants in buildings, contaminant sources, and contaminant source management.
- Building assessment: Assess the built environment from energy, indoor air quality, and climate aspects.
- Building systems: Identify cost-effective low energy systems for providing high quality IEQ levels.
- Performance measurement: Identify simple, and effective methods that include both energy efficiency and IAQ measures, for predicting the performance of buildings.
- Operation and maintenance of buildings: Identify the effectiveness of means and methods of assessing and controlling existing buildings, including measurement techniques to quantify the levels of IAQ.
- Changes to building design and operation: Identify the problems with IAQ caused by the force to reduce energy consumption, and identify strong optimization solutions.
- Experimental data: Generate data that can be used for statistical correlation analyses for factors affecting IAQ, as well as data quantifying productivity in relation to air cleaning and ventilation rates.

CHAPTER 3
METHODOLOGY

Introduction

The objective of this research is to develop a decision model for optimizing the control of indoor air pollutants in commercial buildings in Florida. This chapter briefly describes the nature of the research and the specific methods and concepts that satisfy the research goals. After exploring the research questions, in the research design section, the scope of the research and its main steps are discussed. The research methodology section briefly discusses the use of linear programming as a tool to solve the optimization problem. This chapter also clarifies the target populations that are the subject of research or who may benefit from the decision model. The details of the steps taken in the methodology of this research and the detailed configuration of the research model and parameters are given in Chapter 4.

Research Questions

The major research question to be investigated in this dissertation is given below:

- Can an optimization model be developed to select the optimal IAQ measures in commercial buildings in Florida to meet or exceed the standards required by code?

This study also explores the answers to the following question:

- What are the decision criteria for building owners and managers when choosing a specific indoor air management option?

Research Design

The summary of the scope of the research and the outline of the dissertation is given in Figure 3-1.

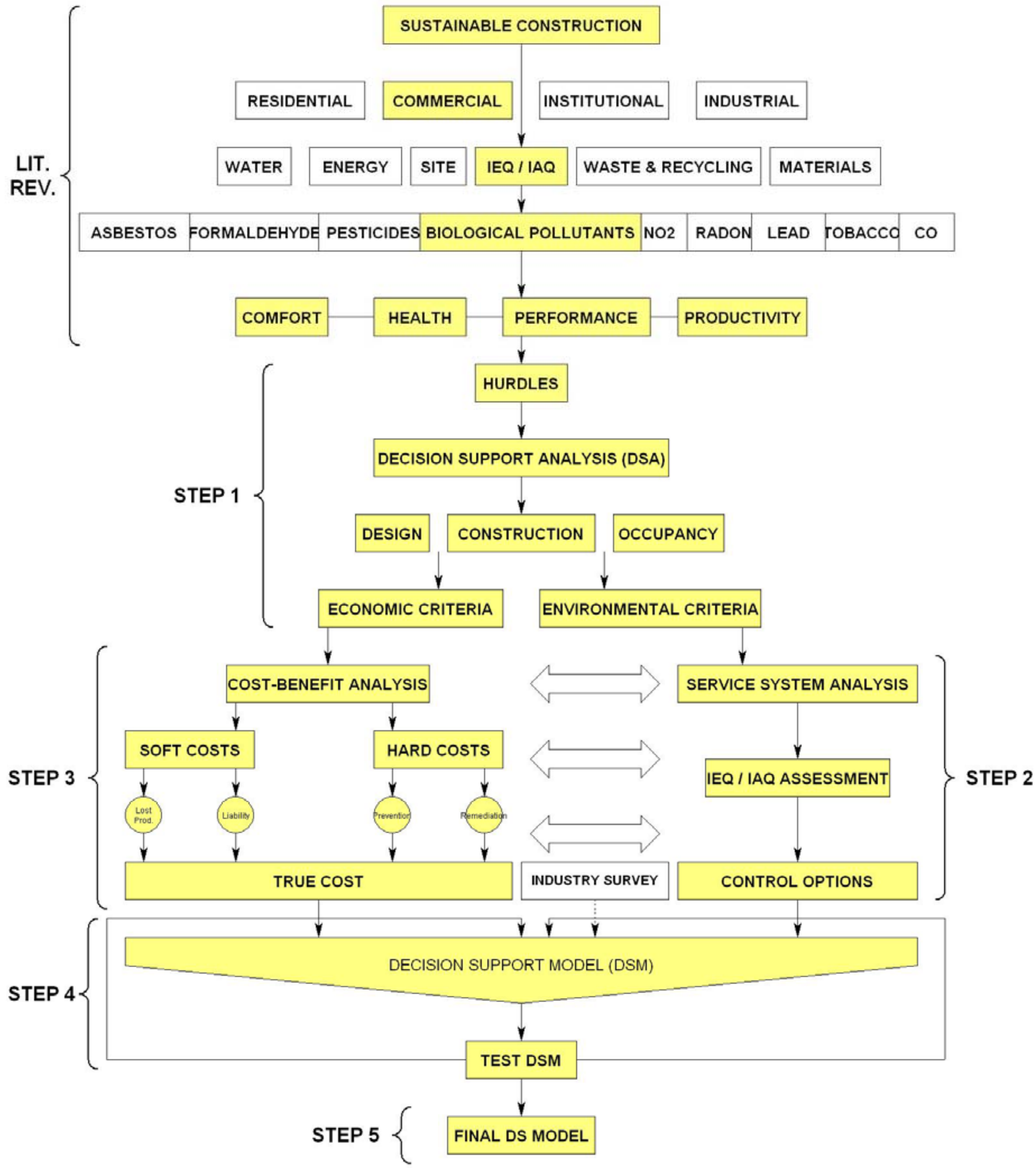

Figure 3-1. Research design.

The steps that are illustrated in Figure 3-1 are explained below in more detail.

Step 1. Identify the indoor-air-pollutant-related IAQ hurdles of the building industry.

One of the hurdles that the building industry is facing is to manage the quality of indoor air. This problem occurs due to financial constraints and the trade-off between better indoor air quality and energy efficiency of a building. Some of the consequences of a better IAQ are healthy, clean, and sustainable air and air systems. The IAQ related cautions should be considered from the design of the project through the construction, and the postconstruction (operation) phases of the building. Industry is facing several problems on each of these phases. This dissertation conducts a broad literature search in order to examine these hurdles under two categories:

- Identify the indoor air pollutant threats for the buildings and its occupants.
- Identify the problems regarding the current indoor air quality technologies in commercial buildings.

This research first identifies the above problems of the building industry by using qualitative research through broad literature review (See Chapter 2). Many studies present the problems regarding the current IAQ technologies in the buildings. There are also studies that show the financial consequences of poor IAQ in buildings. This study defines these problems in terms of their soft and hard financial consequences.

One of the alternative methodologies for this step of the research could be conducting a regional survey among the subjects of the research in Florida. Building Owners and Managers Association (BOMA) would be an adequate source of subjects. This would help clarify the specific IAQ related technical and qualitative problems of the industry.

Step 2. Evaluate the types of IAQ options to control indoor air quality and the factors that affect IAQ in commercial buildings.

Types of IAQ control techniques and the factors that affect the IAQ in commercial buildings have already been described in Chapter 2. This step of the research ensures that the model to be created includes a solution that takes all the factors affecting IAQ into account. The comparison of the available technologies with the optimal solutions in the model enables the researcher to make suggestions towards systems that may not exist but would be a better option than any existing systems. The types of indoor air quality control techniques will include:

- Improved ventilation
- Air cleaning

This study evaluates the above options in terms of their technology, physical effects on IAQ, and the operational factors such as the policies and regulations. This study includes the national ASHRAE Standard 62.1-2001 for acceptable indoor ventilation as a lower constraint assuming that the Florida Building Code mandates all buildings to meet or exceed values mentioned in these standards.

Step 3. Evaluate the true costs of indoor air quality control techniques by combining LCC analysis, and soft and hard costs.

Combining the lifecycle costs, other hard costs, and soft costs generates the true costs of indoor air quality control. From an engineering perspective, LCC are all costs from project inception to disposal of equipment. The LCC analysis includes the ownership and operating costs and uses common value engineering procedures such as described in Isola (1997). However the users of the model will be able to choose the values such as discount and inflation rates.

The required cost parameters and the methodology to help users carry out the cost analysis is provided by an EPA study “A Preliminary Methodology for Evaluating Cost-Effectiveness of Alternative Indoor Air Quality Approaches” by Henschel (1999), and by the actual supplier quotes for the system components. The analysis includes determination of two different types of costs:

- Soft-costs
- Hard costs

There are three areas of soft costs that engineers and their clients need to consider in the design for acceptable IAQ in any building project: the impact on productivity of the occupants, positive or negative; effects on health of the occupants, positive or negative; and the risk of litigation and/or legal liability that may result from any negative impacts. The most compelling category out of three areas is the one associated with worker productivity. In order to calculate the soft costs, this research uses the results of a study by Wargocki et al. (2000). Wargocki et al. (2000) use the amount of outdoor air as the only independent variable in a controlled office environment, in order to determine the function between IAQ and productivity. This function provides a performance index associated with different IAQ conditions. The performance index is used in this research to calculate the savings that may potentially be generated by increasing the amount of work output over the working hours. Soft costs associated with health and litigation, are kept out of the model due to their stochastic nature.

Step 4. Combine the true costs, and the control options, to define and generate a decision model.

Chapter 4 defines the details of the optimization model. However the procedures for building the decision model follows the following five-step procedure:

- Formulate the problem.

Defining the problem includes specifying the objectives and the parts of the system that must be studied before the problem can be solved. In this research the objective is to minimize the true costs of an IAQ control option by increasing the amount of OA, and the air cleaned, inside a given commercial building.

- Observe the system.

In this phase the research is oriented towards the collection of data that would affect the problem determined in the previous section. The data to be collected include: how much an increase in productivity saves the owner in costs; how much an increase in the supplied air amount would increase productivity; how much hard costs are associated with a unit increase in the amount of air or the treatment of the air; how much energy cost occurs by an increase in the unit of outdoor air supply or recirculation air; etc.

- Formulate a mathematical model of the problem.

In this phase a mathematical model of the problem will be developed (Figure 3-2). The model developed in this research includes:

  - Decision Variables
  - Objective Function
  - Constraints

Figure 3-2 illustrates a preliminary illustration of a possible linear modeling example with only two decision variables. It is shown in Figure 3-2, how the value of the objective function of a model might change while changing the values for the decision variables (X1 and X2). According to Figure 3-2, the optimum result of the model would fall on to one of the extreme points around the feasible region that is defined by different constraints.

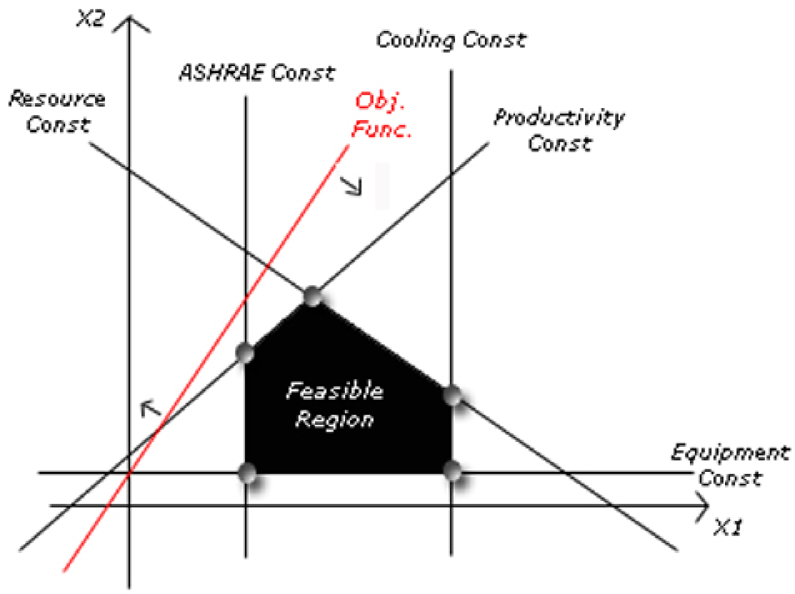

Figure 3-2. Example illustration for the proposed LP model.

- Verify and use the model for prediction.

At this step the goal is to determine if the model developed in the third step is an accurate representation of the real world. In order to manage this, the model is compared to the current situation in a test commercial building in Florida. This process also includes the information from sensitivity analysis.

- Select a suitable alternative.

The available alternative IAQ control options are compared to each other on the basis of the developed model in order to choose the optimum system(s). A possibility is that the best alternative may not exist. However the model helps to choose the feasible alternatives even if a best alternative does not exist.

Step 5. Present the results and conclusions.

In this step, the model that is generated in Step 4 will be presented along with the possible results for different cases. This step will also include the recommendations for optimum alternatives as well as the future work for further developing the model. The results will include the sensitivity analysis in order to determine the range of validity of the optimization and the managerial implications.

Research Methodology

This research uses a quantitative methodology that combines LCC analysis with the soft cost analysis in order to optimize the true costs of indoor air quality control technologies and strategies in buildings. However, this research also uses qualitative literature review techniques to explore the criteria when the decision makers of the building industry are choosing specific IAQ control options.

This research utilizes the methodology of operations research, which is a quantitative methodology that offers considerable assistance to the building owners and managers in their quest for optimal solutions. With the help of mathematical programming this research provides the owners or managers increased ability to analyze their IAQ problems and generate solutions in a structured manner. Linear programming (LP) is used as a preliminary option for this research.

There are basically two assumptions implicit in an LP model. One is that any relationship of two or more variables must satisfy the characteristics of a linear relationship. Second, the model uses deterministic assumptions meaning that the variances in the values are not significant enough to warrant a nondeterministic approach. In summary, an LP model may be considered as a potential tool in determining the optimal allocation of limited resources if and only if the situation under consideration adequately satisfies the linear and deterministic assumptions. In a real world situation some of the constraints and variables in a decision process may have nonlinear relationships such as the relationship between productivity and IAQ. This research simplifies these relationships into a linear level by using piece-wise linear approximations[5].

In order to solve the model there are many software available. Excel Solver ® is one of those alternatives and is used to solve the model created in this research.

Population

There are two target groups that can use the results of this research. One of these is the building owners and managers. The reason this research is oriented towards the building owners and managers, is that owners and managers are the investors in a building's IAQ system. For this reason an important factor is to utilize their perspective to develop the decision model. The second group includes almost everyone that is involved in the creation of a building. This includes architects, engineers, and contractors. This group is the one that will benefit most from the results of this research. Since many times owners leave the decisions to their representatives, this study will be useful for experts that hold the decision power on investing in the IAQ of a building.

Summary of Methodology

The summary of the proposed methodology is illustrated in Figure 3-3 parallel and compared to Simon's decision-making process (Simon 1960). The proposed methodology involves similarities to Simon's decision-modeling process. In this research, well-known intelligence, design, choice, and implementation phases introduced by Simon (1960) are transformed into research, speculation, decision, and implementation phases. In the research phase, the options for different indoor air quality levels will be evaluated. This phase also covers the research on hurdles of the industry regarding IAQ and the

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[5] Chapter 4 provides a broad description of piece-wise linear approximation.

generation of the major parameters of the model. In the speculation phase, the optimization model will be configured in terms of objective function, decision variables, and constraints. The decision phase mainly covers the solution to the model, and the implementation phase is the output of specific recommendations by using the results.

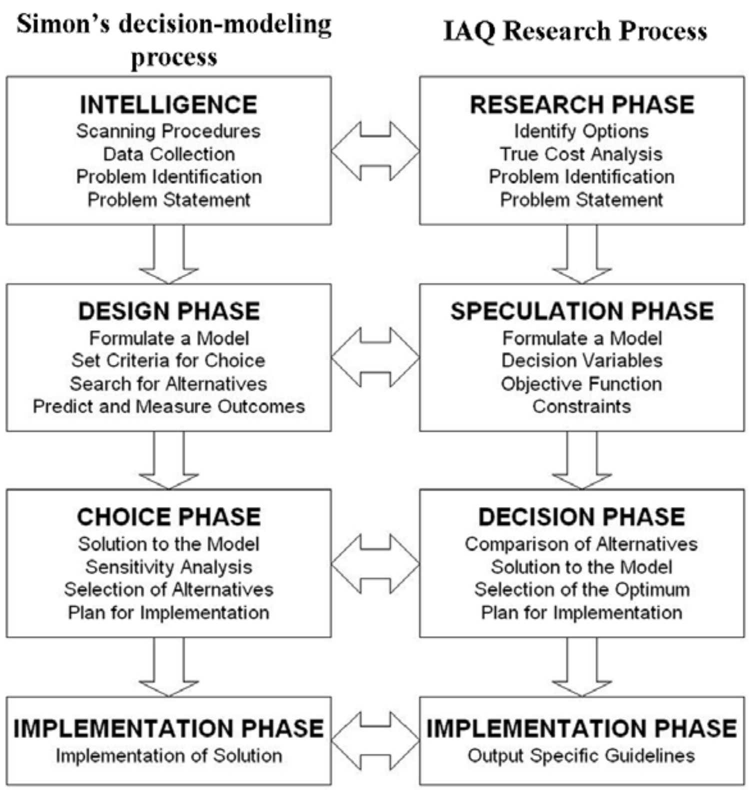


Figure 3-3. Summary of methodology in comparison to Simon's decision modeling process. (Simon 1960)

CHAPTER 4
DEFINING PARAMETERS AND THE OPTIMIZATION MODEL

Introduction

The purpose of this chapter is to present the details of the methodology that was briefly introduced in Chapter 3. This purpose includes broad definitions of the methodologies used to generate the parameters and to generate the optimization model.

In optimization problems, researchers generally use already defined parameters for generating the objective function. Parameter generation in this research is an important part of finding a solution to the generated model. Although many optimization studies leave this phase to the user, this research is generating the parameters in order to provide default values to the users. The parameters that are being used in the model are generated by Life Cycle Cost (LCC) analysis in the following areas:

- LCC for increased outdoor air (OA) to achieve desired reduction in contaminant concentration using increased ventilation by a central or dedicated unit.
- LCC for the increased amount of air cleaned, by calculating the air cleaner efficiency required to achieve desired reduction in contaminant concentration.

In order to calculate the parameters above, this research adapts a preliminary methodology that is developed by the EPA (Henschel 1999). EPA's study provides a number of worksheets to help calculate the LCC of improved ventilation, and air cleaning techniques (Appendix A). Parallel to the objectives of this research, EPA's worksheets are generated as a part of a pre-screening tool designed for decision makers with limited engineering knowledge. These worksheets are slightly modified in order to support the parameter development required by the model. For example, this research reinforces

EPA's preliminary methodology with more up-to-date quotes on equipment prices from several vendors as well as RS Means and government inflation rates. Although the EPA developed a number of these worksheets to calculate costs of different IAQ management options, this research refers to only a total of six worksheets. However some EPA worksheets that are not referred to in this research are converted into and used as simple equations. Definitions and the brief descriptions of the six worksheets adapted from EPA are given below:

- Worksheet 1: This worksheet is designed to help estimate the installed costs for increased OA by using a central unit. It calculates the increased heating and cooling capacities required to condition the increased OA and suggests costs per unit increases in capacities.
- Worksheet 2: This worksheet uses the same methodology as Worksheet 1 except uses different unit cost suggestions to estimate the installed costs for increased OA by a dedicated OA unit.
- Worksheet 3: This worksheet helps calculate the annual operating costs that occur due to increased OA ventilation. Worksheet 3 takes energy efficiency ratings of the HVAC equipment as well as the cooling and heating energy requirements in order to calculate an annual cost.
- Worksheet 4: This worksheet helps to estimate the annual maintenance costs for increased OA by calculating additional labor and hours required for maintenance of specific equipment.
- Worksheet 5: This worksheet combines the annual maintenance, operating, and annualized installed costs to estimate the total annualized costs for increased OA.
- Worksheet 6: Worksheet helps estimating the annual operating costs for central indoor air cleaners by calculating the energy consumptions and suggesting approximate unit costs.

In this methodology, the rough estimates are set as a screening tool to assist the model in making eliminations among the potential decision variables. The better cost estimates can be developed for the control options if the required HVAC expertise is available in-house or as a consulting service. The objective of developing these cost parameters is to facilitate a quick, inexpensive evaluation by users who may not have the required engineering knowledge for an extensive cost analysis. The costs that are used in the computation are the total annual costs. This includes the annual operation and maintenance costs, and annualized installed costs.

Estimating the Costs of Improved Ventilation

The first step in assessing the costs associated with increasing the OA ventilation rate is to estimate the OA increase that will be required. Equation 4-1, based on EPA's worksheets, presents the step-wise procedure for estimating the needed increase, assuming that dilution is the sole mechanism, which reduces the contaminant concentration.

$$C = \frac{d \times (a - b)}{b} \qquad (4\text{-}1)$$

Where,

C = Incremental increase in outdoor airflow rate required to achieve the desired reduction in concentration (cfm).

a = Current average concentration of the contaminant of concern in the building (ppmv).

b = Average concentration to which "a" should be reduced (ppmv).

d = Current flow of OA into the building (cfm).

It is assumed in Equation 4-1 that the concentration of the contaminant of concern is zero in the OA, and that the indoor air is well mixed so that pollutant concentrations assumed at one point represent concentrations at all points inside a building. In this case pollutant concern is assumed to be a homogenate problem throughout the whole section of the building. The OA being provided by the air handler is correspondingly being increased to treat that whole section of the building in a consistent way. In this case, as a first approximation, one might use Equation 4-1 to estimate the additional clean air that would have to be provided to effectively reduce the concentration in the building.

Note that Equation 4-1 disregards the added supply air increasing the mixing of the local contaminant throughout the area served by the air handler. Also the supply air, which is largely recirculated air, will thus increasingly differ from the assumption that there is zero concentration of a given contaminant in the ventilating air. The user would have to consider treating the building by moderately increasing OA flows to the entire portion of the problematic area if a localized source were to be addressed by an increase in direct supply air.

In this study, the model requires the cost per one cfm unit increase in OA ventilation as an input. Consequently the value of C in Equation 4-1 can be taken as 1 (one) cfm to further develop the LCC analysis. Thus the user can calculate the cost associated with increasing the OA amount by one cfm unit and use the result as a default value in the optimization model. The details of these calculations can be seen in the upcoming sections. The LCC calculations of the improved ventilation will be explored under three main categories. These are:

- Installed Costs
- Operation (Energy) Costs
- Maintenance Costs

Estimating Installed Costs for Increased Ventilation

According to EPA, the existing HVAC equipment needs to be modified or adjusted when an increase in the OA is required (Henschel 1999). Consequently an installed cost would occur for making these modifications. An important factor in this study is the concentration on only new construction cases. The installed costs in new construction cases are in fact the incremental increase in the installed costs of the mechanical system resulting from the adjustments that are made in the specifications to increase the OA rate.

Enlarged central units. Worksheet 1 in Appendix A presents a procedure for estimating the installed costs associated with an increasing capacity of the central HVAC units to handle increased OA in the new construction case. Worksheet 1 helps calculate the installed costs due to increased heating and cooling capacities required to condition the increase in OA. This worksheet is adapted from EPA's preliminary methodology for evaluating cost-effectiveness of alternative indoor air quality approaches (Henschel 1999). The worksheet presented in EPA's methodology includes an option of entering up to 3 (three) HVAC units. However in this dissertation calculations are modified for only one HVAC unit. In this case, it is assumed that a system capable of handling and conditioning the increased OA flow is now to be installed instead of the system that had originally been designed for the building that has not been built yet.

Worksheet 1 is based on the following circumstances (Henschel 1999):

- Cooling and Heating Capacity: The originally designed cooling and heating capacities are increased for the HVAC unit to handle the increased OA flow to itself. The air handler, cooling coils, condenser, compressor, heating elements, and controls of each unit are re-designed as required before construction. Since this preliminary worksheet assumes direct-expansion cooling units having electric heat, the calculations would be less accurate for systems that have chillers and furnaces.

- OA Intake Fan (if present): In cases where one or more OA intake fans are required in the new building, the worksheet assumes that intake fans of greater capacity are installed in lieu of the lower capacity, originally designed fans. In the model described in this research, this item has not been included in the cost calculations for testing purposes.

- In systems without economizers the worksheet assumes that intake and exhaust ducting of larger dimensions are installed instead of the original intake and exhaust ducting.

- In systems with no economizers but that have one or more central exhaust fans, worksheet assumes that exhaust fans of greater capacity are installed instead of the original ones.

In order to use the calculations in Worksheet 1, the required increases in heating and cooling capacities are taken from ASHRAE (1997) by using 1% design values for the cooling dry-bulb/mean wet-bulb temperatures. These values for Miami are 4.6-tons/1000cfm for the required increase in cooling capacity and 6-kW/1000cfm for the required increase in heating capacity. The users can modify these values depending on the location of the project. Table 4-1 lists these values for several cities in the US.

Table 4-1. Incremental increases in cooling and heating capacities required by increases in OA ventilation rates.

City	Required Increase in Cooling Capacity (tons per 1000 cfm OA)	Required Increase in Heating Capacity (kW per 1000 cfm OA)
Albuquerque, NM	~0	16
Atlanta, GA	3.3	15
Boston, MA	2.7	18
Chicago, IL	3.3	22
Cincinnati, OH	3.9	18
Cleveland, OH	2.7	20
Dallas-Fort Worth, TX	3.9	14
Denver, CO	~0	21
Houston, TX	4.6	12
Los Angeles, CA	0.5	8
Miami, FL	4.6	12
Minneapolis, MN	2.7	26
New York, NY	3.3	17
Omaha, NE	3.9	23
Pittsburgh, PA	2.1	20
Raleigh, NC	3.9	16
St. Louis, MO	3.9	20
San Francisco, CA	~0	10
Seattle, WA	0.5	13
Washington, D.C.	3.9	16

(Henschel, 1999).

These values in Table 4-1 are computed by EPA using 99% heating dry-bulb temperatures for the various cities, as defined by ASHRAE standards. The heating capacity presented in the table is the incremental power required to increase 1,000 cfm of outdoor air from the 99% value of outdoor temperature to an indoor temperature of 70 ˚F and 50% relative humidity.

New dedicated OA units. Worksheet 2 in Appendix A presents a procedure developed by EPA for estimating the installed costs associated with the use of a dedicated-OA unit in the new construction case. Calculations in Worksheet 2 assume that since a dedicated-OA unit is to be installed in a new building, it will be designed to condition all of the OA entering the building, rather than just the incremental increases in OA.

The EPA presents Worksheet 2, based on the following circumstances (Henschel 1999):

- Cooling and Heating Capacity: One or more rooftop direct-expansion systems with electric heat, dedicated to treating the incoming OA, are added to the original design. These added units have the capacity required to condition all of the OA that is now to be supplied to the building. The cooling and heating capacities of all of the originally designed HVAC units in the building are reduced, since the original units will no longer be required to condition OA, providing a cost savings that partially offsets the cost of the dedicated-OA units. The linear model that is developed in this research, gives the user the option of entering a value for fixed installed costs, which allows the model, produce more sophisticated decisions if desired.

- OA Intake Fan (If present): The air handlers associated with the dedicated-OA units become the intake fans for the entire OA flow into the building. In systems that included OA intake fans in the original design, these intake fans can now be eliminated, which results in cost savings.

- OA Intake Ducting: In systems with economizers, it is assumed that the increased total volume of OA being supplied by the dedicated-OA units is delivered into the originally designed OA intake ducting with no modifications to the original design.

- In systems without economizers the worksheet assumes that intake ducting and exhaust ducting of larger dimensions is installed instead of the original ducting.
- For systems that have central exhaust fans but do not have economizers, Worksheet 2 assumes that exhaust fans of greater capacity are installed instead of the originally designed fans.

Estimating Operating and Maintenance Costs for Increased Ventilation

Estimating the annual operating and maintenance costs is an important step in LCC analysis. In order to complete this estimate, in addition to the installed costs this dissertation suggests using the worksheets in Appendix A, provided by EPA (Henschel 1999).

Annual operating costs. EPA suggests that the annual operating cost associated with an increase in ventilation rate can be the incremental energy cost resulting from:

- Cooling and heating the increased flow of outdoor air
- Operating the enlarged or new intake or exhaust fans (if applicable)

Worksheet 3 in Appendix A presents the method to calculate the annual operating costs for increased ventilation. However it is important to note that this methodology should only be used when thorough modeling of the building energy consumption and costs is not possible.

The system size and characteristics depends on the climate of different regions as well as the number of days and hours the OA is supplied and conditioned (Westphalen & Koszalinski 1999). EPA states that a calculation of heating energy consumption that is based only on the total heating degree-days in a specific geographical location may be misleading; the mechanical system may not be supplying OA to the building during the middle of the night, which is the coldest period of a day. This would definitely impact the heating degree-day figure, which would alter the calculations based on only the geographical location (Henschel 1999).

Accordingly, the EPA's methodology to calculate the operating costs has utilized the DOE-2 building energy computer model to compute the required energy output from the mechanical system per incremental cfm of OA in a variety of climates with alternative mechanical systems. EPA's method assumes that OA is being supplied for 13 hours per day and 5 days per week. Since this research is concentrating on commercial buildings this assumption is also valid for the types of buildings for which the model is being generated. The results in the form of the average Btu of cooling energy output and Btu of heating energy output per incremental cfm for the different cities are given in Table 4-2. The values in Table 4-2 are generated for a small office building for which the input was available from Henschel (1999). The figure for each geographical location is an average for alternative variable-volume and constant-volume systems, and for OA flow rates at a range of 5 to 60 cfm/person at an occupancy density of 7 persons per 1000 ft^2. The values in Table 4-2 are calculated with the assumption that the OA is supplied to the building 13 hours/day (6 am to 7 pm) on weekdays only (excluding holidays)

Table 4-2. Incremental annual cooling and heating energy requirements per unit increase in OA ventilation rate by geographical location.

City	Incremental Additional Annual Cooling Energy Required per Incremental Increase in OA Intake Rate (Btu/yr per incremental cfm)	Incremental Additional Annual Heating Energy Required per Incremental Increase in OA Intake Rate (Btu/yr per incremental cfm)
Chicago, IL	13,000	41,000
Miami, FL	67,000	200
Minneapolis, MN	13,000	63,000
Northern Virginia	20,000	25,000
Raleigh, NC	26,000	16,000
Seattle, WA	3,000	28,000

(Henschel, 1999).

In Worksheet 3, the annual incremental cost of energy is computed by using the required energy output from the mechanical system and also by taking the system efficiency and the unit cost of fuel or electricity into account. In the same sheet users also have the option to calculate the energy cost for new or enlarged fans.

Annual maintenance costs: Worksheet 4 originally developed by EPA in Appendix A provides a preliminary methodology to calculate the annual maintenance costs for increased ventilation. The EPA's preliminary methodology assumes that increases in ventilation cause an increase in maintenance costs only when a new intake or exhaust fan is added or when a new dedicated OA HVAC unit is added. The EPA worksheets assume no increase in maintenance to result from enlargements of existing equipment. Although the worksheet is presented in the Appendix A for some users that may require it, in this research upper bound constraints are avoiding one of the two cases that were explained above. Thus the input data used in this research to test the model, assumes that there would be no significant change in the maintenance costs of the system. As for users that want to add the maintenance cost input to their model, the worksheet suggests figures of 5 hr/yr for each fan, and 20 hr/yr for each dedicated OA unit. The labor rate including or excluding the overhead can be obtained from the latest version of Recommended Standard (RS) Means.

Estimating total annualized costs for increased ventilation: Worksheet 5 in Appendix A is designed to combine the annualized installed costs with annual operating and maintenance costs associated with the increased ventilation. However the model developed in this research uses two different figures for the input cost data. It is possible to combine the installed costs and the annual costs into one single annual cost and eliminate the fixed cost figure. It is also possible to keep the annual O&M costs separate from the installed costs. Worksheet 5 should be used if the user decides to combine all the costs into one annual cost. In this case the annualized amount for the installed costs is determined using the Capital Recovery Factor (CRF). The user can select the number of years over which the installed cost is to be amortized, and the interest rate that is to be charged. The number of years will generally be the estimated lifetime of the system equipments. The value for the interest rate is the rate that is being paid on money borrowed to install the equipment, or the interest rate that could have been obtained on the money if it was invested rather than being used for the installation (Kirk & Isola 1995). Where “n” is the number of years, and “i” is the interest rate CRF could be calculated by using the Equation 4-2 given below (Kirk & Isola 1995):

$$CRF = [i(1+i)^n]/[(1+i)^n - 1]\,. \tag{4-2}$$

The CRF is the fraction of the initial cost that must be amortized each year if after n years, the initial cost is to be recovered with an “i” percent annual interest rate being charged on the unpaid balance. Consequently the total annualized cost computed in the Worksheet 5 is the sum of:

- The CRF multiplied by the incremental total installed cost
- The incremental annual operating cost
- The incremental annual maintenance cost

Estimating the Costs for Air Cleaning

Sometimes it may be appropriate to consider the use of air cleaners to remove the contaminant(s) of concern. For practical reasons, air cleaners are usually considered when ventilation and source management are not the feasible options (Henschel 1999). The model developed allows use all of these techniques together when feasible.

Methodology to calculate the costs of air cleaning includes two classes of indoor air particulate cleaners: “media” air cleaners and electronic air cleaners. Media air cleaners include:

- Pleated filter panels
- Bag filters
- Variations of the above types (e.g., pocket filters)

Electronic air cleaners are electrostatic precipitators. The EPA methodology used only considers particulate air cleaners with an average removal efficiency of 65% or greater as measured in ASHRAE standard 52.1-1992 (ASHRAE 1992). The methodology also assumes that lower efficiency filters are already present on the HVAC system, to protect the fan and coils. Users of the model also have the option to modify the cost data by including high-efficiency particulate air (HEPA) filters, which offer 99.97% removal efficiency. These types of filters are generally used in hospital operation rooms. The cost data generated by EPA’s methodology does not include HEPA filters.

The air cleaners considered for gaseous contaminants involve the use of beds of dry, granular material acting by physical adsorption, chemical absorption, or catalysis (Henschel 1999). Such air cleaners can be considered for the control of a variety of gaseous contaminants (ASHRAE 1995), however EPA’s cost calculations are more focused on the VOCs.

The worksheets that are adapted from EPA’s preliminary study address the incremental costs of a larger fan motor and of removing the heat generated by the larger motor. However the worksheets do not intend to calculate any costs associated with modifying the mechanical room or the HVAC equipment to house the air cleaner, since these costs will be very building specific. Additionally, the installed costs for the air cleaners computed in EPA's worksheets assume that there are no particular complications in the installation, which would significantly increase installation labor hours and materials.

Estimating Installed Costs for Air Cleaners

The following items generate the costs associated with installation of a central air cleaner:

- Obtaining and installing the air cleaner itself
- A larger motor for the central air handling fan, to compensate for the pressure drop across the cleaner (for media filters and gaseous air cleaners)
- Cooling capacity that may potentially increase to remove the additional heat produced by the larger fan

In order to calculate the installed costs for the air cleaners, Equation 4-3 can be used as extracted from the worksheets developed by Henschel (1999). According to the equation, installed costs are a simple function of total flow through the air cleaner and a vendor quote for 1000 cfm of OA.

$$E = Q \times V \tag{4-3}$$

Where,

E = Installed costs

Q = Total flow through the air cleaner

V = Vendor quote ($/1000 cfm) OR Refer to Table 4-3.

In Equation 4-3 it is important that the users first select an appropriate air cleaner based upon the performance requirements. With this selection the user may then either obtain an estimate from a vendor for this type of air cleaner, or may use a simplified option given by Table 4-3. The table presents rough installed costs per 1,000 cfm air for different types of air cleaners.

Table 4-3. Approximate installed costs of various in-duct particulate air cleaners

Type of Air Cleaner	Total Unit Installed Cost [a] ($/1000 cfm)
Pleated panel cartridge filter, ASHRAE 65	142
Pleated panel cartridge filter, ASHRAE 85	142
Pleated panel cartridge filter, ASHRAE 95	148
Electronic Air Cleaner	496

[a] Adapted from Henschel (1996), updated by inflation rates from http://inflationdata.com.

The installed costs given in Table 4-3 include the cost of taking the air through the filter and of the increase in fan motor horsepower, but exclude any costs for increased cooling or heating capacity.

Estimating Operating and Maintenance Costs for Air Cleaners

Annual operating costs: The methodology by Henschel (1999) includes the following items when calculating the annual operating costs:

- The increase in power consumption by the fan motor
- Power consumption by the corona wires and plates (electronic air cleaner)
- Added power consumption by the cooling system

Worksheet 6 in Appendix A presents a method for estimating the energy costs. The worksheet that is modified from Henschel (1999) estimates incremental additional fan horsepower requirements by multiplying the total airflow through the air cleaner times the average pressure drop across it, accounting for fan/motor efficiency, and applying the appropriate conversion factors. Annual energy later is calculated by multiplying this power requirement times the number of hours per year that the fan will be operating. The annual operating cost for the larger fan motor is determined from this energy consumption and based on the unit cost of electricity.

The default values are available for pressure drop, fan efficiency, hours of fan operation, and unit energy costs. If the user does not have these values available the following values can be used:

- Pressure drop: 1 in. WG
- Electric Input Ratio (EIR) for the cooling system: 0.34 kW/kW
- Hours of fan operation: 3,276 hr/yr (for 13 hr/day, 5 day/wk)

Worksheet 6 in this research calculates the operating costs of media air cleaners for particulate matter. However preliminary methodologies for calculating cost of "electronic air cleaners for particulate matter" and the cost of "air cleaners for gaseous contaminants" are available through EPA.

Annual maintenance costs: Maintenance costs for air cleaning include the materials and labor costs associated with periodic replacement of the filter media for media particulate air cleaners. Henschel (1999) developed a worksheet that is converted to Equation 4-4 in order to calculate a rough estimate for the maintenance of media particulate air cleaners. Henschel (1999), in his study, includes more information regarding different types of cleaners if required. Table 4-4 includes the price information to be used in Equation 4-4. If the user has more project specific data, then these data could be easily replaced with more accurate ones in the model.

$$\mathrm{T} = \frac{\omega \times F_i}{1000 \times N} \text{ (\$/yr)} \qquad (4\text{-}4)$$

Where,

$\mathrm{T} =$ Annual cost of replacing the particulate media filters

$\omega =$ Approximate unit cost for replacing filters per MCFM (Table 4-4)

$F_i =$ Amount of air through cleaner i (i=1,2,3) (cfm)

$\mathrm{N} =$ Number of times per year that the filter media will be replaced.

Table 4-4. Approximate replacement costs of media cartridges for particulate media air cleaners

Type of Air Cleaner	Unit Cost of Replacement Cartridges[a] ($/MCFM)
Plated panel cartridges, ASHRAE 65	45
Plated panel cartridges, ASHRAE 85	45
Plated panel cartridges, ASHRAE 95	50

[a] Adapted from Henschel (1996), updated by inflation rates from http://inflationdata.com. It is assumed that only minimal labor is required to install the replacement of cartridges.

Estimation of Income Function from Increased Productivity due to Increased IAQ

The effects of indoor air quality on productivity were discussed in Chapter 2. Wargocki (2000) conducted one of the important studies that this research has used in order to build the cost data for productivity. Wargocki (2000) conducted three studies that involved 90 subjects. Using similar procedures and blind exposures, the studies showed that increasing air quality (by decreasing the pollution load or by increasing the ventilation rate, with otherwise constant indoor climate conditions) could improve the performance of simulated office work (text typing, addition, and proof-reading). The results imply that doubling the outdoor air supply rate at constant pollution load, or a two-fold decrease of pollution load at constant ventilation rate, can increase overall performance by 1.9%. Inspired from Wargocki's results, imaginary data in Table 4-5 was generated to calculate the increased income as a result of increased productivity.

Table 4-5. Ventilation rate (cfm per person) vs. performance index

17	0.99000	44	1.021972	71	1.028903	98	1.032958	125	1.035835
20	1.000000	47	1.023025	74	1.029444	101	1.033322	128	1.036109
23	1.006931	50	1.023978	77	1.029957	104	1.033672	131	1.036375
26	1.010986	53	1.024849	80	1.030445	107	1.034011	134	1.036635
29	1.013862	56	1.025649	83	1.030910	110	1.034339	137	1.036888
32	1.016094	59	1.026390	86	1.031354	113	1.034657	140	1.037135
35	1.017917	62	1.027080	89	1.031780	116	1.034965	143	1.037376
38	1.019459	65	1.027725	92	1.032188	119	1.035263		
41	1.020794	68	1.028332	95	1.032580	122	1.035553		

The data listed in Table 4-5 is generated by using log (e) function and is partially integrated in the MS Excel ® sheet where the model uses a piece-wise linearization in order to control the estimated profit generated by the total amount of outdoor air. One of the reasons for choosing this method is due to the limitations of the linear programming on a nonlinear problem. If the nonlinear productivity function is linearized by using only one line, the model produces results for either the lower bound or upper bound that is defined with the constraints. Once the profit due to increased productivity becomes more than the cost, the model pushes the results towards bringing as much air as possible. On the other hand, if the profit from increased productivity comes out to be less than the cost of bringing OA, then the model goes down to the lower constraint and tries to bring as little air as possible.

The values for the performance index were given in Table 4-5. The graphic that shows the plot of those values is given in Figure 4-1.

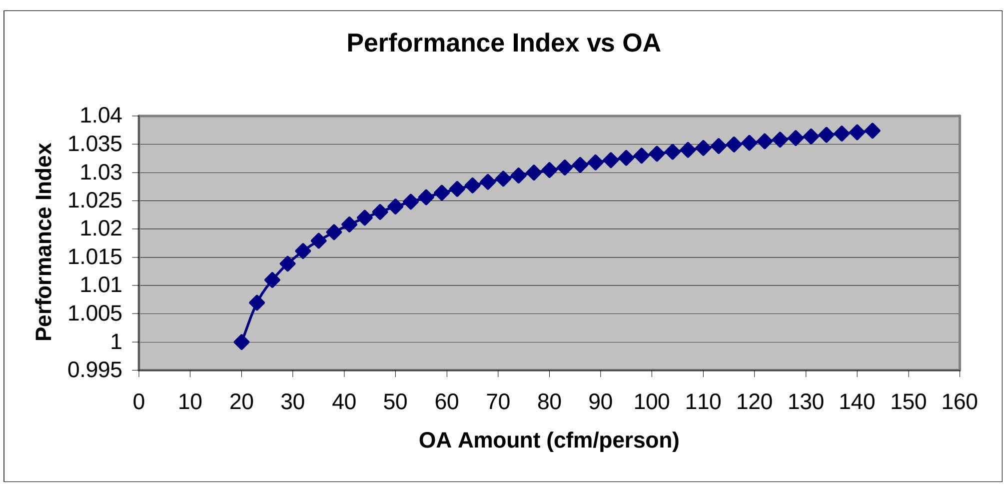


Figure 4-1. The performance index and its correlation with the supplied OA amount.

Although performance index is the value that is defined in Wargocki's (2000) study, this dissertation subtracts 1 (one) from these values so when they are multiplied with the total salary of the occupants of the building, only the profit can be calculated. A more detailed description of this calculation will be explained in the "User Defined Independent Variables as Input Data" subsection. The final numbers in the productivity curve after subtracting 1 from the performance index are illustrated in Figure 4-2. This new value in this research will be referred to as "Performance Profit Index" (PPI).

Since this research is assuming linearity in the functions used in the model, the productivity function is linearized by slightly underestimating the PPI values. Many studies that choose to linearize a nonlinear function chooses one of the two options:

- Piece-wise linearization by overestimating
- Piece-wise linearization by underestimating

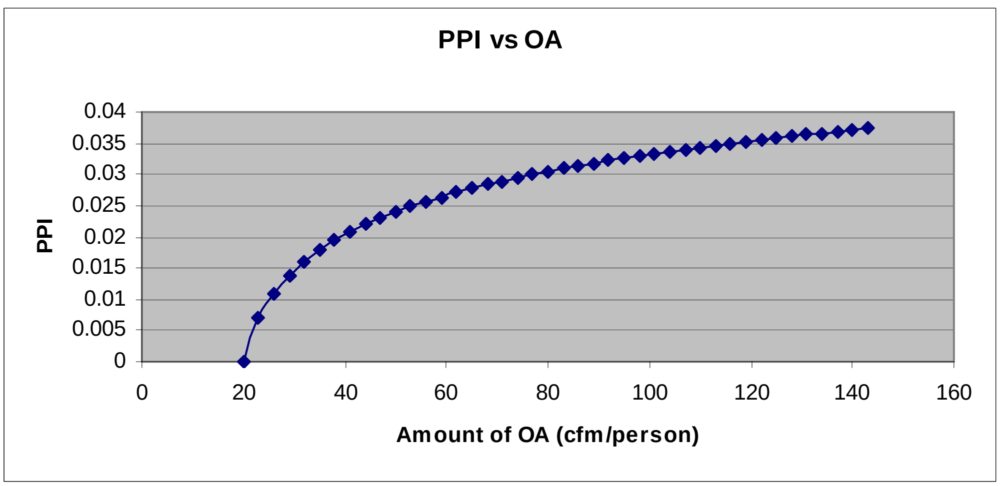


Figure 4-2. PPI and its correlation with the amount of OA.

Piece-wise linearization is used in many studies by choosing either to overestimate or underestimate. Examples of piece-wise linearization of an exponential function are given in Figure 4-3. The model developed in this research however would only be sound if at least a number of segments are created. Otherwise the model as the total amount of OA brought into the building would still create solutions at the extreme OA values. If the PPI versus OA function was to be linearized at point η , in only two lines this would only limit the OA solutions to either 20, η , or 140. However linearizing this function to at least “n” number of lines would require the user to include additional constraints. In order to simplify the configuration of the model, the PPI versus OA function is linearized with 11 lines at points, 20, 26, 32, 38, 44, 50, 56, 62, 68, 74, 80, and 86 (cfm). These functions and their integrations in the optimization model will be discussed in the “Defining the Optimization Model” section. The piece-wise linearization of the PPI vs. OA function is given in Figure 4-4.

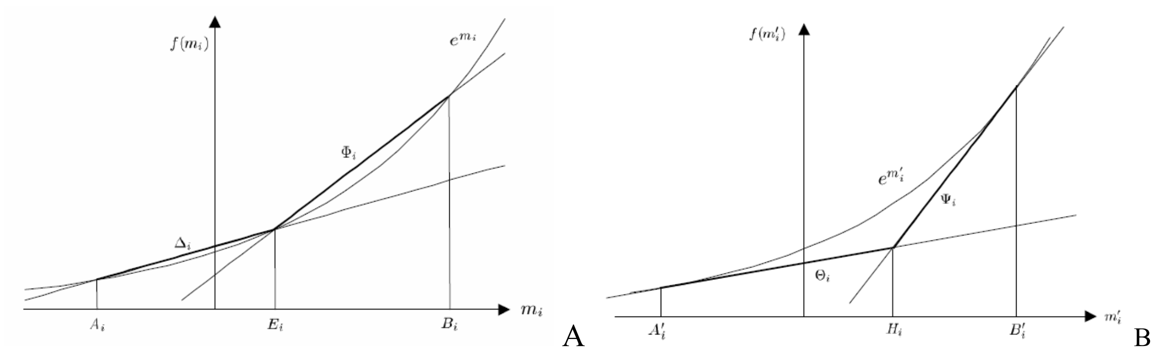


Figure 4-3. An example for piecewise linear overestimate and underestimate of an exponential function. A) Overestimating, B) Underestimating (Irion et al. 2004)

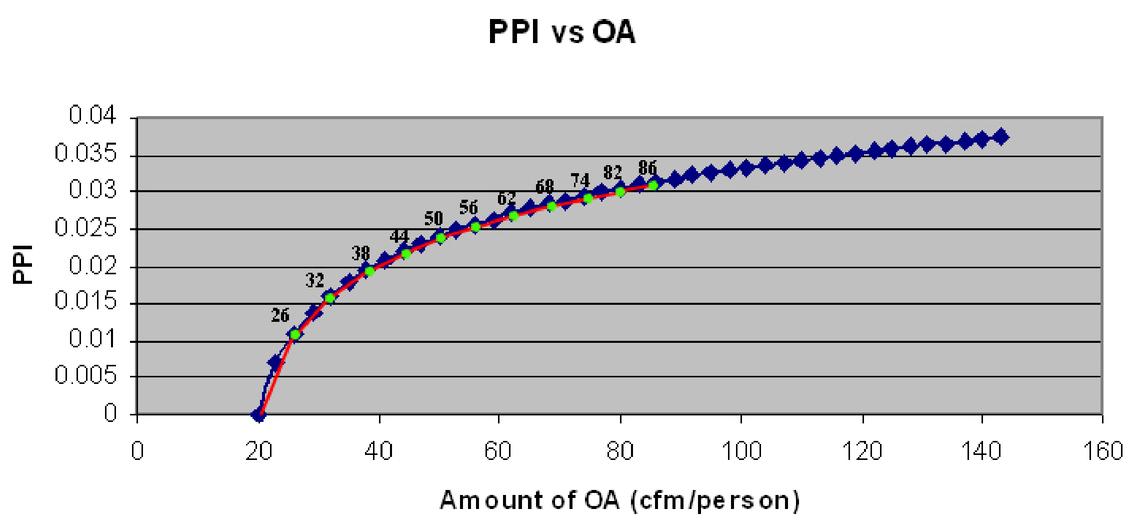


Figure 4-4. Piece-wise linearization of the PPI vs. OA function.

In order to calculate the equation of the lines presented in Figure 4-4, the values obtained from Figure 4-4 or Table 4-5 can be inserted in Equation 4-5. The value of the slope (m) can be calculated by finding the tangent of the θ: angle for each linear segment by using Equation 4-6.

$$y = mx + c \tag{4-5}$$

Where,

$m =$ The slope of the line

$c =$ The constant.

$$\mathrm{Tan}(\theta) = \frac{(\text{Max PPI - Min PPI})}{(\text{Max OA - Min OA})} = m\,. \tag{4-6}$$

This research disregards the correlation between the amount of air cleaned with the productivity levels and PPI. If any scientific data are developed in the future, a new linear function can be calculated by using similar methods shown for OA vs. PPI calculations.

Defining the Optimization Model

The optimization study includes three major parts as listed below:

- Improved ventilation by central unit
- Improved ventilation by a dedicated unit
- Air cleaning

These areas are all combined in an objective function in order to set the values for the decision variables that are subject to the constraints. An important factor to note is that using the preliminary methodology developed by EPA that is introduced earlier can help estimate the rough values for the input unit costs. However it is also important to evaluate the model not in terms of the actual numbers that will be constantly changing due to inflation rates and other economic and technological developments, but of the relationships among the IAQ control options. The model is developed as a preliminary model that is basically simplified in many terms to clarify the application of linear programming methodologies in construction management. Although more complex optimization methodologies are widely used in the engineering side of this area, construction managers and the building owners and managers are still not aware of the possibilities that optimization studies can offer in making preliminary decisions.

Decision Variables

Decision variables are the dependent variables in LP that are subject to changing while optimizing the objective function. There are a total of eleven decision variables in this research. The units of all the variables except the binary ones and the productivity variable are cubic feet per minute per person and all the cost values in the model are annual. Decision variables of the model in this research are listed below:

X_1 = Amount of OA supplied by a central unit (cfm/person)

X_2 = Amount of OA supplied by a dedicated unit (cfm/person)

W = Profit generated by increased productivity ($)

F_1 = Amount of air through cleaner 1 (cfm/person)

F_2 = Amount of air through cleaner 2 (cfm/person)

F_3 = Amount of air through cleaner 3 (cfm/person)

Y_1 = “1” if central unit is used, “0” if not

Y_2 = “1” if dedicated unit is used, “0” if not

B_1 = “1” if cleaner 1 is used, “0” if not

B_2 = “1” if cleaner 2 is used, “0” if not

B_3 = “1” if cleaner 3 is used, “0” if not

The details explanations of the above decision variables are given below:

a) (X_1) Amount of OA supplied by a central unit

This variable represents the amount of outdoor air that is being supplied to the building by a central HVAC unit in cfm/person units. ASHRAE 62.1-2001 standards mandate the total amount of OA supplied in commercial buildings as 20 cfm per person. However the model investigates in more depth to explore if bringing more OA would still be economically feasible.

b) (X_2) Amount of OA supplied by a dedicated unit

The difference of the OA by the dedicated unit from the central unit appears only when dealing with fixed installed costs. The operating and maintenance costs associated with this variable are supposed to be exactly the same as the OA by the central unit. Thus the model will choose to bring OA into the building by either a dedicated or central unit depending on their fixed installed costs.

c) (F_i) Amount of air through cleaner "i" (for i=1,2,3)

This is the amount of air that passes through the air cleaners that are located possibly in three different locations. These locations are illustrated in Figure 4-5. The relations among these different locations will be discussed under the constraints section. According to Figure 4-5, if a cleaner is located on location1 then it will only clean the outdoor air supplied to the system. If it is located in Location 2 then it will only clean the recirculating air. If it is located on Location 3 then it will be able to filter both recirculating air and the outdoor air.

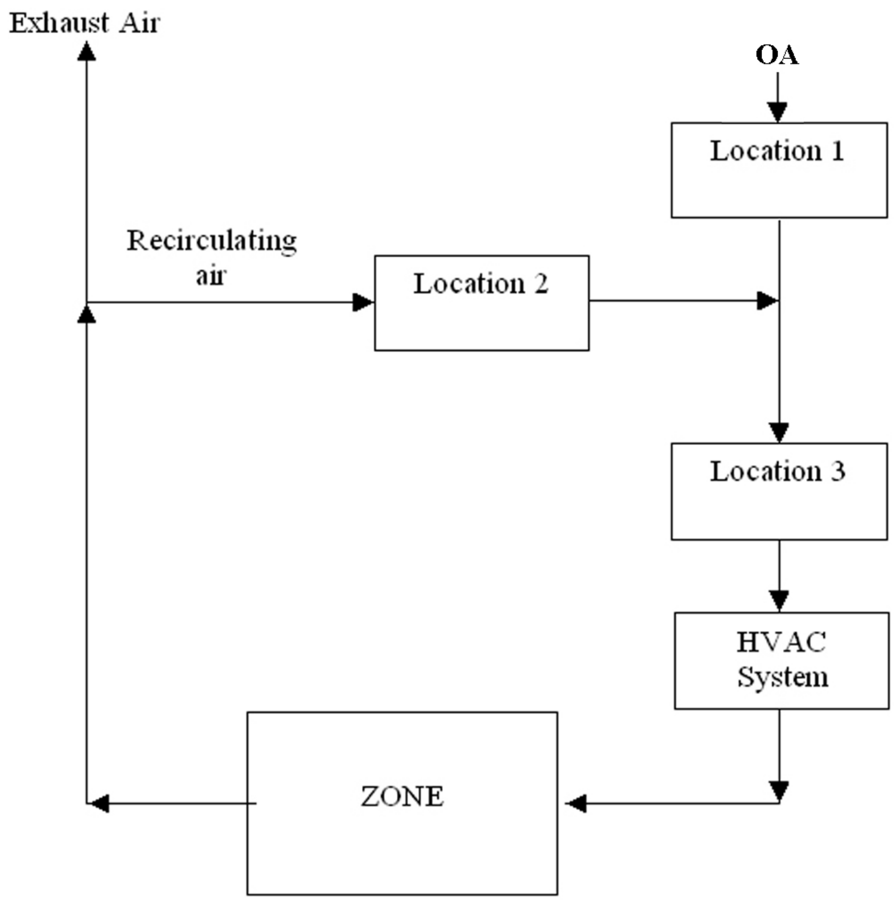


Figure 4-5. Possible air cleaner locations.

d) (Y_1) <u>Binary variable for central air unit</u>

This variable is the binary variable for the central unit. It gives the model the option of either using this unit or not. If the model finds it optimum to use the central air unit, the value of this decision variable appears in the solution as “1” and “O” if not used.

e) (Y_2) <u>Binary variable for dedicated unit</u>

This variable is the binary variable for the dedicated unit. It gives the model the option of either using this unit or not. If the model finds it optimum to use the dedicated air unit the value of this decision variable appears in the solution as “1” and “O” if not used.

f) (B_i) Binary variable for air cleaners (for i=1,2,3)

This variable is the binary variable for each of the air cleaners. B_1 represents the binary for location 1, B_2 is the binary variable for location 2, and B_3 is the binary variable for air cleaner in location 3 (See Figure 4-3). Depending on these variables being "1" or "0" the user can decide which one(s) should be used or not.

Objective Function

The objective function of the model is given in Equation 4-7. The objective of the model in managerial terms is to minimize the true costs of indoor air quality management options. In more detail, it is to minimize the overall cost of providing outdoor air and cleaning air in a commercial building while maximizing the benefits of increased worker productivity. Equation 4-7 represents the summation of three major costs. These are the cost of OA by a central unit, OA by a dedicated unit, and cleaning air in three possible locations. The cost of bringing OA by a central unit includes the variable cost (VC), revenue generated by increased productivity (R), and the fixed costs (FC).

$$\mathrm{Min}\, z = \sum_{i=1}^{2}(\underbrace{\mathrm{A}_i X_i}_{\mathrm{VC}} + \underbrace{C_i Y_i}_{\mathrm{FC}}) + \sum_{j=1}^{3}(\underbrace{F_j D}_{\mathrm{VC}} + \underbrace{B_j E}_{\mathrm{FC}}) - \underbrace{W}_{\mathrm{R}} \tag{4-7}$$

Where,

z = The total annual cost of the IAQ control ($)

A_1 = Marginal cost of air by central unit ($ x person/cfm)

A_2 = Marginal cost of air by dedicated unit ($ x person/cfm)

C_1 = Fixed cost for central unit ($)

C_2 = Fixed cost for dedicated unit ($)

D = Cost for cleaning air ($ x person/cfm)

E = Fixed cost for air cleaners ($)

P_1 = Money saved by increased productivity by central unit (See Eq. 4-7) ($)

P_2 = Money saved by increased productivity by dedicated unit (See Eq. 4-7) ($)

P_3 = Money saved by increased productivity by air cleaners (See Eq. 4-7) ($)

X_1 = Amount of OA supplied by a central unit (cfm/person)

X_2 = Amount of OA supplied by a dedicated unit (cfm/person)

F_1 = Amount of air through cleaner 1 (cfm/person)

F_2 = Amount of air through cleaner 2 (cfm/person)

F_3 = Amount of air through cleaner 3 (cfm/person)

Y_1 = "1" if central unit is used, "0" if not

Y_2 = "1" if dedicated unit is used, "0" if not

B_1 = "1" if cleaner 1 is used, "0" if not.

B_2 = "1" if cleaner 2 is used, "0" if not.

B_3 = "1" if cleaner 3 is used, "0" if not.

W = Profit generated by increased productivity by using PPI function. ($)

Although the data stating the dependency among the variables X_1, X_2, and F_j are not clearly set with the current literature and studies, there is a strong belief that in fact there should be a relationship (Wargocki 2000). If data become available then this dependency can be reflected in the model by including a function of X_i and F_j in the calculation of W. This may create a more accurate and actual representation of the IAQ measures and productivity. However the new objective function in that case would become a nonlinear function, which would require a more complex solution to the model. Thus solving the model with MS. Excel Solver ® would not be possible anymore. On the other hand there are other software and tools available for this type of optimization such as Lingo ®. Once the data and verification are available one should consider using these software to complete the solution of the model.

Decision Constraints

Decision constraints of the model are a set of constraints that the model is limited with while changing the value of the decision variables to optimize the objective function. The decision constraints that the objective function (See Equation 4-7) is subject to, are given below:

1. $X_1 + X_2 \leq 140\, cfm$
2. $X_1 + X_2 \geq 20\, cfm$
3. $Y_1 + Y_2 \geq 1$
4. $B_1 + B_2 + B_3 \geq 1$
5. $X_1 - 140 Y_1 \leq 0$
6. $X_2 - 140 Y_2 \leq 0$
7. $F_i - 140 B_i \leq 0$
8. $F_1 + F_2 - F_3 \leq 0$
9. $X_1 + X_2 - (F_1 + F_2 + F_3) \leq 0$
10. $- 1831.02\ X_1 - 1831.02\ X_2 + W <= -36620.41$
11. $- 851.38\ X_1 - 851.38\ X_2 + W <= -11149.65$
12. $- 560.79\ X_1 - 560.79\ X_2 + W <= -1850.81$

13. $-418.36\ X_1 - 418.36\ X_2 + W <= 3542.52$

14. $-334.45\ X_1 - 334.45\ X_2 + W <= 7256.39$

15. $-278.42\ X_1 - 278.42\ X_2 + W <= 10057.78$

16. $-238.50\ X_1 - 238.50\ X_2 + W <= 12293.41$

17. $-208.61\ X_1 - 208.61\ X_2 + W <= 14146.98$

18. $-185.38\ X_1 - 185.38\ X_2 + W <= 15726.56$

19. $-166.81\ X_1 - 166.81\ X_2 + W <= 17100.76$

20. $-151.62\ X_1 - 151.62\ X_2 + W <= 18315.65$

21. All variables ≥ 0

Constraint 1. This constraint mandates that the amount of OA taken into the building does not go over 140 cfm of OA since this would require a replacement or upgrade of the equipment.

Constraint 2. This constraint mandates that the total amount of OA supplied by both units should be at least 20 cfm per person, which is the requirement of ASHRAE Standard 62.1-1999 for commercial buildings.

Constraint 3. This binary constraint requires the model to select at least one of the HVAC units (dedicated or central).

Constraint 4. This binary constraint requires the model that at least one of the air cleaners at one of the possible locations shall be selected. If the user decides that only one of the cleaners should be selected then the "≥" should be replaced with "=".

Constraint 5. This constraint is similar to the Big M method. It makes sure that if the model decides not to use the central unit, Y_1 will be zero (0), thus the model will automatically give X_1 the value of zero (0) so it will not be included in the objective function cost calculations.

Constraint 6. This constraint is similar to the Big M method. It makes sure that if the model decides not to use the dedicated unit, Y_2 will be zero (0), thus the model will automatically give X_2 the value of "0" so it will not be included in the objective function cost calculations.

Constraint 7. This constraint is very similar to Constraint 5 and 6. It assures that if any of the cleaners are not used, then the variable associated with that cleaner becomes zero (0) to make sure the costs associated with that specific cleaner are not calculated in the objective function.

Constraint 8. This constraint makes sure that the air, which flows through three different locations, creates a closed network. This is assured by equalizing everything going into the zone being equal to everything coming out. Thus the OA plus the recirculated air equals the air supplied into the zone.

Constraint 9. This constraint assures that the amount of air cleaned is not greater than the amount of air supplied into the zone.

Constraint 10-20: These constraints are used to linearize the PPI function introduced earlier. However the coefficients of these constraints vary depending on the chosen total salary. The constraints shown are configured for an average salary of $1,000,000. The coefficient should be adjusted when there is a change in the total salary by using the segments and associated values in Table 4-5.

Constraint 11. This constraint is known as the nonnegativity constraint and assures that none of the variables defined previously result in a negative value.

User-Defined Independent Variables as Input Data

There are two very important independent variables in the optimization model:

- Number of employees inside the building
- Average salary of the employees

These variables are necessary in order to solve the model and find an optimum decision. All the "cost for OA air and cost for cleaning air" calculations are in terms of cfm per person. Thus if there is only one person in a zone, and if the model decides to bring 20 cfm per person, that means the system should supply 20 cubic feet of air every minute. However in the same exact setting, if there are 2 people in the zone then the HVAC system should supply 2 x 20 cfm/person, which would be 40 cubic feet of OA every minute. If the cost of supplying 20 cfm/person OA is "X" amount of dollars then supplying OA to the entire building would cost: $(X x Number of occupants).

Another important information to know is the average salary of the employees inside the building. The basic reason for that derives from the productivity issues. Since the model is trying to optimize the cost, which includes the savings from the increased productivity, the average salary makes a difference in terms of how much the increased performance is actually saving the employer. For instance if the average salary of the employees in a building is $30K then increasing their performance index to 1.02 would actually save: $\$30{,}000 \times (1.02 - 1) = \$600$ per employee.

The actual savings is calculated by multiplying the above savings per person by the number of employees. The above calculations are embedded in the MS Excel ® spreadsheet while configuring the input parameters for the model. The two independent variables in this study are left blank to be completed by the user to create a building-specific model. However, the user also would have the option to change some of the variables that are used in the cost calculations. If not, the default values are used in the model developed in this research. Below are some of the values that the user may have control over for more accurate results:

- Energy efficiency ratings for HVAC equipment (1 Btu/h per Btu/h)
- Cooling capacity of the HVAC (4.6 tons/1000cfm)
- Heating capacity of the HVAC (12 kW/1000cfm)
- The unit costs for electricity (or gas) ($0.09/kWh)
- Unit costs for heating and/or cooling capacity
- Location of the building
- Electric Input Ratio (EIR) of the equipment (10 Btu/h/W)

Appendix B presents the sample MS. Excel Solver ® screens in which the model is integrated. Configuration of the cells for variables, constraints, and the objective function are shown in Figure B-1 and the Solver module is shown in Figure B-2 and Figure B-3.

Summary

Defining parameters is a crucial part of an optimization problem. Chapter 4 as a part of the methodology explores some methods to generate these parameters. By using the equations and the worksheets introduced in this Chapter, one would be able to generate preliminary data for the unit annual costs of bringing OA air into the building and cleaning the indoor air. This chapter provides worksheets and equations for calculating LCC of IAQ systems. The decision model is defined by determining the decision variables, constraints, and the objective function. The set of constraints can be expanded by adding specific constraints that limit the amount of ventilation due to issues in air velocity, sound insulation, etc. An important point is that the assumptions and limitations section in Chapter 1 has very important information to keep the generated model valid. Chapter 5 discusses the solutions to the model that is defined in this chapter and determines if there is a feasible region defined by the model or not..

CHAPTER 5
RESULTS AND DISCUSSION

Introduction

In order to test the model and show that the model can find solutions in the feasible region a user initially needs to plug in the data that the model requires. An LP can generate several different results. The major possibilities other than finding one optimal solution, are listed below:

- Alternative or multiple optimal solutions
- Infeasible LP's
- Unbounded LP's

This section of the dissertation is moving towards the solution of the model to observe if any of the above cases apply. If not, then the optimum solutions generated by the model are presented by solving the model with sound imaginary input data. This chapter also explores the sensitivity analysis by answering "what if" questions about the generated solutions.

Solution to the Model

Before hitting the solve button on the Solver ® menu, it is important to make sure that the model is transformed on the spreadsheet correctly. Figure 5-1 presents how decision variables, objective function, constraints, and the input data are transformed into the MS Excel ® spreadsheet. Cells A6 to A16 contain the names of each decision variable that was described in Chapter 4. The results for decision variables are expected to appear in cells F6 to F16. These cells are locked so the user has no control over changing the values in these cells. Since no cost or demographic data are plugged in yet,

Figure 5-1 shows “0” for these values (decision variables). The objective function is programmed in cell C21. The formula embedded in the objective function cell is an exact transformation of Equation 4-7.

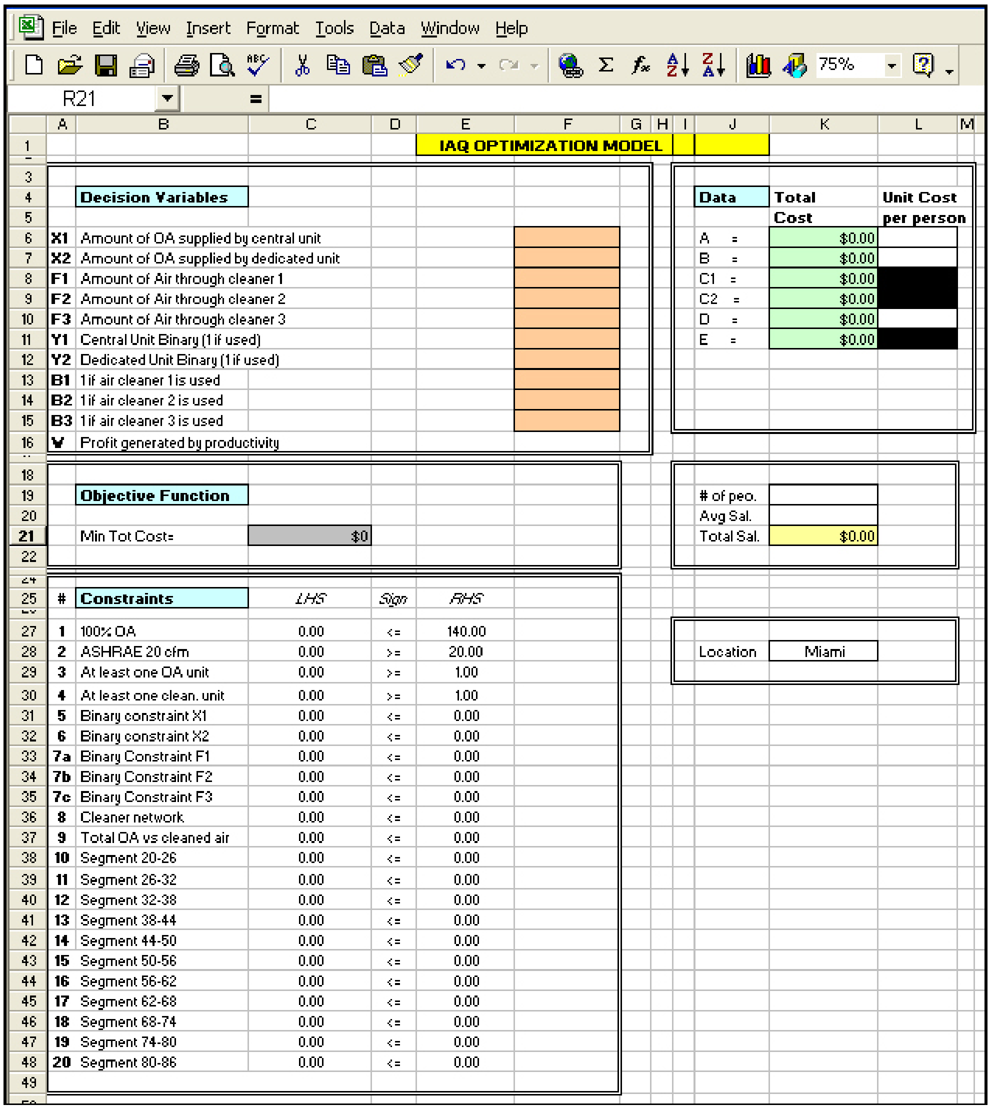


Figure 5-1. MS EXCEL ® Spreadsheet developed to correspond to the generated optimization model.

The names of the model’s constraints that were described in Chapter 4, are located in cells B27 to B48. Constraint number 11, which is the non-negativity constraint, will be implemented in the Solver ® menu window. The cost data to be input by the user are given in cells K6 through K11. These include the unit costs of bringing one cfm of OA into the building by a dedicated or central unit and cleaning one cfm of air. These costs can be calculated by following the instructions in Chapter 4 and the worksheets given in Appendix A.

Cells K19 and K20 are for the user to input the number of occupants in the building and the average salary of the employees. Then MS Excel ® calculates the total salary costs for the owner in Cell K21 by simply multiplying the average salary by the number of occupants (K19 x K20).

In order to test if the model is working this research solves the model for two different sets of input data. The only difference between the two imaginary cases derives from the change in the cost data used as input. The change in number of employees and the average salary and their effects on the solution will be discussed in sensitivity analysis. Although the cost data according to the worksheets should not be changing for different buildings in the same region, the difference may be a result of the variation in the energy efficiency of the buildings or the default values such as the energy efficiency of the equipment used in the buildings.

Case 1

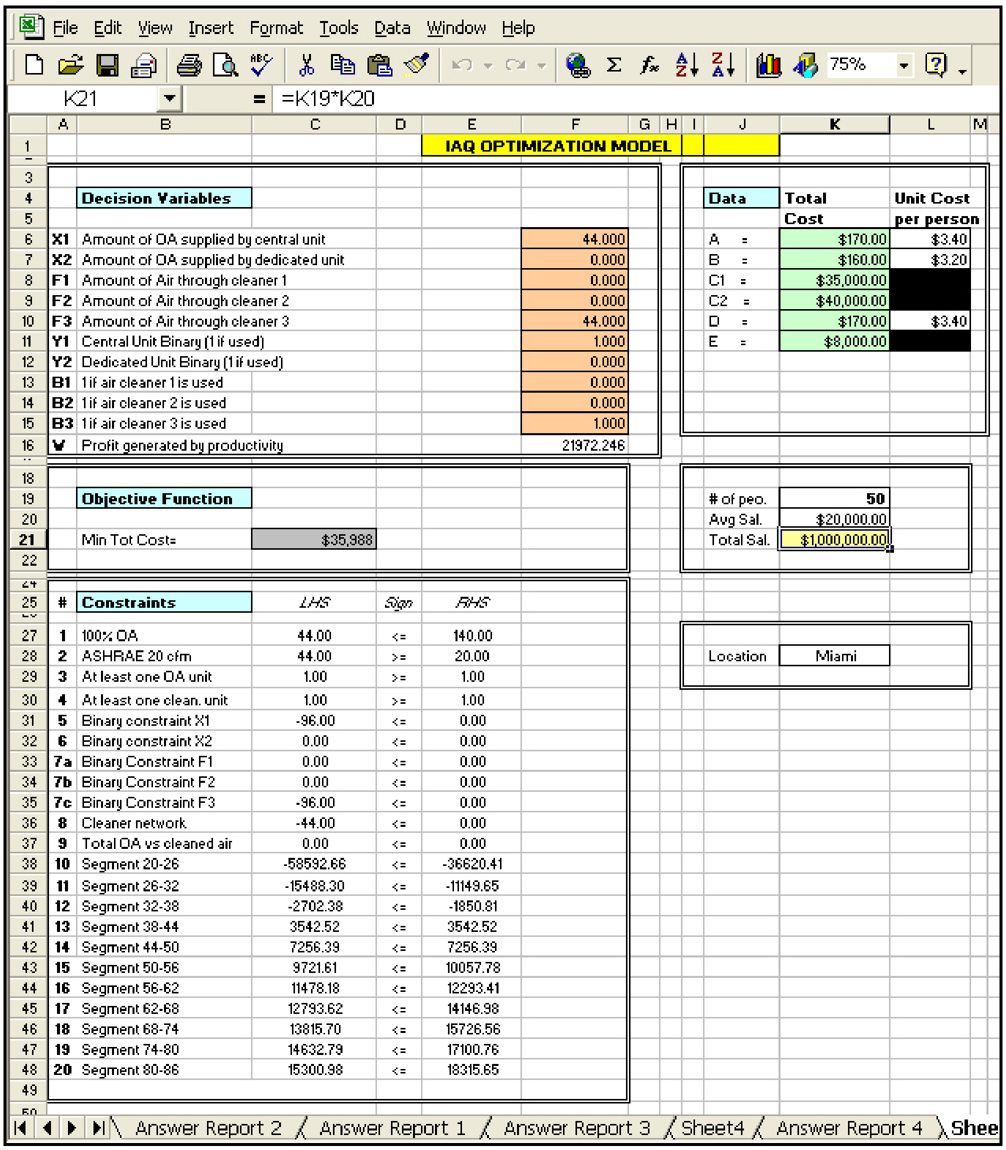
The building used in the first case is assumed to be located in Miami and is a middle-sized commercial building. Cost data that is used in this case are rough estimates. These costs may significantly vary due to changes in system design and the operating and maintenance unit costs. In the first case study, the following demographic data are used to solve the model.

- Number of occupants: 50
- Average salary of the occupants: $20,000

The cost data are set as follows:

- Cost of OA by central unit: $3.40 cfm/person
- Cost of OA by dedicated unit: $3.20 cfm/person
- Cost of cleaning air: $3.40 cfm/person
- Fixed cost for central unit: $35,000
- Fixed cost for dedicated unit: $40,000
- Fixed cost for air cleaner: $8,000

When these values are used as input in the model, the results generated by MS Excel Solver ® are shown in Figure 5-2.



K21 = =K19*K20

IAQ OPTIMIZATION MODEL

	Decision Variables	
X1	Amount of OA supplied by central unit	44.000
X2	Amount of OA supplied by dedicated unit	0.000
F1	Amount of Air through cleaner 1	0.000
F2	Amount of Air through cleaner 2	0.000
F3	Amount of Air through cleaner 3	44.000
Y1	Central Unit Binary (1 if used)	1.000
Y2	Dedicated Unit Binary (1 if used)	0.000
B1	1 if air cleaner 1 is used	0.000
B2	1 if air cleaner 2 is used	0.000
B3	1 if air cleaner 3 is used	1.000
V	Profit generated by productivity	21972.246

Data		Total Cost	Unit Cost per person
A	=	$170.00	$3.40
B	=	$160.00	$3.20
C1	=	$35,000.00	
C2	=	$40,000.00	
D	=	$170.00	$3.40
E	=	$8,000.00	

Objective Function

Min Tot Cost= $35,988

# of peo.	50
Avg Sal.	$20,000.00
Total Sal.	$1,000,000.00

Location: Miami

#	Constraints	LHS	Sign	RHS
1	100% OA	44.00	<=	140.00
2	ASHRAE 20 cfm	44.00	>=	20.00
3	At least one OA unit	1.00	>=	1.00
4	At least one clean. unit	1.00	>=	1.00
5	Binary constraint X1	-96.00	<=	0.00
6	Binary constraint X2	0.00	<=	0.00
7a	Binary Constraint F1	0.00	<=	0.00
7b	Binary Constraint F2	0.00	<=	0.00
7c	Binary Constraint F3	-96.00	<=	0.00
8	Cleaner network	-44.00	<=	0.00
9	Total OA vs cleaned air	0.00	<=	0.00
10	Segment 20-26	-58592.66	<=	-36620.41
11	Segment 26-32	-15488.30	<=	-11149.65
12	Segment 32-38	-2702.38	<=	-1850.81
13	Segment 38-44	3542.52	<=	3542.52
14	Segment 44-50	7256.39	<=	7256.39
15	Segment 50-56	9721.61	<=	10057.78
16	Segment 56-62	11478.18	<=	12293.41
17	Segment 62-68	12793.62	<=	14146.98
18	Segment 68-74	13815.70	<=	15726.56
19	Segment 74-80	14632.79	<=	17100.76
20	Segment 80-86	15300.98	<=	18315.65

Figure 5-2. Case 1–MS Excel ® screen for solution.

According to Figure 5-2, the optimum solution to the above case would require bringing 44 cfm/person OA by using the central unit. Also the solution suggests using an air cleaner in location 3 and cleaning 44 cfm of air/person. The number “0” (zero) corresponding the binary variables indicate that in this hypothetical situation, it is not optimal to use a dedicated unit, cleaner location 1, and cleaner location 2. The objective function is displayed to be $35,988.00. This means that the cost of the system (when the productivity increase is taken into consideration) would be approximately $36K annually. The answer sheet that shows the binding and not binding constraints as well as the final values of the objective function and the variables is given in Figure 5-3.

Target Cell (Min)

Cell	Name	Original Value	Final Value
$C$21	Min Tot Cost=	$0	$35,988

Adjustable Cells

Cell	Name	Original Value	Final Value
$F$6	Amount of OA supplied by central unit	0.000	44.000
$F$7	Amount of OA supplied by dedicated unit	0.000	0.000
$F$8	Amount of Air through cleaner 1	0.000	0.000
$F$9	Amount of Air through cleaner 2	0.000	0.000
$F$10	Amount of Air through cleaner 3	0.000	44.000
$F$11	Central Unit Binary (1 if used)	0.000	1.000
$F$12	Dedicated Unit Binary (1 if used)	0.000	0.000
$F$13	1 if air cleaner 1 is used	0.000	0.000
$F$14	1 if air cleaner 2 is used	0.000	0.000
$F$15	1 if air cleaner 3 is used	0.000	1.000
$F$16	Profit generated by productivity	0.000	21972.246

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$C$27	100% OA LHS	44.00	$C$27<=$E$27	Not Binding	96
$C$29	At least one OA unit LHS	1.00	$C$29>=$E$29	Binding	0.00
$C$30	At least one clean. unit LHS	1.00	$C$30>=$E$30	Binding	0.00
$C$31	Binary constraint X1 LHS	-96.00	$C$31<=$E$31	Not Binding	96
$C$32	Binary constraint X2 LHS	0.00	$C$32<=$E$32	Binding	0
$C$33	Binary Constraint F1 LHS	0.00	$C$33<=$E$33	Binding	0
$C$34	Binary Constraint F2 LHS	0.00	$C$34<=$E$34	Binding	0
$C$35	Binary Constraint F3 LHS	-96.00	$C$35<=$E$35	Not Binding	96
$C$36	Cleaner network LHS	-44.00	$C$36<=$E$36	Not Binding	44
$C$37	Total OA vs cleaned air LHS	0.00	$C$37<=$E$37	Binding	0
$C$38	Segment 20-26 LHS	-58592.66	$C$38<=$E$38	Not Binding	21972.2458
$C$39	Segment 26-32 LHS	-15488.30	$C$39<=$E$39	Not Binding	4338.64583
$C$40	Segment 32-38 LHS	-2702.38	$C$40<=$E$40	Not Binding	851.578083
$C$41	Segment 38-44 LHS	3542.52	$C$41<=$E$41	Binding	0
$C$42	Segment 44-50 LHS	7256.39	$C$42<=$E$42	Binding	0
$C$43	Segment 50-56 LHS	9721.61	$C$43<=$E$43	Not Binding	336.166108
$C$44	Segment 56-62 LHS	11478.18	$C$44<=$E$44	Not Binding	815.230928
$C$45	Segment 62-68 LHS	12793.62	$C$45<=$E$45	Not Binding	1353.36195
$C$46	Segment 68-74 LHS	13815.70	$C$46<=$E$46	Not Binding	1910.86226
$C$47	Segment 74-80 LHS	14632.79	$C$47<=$E$47	Not Binding	2467.97109
$C$48	Segment 80-86 LHS	15300.98	$C$48<=$E$48	Not Binding	3014.67191
$C$28	ASHRAE 20 cfm LHS	44.00	$C$28>=$E$28	Not Binding	24.00
$F$11	Central Unit Binary (1 if used)	1.000	$F$11=binary	Binding	0.000
$F$12	Dedicated Unit Binary (1 if used)	0.000	$F$12=binary	Binding	0.000
$F$13	1 if air cleaner 1 is used	0.000	$F$13=binary	Binding	0.000
$F$14	1 if air cleaner 2 is used	0.000	$F$14=binary	Binding	0.000
$F$15	1 if air cleaner 3 is used	1.000	$F$15=binary	Binding	0.000

Figure 5-3. Case 1–Answer sheet generated by MS Excel Solver ®.

Case 2

The second case assumes that the same building in Case 1 has lower energy efficiency or less efficient equipment thus may have higher amounts of marginal annual costs. Thus the cost data in the second case is slightly higher then data used in Case 1. The demographic input data for this case remain the same as the data used in Case 1.

- Number of occupants: 50
- Average salary of the occupants: $20,000

The cost data are adjusted as listed below:

- Cost of OA by central unit: $4.90 cfm/person
- Cost of OA by dedicated unit: $4.70 cfm/person
- Cost of cleaning air: $4.80 cfm/person
- Fixed cost for central unit: $32,500
- Fixed cost for dedicated unit: $37,500
- Fixed cost for air cleaner: $7,500

The solution of the second case is given in Figure 5-4. The results show that the objective function (the total annual cost of the system), increases to $38,971.00 due to high unit costs in spite of the decrease in the fixed costs. One of the results worthy of note is that the total amount of OA recommended in Case 2 is only 38-cfm/person. The solution shows that due to increased unit prices for bringing OA into the building, the savings expected by the increase in productivity is not high enough to encourage a further increase in the ventilation rate. According to Figure 5-5, bringing 38-cfm/person OA by using the central unit and cleaning 38-cfm/person air by cleaner in location 3, provides the optimum cost. The reason the model chooses to use the central unit rather than the dedicated unit in both cases is because of the fixed costs associated with them. Although the unit cost of air brought by the dedicated unit seems to be cheaper, it is not economical enough to compensate the $5,000.00 difference in the fixed costs of these systems.

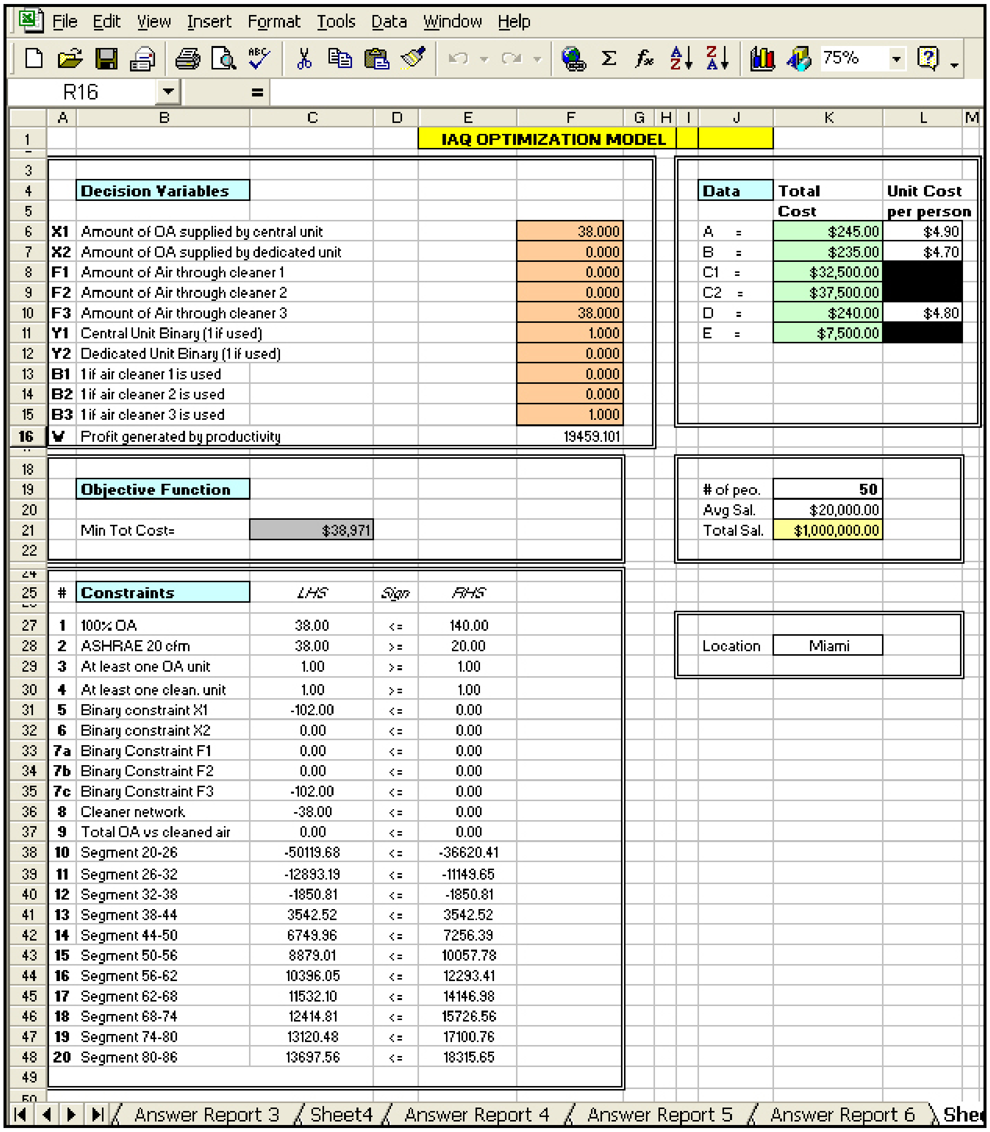


Figure 5-4. Case 2–MS Excel ® screen for solution.

The binding and not binding constraints are listed in Figure 5-5. The results for the decision variables would stay the same as long as the binding state of the constraints stay the same. Once the change in the input values cause a change in the binding status of a constraint, the optimum solution for the model shifts to another extreme point and thus may change the values of the decision variables. This research discusses the “what if” questions regarding both cases in the sensitivity analysis section.

Target Cell (Min)

Cell	Name	Original Value	Final Value
$C$21	Min Tot Cost=	$38,971	$38,971

Adjustable Cells

Cell	Name	Original Value	Final Value
$F$6	Amount of OA supplied by central unit	38.000	38.000
$F$7	Amount of OA supplied by dedicated unit	0.000	0.000
$F$8	Amount of Air through cleaner 1	0.000	0.000
$F$9	Amount of Air through cleaner 2	0.000	0.000
$F$10	Amount of Air through cleaner 3	38.000	38.000
$F$11	Central Unit Binary (1 if used)	1.000	1.000
$F$12	Dedicated Unit Binary (1 if used)	0.000	0.000
$F$13	1 if air cleaner 1 is used	0.000	0.000
$F$14	1 if air cleaner 2 is used	0.000	0.000
$F$15	1 if air cleaner 3 is used	1.000	1.000
$F$16	Profit generated by productivity	19459.101	19459.101

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$C$27	100% OA LHS	38.00	$C$27<=$E$27	Not Binding	102
$C$29	At least one OA unit LHS	1.00	$C$29>=$E$29	Binding	0.00
$C$30	At least one clean. unit LHS	1.00	$C$30>=$E$30	Binding	0.00
$C$31	Binary constraint X1 LHS	-102.00	$C$31<=$E$31	Not Binding	102
$C$32	Binary constraint X2 LHS	0.00	$C$32<=$E$32	Binding	0
$C$33	Binary Constraint F1 LHS	0.00	$C$33<=$E$33	Binding	0
$C$34	Binary Constraint F2 LHS	0.00	$C$34<=$E$34	Binding	0
$C$35	Binary Constraint F3 LHS	-102.00	$C$35<=$E$35	Not Binding	102
$C$36	Cleaner network LHS	-38.00	$C$36<=$E$36	Not Binding	38
$C$37	Total OA vs cleaned air LHS	0.00	$C$37<=$E$37	Binding	0
$C$38	Segment 20-26 LHS	-50119.68	$C$38<=$E$38	Not Binding	13499.2672
$C$39	Segment 26-32 LHS	-12893.19	$C$39<=$E$39	Not Binding	1743.53387
$C$40	Segment 32-38 LHS	-1850.81	$C$40<=$E$40	Binding	0
$C$41	Segment 38-44 LHS	3542.52	$C$41<=$E$41	Binding	0
$C$42	Segment 44-50 LHS	6749.96	$C$42<=$E$42	Not Binding	506.437328
$C$43	Segment 50-56 LHS	8879.01	$C$43<=$E$43	Not Binding	1178.76954
$C$44	Segment 56-62 LHS	10396.05	$C$44<=$E$44	Not Binding	1897.36677
$C$45	Segment 62-68 LHS	11532.10	$C$45<=$E$45	Not Binding	2614.8748
$C$46	Segment 68-74 LHS	12414.81	$C$46<=$E$46	Not Binding	3311.75019
$C$47	Segment 74-80 LHS	13120.48	$C$47<=$E$47	Not Binding	3980.28079
$C$48	Segment 80-86 LHS	13697.56	$C$48<=$E$48	Not Binding	4618.09841
$C$28	ASHRAE 20 cfm LHS	38.00	$C$28>=$E$28	Not Binding	18.00
$F$11	Central Unit Binary (1 if used)	1.000	$F$11=binary	Binding	0.000
$F$12	Dedicated Unit Binary (1 if used)	0.000	$F$12=binary	Binding	0.000
$F$13	1 if air cleaner 1 is used	0.000	$F$13=binary	Binding	0.000
$F$14	1 if air cleaner 2 is used	0.000	$F$14=binary	Binding	0.000
$F$15	1 if air cleaner 3 is used	1.000	$F$15=binary	Binding	0.000

Figure 5-5. Case 2-Answer sheet generated by MS Excel Solver ®.

Sensitivity Analysis

Sensitivity analysis is a procedure to determine the sensitivity of the outcomes of an alternative to changes in its parameters. If a slight change in a parameter results in relatively large changes in the results, the results are considered to be sensitive to that parameter. This may mean that the parameter has to be determined very precisely or that it has to be reconfigures for a lower sensitivity. One of the challenges in creating the sensitivity analysis report by using MS Excel Solver ® is that the reports generated for problems that involve integer constraints are not meaningful. In order to get the sensitivity report from the solver, after solving the problem, the results for the binary variables can be plugged in directly. It is also important to take the binary variables from the list of decision variables in the solver module. Binary constraints also should be removed from the constraints section in the solver window. After executing the above steps the model will not be considered to be an integer programming, thus a sensitivity report can be generated by MS Excel Solver ®.

The sensitivity report for Case 1 is given in Figure 5-6. According to the "Allowable Increase/Decrease" columns, provided the coefficient of X_1 in the objective function lies between 170+78.86=248.86 and 170-5.55=164.45, the values of the variables in the optimal LP solution will remain unchanged. Similarly, if the coefficient of X_2 goes above 160+10=170 then the model will not be valid anymore and will need to be solved again with the new coefficient values. However it is important to note that the actual optimal solution value will change as the objective function coefficient of X_1 or X_2 are changing. If the coefficient of W (profit from increased productivity) lies between –1+0.19=–0.81 and –1–0.02=–1.02 the values for the decision variables would remain the same.

If the right hand side value of the total maximum OA constraint, which forces the total amount of OA below 140-cfm/person, stays above 140–96=44, the value of the decision variables will remain unchanged. Similarly, if the right hand side value of the ASHRAE constraint stays below 20+24=44, the results of the solution would remain unchanged.

Adjustable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$F$6	Amount of OA supplied by central unit	44.00	0.00	170.00	78.86	5.55
$F$7	Amount of OA supplied by dedicated unit	0.00	0.00	160.00	10.00	1E+30
$F$8	Amount of Air through cleaner 1	0.00	0.00	170.00	0.00	1E+30
$F$9	Amount of Air through cleaner 2	0.00	0.00	170.00	0.00	1E+30
$F$10	Amount of Air through cleaner 3	44.00	0.00	170.00	78.86	0.00
$F$16	Profit generated by productivity	21972.25	0.00	-1.00	0.19	0.02

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$C$27	100% OA LHS	44.00	0.00	140.00	1E+30	96.00
$C$28	ASHRAE 20 cfm LHS	44.00	0.00	20.00	24.00	1E+30
$C$29	At least one OA unit LHS	1.00	0.00	1.00	0.00	1E+30
$C$30	At least one clean. unit LHS	1.00	0.00	1.00	0.00	1E+30
$C$31	Binary constraint X1 LHS	-96.00	0.00	0.00	1E+30	96.00
$C$32	Binary constraint X2 LHS	0.00	-10.00	0.00	44.00	0.00
$C$33	Binary Constraint F1 LHS	0.00	0.00	0.00	22.00	0.00
$C$34	Binary Constraint F2 LHS	0.00	0.00	0.00	22.00	0.00
$C$35	Binary Constraint F3 LHS	-96.00	0.00	0.00	1E+30	96.00
$C$36	Cleaner network LHS	-44.00	0.00	0.00	1E+30	44.00
$C$37	Total OA vs cleaned air LHS	0.00	-170.00	0.00	44.00	96.00
$C$38	Segment 20-26 LHS	-58592.66	0.00	-36620.41	1E+30	21972.25
$C$39	Segment 26-32 LHS	-15488.30	0.00	-11149.65	1E+30	4338.65
$C$40	Segment 32-38 LHS	-2702.38	0.00	-1850.81	1E+30	851.58
$C$41	Segment 38-44 LHS	3542.52	-0.07	3542.52	317.57	506.44
$C$42	Segment 44-50 LHS	7256.39	-0.93	7256.39	202.05	506.44
$C$43	Segment 50-56 LHS	9721.61	0.00	10057.78	1E+30	336.17
$C$44	Segment 56-62 LHS	11478.18	0.00	12293.41	1E+30	815.23
$C$45	Segment 62-68 LHS	12793.62	0.00	14146.98	1E+30	1353.36
$C$46	Segment 68-74 LHS	13815.70	0.00	15726.56	1E+30	1910.86
$C$47	Segment 74-80 LHS	14632.79	0.00	17100.76	1E+30	2467.97
$C$48	Segment 80-86 LHS	15300.98	0.00	18315.65	1E+30	3014.67

Figure 5-6. Case 1–MS Excel Solver ® sensitivity report

The sensitivity report for Case 2 is given in Figure 5-7. According to the report, the "Allowable Increase/Decrease" columns indicate that, provided the coefficient of X_1 in the objective function lies between 245+75.79=320.79 and 245–10=235, the values of the variables in the optimal LP solution will remain unchanged. Also, if the coefficient of X_2 stays below 235+10=245, the values for the decision variables would not change. However it is important to note that for the ranges mentioned above, the actual optimal solution value would change as the objective function coefficient of X_1 or X_2 is changing. Similarly, if the coefficient of the decision variable, W lies between –1+0.14=–0.86 and

–1–0.16=–1.16 the solution to the model will still remain valid while the objective function value changing.

If the right hand side value of the ASHRAE constraint, which forces the total amount of OA above 20-cfm/person, stays below 20+18=38, the value of the decision variables will remain unchanged. Also, if the right hand side value of the maximum total OA constraint stays above 140-102=38, the results of the case would remain the same.

Adjustable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$F$6	Amount of OA supplied by central unit	38.00	0.00	245.00	75.79	10.00
$F$7	Amount of OA supplied by dedicated unit	0.00	0.00	235.00	10.00	1E+30
$F$8	Amount of Air through cleaner 1	0.00	0.00	240.00	0.00	1E+30
$F$9	Amount of Air through cleaner 2	0.00	0.00	240.00	0.00	1E+30
$F$10	Amount of Air through cleaner 3	38.00	0.00	240.00	75.79	0.00
$F$16	Profit generated by productivity	19459.10	0.00	-1.00	0.14	0.16

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$C$27	100% OA LHS	38.00	0.00	140.00	1E+30	102.00
$C$28	ASHRAE 20 cfm LHS	38.00	0.00	20.00	18.00	1E+30
$C$29	At least one OA unit LHS	1.00	0.00	1.00	0.00	1E+30
$C$30	At least one clean. unit LHS	1.00	0.00	1.00	0.00	1E+30
$C$31	Binary constraint X1 LHS	-102.00	0.00	0.00	1E+30	102.00
$C$32	Binary constraint X2 LHS	0.00	-10.00	0.00	38.00	0.00
$C$33	Binary Constraint F1 LHS	0.00	0.00	0.00	19.00	0.00
$C$34	Binary Constraint F2 LHS	0.00	0.00	0.00	19.00	0.00
$C$35	Binary Constraint F3 LHS	-102.00	0.00	0.00	1E+30	102.00
$C$36	Cleaner network LHS	-38.00	0.00	0.00	1E+30	38.00
$C$37	Total OA vs cleaned air LHS	0.00	-240.00	0.00	38.00	102.00
$C$38	Segment 20-26 LHS	-50119.68	0.00	-36620.41	1E+30	13499.27
$C$39	Segment 26-32 LHS	-12893.19	0.00	-11149.65	1E+30	1743.53
$C$40	Segment 32-38 LHS	-1850.81	-0.47	-1850.81	572.14	851.58
$C$41	Segment 38-44 LHS	3542.52	-0.53	3542.52	317.57	851.58
$C$42	Segment 44-50 LHS	6749.96	0.00	7256.39	1E+30	506.44
$C$43	Segment 50-56 LHS	8879.01	0.00	10057.78	1E+30	1178.77
$C$44	Segment 56-62 LHS	10396.05	0.00	12293.41	1E+30	1897.37
$C$45	Segment 62-68 LHS	11532.10	0.00	14146.98	1E+30	2614.87
$C$46	Segment 68-74 LHS	12414.81	0.00	15726.56	1E+30	3311.75
$C$47	Segment 74-80 LHS	13120.48	0.00	17100.76	1E+30	3980.28
$C$48	Segment 80-86 LHS	13697.56	0.00	18315.65	1E+30	4618.10

Figure 5-7. Case 2-MS Excel Solver ® sensitivity report

The sensitivity reports given in Figure 5.6 and 5.7 provide a number of informational data about the range of validity of the model. However it does not include clear data regarding the effect of the demographic data. In order to see the impacts of these user-defined values on the results, the model is solved for a number of times to explore some thresholds values.

As a result, it is observed that in Case 1, changing the number of occupants does not change the optimal values of variables. However it changes the total cost of the system. One of the threshold values of the number of occupants is 306. If the number of occupants is more than 306, the total cost starts taking negative values as long as the fixed costs remain the same. This means that, for Case 1, when the number of occupants goes above 306, the owner can compensate the cost of the system in the first year and can start making a profit. To generalize, in Case 1 the number of occupants has an indirect correlation with the total annual cost of the system.

In Case 1, if the average salary of the occupants in the building does not stay between $16,235.00 and $20,331.00, the values for the decision variables do not stay optimal anymore. This means the model with a new total salary beyond this range needs to be solved again in order to find the new objective value and more importantly the new values for decision variables. This is mainly due to the shift of the optimum extreme point to a different extreme point, which happens when at least one of the constraints changes its state of being binding or not binding. In general if the total salary of the occupants increases, the objective function (the total cost of the system) decreases due to the increase in total savings by increased productivity.

It is observed that in Case 2 changing, the number of occupants does not change the optimal values of variables. However it changes the total cost of the system. The threshold value of the number of occupants for Case 2 is above 1000 people. This means that in this case it is almost impossible for the owner to start making profit due to limitations avoiding to exceed the number of occupants allowed in a commercial building. However in Case 2, the number of occupants has an indirect correlation with the total annual cost of the system (objective function).

In Case 2, if the average salary of the occupants in the building stays between \$17,298.00 and \$23,158.00, the values for the decision variables remain the same. This means that the model with a value outside of this range needs to be solved again in order to find the new objective value and the new values of the decision variables. This is mainly due to the shift of the optimum extreme point to a different extreme point, which happens when at least one of the constraints changes its state of being binding or not binding. In general if the total salary of the occupants increases, the objective function (the total cost of the system) decreases due to the increase in total savings by increased productivity. In general for both cases, if the total salary of the occupants increases, the objective function (the total cost of the system) decreases.

Summary of Chapter

The solution to the optimization problem is generated by the use of MS. Excel Solver ®. In order to generate the solution, two imaginary cases are developed. The parameters associated with each case are plugged in the spreadsheet and the model is solved. The results showed that the ASHRAE minimum requirement of 20-cfm/person OA might not always be the optimum decision in all cases when the productivity costs are taken into consideration. The solution to Case 1 indicates that 44 cfm/person would provide the most optimum solution for that specific case. Also the results of the Case 2 showed that using less efficient equipment would increase the total cost of IAQ control system while decreasing the amount of OA brought into the building. The results in this chapter also included the sensitivity reports and generated the correlations among the number of occupants, total cost of the system, and the total salary of the occupants in a building.

CHAPTER 6
CONCLUSION

Planning, design, and construction work should be based not on tight but on generous estimates as regards the time required for each phase. An extensive reserve capacity should be designed and built into the building and its systems. Indoor air quality is a crucial part of the efforts towards more sustainable systems in construction and building technologies. The benefits of a better IAQ are widely known although the quantity of potential savings has not been very clear to a majority of the audience. This problem causes the building owners and managers, architects, or the contractors to choose systems and options that increase energy efficiency and decrease the hard costs which eventually decrease IAQ in their buildings.

This study develops an optimization model that takes the operation and maintenance costs of a better IAQ into account, combines them with potential soft cost savings and quantifies the true cost of a system under different circumstances. This study demonstrates that an optimization study by using linear programming can be used to pre-screen the optimal IAQ measures in commercial buildings in Florida. As a result, this study shows that meeting the minimum code recommendations may not always create the most optimum cost saving results. It is also clear that there is an indirect relationship between the total salary and the total cost of an IAQ system when the initial cost of the system is held constant. The same indirect relationship is also observed between the number of the occupants and the total cost of the system in commercial buildings when the fixed costs are held constant.

The model uses mixed integer linear programming to generate the optimization study. One of the advantages of linear programming is the simplicity and the speed of the solution generation. However, it has been discussed earlier that there are several matters in this area that have non-linear correlations. This study mostly deals with the nonlinear functions by piece-wise linearization with underestimating. Future studies may consider configuring a nonlinear optimization problem that concentrates more on the correlations among productivity, air cleaning, and ventilation. However this would also require more studies developing realistic data for the effects of air cleaning and ventilation on productivity. Future research should also concentrate on the correlation between ventilation and air cleaning, which when proved would transform a linear objective function to a non-linear function. Users with different specific cases can also consider re-evaluating the constraints list provided in this study. The constraints regarding air velocity, noise, and many more can be easily integrated in the model to represent more accurate scenarios.

Future studies may also concentrate on including other soft costs introduced in this study but excluded from the model due to their stochastic nature such as litigation and health related costs. Thus stochastic modeling studies may be conducted towards an improved financial representation of the benefits of a better IAQ in commercial buildings. Integrating marginal cost calculation methodologies into spreadsheet would be a very useful contribution towards improving the proposed optimization model. Also integration of the developed optimization models for IAQ into the green building assessment tools such as LEED™ would strengthen the foundation of building assessment methods.

The significance of the presented methodology derives from the determination of the optimum IAQ measures for commercial buildings. Another significant contribution of this research is introducing the idea of applying operations research methodologies in the sustainable construction area. The methodology studied in this research can be used as a basis for similar building-related decisions such as buildings with different sizes, occupation, location, climate, business structure or different management problems. This study is unique in terms of utilizing the mixed integer linear programming in sustainable construction-related managerial decisions. Studies adapting the proposed optimization model would contribute to the current sustainable building research by quantifying the benefits of better IAQ. This model also contributes to the clarification of arguments on the conflicts among IAQ and energy efficiency issues, which would eventually help promote sustainable buildings.

APPENDIX A
WORKSHEETS

This section includes 6 worksheets that are adapted from an EPA study introduced earlier (Henschel 1999). The worksheets are slightly modified and simplified for more specific use.

Worksheet 1. Estimating the installed costs for increased OA (Central units)[6]

1. Enter incremental increase in OA intake _____________ cfm

2. Enter the required cooling and heating capacity required for the HVAC unit in the building, to treat the increased OA (Refer to Table 4.1)

2a. Cooling capacity ______tons/1000 cfm

2b. Heating capacity ______ kW/1000cfm

3. Compute the incremental additional cooling capacity required for the HVAC unit to treat the increased OA (Line 1 x Line 2a ÷ 1000) ________tons

4. Enter the incremental cost per ton of increased cooling capacity corresponding to the capacity of HVAC unit.
($1250 if cooling capacity range between 0-20 tons)
($1120 if cooling capacity range is > 20 tons) $________/ton

[6] For systems with economizers where the required OA increase can be achieved without enlarging the OA intake duct and without increasing the dimensions of the central exhaust ducting compared to initial design.

5. Compute the estimated incremental increase in the installed costs to provide increased cooling capacity. (Line 3 x Line 4) $ _________

6. Compute the incremental additional heating capacity for the HVAC unit in the building, to treat the increased OA.
(Line 1 x Line 2b ÷ 1000) _________kW

7. Enter the incremental cost per ton of increased heating capacity corresponding to the capacity of the HVAC unit.
($95 if heating capacity range is between 0-10 kW)
($75 if heating capacity range is between 11-20 kW)
($50 if heating capacity range is between 21-40 kW)
($30 if heating capacity range is between 41-100 kW)
($18 if heating capacity range is > 100 kW) $_______/kW

8. Compute the estimated incremental increase in the installed cost of the HVAC unit to provide increased heating capacity.
(Line 6 x Line 7) $ __________

9. Enter the total incremental increase in installed cost resulting from the specification of an HVAC system having a greater cooling and heating capacity. (Line 5 + Line 8) $ __________

Worksheet 2. Estimating the installed costs for increased OA (dedicated OA unit)[7]

1. Enter the total OA intake rate that is required for the building. _________ cfm

2. Enter the required cooling capacity per 1000 cfm OA for the climate of the city building is located. (Refer to Table 4.1) _____ tons/1,000 cfm

3. Compute the total cooling capacity required to treat the increase in OA flow into the building. (Line 1 x Line 2 ÷ 1000) __________ tons

4. Enter the total cost per ton of increased cooling capacity corresponding to the capacity of HVAC unit.
($1500 if cooling capacity range between 0-5 tons)
($1250 if cooling capacity range is > 6 tons) $ __________

5. Compute the estimated total installed costs of HVAC unit (excluding heating). (Line 3 x Line 4) $ __________

6. Enter the required heating capacity per 1000 cfm OA for the climate of the user's city. (Refer to Table 4-1) ______ kW/1000 cfm

7. Compute the total heating capacity required to treat the increased OA flow into the building. (Line 1 x Line 6 ÷ 1000) __________ kW

8. Enter the total installed cost per kW of installing the required heating capacity into the dedicated-OA unit.
($125 if heating capacity range is between 0-10 kW)
($80 if heating capacity range is between 11-20 kW)

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[7] It is assumed that a single rooftop direct expansion HVAC unit is installed, dedicated to treating the total OA flow being supplied to the building.

($50 if heating capacity range is between 21-40 kW)

($30 if heating capacity range is between 41-100 kW)

($18 if heating capacity range is > 100 kW) $_________/kW

9. Compute the total installed cost of incorporating the required heating capacity into the dedicated OA unit. (Line 7 x Line 8) $__________

10. Compute the total cost of the new dedicated-OA unit treating the total OA flow entering the building. (Line 5 + Line 10) $__________

Worksheet 3. Estimation of Annual Operating Costs for Increased OA

1. Enter the incremental increase in OA intake rate that is required for the entire building, beyond the originally designed rate (use 1 cfm for a unit cost). __________ cfm

2. Enter the overall Energy Efficiency Ratio (EER) for the cooling system in the building. (As default, assume EER=10 Btu/h/W) (If the compressor/condenser of the cooling system is driven by a source other than an electric motor, system efficiency should be expressed in the appropriate units of Btu/hr cooling output per unit energy input. ______Btu/h/W

3. Enter the overall efficiency of the heating system in the building.
(As default, assume an efficiency of 1.0 for electricity and 0.7 for gas or oil.) _____Btu/h per Btu/h

4. Enter the unit costs of the applicable utilities used as energy sources in the building:

4a. Cost of electricity, if applicable (Default: $0.09/kWh) ________$/kWh

4b. Cost of natural gas, if applicable (Default: $0.7/therm) ________$/therm

4c. Cost of fuel oil, if applicable (Default: $2.2/gal) _________$/gal

5. Enter the average number of hours per day, and the days per week, that OA is being supplied to the building.

5a. Hours per day ________hours/day

5b. Days per week ______days per week

6. Enter the value for the annual cooling energy that is required by the air stream, per incremental cfm of OA (Refer to Table 4-2) _______Btu/yr/cfm

7. Table 4-2 is based on operation at 13 hours/day and 5 days/week. If the user's system operates on a significantly different cycle, correct the figure on Line 6.

(Line 6) x (Line 5a ÷13) x (Line 5b ÷ 5) ________Btu/yr/cfm

8. Calculate the total energy input required to the cooling system, considering system efficiency:

(Line 1) x (Line 7) ÷ (Line 2) ÷ 1000 W/kW

[Note: The form of this equation assumes that the cooling system is driven by a compressor having an electric motor, that Line 8 thus has the units of kWh/yr. If this is not the case, modify the units of Line 2 (and thus of Line 9) accordingly] ________kWh/yr

9. Calculate the annual energy cost associated with cooling the incremental additional OA: (Line 8) x (Line 4a) $_______/yr

10. Enter the value for the annual heating energy that is required by the air stream, per incremental cfm of OA (Refer to Table 4-2) ________Btu/yr//cfm

11. Correct the annual heating energy on Line 10 if the user's system operates on a significantly different cycle from 13 hr/day, 5 days/week:

(Line 10) x (Line 5a ÷ 13) x (Line 5b ÷ 5) ________Btu/yr/cfm

12. Calculate the total energy input required to the heating system, considering system efficiency:

(Line 1) x (Line 11) ÷ (Line 3) __________Btu/yr

13. Compute the amount of input energy to the system that is required to provide the Btu's indicated on Line 12:

13a. Line 12 x (1 kWh/3413 Btu) (electric heat) __________kWh/yr

13b. Line 12 x (1 therm/100,000 Btu) (gas heat) _________therms/yr

13c. Line 12 x (1 gal/140,000 Btu) (fuel oil heat) _________gal/yr

14. Calculate the annual energy cost associated with heating the incremental additional OA (Line 13a x Line 4a for electric; Line 13b x Line 4b for gas; Line 13c x Line 4c for oil) $___________/yr

15. Calculate the total annual energy cost associated with cooling and heating the incremental additional OA (Line 9 + Line 14) $___________/yr

Worksheet 4. Estimation of annual maintenance costs for increased OA

1. Enter the number of new OA intake fans, if applicable. ________fans

2. Enter the number of new central exhaust fans, if applicable ________ fans

3. Enter the total number of new fans, if applicable _________fans

4. Enter the estimated additional maintenance labor hours per year per new fan. (Default: 5 hours/year/fan) _______hr/yr/fan

5. Enter the estimated hourly labor rates for fan maintenance personnel. $________/hr

6. Compute the annual maintenance cost increase for additional fans (Line 3 x Line 4 x Line 5) $_______ /yr

7. Enter the number of new dedicated-OA units, if applicable _______ units

8. Enter the estimated additional maintenance labor hours per year per new dedicated-OA unit. (Default 20 hours/yr//unit) ________hr/yr/unit

9. Enter the estimated hourly labor rates for HVAC maintenance personnel. $ ________/hr

10. Compute the annual maintenance cost increase for the new dedicated-OA units. (Line 7 x Line 8 x Line 9) $________/yr

11. Compute the total incremental annual maintenance cost associated with the increase in OA ventilation rate (Line 6 + Line 10, as applicable) $_________/yr

Worksheet 5. Estimation of total annualized costs for increased OA

1. Enter the total installed cost of the equipment required for the increase in ventilation rate. $__________

   Obtain this value from:

   Worksheet 1, Line 9 or Worksheet 2, Line 10

2. Enter the total incremental annual operating cost associated with the increase in ventilation rate (Worksheet 3, Line 15) $__________/yr

3. Enter the total incremental annual maintenance cost associated with the increase in ventilation rate (Worksheet 4, Line 11) $__________/yr

4. Enter the equipment lifetime, n, that will be assumed for these calculations (commonly 10 or 20 years) __________yr

5. Enter the annual interest rate, i, that will be assumed for these calculations. __________%

6. Using the values n and i, calculate the appropriate value for CRF by using Formula 4.2 in Chapter 4. ___________

7. Compute the average annual capital charge (Line 1 x Line 6) $_________/yr

8.Compute the annual operating and maintenance (O&M) costs associated with the increase in ventilation rate (Line 2 +Line 3) $________/yr

9. Compute the total annualized cost associated with the increase in OA ventilation rate (Line 7 + Line 8) $ ________/yr

Worksheet 6. Estimation of annual operating costs for central indoor air cleaners

1. Enter the total flow through the air cleaner _________ cfm

2. Enter the number of hours per year that the central air handler (and the indoor air cleaner) will be operating. (Default: 3,276 hr/yr, for 13 hr/day, 5 days/week, excluding holidays) ________ hr/yr

3. Enter the unit cost of electricity (Default: \$0.09/kWh) \$________/kWh

4. Enter the Electric Input Ratio (EIR) for the cooling system on which the air cleaner is to be installed. (Default: 0.34 kW/kW) ________kW/kW

5. Enter the overall energy efficiency of the central air handler. (Default: 0.50 for fans<1000 cfm or 0.65 for fans>1000 cfm) ________hp out/hp in

6. Enter the average pressure drop across the filter over its lifetime (ranging from unloaded at the outset, to completely loaded with collected particulate prior to replacement of the media) (Default: 1 in. WG) _______ in. WG

7. Compute the required incremental additional power input to the fan/motor, required to enable the flow on Line 1 to overcome the added pressure drop identified in Line 6. (Line 1) x (Line 6) x [(5.19 lb/ft^2)/(in.WG)] x [(1 hp)/(33,000 ft-lb/min)] ÷ (Line 5) _______ hp in

8.Compute the incremental annual energy consumption resulting from the added fan power: ________kWh/yr

(Line 7) x (0.746 kW/hp) x (Line 2)

9. Compute the incremental annual energy cost associated with the increased fan power required to handle the filter pressure drop: (Line 8) x (Line 3) $ ________/yr

10. Compute the incremental additional energy input required to the cooling system, to remove the additional heat created by this increase in fan power. ________kWh/yr

11. Compute the incremental annual energy cost associated with the increased cooling energy consumption necessitated by the increase in fan power. (Line 10 x Line 3) $_________/yr

12. Compute the total incremental annual operating cost associated with the addition of a media filter for indoor particulate control (Line 9 + Line 11) $_________/yr

APPENDIX B
MS EXCEL SOLVER

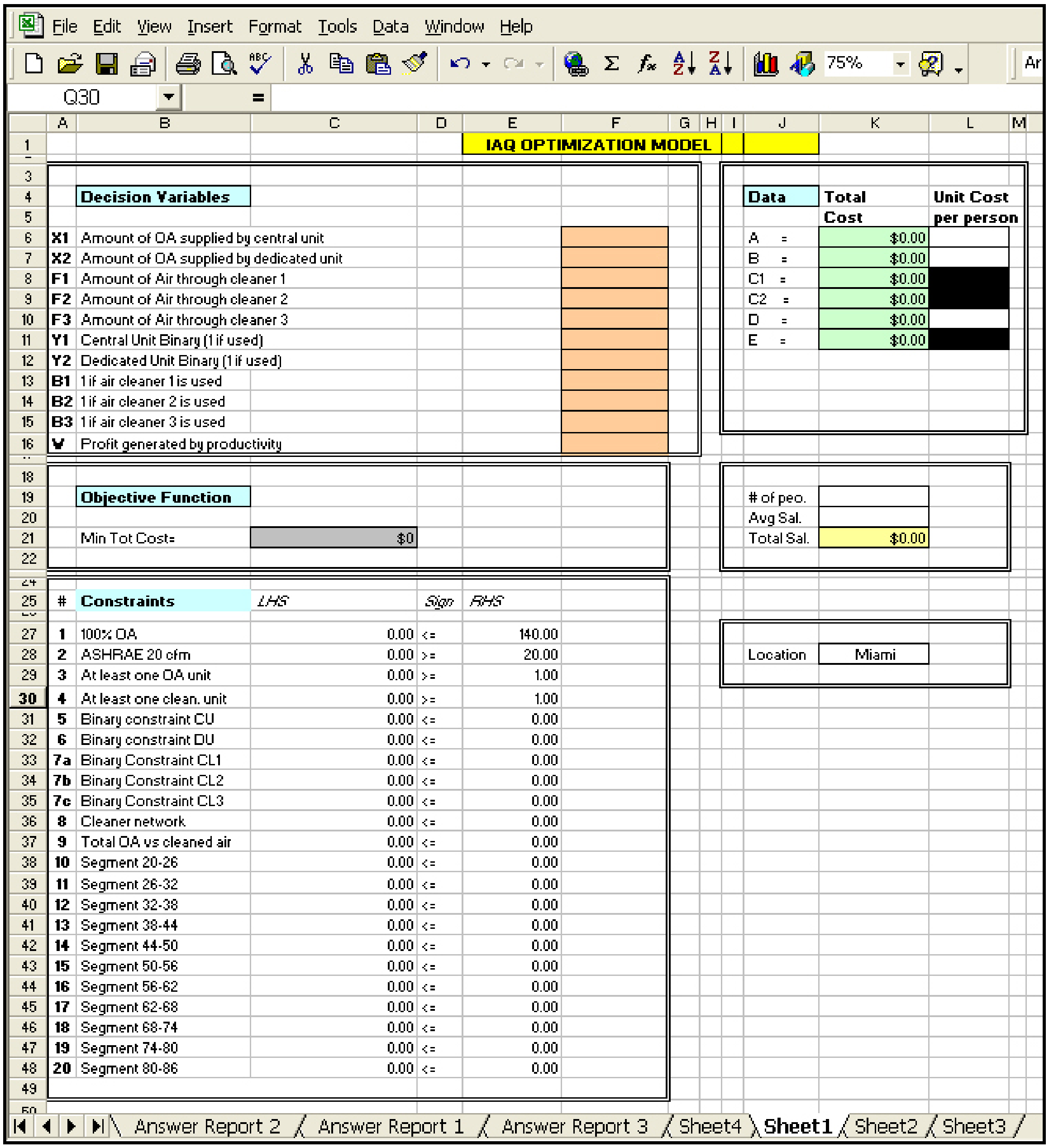

Figure B-1. MS Excel screen that shows the configuration of the variables, constraints, and the objective function on a spreadsheet.

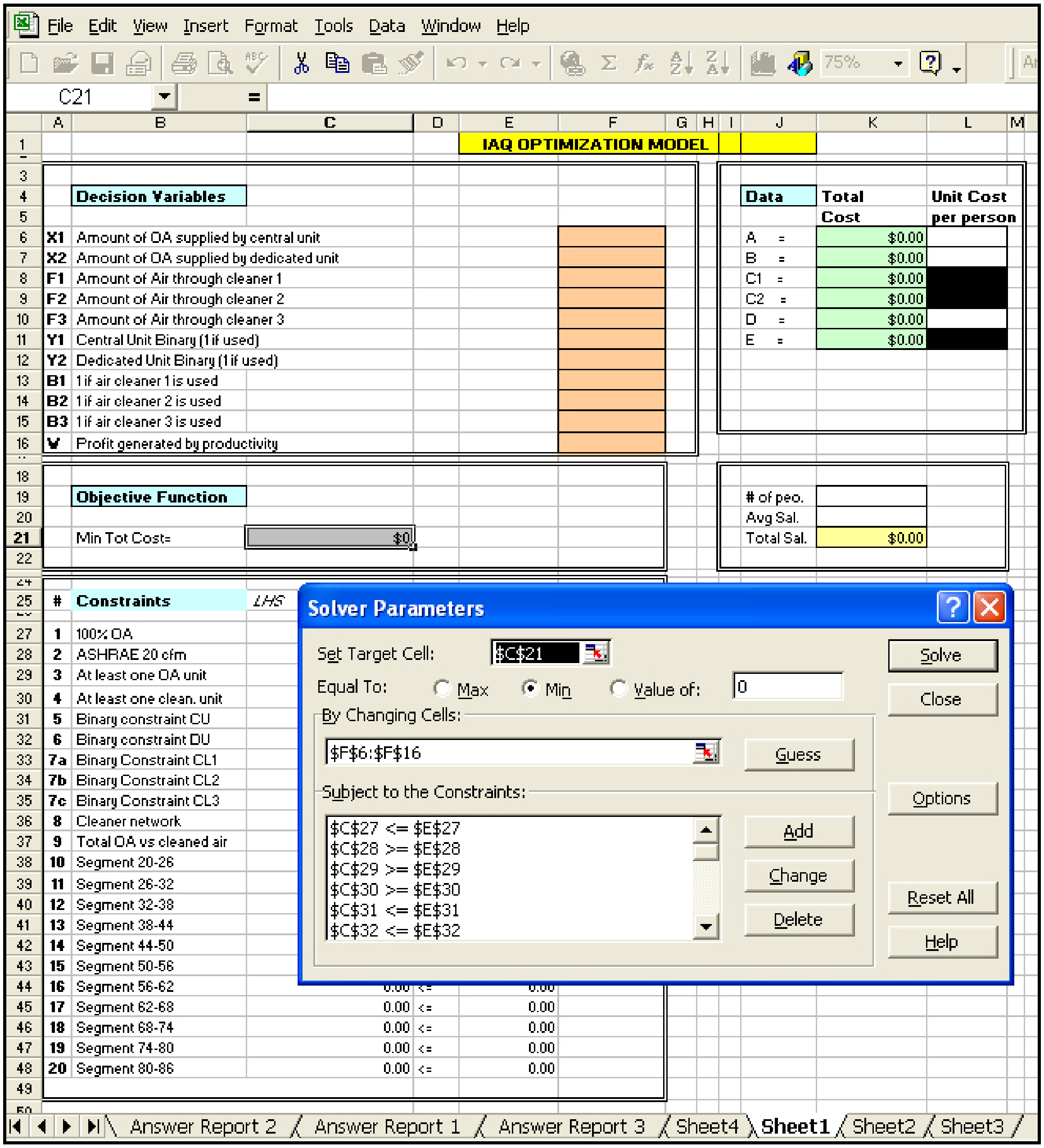

Figure B-2. MS Excel and Solver screen showing the integration of objective function and the constraints in to the Solver module.

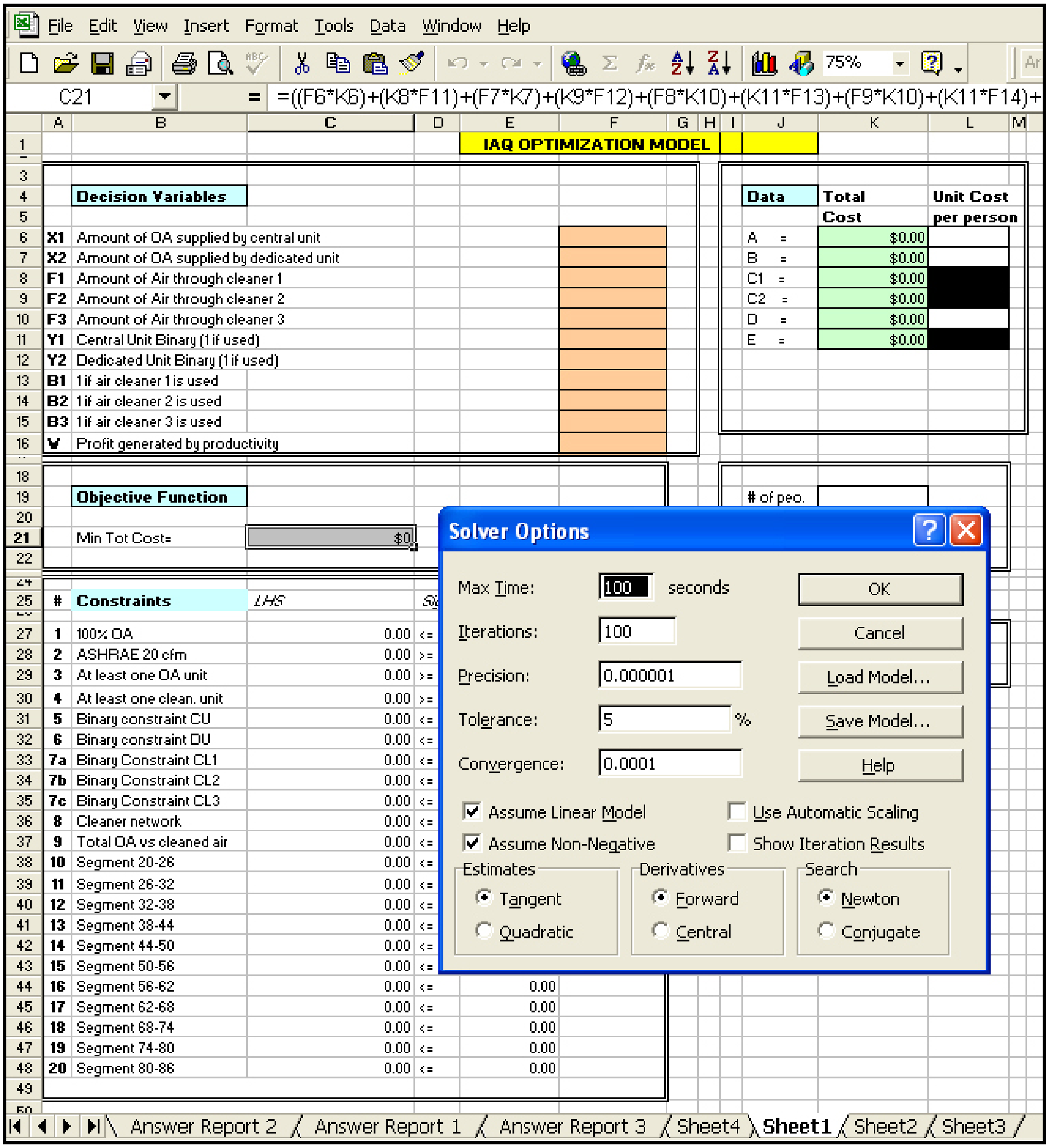

Figure B-3. MS Excel screen and the options menu of the Solver module.

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BIOGRAPHICAL SKETCH

Bilge Gokhan Celik was born in Monterey, California, on April 1978. He has graduated from Anadolu University in Turkey in 2000 with a bachelor's degree in architecture. He has completed his Master of Science degree in the Natural and Applied Sciences Institute of Anadolu University in 2002 with a major in architecture and a minor in building construction.

Since 2000, Bilge Gokhan Celik has worked on many architectural as well as construction, preservation and interior design projects in Turkey, and in the USA. Bilge Gokhan Celik has also worked as a graduate research/teaching assistant in both Anadolu University and the University of Florida. Bilge Gokhan Celik has been studying for his Doctor of Philosophy degree in the School of Building Construction at the College of Design, Construction, and Planning since 2002.