

**ASSURANCE OF INDOOR ENVIRONMENTAL QUALITY
THROUGH BUILDING DIAGNOSTICS
AT SCHEMATIC DESIGN**

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Assurance Of Indoor Environmental Quality Through Building Diagnostics At Schematic Design

A. Susanne Metzger

(ABSTRACT)

With increasing knowledge about the indoor climate in recent years, preventive methods to avoid health problems caused by deficient building performance may become preferable to reactive methods. Benefits from preventive actions have been suggested for late building design phases, construction, and building operations, however, few data are available that demonstrate the benefits of preventive actions in early planning phases.

In a case study, expected building performance in respect to indoor air quality and thermal conditions in a large judicial facility in North America was evaluated retrospectively at the end of the schematic design and substantial completion phases. A process for evaluation of building performance at schematic design is developed from existing procedures for building diagnostics in operating buildings. Criteria for evaluation of expected building environmental quality at schematic design as available from standards and guidelines are presented.

The results of the study show that building diagnostics at schematic design can be an effective mean of prevention of occupant health problems. Further findings indicate that the assurance of indoor environmental quality can be improved, if the criteria for expected building performance are defined and complied with from early on. It is concluded that implementation of building diagnostics in early project phases can reduce the likelihood of adverse health effects in operating buildings.

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1.1 Problem Statement

Occupant exposure to microbial, chemical and building-physical factors in indoor environments can lead to a series of health symptoms ranging from discomfort to clinical disease. The measures for removal of the causes of adverse exposure and for improvement of building system performance can be excessive and cost intensive, and there is no guarantee that occupant health symptoms after mitigation will have disappeared.

There is evidence from studies of problem buildings that omissions in the design phase, namely in the design specifications, site planning, building systems planning and occupancy planning have caused or contributed to the problems with the quality of the indoor climate.

While the strategic advantage for quality assurance of industrial products in the early design phases has been acknowledged, the potential of providing for occupant well-being in the early stages of building design has not been recognized. In early planning phases, requirements for the prospective building are defined, and the basic concept for further refinement in later phases is developed. Inadequate selection of systems and materials, and omission of critical information can result in failure to fulfill the requirements for indoor environmental quality. It is therefore possible to enter the construction phase with plans and specifications for a building that will not perform within acceptable limits.

If problems with building performance are to be prevented and costs avoided, omissions have to be detected and corrected as early as possible. In the building operation phase, building diagnostics is used for fault detection and analysis in the system 'occupant-building-building system'. Although it is in practice mainly applied after occurrence of user symptoms, building diagnostics can also be used prior to the operation phase.

Measures for early detection of problems at the early planning stages seem advantageous considering that the expenses for changes are small compared to those in later phases. Since the operation and maintenance criteria are in the process of being developed, the effectiveness of implemented measures can be expected to be high. In addition, planning errors can be detected early, and the transfer of faults in the next planning phase can be prevented.

So far, few data exist to demonstrate the benefits of preventive actions in early planning phases. To improve the knowledge about the potential for prevention of occupant problems through early measures, a method will be developed, and its analytic and predictive capabilities will be evaluated in a case study. The findings are expected to give insight in the controlling factors in the planning for occupant well-being.

1.2 Objectives

The objectives of this thesis are

- a) to improve the level of confidence that a facility will perform as intended
- b) to assess the potential for prevention of occupant health and building performance problems in the early planning phases

1.3 Scope

From procedures for building diagnostics in operating buildings, procedures for application at schematic design are developed. The evaluation criteria are based on requirements for indoor air quality and thermal conditions in buildings intended for human occupancy. The method is tested in a case study in which building performance at schematic design is compared with that at substantial completion. A judicial facility in North America serves as a case study. At the time of evaluation, the facility is completed and operating. The evaluation of building performance is based on available building documents and is conducted in retrospective.

1.4 Approach

The thesis is presented in nine chapters:

In Chapter 1, the thesis is introduced.

In Chapter 2, three kinds of literature are reviewed, literature related to experienced symptoms, to identified causes and to existing control methods. First, the literature of health and building symptoms associated with unintended performance is reviewed, and the extent of the problems is quantified. Then, design omissions that have been identified as sources of problems in investigated problem buildings are reviewed. Finally, existing methods for quality assurance at schematic design are reviewed.

In Chapter 3, the hypothesis is developed and presented, and the expected performance of predictive methods in early planning phases are stated.

In Chapter 4, a method for evaluation of building performance at schematic design is developed for testing of the hypothesis. After analysis of the quality system at schematic design, evaluation criteria and procedures are developed from standards, guidelines and research studies related to the achievement of indoor air quality and thermal conditions. The chapter ends with a description of the method and the procedures.

In Chapter 5, the method is validated in a case study. A building project at schematic design is reviewed using the developed criteria and procedures, and the expected building performance at substantial completion is predicted. The results of an expert review of building performance at substantial completion are reviewed. Then, the hypothesis is tested based on the findings from the case study.

In Chapter 6, the findings are discussed in regard of two fundamental requirements of the method if problems in operating buildings are to be prevented through measures at early planning stages: In the first section, the possibilities of the diagnostic method at schematic design are discussed. In the second section, the performance of the method over time in the prediction of building quality is discussed.

In Chapter 7, conclusions are drawn from the results of the hypothesis testing and from the discussion.

In Chapter 8, recommendations in respect to implementation of the method and assurance of occupant well-being are made.

In Chapter 9, related needs for investigation in future research projects are identified.

The remainder of this thesis contains appendices, references and the author's vita.

2.1 Manifestations of Problems with Indoor Environmental Quality

2.1.1 Occupant Health Symptoms

It is commonly assumed that human life benefits from buildings through added comfort and quality. However, since the 1960's, occupant complaints about building environments have been increasing in number and intensity.¹

The symptoms in complaint buildings are significantly similar in a great variety of facilities. The most frequently reported health problems range from thermal discomfort to irritation of mucous membrane, eye, skin, sinus and throat, and include sensations such as headache, dizziness, fatigue, nausea and allergic reactions.^{2,3,4} Clinical illnesses such as humidifier fever or Legionnaire's disease have also been found. Typically, the symptoms increase gradually in intensity and persist over long time periods.⁵

Based on the experience with the reported health problems in the last three decades, researchers have been able to identify two separate patterns of illness in buildings. These two patterns have been named "Sick Building Syndrome" and "Building-Related Illness".⁶

¹ Stolwijk JAJ. 1984. The "Sick Building" Syndrome. Proceedings of the Third International Conference on Indoor Air Quality and Climate. Swedish Council for Building Research. Stockholm. 1:23-29

² Stolwijk JAJ. 1984. *ibid.*

³ World Health Organization. 1983. Indoor Air Pollutants: Exposure and Health Effects. Copenhagen: WHO Regional Office for Europe.

⁴ Akimenko VV, Anderson I, Lebowitz MD, Lindvall T. 1984. The "Sick" Building Syndrome. Proceedings of the Third International Conference on Indoor Air Quality and Climate. Swedish Council for Building Research. Stockholm. 6:87-97

⁵ World Health Organization. 1983. *ibid.*

⁶ National Research Council. 1987. Indoor Pollutants. National Academy Press. Washington, D.C.

2.1.1.1 “Sick Building Syndrome”

To this date, “Sick Building Syndrome” is still being researched. It is characterized by an absence of physical signs and clinical illness, but can be diagnosed by complaints from affected occupants.

Patients with “Sick Building Syndrome” may suffer from one or several generic signs of illness. Occupant complaints differ in type, frequency and intensity. Typical symptoms are:

2.1.1.1.1 Nasal Symptoms. Occupants complain about nasal stuffiness, nasal irritation and rhinorrhea. Nasal stuffiness disappears after the occupants have left the building. Nasal irritation and rhinorrhea are often experienced in conjunction with allergic reactions or allergies.⁷

2.1.1.1.2 Ocular Symptoms. Patients have dry or itchy eyes without visible inflammation. These symptoms have been attributed to the absence of foam in the eye canthus, decreased stability of the precorneal tear film, and epithelial damage.⁸

2.1.1.1.3 Oropharyngeal Symptoms. These are characterized by dryness of throat without any visible signs of inflammation.⁹

2.1.1.1.4 Cutaneous Symptoms. Occupants complain about dry skin and skin rash on exposed skin surfaces¹⁰. Mitigation of the symptoms is only possible over longer time periods.

2.1.1.1.5 Respiratory Symptoms. Occupants describe these symptoms as “chest tightness” or “difficulty breathing”. The symptoms are related to the lower respiratory tract. The health problems improve after the occupants have left the building.¹¹

2.1.1.1.6 General Symptoms. Occupants report headaches on the forehead, sometimes in conjunction with work-related migraine, and excessive tiredness. Complaints about bad odors and taste are also frequently reported. The symptoms increase with the duration of exposure to the causative agents.¹²

2.1.1.1.7 Constitutional Symptoms. Examples are eczema and sinusitis. The symptoms of sinusitis are running nose and sore throat, and usually resolve after removal of the causative agents. Skin problems are often multi-factorial. Examples are dermatitis, allergic dermatitis,

⁷ European Concerted Action. 1989. Indoor Air Quality and Its Impact on Man. COST Project 613. Environment and Quality of Life. Report No.4. Sick Building Syndrome. A Practical Guide. Commission of the European Communities, Directorate General for Science, Research and Development, Joint Research Centre - Institute for the Environment. Office for Publications of the European Communities. Luxembourg.

⁸ Franck C. 1986. Eye symptoms and signs in buildings with indoor climate problems (“office eye syndrome). *Acta Ophthalmologica* 64. 306-311

⁹ European Concerted Action. 1989. *ibid.*

¹⁰ Rycroft RJG. 1985. Low humidity and microtrauma. *American Journal of Industrial Medicine*. 8., 371-373

¹¹ European Concerted Action. 1989. *ibid.*

¹² European Concerted Action. 1989. *ibid.*

photodermatitis, and irritant dermatitis. Symptoms range from dry, itchy skin to hives and eczema.¹³

2.1.1.2 “Building-Related Illness”

The second group of health problems in buildings is “Building-Related Illness” which includes allergy, non-allergic hypersensitivity reactions, and building-related infections. “Building-Related Illness” is characterized by specific physical signs and clinical illness in affected occupants.

2.1.1.2.1 Building-Related Allergies

Building-related allergies are hypersensitivity reactions in individual occupants. They are based on immunological reactions caused by antibodies or blood cells after contact with an antigen, typically introduced via nose, mouth or skin. Agents found in buildings and known to induce allergies are pollen, animal hair and dander, dust mites and mold. Known building-related allergies are asthma, hypersensitivity pneumonitis, humidifier fever, allergic tracheo-bronchitis and allergic rhinitis.

2.1.1.2.1.1 Building-Related Asthma. Occupants have difficulty breathing caused by a contraction of the bronchi. The attacks occur irregularly, and are temporary. This disease is not chronic, but severe attacks can potentially cause death.¹⁴ Asthma attacks may continue to appear after source removal through possible non-specific hypersensitivity and cross-sensitization.¹⁵

2.1.1.2.1.2 Hypersensitivity Pneumonitis. The related symptoms are acute pneumonias, fever, fatigue, cough, chest tightness, and breathing problems.¹⁶

2.1.1.2.1.3 Humidifier Fever. The symptoms are flu-like and include lethargy, chills, muscle aches, headache and fever, as well as cough and breathing problems in more severe cases. The attacks occur in a 12 hour period, usually at the beginning of a work week. Lung function is normal between attacks, and chest radiographs will not show any abnormalities.¹⁷

2.1.1.2.1.4 Allergic Tracheo-Bronchitis. Related symptoms are cough, chest tightness, and chest pain. Physical signs are limited to an inflammation of the upper airways. This allergy is suspected to be caused by fungal contamination. The conditions improve on the days away from the contaminated environment, and after source removal.¹⁸

¹³ Hodgson MJ, Kreiss K. 1987. Building-Associated Diseases: An Update. Proceedings of IAQ '87: 1-15

¹⁴ Lindvall T. 1992. The Sick Building Syndrome. Overview and Frontiers. Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality. State of the Art in SBS. Knoppel H, Wolkoff P (eds), pp. 1-4.

¹⁵ Hodgson MJ, Kreiss K. 1987. *ibid.*

¹⁶ Kreiss K. 1989. The Epidemiology of Building-Related Complaints and Illness. In: Occupational Medicine: State of the Art Reviews. 4,4, 575-592.

¹⁷ Hodgson MJ, Kreiss K. 1987. *ibid.*

¹⁸ Hodgson MJ, Kreiss K. 1987. *ibid.*

2.1.1.2.1.5 Allergic Rhinitis. Affected occupants have a history of nasal symptoms and experience repetitive sneezing. This form of nasal allergy is not well understood, although believed to be a fairly common problem in buildings.¹⁹

2.1.1.2.2 Non-Allergic Hypersensitivity Reactions from Specific Sources

Non-allergic hypersensitivity reactions are characterized by an increase in tissue sensitivity from environmental exposure to tobacco smoke, dust, chemicals, odors, cold and moisture. The symptoms are similar to the ones of allergies, and mainly affect the respiratory system, but are not caused by immunological reactions.²⁰

Occupant health is affected when individuals are exposed to specific sources of chemical origin introduced to the indoor environment through outdoor air, occupant activities, building materials or building systems. Some fibrous and chemical substances are strongly suspected or known to cause cancer via inhalation. These include asbestos, radon, environmental tobacco smoke, volatile organic compounds, polychlorinated biphenyls and their combustion products, and some pesticides. Neurotoxic substances - such as organic solvents and carbon monoxide - pose a health risk to especially the foetus and young children through their potential of causing molecular and behavioral abnormalities. The leading causes of work-related illness, neurotoxic substances are suspected to be linked to Parkinson's disease and Alzheimer's disease.²¹

2.1.1.2.2.1 Formaldehyde. The symptoms of exposure to unacceptable levels of formaldehyde are mucous membrane irritation, irritation of eyes, and upper and lower respiratory tract²², allergic disorders, and asthma²³.

2.1.1.2.2.2 Nitrogen Dioxide. Exposure to nitrogen dioxide above acceptable levels will cause irritation of the respiratory system and respiratory illness. Nitrogen dioxide is mainly deposited in the lungs where it forms nitric and nitrous acids resulting in lung damage. At low concentrations, it may cause bronchitis, bronchiolitis, and pneumonia. At high concentrations, occupants may develop fatal pulmonary edema and bronchopneumonia.²⁴

2.1.1.2.2.3 Ozone. Ozone is an irritant to the respiratory tract and the eyes. It is a highly reactive oxidant with a distinctive, sharp odor. Due to its chemical reactivity, it is toxic to humans in high concentrations. In low concentrations, ozone is known to decompose rubber-based building materials.²⁵

2.1.1.2.2.4 Carbon Monoxide. Symptoms of poisoning are headache, fatigue, nausea, loss of motor control, and coma (at levels above 20%). Inhaled carbon monoxide binds to

¹⁹ Kreiss K. 1989. *ibid.*

²⁰ Lindvall T. 1992. *ibid.*

²¹ Lindvall T. 1992. *ibid.*

²² Wanner HU, Kuhn M. 1986. Indoor air pollution by building materials. *Environment International*. 12: 311-315

²³ Hendrick DJ, Lane DJ. 1977. Occupational formalin asthma. *British Journal of Industrial Medicine*. 34: 11-18

²⁴ Lambert WE, Samet JM. 1989. The Role of Combustion Products in Building-Associated Illness. *Occupational Medicine: State of the Art Reviews*. 4,4,10: 723-733

²⁵ McIntyre DA. 1980. *Indoor Climate*. Applied Science Publishers, London.

hemoglobin to form carboxyhemoglobin. The rate of accumulation in the body depends on the level of ambient carbon monoxide, and the person's alveolar ventilation, lung characteristics, total hemoglobin mass, and carboxyhemoglobin level. The transfer of carbon monoxide into the body depends on breathing rates and the distribution of ambient carbon monoxide. Poisoning occurs due to reduction of oxygen transport in the lungs. Small persons, women, children, anemic persons, and people with chronic pulmonary disease are special risk groups. Inhalation of low levels of ambient carbon monoxide indoors over longer time periods can result in occult carbon monoxide poisoning with symptoms of headache and dizziness (at levels greater than 10%).²⁶

2.1.1.2.2.5 Carbonless Copy Paper. In the past, exposure to carbonless copy paper has reportedly led to mucous membrane irritation, hoarseness, coughing, skin irritation, headache, and fatigue.²⁷

2.1.1.2.2.6 Glass Fibers. After skin contact with man-made mineral fibers, occupants may experience itching without physical signs of skin rash.²⁸ The symptoms are likely to disappear after removal of the fibers through showering and washing of worn clothing.

2.1.1.2.2.7 Asbestos. Respirable asbestos fibers cause lung damage resulting in asbestosis (lung scarring) or lung cancer and mesothelioma (chest and abdominal cancer). There are no known short-term symptoms.²⁹

2.1.1.2.2.8 Environmental Tobacco Smoke. Passive smoking is known to produce occupant symptoms of mucous membrane irritation, and irritation of eyes, throat, and nose. Passive and active smoking affects the bronchial or alveolar immune defense system, and may lead to childhood asthma and lung cancer in adults.³⁰

2.1.1.2.2.9 Detergents. Detergents such as carpet and oven cleaners may cause eye and respiratory irritation during application or during drying.³¹ The related symptoms are coughing and sensation of dry throat.

2.1.1.2.2.10 Lead. Lead can be found in water, food, paints, dust, and soil, and enters the body through inhalation or indigestion. At low concentrations, it affects the brain, the central nervous system, blood cells, and the kidneys. At high concentrations, convulsion, coma or death can occur. In the foetus and in young children, lead can cause behavioral disorders, and delay mental and physical development.³²

²⁶ Lambert WE, Samet JM. 1989. *ibid.*

²⁷ Kreiss K. 1989. *ibid.*

²⁸ Kreiss K, Hodgson MJ. 1984. Building-associated epidemics. In Walsh PJ, Dudney CS, Copenhaver ED (eds). *Indoor Air Quality*. Boca Raton, CRC Press. 87-108

²⁹ United States Environmental Protection Agency and the United States Consumer Product Safety Commission. 1995. *The Inside Story. A Guide to Indoor Air Quality*. Office of Radiation and Indoor Air.

³⁰ Committee on Passive Smoking. 1986. *Environmental Tobacco Smoke*. Washington, DC.

³¹ Kreiss K, Gonzalez MG, Conright KL, Scheere AR. 1982. Respiratory irritation due to carpet shampoo. Two outbreaks. *Environment International* 8: 337-342.

³² United States Environmental Protection Agency and the United States Consumer Product Safety Commission. 1995. *ibid.*

2.1.1.2.2.11 Radon. Radon is a natural soil gas and enters buildings through the basement and through building areas that are in direct contact with the soil. Radon may cause lung cancer. No short-term symptoms are known.³³

2.1.1.2.2.12 Pesticides. Pesticides can be introduced through air handling systems, and faulty storage or application of the chemicals. Some pesticides have been found to induce symptoms of headache, dizziness, muscle twitching, weakness, tingling sensation and nausea. Exposure to pesticides over longer time periods can lead to cancer.³⁴

2.1.1.2.2.13 Vehicle Exhaust. Entrained exhaust from combustion engines can be recognized by odor and through minor forms of irritation. Acute forms of occupant response are signaled by eye and airways irritation, neurobehavioral symptoms, and elevated levels of carboxyhemoglobin³⁵.

2.1.1.2.3 Building-Related Infections

Building-related infections can have bacterial, fungal or viral causes.

2.1.1.2.3.1 Infectious Disease from Indoor Air Exposure. Examples for infectious disease transmitted by air in buildings are tuberculosis, varicella (chicken pox), influenza, cold, rubella, measles, and smallpox. Infections can be related to specific activities (laboratory) in hospitals and research facilities.

2.1.1.2.3.2 Q Fever. Sources of this disease with epidemic potential are infected sheep, goats or cattle in buildings, or laboratory cultures of the causative organism (*Coxiella burnetti*). The symptoms are fever, chills, headache, muscle aches, and, though less frequently, pneumonia, hepatitis and endocarditis.³⁶

2.1.1.2.3.3 Legionellosis. Legionnaire's disease was first observed in 1976, when an outbreak of this bacterial pneumonia caused 29 deaths and 153 cases of potential infection in a hotel in Philadelphia.³⁷ After an incubation period of 5 to 6 days, infected occupants experience pneumonia, gastrointestinal infections, kidney infections and symptoms related to the central nervous system. Transmission of the bacteria occurs via air and water.

2.1.1.2.3.4 Pontiac Fever. This highly infectious disease is caused by the same bacteria that is responsible for legionella pneumophila. Its incubation time is 36 hours, after which affected

³³ United States Environmental Protection Agency and the United States Consumer Product Safety Commission. 1995. *ibid.*

³⁴ United States Environmental Protection Agency and the United States Consumer Product Safety Commission. 1995. *ibid.*

³⁵ Watson AY, Bates RR, Kennedy D (eds). 1988. *Air Pollution. The Automobile and Public Health.* Washington D.C., National Academy Press.

³⁶ Kreiss K. 1989. *ibid.*

³⁷ Fraser DW, Tsai FR, Orenstein W, et al. 1977. Legionnaire's disease: Description of an epidemic of pneumonia. *N. Engl. Journal of Medicine.* 297: 1189-1197

occupants will show signs of fever, chills, headache and muscle ache. This disease was first diagnosed in Michigan in 1968.³⁸

2.1.1.2.3.5 Aspergillosis. *Aspergillus fumigatus* spores mainly affect persons with weakened or impaired immune systems³⁹, and causes several types of pulmonary illnesses: Noninvasive aspergillosis, semi-invasive aspergillosis, and allergic bronchopulmonary aspergillosis. In noninvasive and semi-invasive aspergillosis, the fungus invades the lung and forms a fungus ball. In allergic bronchopulmonary aspergillosis, the spores cause a hypersensitivity reaction. The related symptoms are similar to those observed in persons with asthma.⁴⁰

2.1.1.2.3.6 Pulmonary Hemosiderosis. The spores of the fungus *stachybotrys atra* mainly affect children of six months or younger. The symptoms are bleeding of the lungs, coughing blood, nosebleeds, and chest congestion with anemia. The mold spores damage the blood vessels in the lung, and the bleeding results from exposure to environmental tobacco smoke or stress from disease. The link between pulmonary hemosiderosis and *stachybotrys atra* was made in Cleveland, Ohio, in 1994, based on epidemiological data. Of 34 cases in the Cleveland area in the four year period after detection of the fungus, 10 infants have died. It is suspected that some death cases previously attributed to sudden infant death syndrome in this area may have actually been infected with *stachybotrys*.⁴¹

2.1.1.3 Other Symptoms in Both Building Categories

Other categories of symptoms that are found in occupants of buildings with “Sick Building Syndrome” and “Building-Related Illness” can be described as follows:

2.1.1.3.1 Physiological Symptoms. Occupants show signs of dissatisfaction or dislike with the environmental conditions due to the sensation of discomfort from environmental stressors. Occupant dissatisfaction typically relates to thermal (“too hot”, “too cold”, “too dry”, “too humid”, “drafty”), air quality (“stuffy”, “musty”, “smelly”), acoustic (noisy, vibrations) or lighting (“too bright”, “too dim”) conditions, as well as dissatisfaction with ergonomic conditions (uncomfortable chair) and crowding (lack of privacy).

2.1.1.3.2 Psychological Symptoms. In cases of failed problem resolution or communication problems, occupants may display signs of frustration, anger or outrage⁴².

³⁸ Kaufmann AM, McDade JE, Patton CM, et al. 1981. Pontiac Fever: Isolation of the etiologic agent (*Legionella pneumophila*) and demonstration of its mode of transmission. *American Journal of Epidemiology*. 114: 337-347.

³⁹ Burge HA. 1989. Indoor Air and Infectious Disease. *Occupational Medicine: State of the Art Reviews*. 4,4, October - November. Philadelphia.

⁴⁰ Pearson GDN, Hunsaker AR. 1996. Invasive Aspergillosis with Air Crescent. BrighamRAD Design Team, Brigham and Women’s Hospital, Department of Radiology, Harvard Medical School. Internet, homepage.

⁴¹ Dearborn DG, et al. 1997. *Stachybotrys*. Pulmonary Hemorrhage and Hemosiderosis in Infants. Case Western Reserve University. Internet, homepage.

⁴² Bicevskis M. 1995. Minimizing Outrage in Building Occupants. *Indoor Air. An Integrated Approach*. Morawska L, Bofinger ND, Maroni M (Eds.). Elsevier Science Ltd. 475-478

2.1.1.3.3 Behavioral Symptoms. In order to compensate for unwanted conditions, occupants rearrange their environments (closing of supply air grilles, moving away from window to avoid thermal radiation) or introduce additional equipment to cope with the perceived problems (such as fans, humidifiers, and blinds). Occupants in complaint buildings often report “difficulty concentrating” or problems with motivation. In cases where occupants have lost confidence in the building and the building operators to resolve the experienced problems, communications between occupants and owners/operators may be complicated through occupant mistrust.

2.1.2 Building Symptoms

Indications for problems with indoor environmental quality can also be found in the physical building and related processes. As the reviewed literature shows, deficiencies observed in buildings with “Sick Building Syndrome” or “Building-Related Illness” are mainly related to lack of building hygiene, systems performance deficiencies, lack of maintenance, and unintended use of spaces.

2.1.2.1 Lack of Building Hygiene

In many complaint buildings, there are obvious problems with housekeeping and preservation of building components.

2.1.2.1.1 Deterioration. Building symptoms include deteriorated building envelope systems, such as leaking windows and roofs, floor cracks, and deterioration in HVAC systems, such as rusty ductwork or deteriorated duct lining.⁴³

2.1.2.1.2 Excessive Dirt. Complaint buildings may display a lack of cleanliness in the functional as well as in the support areas. Dirt and dust may be accumulating in the direct vicinity of the occupant breathing zone. Mechanical rooms may be dirty, used as a storage, or completely neglected leading to undetected problems such as water accumulating on the floor, and clogged condensate floor drains.^{44,45}

Air handling systems are often excessively dirty, sometimes due to their inaccessibility. Symptoms include dirt, mold and perishable items (food) in ductwork, duct linings, air handlers and plenums, and dirty coils and drain pans.^{46,47}

2.1.2.1.3 Odors. Occupants in complaint buildings may complain about unacceptable odors

⁴³ Rask DR, Lane CA. 1989. Resolution of the Sick Building Syndrome: Part II, Maintenance. Proceedings of IAQ 89. 173-178

⁴⁴ Rask DR, Lane CA. 1989. *ibid.*

⁴⁵ Downing CC, Bayer CW. 1992. Operation and Maintenance for Quality Indoor Air. Proceedings of IAQ '92: 372-374

⁴⁶ Rask DR, Lane CA. 1989. *ibid.*

⁴⁷ Downing CC, Bayer CW. 1992. *ibid.*

that sometimes stem from other functional areas (cafeteria, bathrooms) or unrestricted smoking.

2.1.2.2 Deficiencies in Building System Performance

Complaint buildings frequently show problems with managing existing loads. The symptoms are caused by lack of capacity of building systems to manage environmental loads, and deficiencies in system controls in initiating and controlling system functions.

2.1.2.2.1 Problems with System Capacity. Loads from indoor and outdoor sources that have not been accounted for by the related building systems can result in physiological and contaminant problems indoors.⁴⁸ HVAC system capacity may be inadequate due to faulty duct dimensions.⁴⁹

Inadequate make-up air for ventilation and poor air distribution in occupied spaces are frequent causes for unacceptable indoor air quality.⁵⁰

Lighting systems may not fulfill the requirements for the specified tasks. They may be inadequate in respect to illuminance as well as color. Also, lighting problems may arise from coordination problems between artificial and natural lighting.⁵¹

2.1.2.2.3 Problems with System Control. Controls may be out of calibration or partly disabled causing inability of the HVAC systems to operate according to the specified criteria for operation. Unbalanced HVAC systems can result in overpressurization of occupied spaces thereby obstructing outdoor air supply.^{52,53}

2.1.2.3 Maintenance Deficiencies

2.1.2.3.1 Absence of a Comprehensive Maintenance Program. In a large amount of case studies, the importance of effective operation and maintenance procedures is stressed. Many building problems are related to the absence of a comprehensive maintenance program.⁵⁴ System maintenance in these cases is conducted in reactive (repairs) rather than pro-active (monitoring, periodic inspections) ways. Symptoms related to reactive maintenance procedures are irregular filter changes, problems caused by inadequate application and storage of chemicals indoors, and

⁴⁸ Turner WA, Bearg DW. 1987. Delivering Designed cfm of Outside Air to the Occupants - Problems and Solutions. Proceedings of IAQ '87. Practical Control of Indoor Air Problems. Arlington, Virginia. 179-182

⁴⁹ Turner WA, Bearg DW. 1987. *ibid.*

⁵⁰ Woods JE, Janssen JE. 1987. Resolution of the "Sick" Building Syndrome. Proceedings of IAQ 87. Practical Control of Indoor Air Problems. Arlington, Virginia. 338-348

⁵¹ Wilkins AJ, Nimmo-smith MI, Slater A, Bedocs L. 1988. Fluorescent lighting, headaches and eyestrain. Proceedings of CIBSE National Lighting Conference, Cambridge, UK. 188-196

⁵² Rask DR, Lane CA. 1989. *ibid.*

⁵³ Indoor Air Quality Update. 1996. Commissioning Finds Causes for Building Environmental Problems. Cutter Corporation. April 1996:10-13

⁵⁴ Rask DR, Lane CA. 1989. *ibid.*

unnoticed break-down of system components and related devices.⁵⁵

The absence of a maintenance program can lead to failure to comply with the criteria of operation:

Manual alterations of system components in automated systems may contribute to energy savings, but also cause the larger system to malfunction. Shut-down of individual system parts may affect system control (logic) or capacity (e.g. through closed outdoor air dampers).⁵⁶

HVAC systems were found to be completely shut down in buildings designed for mechanical ventilation.⁵⁷

Economizer cycles need to be evaluated regarding their impact on the building-specific indoor environmental conditions.⁵⁸

2.1.2.3.2 Absence of Building Documentation. In many buildings, a complete set of drawings of the facility “as-built” is unavailable or inaccessible for maintenance personnel.⁵⁹

2.1.2.3.3 Lack of Staff Training. Maintenance personnel may be untrained or inexperienced⁶⁰, or have problems understanding automated building systems⁶¹. Lack of systems knowledge usually leads to misinterpretations of signals or ignoring of system faults, thereby increasing the rate of system failure, system down-time and reducing overall system life.

2.1.2.4 Unintended Use

The risk that specified building system performance is not met by the actual building increases with the number of modifications of building systems and spaces over the building life. Changes in building operations and maintenance are often not documented, or existing and accessible building documentation is not updated.

2.1.2.4.1 Changes in Space Use. Problems seem to increase, when building functions or occupant activities are not clearly separated, but mixed or frequently changed.⁶²

Since space requirements are developed on the basis of program requirements, misuse of spaces, such as using mechanical rooms as storage⁶³, or using storage areas as work spaces⁶⁴, are likely to produce problems with indoor environmental quality.

⁵⁵ Downing CC, Bayer CW. 1992 .ibid.

⁵⁶ Downing CC, Bayer CW. 1992 .ibid.

⁵⁷ Bayer CW, Black MS. Indoor Air Quality Evaluations of Three Office Buildings. 294-313.

⁵⁸ Downing CC, Bayer CW. 1992 .ibid.

⁵⁹ Rask DR, Lane CA. 1989. ibid.

⁶⁰ Rask DR, Lane CA. 1989. ibid.

⁶¹ Downing CC, Bayer CW. 1992 .ibid.

⁶² Downing CC, Bayer CW. 1992 .ibid.

⁶³ Rask DR, Lane CA. 1989. ibid.

⁶⁴ Armstrong CW, Sherertz PC, Llewellyn GC. 1989. Sick Building Syndrome Traced to Excessive Total Suspended Particulates. Proceedings of IAQ 89. 3-7

2.1.2.4.2 Unintended Systems Operation. Building symptoms caused by modified building elements are often a function of maintenance problems, when occupants attempt to ‘fix’ unwanted conditions, but lack of occupant-based controls. Occupants frequently choose to cover diffusers to avoid draft from the HVAC system.⁶⁵ Also, furniture can obstruct proper airflow to and from occupied spaces.⁶⁶

Examples for unintended systems operation include running HVAC systems without air filters, and, in automated building systems, permanent shut-down of individual components without prior evaluation of the effects on the entire system.⁶⁷

2.1.3 Extent of Problems

2.1.3.1 Frequency of Health Symptoms

It has been estimated that 20 to 30% of non-industrial buildings have problems with indoor environmental quality.⁶⁸ In 5 to 10% of these, “Building-Related Illness” is present, and in 10 to 25% “Sick Building Syndrome”.⁶⁹ An estimated 70 to 80% of buildings are without known problems, 10 to 20% of which have undetected problems that have not yet had a measurable impact on occupant health. Unacceptable exposure in buildings with undetected problems is likely should the problems develop further.

Thus, in the current building stock, an estimated 30 to 70% of occupants in residential or commercial buildings are exposed to indoor environmental conditions posing a health risk. About 9 to 25% of occupants are at risk of adverse health effects in both, commercial and residential buildings.⁷⁰

2.1.3.2 Frequency of Building Symptoms

It can be assumed that in all buildings with reports of health problems, building systems and operations are faulty contributing to or causing the adverse health effects.

In 1988, two building investigators (Woods/Robertson) reported inadequate outdoor air in 75/64 cases, ineffective air distribution in 75/46 cases, inadequate filtration in 65/57 cases, inadequate drain lines and pans in 60/63 cases, contaminated ductwork in 45/38 cases, and in 20/18 cases, malfunctioning humidifiers were affecting the indoor environmental conditions.^{71,72}

⁶⁵ Downing CC, Bayer CW. 1992 .ibid.

⁶⁶ Rask DR, Lane CA. 1989. ibid.

⁶⁷ Downing CC, Bayer CW. 1992 .ibid.

⁶⁸ Woods JE. 1990. Continuous Accountability: A Means to Assure Acceptable Indoor Environmental Quality. Proceedings of the Fifth International Conference on Indoor Air Quality and Climate. 5:85-94

⁶⁹ Woods JE. 1990. ibid.

⁷⁰ Woods JE. 1990. ibid.

⁷¹ Woods JE. 1988. Recent Developments for Heating, Cooling, and Ventilating Buildings: Trends for Assuring Healthy Buildings. Proceedings of Healthy Buildings ‘88. Berglund, Lindvall (Eds.). Swedish Council for Building Research. 99-107

2.1.4 Affiliated Costs

With respect to poor indoor environmental quality, there are three stages of building quality at which increased costs incur. The first stage is characterized by an increase of system performance deficiencies due to undetected problems. The second stage involves costs related to the process of identifying the system performance deficiencies and accommodation of affected persons. After problem resolution, additional costs incur at the third stage for preventive measures.

2.1.3.1 Costs due to Undetected Problems

2.1.3.1.1 Increased Service Costs. System performance deficiencies, such as control problems, and faulty operation and maintenance procedures typically lead to an increase of service calls and repair cost. Also, energy consumption increases due to inefficient system operation. Detection of these trends is complicated in building managements that lack of experienced and well-trained personnel and do not have detailed records of building performance over several years.

In addition, there are indications that the efforts to save space, utility cost and spending for operation and maintenance actually offset the costs associated with the systems deficiencies⁷³ complicating problem detection by merely monitoring costs.

2.1.3.1.2 Absenteeism. Health problems in buildings with undetected problems are not obvious. Health symptoms and absenteeism result in 5% or less lost salary or wages from time away from work, a value considered normal in work environments.⁷⁴

2.1.3.1.3 Lost Productivity. It has been estimated that there may be costs of up to \$2 billion from lost productivity in undetected problem buildings nationwide from the environmental impacts of building deficiencies and energy saving measures on occupant well-being.⁷⁵

2.1.3.2 Costs during Complaint Investigation

The second stage is characterized by costs caused by occupant complaints and complaint investigation.

2.1.3.2.1 Cost for Problem Diagnosis. Depending on the experienced health problems, building investigations may cost substantial amounts of money, and usually require follow-up measurements to verify the results of the investigation and to prove the effectiveness of the implemented mitigation procedures.

⁷² Robertson G. 1988. Sources, Nature and Symptomology of Indoor Air Pollutants. Proceedings of Healthy Buildings '88. Berglund, Lindvall (Eds.). Swedish Council for Building Research. 507-516

⁷³ Woods JE. 1990. *ibid.*

⁷⁴ Woods JE. 1989. Cost Avoidance and Productivity in Owning and Operating Buildings. Occupational Medicine: State of the Art Reviews. Philadelphia, Pennsylvania. 753-770.

⁷⁵ Woods JE. 1990. *ibid.*

2.1.3.2.2 New Criteria for Operation and Maintenance. Often, as a method for preventing future problems, criteria for operation and maintenance become more stringent resulting in higher cost for energy and labor.

2.1.3.2.3 Medical Costs. Where occupants turn to physicians for medical assistance, costs incur to the health care system and to individuals for health insurance policies. It has been estimated that the white collar work force spends about \$500 million per year for medical assistance to deal with building-related health symptoms.⁷⁶

2.1.3.2.4 Reduced Revenue. Estimated costs of \$10 billion per year result from reduced revenue in commercial settings.⁷⁷

2.1.3.2.5 Extended Patient Care. In hospitals, where patients are affected in addition to the staff, it is assumed that extended patient care due to indoor environmental problems consume an annual \$2 million.

2.1.3.2.6 Unaccounted Costs. Other individuals affected from building deficiencies are students, patients, hotel guests and persons with short-term exposure in problem buildings. Estimates of population exposure in residential buildings show 15 to 25 million individuals at risk of contracting “Building-Related Illness” and 35 to 45 millions risking symptoms related to “Sick Building Syndrome”. These numbers are higher in cases where persons are exposed to unhealthy conditions at home and at work.⁷⁸

It is suspected that indoor environmental problems in schools have an impact on students’ learning ability, yet, sufficient evidence to support this hypothesis is still required. However, the additional costs for dealing with the effects on teachers, staff and building components probably compare to those in commercial environments.

2.1.3.3 Costs after Problem Resolution

The amount of additional cost at this stage depends on the effectiveness of the mitigation measures, and the selected prevention techniques.

2.1.3.3.1 Increased Operation and Maintenance Cost. Caused by more stringent standards for building operations and maintenance, related costs for energy, labor and systems may rise to a higher level than prior to the occupant complaints.

2.1.3.3.2 Loss of Planned Savings. System integrated features to save energy may have to remain disabled to prevent conflicts with the new requirements.

2.1.3.3.3 Additional Training. Also, operators and occupants may have to obtain additional and more frequent training in an effort to correctly interpret early warning signals.

⁷⁶ Woods JE. 1990. *ibid.*

⁷⁷ Woods JE. 1990. *ibid.*

⁷⁸ Woods JE. 1990. *ibid.*

2.1.3.4 Litigation Costs

In addition to the expenditures for resolving the health and building performance problems, costs from litigation initiated by building occupants may arise. Related law cases are based on breach of express or implied warranties, misrepresentation or fraud, liability as a landowner, negligence, and strict liability.⁷⁹

2.1.3.4.1 Responsible Parties. All professionals involved in the design, construction, operation and maintenance of buildings are likely to be involved in law suits initiated by building occupants seeking reimbursement for their experienced health problems.

2.1.3.4.2 Negligence. Failure to provide a design that meets generally recognized safety standards is considered negligent. To exclude negligence in court cases, emissions from building materials have to be tested, since the scientific and industry literature points at the health risk of various products.⁸⁰

Not using established knowledge in the operation of buildings is legally interpreted as accepting risk and as inherent responsibility.⁸¹

2.1.3.4.3 Liability. A second theory used in the dispute of IAQ problems is strict liability. The plaintiffs have to prove that the actual cause of their injuries originates in a product deficiency.⁸² Defects can originate in product design or in the manufacturing process. HVAC systems are commonly defined as one product rather than a conglomerate of several products. In some jurisdictions, a building is defined as a product.⁸³

2.1.3.4.4 Punitive Damages. In recent years, a trend towards emphasis of the rights of building users can be observed, which may result in more frequent payments of punitive damages for the parties held responsible for a building problem.^{84,85} Based on the reviewed literature, amounts previously ranged from \$622,500 in a case that was settled⁸⁶ to several million Dollars. Theoretically, there is no upper limit for punitive damages in the litigation of indoor environmental quality problems.⁸⁷

⁷⁹ Kirsch LS. 1992. Legal Implications of Indoor Air Quality. Proceedings of Indoor Air Quality. 403-406

⁸⁰ Kirsch LS. 1992. *ibid.*

⁸¹ Kirsch LS. 1992. *ibid.*

⁸² Pierce S, Ortego JJ. 1993. *ibid.*

⁸³ Pierce S, Ortego JJ. 1993. Emerging Trends in U.S. Indoor Air Pollution Litigation. *Toxicological and Environmental Chemistry*, 40: 143-154. Gordon and Bresch Science Publishers.

⁸⁴ Kirsch LS. 1992. *ibid.*

⁸⁵ Pierce S, Ortego JJ. 1993. *ibid.*

⁸⁶ Kirsch LS. 1992. *ibid.*

⁸⁷ Besch EL, Besch HJ. 1989. Managing an indoor air quality (IAQ) problem in a public building. Proceedings of IAQ 89: 109-113.

2.1.4 Potential for Recovery

In the past decades, the knowledge about factors related to indoor environmental problems has improved, and the awareness about the importance of investing into mitigation procedures and pro-active measures has increased. Yet, there is still a real risk that the building problems cannot be resolved, or that occupants in mitigated buildings continue to complain about problems with the indoor environmental quality.⁸⁸

2.1.4.1 Methodological Problems. Multi-factorial problems often require interdisciplinary approaches. As case studies show, problem resolution is often focused on engineering aspects while ignoring occupant concerns and failing to involve occupants in the management of indoor environmental problems.^{89,90} Such buildings are characterized by symptoms associated with “Sick Building Syndrome”, but show an absence of system performance deficiencies.⁹¹ In problem investigations requiring an absence of occupant complaints to prove effectiveness of the implemented mitigation measures, these buildings will not pass as resolved cases, but question the validity of the results of the investigation and the investments for the required building renovations.

2.1.4.2 Problems with Occupant Involvement. From a psychological perspective, problems with indoor environmental quality induce stress due to the social dynamics of crisis buildings.⁹² The underlying biological, chemical, physical and social factors in an organizational setting initiate the occupant health problems. Several triggering events are responsible for an increasing awareness of the health problems in affected occupants. Failure to intervene in this process of crisis development from early on through effective communication patterns between building management and occupants, equal access to information, social support through committees representing involved parties, and improvement of occupant control about environmental conditions has led to continuing occupant mistrust and perception of threat toward building conditions that were actually complying with health standards.^{93,94}

2.2 Identified Causes

2.2.1 Exposure in Problem Buildings

The observation that occupant health problems lessened or disappeared when away from the complaint buildings led to the conclusion that the symptoms were probably related to building

⁸⁸ Witherspoon JA, Landrus G. 1992. The Creation of a Sick Building. Proceedings of IAQ '92: 103-107

⁸⁹ Besch EL, Besch HJ. 1989. *ibid.*

⁹⁰ Lee BL, Rattan G, Hay R. 1987. Management of an acute indoor air problem in a city office building. Proceedings of IAQ '87: 150-156

⁹¹ Witherspoon JA, Landrus G. 1992. *ibid.*

⁹² Baker DB. 1989. Social and Organizational Factors in Office Building-Associated Illness. Occupational Medicine: State of the Art Reviews. Philadelphia, Pennsylvania. 607-624.

⁹³ Baker DB. 1989. *ibid.*

⁹⁴ Witherspoon JA, Landrus G. 1992. *ibid.*

conditions.⁹⁵ It was assumed from early on that the symptoms are probably not caused by a single irritant, but by a complex set of sensory stimuli in the indoor air.^{96,97} However, some environmental stressors could be linked to specific patterns of human response and system parameters:

2.2.1.1 Biological Causes

Biological allergens originate in fungi, bacteria, amoebae, and insects in environments with sources of water and carbon. The allergens are transmitted via inhalation or through contact with a carrier.

Air handling systems have a variety of components potentially providing ideal conditions for fungal and microbial growth. Hypersensitivity pneumonitis was reportedly caused by microbial contamination in air handling units,^{98,99,100,101} by a contaminated furnace filter¹⁰², and by chronic water damage in buildings.^{103,104,105}

Biological stressors can also induce asthma. It is assumed that biocides used in humidification systems may cause office-associated asthma.¹⁰⁶ Bioaerosols from home cool-mist vaporizers have reportedly caused an exacerbation of asthma.¹⁰⁷ Epidemic asthma in a printing factory was associated with a contaminated humidifier.¹⁰⁸

Allergic asthma and rhinoconjunctivitis can be contracted from house dust mites, pets, insects,

⁹⁵ World Health Organization. 1983. *ibid.*

⁹⁶ Stolwijk JAJ. 1984. *ibid.*

⁹⁷ World Health Organization. 1983. *ibid.*

⁹⁸ Bernstein RS, Sorenson W, Garabant D, et al. 1984. Exposures to respirable, airborne penicillium from a contaminated ventilation system: clinical, environmental and epidemiologic aspects. *American Industrial Hygiene Association Journal* 44:161-169

⁹⁹ Hodgson MJ, Morey PR, Simon JS, et al. 1987. An outbreak of recurrent acute and chronic hypersensitivity pneumonitis in office workers. *American Journal of Epidemiology*: 125:631-638

¹⁰⁰ Reed CE, Swanson MC, Lopez M, et al. 1983. Measurement of IgG antibody and airborne antigen to control an industrial outbreak of hypersensitivity pneumonitis. *Journal of Occupational Medicine*: 25:207-210

¹⁰¹ Woodard ED, Friedlander B, Leshner RJ, et al. 1988. Outbreak of hypersensitivity pneumonitis in an industrial setting. *JAMA* 259:1965-1969

¹⁰² Hodgson MJ. 1989. Clinical diagnosis and management of building-related illness and the Sick-Building-Syndrome. *Occupational Medicine: State of the Art Reviews*. 4:4, October-November 1989. 593-606

¹⁰³ Hodgson MJ, Morey PR, Attfield M, et al. 1985. Pulmonary disease associated with cafeteria flooding. *Arch. Environ. Health*. 40: 96-101

¹⁰⁴ Morey PR. 1984. Case Presentations: Problems caused by moisture spaces of office buildings. *Annual American Conference of Governmental Industrial Hygienists*. 10:121-127

¹⁰⁵ Morey PR, Hodgson MJ, Sorenson WG, et al. 1984. Environmental studies in moldy office buildings: Biological agents, sources and preventive measures. *Annual American Conference of Governmental Industrial Hygienists*. 10:21-35

¹⁰⁶ Finnegan MJ, Pickering CAC. 1986. Building-related illness. *Journal of Clinical Allergy*. 16:389-405

¹⁰⁷ Solomon WR. 1974. Fungus aerosols arising from cold-mist vaporizers. *Journal of Allergy and Clinical Immunology*. 54:222-228

¹⁰⁸ Burge PS, Finnegan M, Horsfield N, et al. 1985. Occupational asthma in a factory with a contaminated humidifier. *Thorax* 40:248-254

and molds indoors as well as molds and pollen from outdoors. The infection occurs through airborne allergens or through contact with carriers of the sources, e.g. pets.¹⁰⁹

Infections with legionellosis are known to be spread by aerosols originating in cooling towers, evaporative condensers, humidifiers, whirlpools, shower heads and cooling systems for industrial processes.¹¹⁰

Pontiac fever has been caused by biological contamination in air handling systems, whirlpool spas, steam turbine condensers, and industrial coolants.¹¹¹

2.2.1.2 Chemical Causes

Chemical stressors are responsible for health and comfort problems ranging from annoyance and irritation to cancer. Data from field and experimental studies indicate that the combined effect of various volatile organic compounds is more significant in the development of health symptoms than individual gaseous contaminants.¹¹²

Volatile organic compounds affect the human sensory system and may cause sensory dysfunction, annoyance, hypersensitivity reactions, mucosal irritation, effects on the nervous system functions, aberrant social behavior, paralysis, and memory impairment.¹¹³ Volatile organic compounds in buildings originate from sources such as fabrics, carpets, insulation materials, adhesives, caulks, sealants, insecticides, aerosol products, combustion appliances, occupants and outside air. In addition, volatile organic compounds indoors are emitted during the processes of cleaning, disinfecting, deodorizing, polishing (furniture), painting, finishing and refinishing products, personal grooming (cosmetics, perfumes, and personal hygiene products), and smoking.¹¹⁴ Special operations such as printing, office machine repair, blue printing, photographic processing, and food service operations produce high levels of volatile organic compounds. The presence of volatile organic compounds indoors is prolonged through the material-specific source and sink potential where non-source materials may act as secondary sources.¹¹⁵

Causation of eye irritation from combined exposure to ozone, formaldehyde, and other volatile organic compounds has been established.¹¹⁶ Eye and respiratory problems have been specifically linked to detergent residues from carpet cleaning. During application of aerosol oven cleaner,

¹⁰⁹ Working Group 4. 1991. Effects of Indoor Air Pollution on Human Health. Report No. 10. Commission of the European Communities.

¹¹⁰ Kreiss K. 1989. The Epidemiology of Building-Related Complaints and Illness. *Occupational Medicine: State of the Art Reviews*. 4:575-592

¹¹¹ Friedman S, Spitalny K, Barbaree J, et al. 1987. Pontiac fever outbreak associated with a cooling tower. *American Journal of Public Health*. 77:568-572

¹¹² Molhave L. 1985. *Volatile Organic Compounds. Indoor Air and Human Health*. Chelsea, MI: Lewis Publishers.

¹¹³ Working Group 4. 1991. *ibid*.

¹¹⁴ Working Group 4. 1991. *ibid*.

¹¹⁵ Working Group 4. 1991. *ibid*.

¹¹⁶ Wolkoff P. 1992. Some studies of human reactions from the emissions of building materials and office machines. In: H. Knoepfel and P. Wolkoff (eds.): *Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality - State of the Art in SBS*. 231-246

cough and dry throat can be observed.^{117,118} In one case, exposure to photochemicals has caused respiratory problems and respiratory disease in hospital staff.¹¹⁹

In controlled and field studies, carbonless copy paper has been identified as the source of mucous membrane irritation, hoarseness, coughing, skin irritation, headache and fatigue.¹²⁰

Formaldehyde has been established as a cause for mucous membrane irritation.¹²¹ It is found in composite wood products such as particle board, and in insulation materials, carpet glues and fabric finishes. It has been suggested that effects of formaldehyde on the respiratory system promote allergic responses.¹²²

Chemical sources may be introduced to the occupied space by external sources:

In one reported case, annoyance from odors was caused by a chemical room deodorizer in a building where the chemicals were applied in a mechanical room and disseminated throughout the zones served by the air handling units.¹²³

Carbon monoxide is known to effect cardiovascular activity potentially causing death.¹²⁴ Combustion products from parking garages or boiler stacks have entered the indoor environment and caused carbon monoxide poisoning in occupants.¹²⁵

In high concentrations, pesticides can cause poisoning in building occupants. A pesticide application outdoors caused occupant health problems when the fumes entered the building and accumulated in the occupied space.¹²⁶

Radon or its decay products are known to cause lung cancer. There are no known short-term symptoms.¹²⁷ Radon typically enters a building through basement walls.

Benzene and nitrosamines are known carcinogens that have been found on filters of recirculating kitchen exhaust fans.¹²⁸

¹¹⁷ Kreiss K. 1989. *ibid.*

¹¹⁸ Kreiss K, Gonzalez MG, Conright KL, Scheere AR. 1982. Respiratory irritation due to carpet shampoo; two outbreaks. *Environment International*. 8:337-342

¹¹⁹ Bakke JV, Eldoen G. 1996. Occupational diseases caused by indoor pollution in a X-ray department of a hospital. *Indoor Air '96. Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan*. 1:605-610

¹²⁰ Kreiss K. 1989. *ibid.*

¹²¹ Kreiss K. 1989. *ibid.*

¹²² Garrett MH, Hooper MA, Hooper BM. 1996. Low levels of formaldehyde in residential homes and a correlation with asthma and allergy in children. *Indoor Air '96. Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan*. 1:617-622

¹²³ Black MS, Bayer CW, Brackett HL. 1987. An office building IAQ problem involving volatile organic compounds. *Proceedings of IAQ '87*. 72-86

¹²⁴ Working Group 4. 1991. *ibid.*

¹²⁵ Kreiss K. 1989. *ibid.*

¹²⁶ Hodgson MJ, Block GD, Parkinson DK. 1986. Organophosphate poisoning in office workers. *Journal of Occupational Medicine*. 28:434-437

¹²⁷ Working Group 4. 1991. *ibid.*

¹²⁸ Working Group 4. 1991. *ibid.*

2.2.1.3 Building-Physical Causes

The physiological effects of temperature on people are discomfort and heat and cold stress. In field studies, a significant correlation between room temperatures above 22°C and the appearance of SBS symptoms was found.^{129,130} The assumption that mental processes are affected by temperature could be confirmed in experimental settings where mental work capacity started to decline at temperatures above 24°C.^{131,132}

Indoor relative humidity of less than 20% can cause drying of the mucous membrane and of the skin, and dermatitis.¹³³ There are indications that relative humidity is affecting complaints associated with “Sick-Building-Syndrome” by providing for environmental conditions such as build-up of static electricity, increased emissions, and variations of respirable suspended particulates. Relative humidity values above 70% are associated with mold growth and surface condensation. Surface condensation is known to produce structural damage in cold climate buildings.

Man-made mineral fibers such as fiber glass or mineral wool are used in duct work, ceiling tiles and insulation. The fibers become airborne when damage to the material occurs through age, moisture, and microbial growth, or when the fibers are disturbed by an airstream.^{134,135} The observed health problems include itchy skin and skin rash.

Asbestos is known to cause lung cancer at low concentrations.¹³⁶ Transmission occurs through inhalation of the fibers near the source or near a sink, e.g. fibers on clothing.

Glare and noise have caused headache and muscle pain.¹³⁷ There are indications that inadequate lighting may cause eye strain and headache.¹³⁸ Vibrations have been linked to complaints of irritability and dizziness.¹³⁹

¹²⁹ Jaakkola JJK, Heinonen OP. 1987. Mechanical ventilation in an office building and sick building syndrome, a short-term trial. *Indoor Air '87. Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Berlin, 17-21 August 1987.* Institut fuer Wasser-, Boden- und Lufthygiene, Berlin. 2:454-458

¹³⁰ Valbjorn O, Skov P. 1987. Influence of indoor climate on the sick building syndrome prevalence. *Indoor Air '87. Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Berlin, 17-21 August 1987.* Institut fuer Wasser-, Boden- und Lufthygiene, Berlin. 2:593-597

¹³¹ Wyon DP. 1974. The effects of moderate heat stress on typewriting performance. *Ergonomics* 17: 309-318

¹³² Wyon DP, Holmberg I. 1973. Systematic observation of classroom behaviour during moderate heat stress. Thermal comfort and moderate heat stress. *Proceedings of CIB (W45) Symposium, Garston 13-15 September 1972, Building Establishment Report n.2 (HMSO), London.*

¹³³ Working Group 1. 1989. Sick Building Syndrome. Report No.4. Commission of the European Communities.

¹³⁴ Kreiss K, Hodgson MJ. 1984. Building-associated epidemics. In Walsh PJ, Dudney CS, Copenhaver ED (eds): *Indoor Air Quality.* Boca Raton, CRC Press. 87-108

¹³⁵ Morey PR. 1984. *ibid.*

¹³⁶ Working Group 4. 1991. *ibid.*

¹³⁷ Wallace LA, Nelson CJ, Dunteman G. 1991. Workplace Characteristics Associated with Health and Comfort Concerns in Three Office Buildings in Washington, DC. *Indoor Air Quality.* 56-60

¹³⁸ Wilkins AJ, Nimmo-Smith MI, Slater A, Bedocs L. 1988. Fluorescent lighting, headaches and eyestrain. *Proceedings of CIBSE National Lighting Conference, Cambridge, UK.* 188-196

¹³⁹ Hodgson MJ, Permar E, Squire G, Cagney W, Aller A, Parkinson DK. 1985. Vibrations as a cause of “tight-building syndrome” symptoms. Report to the Physical Plant Department, University of Pittsburgh. 2:449-453

Exposure to electromagnetic radiation is thought to play a role in the development of cancer, but there is currently insufficient data to prove this link.¹⁴⁰

2.2.1.4 Psycho-Social Causes

Some health problems in buildings could be explained through the nature of the performed task, e.g. eye irritation in occupants at visual display terminals could be traced to a reduced blink frequency in office workers while concentrating on the images on their monitors.¹⁴¹

However, in experiments, unbiased subjects could not perceive differences between “sick buildings” and those without known problems.¹⁴² Therefore, it is suspected that factors beyond the physical condition of the building contribute to the “sick building” problem.

It is now understood that while the source of the stress is in the environment, psycho-social stressors can modify physiological processes and health symptoms.¹⁴³

The concept of psycho-social response in problem buildings originates in the occupational stress model where the environmental stressors at work (physical environment, job structure, work task, organizational factors, and extra-organizational factors (home, career)) have two effects on a worker: One, a direct toxic effect requiring physiological response or adaptation, and two, aversive factors (odor, discomfort) leading to a psychological or behavioral response.¹⁴⁴

Organizational factors can be both, stressors or modifiers.¹⁴⁵ Organizational factors acting as stressors are based on individual perception within a social setting, and impact personal motivation, performance, innovation, and stress.¹⁴⁶ Organizational factors acting as modifiers reduce the stress from the environmental conditions by controlling the stress symptoms, e.g. through emotional support and information within a social group.¹⁴⁷

The prevalence of symptoms in problem buildings correlates with the factors ‘job category’ and ‘gender’ in that managers typically report fewer symptoms than staff, and women report more problems than men.¹⁴⁸ These findings are based on differences in the degree of personal control over the work process, the extent of occupant-based control over the environment, the relevance of working on visual display units, and the frequency of environmental measurements in buildings.

¹⁴⁰ Working Group 4. 1991. *ibid.*

¹⁴¹ Wolkoff P. 1992. *ibid.*

¹⁴² Berglund B, Berglund U, Engen T. 1984. Do “sick buildings” affect human performance? How should one assess them? Reports from the Department of Psychology, University of Stockholm. 609

¹⁴³ Baker DB. 1989. Social and organizational factors in office building-associated illness. *Occupational Medicine: State of the Art Reviews*. 4,4:607-624

¹⁴⁴ Baker DB. 1989. *ibid.*

¹⁴⁵ Baker DB. 1989. *ibid.*

¹⁴⁶ Michaela JL, Boni SM, Schechter CB, et al. 1989. A hierarchically nested model for estimation of influences on organizational climate: Rationale, methods, and demonstration.

¹⁴⁷ LaRocco JM, House JS, French JR. 1980. Social support, occupational stress, and health. *Health and Social Behavior*. 21:202-218

¹⁴⁸ Burge S, Hedge A, Wilson S, et al. 1987. Sick building syndrome: A study of 4373 office workers. *Ann. of Occupational Hygiene*. 31:493-504

Biological, chemical and physical stressors can act as sources of psychological stress producing a state of general discomfort. When environmental stressors cause arousal in an occupant, and simultaneous perception of odors and stuffy air suggest air quality problems to the individual, the occupant may perceive the environment as a threat.¹⁴⁹ The individual level of stress varies from person to person due to individual differences in the interpretation of discomfort and illness, and the suspected causative environmental factors.¹⁵⁰

2.2.1.5 Multi-Factorial Causes

The findings above point to multi-factorial causes of occupant health problems, i.e. interactions between biological, chemical, physical and psycho-social factors producing the reported health problems.¹⁵¹ Often, the exact combinations of the relevant factors or the process of interaction leading to the reported human response cannot be established in retrospective.

In many cases, a mix of contaminants or factors in low concentration is more detrimental to human health than the sum of its individual effects:

It is now known, that material emissions increase with increasing temperatures^{152,153}, a finding that is useful for the evaluation of emission control methods based on thermal effects.

It is also known that microbials grow best in humid environments. In at least three reported cases, respiratory disease in schools could be traced to high levels of humidity in combination with microbial contamination.¹⁵⁴

Chemical contaminants can be distributed in occupied spaces as a result of pressurization of the spaces in respect to the contaminant source. Such cases have repeatedly led to health problems in buildings, especially involving carbon monoxide contamination.¹⁵⁵

2.2.2 Design Omissions in Problem Buildings

The causes of the reported health effects can be found in all phases of the building life, planning, design, construction, and operation and maintenance. Unacceptable exposure can be defined as a lack of control of environmental stressors. It is often difficult to determine the causative incident

¹⁴⁹ Baker DB. 1989. *ibid.*

¹⁵⁰ Carlton-Foss JA. 1984. Comfort and discomfort in office environmental problems. *Annual American Conference of Governmental Industrial Hygienists*. 10:93-112

¹⁵¹ Baker DB. 1989. *ibid.*

¹⁵² Working Group 1. 1989. *ibid.*

¹⁵³ Girman JR. 1989. Volatile organic compounds and building bake-out. *Occupational Medicine: State of the Art Reviews*. 4,4:695-712

¹⁵⁴ Bayer CW, Downing CC. 1992. Indoor Conditions in Schools with Insufficient Humidity Control. *Environments for People*. 197-200

¹⁵⁵ Morey, PR, Shattuck, DE. 1989. Role of Ventilation in the Causation of Building-Associated Illnesses. In: *Occupational Medicine: State of the Art Reviews*. 4,4, October-December 1989. Philadelphia, Hanley & Belfus.

or specific omission of control in a building process that led to the experienced problems.

However, some case studies have clearly identified factors during building design that caused or contributed to the unacceptable conditions:

2.2.2.1 Omissions during Site Planning

2.2.2.1.1 Outdoor Air Contamination. The potential for introduction of outdoor contaminants through building systems and infiltration is influenced by the location of a building in respect to the outdoor sources of contamination. Outdoor contaminants can originate in processes directly on or adjacent to the building site. Wind speed and direction, and climatic and seasonal weather conditions influence the exposure of the building to airborne contaminants:

In a building located in close vicinity to an interstate highway, 55% of occupants complained about headache and upper respiratory problems, 47% of them had missed work due to the health symptoms.¹⁵⁶ An investigation of the problem revealed that in some areas, acceptable levels of total suspended particulates were exceeded by a factor of 17. The origin of the particulates could be identified as the traffic on the highway 50 feet away from the building. The soot had reached the occupied spaces through gaps in the filtration system.

2.2.2.1.1 Ground Contamination. The indoor environment can become contaminated through hazardous materials on-site or through soil gases from natural resources or past land use. The potential for contamination from ground sources depend on the ground material and composition as well as on existing site contours.

In a related case involving a shopping center, occupant health problems and complains about annoyance from odor were caused by gases trapped beneath the building's concrete floor.¹⁵⁷ The gases could be traced to spills from a gasoline tank located next to the shopping center in a slightly uphill position. Run-off from a recent spill had accumulated underneath a store and given off vapors through cracks and seams in the concrete floor.

2.2.2.2 Omissions regarding Occupancy and Building Use

2.2.2.2.1 Premature Occupancy. The materials and processes specified at design reach their emission peaks during building construction. The curing period of newly installed dry and wet materials is about 60 days, during which emissions constantly decrease until they reach a steady rate. Emissions from materials older than 60 days are usually in the acceptable range, if the

¹⁵⁶ Armstrong CW, Sheretz PC, Llewellyn GC. 1989. Sick building syndrome traced to excessive total suspended particulates (TSP). Proceedings of IAQ '89: 3-7.

¹⁵⁷ Barboza PE, Militana LM. 1990. Detection and Control of Indoor Air Contaminants. Proceedings of IAQ '87: 58-65.

building is maintained and operated according to standards. Severe forms of building-related illness resulted from early occupancy in zones where specified materials had not fully cured.¹⁵⁸

2.2.2.2.1 Occupancy during Renovation. The effects of the renovation activities in redesign projects may cause occupant health problems in occupied zones when the construction area is not clearly separated from the occupied area.

During renovation activities in an office building, dust, fumes and particles from demolition processes in an unisolated construction site were distributed into occupied areas through a ventilation system serving multiple zones. Symptoms in office workers included headaches, coughing, nosebleeds, asthma attacks, and tachycardia.¹⁵⁹

2.2.2.2.1 Multiple Use and Flexibility. The objective of building systems is to control environmental loads within acceptable ranges. When occupant density increases due to organizational changes, or due to changes in building use or schedule, building systems may reach maximum capacity before the loads can be controlled within specified ranges.

Occupants in an open-landscape office reported headaches, eye irritation, and inability to concentrate, and complained about “too warm” conditions in their office space.¹⁶⁰ A problem investigation revealed that over a time period of several years, heat sources such as people and computers were accommodated in the space without regard to the capacity of the HVAC system. In the occupied spaces, temperature control was zone-based instead of occupant-based leading to the highest temperatures in zones with the highest occupant densities.

Renovation projects result in changes to existing building processes. In projects involving parts of flexible or multi-use buildings, lack of integration of existing building systems into the new setting led to occupant complaints of respiratory irritation, dizziness, headache, thermal discomfort, fatigue and eye irritation.¹⁶¹ The health symptoms were caused by poor air circulation from an HVAC system that was not reconfigured during design to match the new requirements.

2.2.2.3 Omissions in the Design of Building Systems

2.2.2.3.1 Inadequate Location of Outdoor Air Intakes. The problems arising from inadequate location of outdoor air intakes are cross-contamination through exhaust air from other functional areas, re-entrainment of used air, and entrainment of contaminated outdoor air into the building. Contaminated make-up air can be introduced from outside and distributed throughout the building via the HVAC system.

¹⁵⁸ Woods JE. 1994. Written Testimony. OSHA proposed rulemaking on indoor air quality in indoor work environments. Washington, DC.

¹⁵⁹ Lee BL, Rattan G, Hay R. 1987. Management of an Acute Indoor Air Pollution Problem in a City Office Building. Proceedings of IAQ '87: 150-156.

¹⁶⁰ Morey,PR, Shattuck, DE. 1989. *ibid.*

¹⁶¹ Morey,PR, Shattuck, DE. 1989. *ibid.*

Entrained gases and particulates may accumulate in the air handling equipment and ductwork, or settle in occupied zones:

In a building located near an interstate highway, soot from traffic had accumulated in the ventilation system and had caused upper respiratory illness and headaches in a significant number of occupants.¹⁶² The problems were caused by outdoor air intakes drawing contaminated air from a nearby highway.

The presence of contaminant sources close to buildings can lead to problems with indoor air quality. Contaminants from vehicles at loading docks may enter a building through the outdoor air supply and lead to indoor environmental problems.^{163,164}

A building can become contaminated by re-introduction of exhaust air via outdoor air supply. In a related case, a toilet exhaust discharge located within five feet of a major make-up air intake had resulted in odor problems indoors.¹⁶⁵

2.2.2.3.2 Inadequate Outdoor Air Quantities. Inadequate or lack of outdoor air in buildings is a frequently reported cause of occupant symptoms.^{166,167,168,169,170,171} Lack of outdoor air in buildings has been attributed to measures of energy and cost savings during building design and construction.¹⁷²

When exhaust or supply ductwork is missing or not put to use, outdoor air is prohibited from entering the ventilation system. In one reported case, the omission of outdoor air supply ducts resulted in an indoor carbon dioxide level that was ten times the measured outdoor level.¹⁷³

Restricted outdoor air supply in connection with unbalanced exhausts has led to negative pressurization in buildings. In one case, the pressure differential resulted in indoor contamination with unfiltered outside air and exhaust fumes from an underground garage.¹⁷⁴

¹⁶² Armstrong CW, Sheretz PC, Llewellyn GC. 1989. *ibid.*

¹⁶³ Woods JE, Janssen JE, Morey PR, Rask DR. 1987. Resolution of the "Sick" Building Syndrome. *IAQ '87. Practical Control of Indoor Air Problems*, Arlington, Virginia, May 1987: 338-348.

¹⁶⁴ Morey, PR, Shattuck, DE. 1989. *ibid.*

¹⁶⁵ Woods JE, Janssen JE, Morey PR, Rask DR. 1987. Resolution of the "Sick" Building Syndrome. *ibid.*

¹⁶⁶ Woods JE, Janssen JE, Morey PR, Rask DR. 1987. Resolution of the "Sick" Building Syndrome. *ibid.*

¹⁶⁷ Gamble J, Morey P, Richards T, et al. 1986. Building-Related Respiratory Problems -Problems in Identification. *Proceedings of IAQ '86: 16-30.*

¹⁶⁸ Morey PR, Jones WG, Clere JL, Sorenson WG, et al. 1986. Studies on Sources of Airborne Microorganisms and on Indoor Air Quality in a Large Office Building. *Proceedings of IAQ '86: 500-509.*

¹⁶⁹ Salisbury SA. 1986. Measuring Carbon Dioxide Levels as an Indicator of Poor Building Ventilation. A Case Study. *Proceedings of IAQ '86: 78-82.*

¹⁷⁰ Samimi BS, Seltzer JM. 1992. Sick Building Syndrome due to Insufficient and/or Nonuniform Fresh Air Supply in a Multi-Storey Office Building. *Proceedings of IAQ '92: 451-454.*

¹⁷¹ Sundell J, Lindvall T, Stenberg B. 1992. The Importance of Building and Room Factors for SBS and Facial Skin Symptoms in Office Workers. *Proceedings of IAQ '92: 29-33.*

¹⁷² Berglund B, Berglund U, Lindvall T. 1984. Characterization of Indoor Air Quality and "Sick Buildings". *ASHRAE Transactions 1984, vol. 90, Part 1B: 1045-1055.*

¹⁷³ Salisbury SA. 1986. *ibid.*

¹⁷⁴ Robertson G. 1988. Source, Nature and Symptomology of Indoor Air Pollutants: "Sick Building Syndrome". *Proceedings of Healthy Buildings 88, Vol. 1. Swedish Council for Building Research, 1988: 507-516.*

2.2.2.3.3 Inadequate Air Distribution. Problems with air distribution may lead to poor mixing of air in rooms, within occupied zones and in the occupant breathing zone. Inadequate air distribution is a cause for ineffective removal and dilution of contaminants.

Reported design deficiencies of poor air distribution point to the number and location of air exhausts and supplies in a zone. The resulting pressure differential may lead to a concentrated contaminant build-up around the points of exhaust. If exhaust and return air are at a close range, there is an increased risk of short-circuiting of supply air preventing proper air-mixing in occupied rooms.^{175,176}

2.2.2.3.4 Ineffective Filtration. In addition to the ventilation and air distribution deficiencies mentioned above, there are known cases of inadequate filtration exacerbating the indoor pollution problem by allowing debris and particulates to enter and to be spread throughout a building.^{177,178,179} Filters may be undersized or inefficient by design. Also, problems have been reported from louvers in mixing boxes of variable air systems that open into ceiling voids. Under certain temperature conditions, these louvers may open admitting unfiltered air into the air supply system. This design fault has caused fiberglass, asbestos, fungi and tobacco smoke to be cycled through an office area.¹⁸⁰

2.2.2.3.5 Inadequate Drainage of Condensate. Inadequate drainage of HVAC condensate has led to microbial contamination of indoor air when the contaminants were distributed by HVAC system components.^{181,182,183}

2.2.2.3.6 Inadequate Temperature Control. In many problem buildings, difficulties with temperature control cause or contribute to indoor environmental problems.¹⁸⁴ Both location and sensitivity of thermostats influence room temperature. One investigator could establish an association of occupant symptoms with thermal problems in 55% of investigated cases.¹⁸⁵

2.2.2.3.7 Inadequate Humidity Control. In hot and humid climates, where outdoor humidity levels range from 75% to 90% for most of the year, design deficiencies in HVAC systems relate to the capability of systems to remove moisture from the supplied air. Some systems have been

¹⁷⁵ Woods JE, Janssen JE, Morey PR, Rask DR. 1987. Resolution of the "Sick" Building Syndrome. *ibid.*

¹⁷⁶ Samimi BS, Seltzer JM. 1992. *ibid.*

¹⁷⁷ Woods, JE. 1988. Recent Developments for Heating, Cooling, and Ventilating Buildings: Trends for Assuring Healthy Buildings. *Proceedings of Healthy Buildings 88, Vol. 1. Swedish Council for Building Research: 99-107.*

¹⁷⁸ Armstrong CW, Sheretz PC, Llewellyn GC. 1989. *ibid.*

¹⁷⁹ Robertson G. 1988. *ibid.*

¹⁸⁰ Robertson G. 1988. *ibid.*

¹⁸¹ Gamble J, Morey P, Richards T, et al. 1986. *ibid.*

¹⁸² Morey PR, Jones WG, Clere JL, Sorenson WG, et al. 1986. *ibid.*

¹⁸³ Woods, JE. 1988. *ibid.*

¹⁸⁴ Gamble J, Morey P, Richards T, et al. 1986. *ibid.*

¹⁸⁵ Woods, JE. 1988. *ibid.*

found to manage sensible cooling load ignoring the latent cooling load.¹⁸⁶ One building investigator reported symptoms associated with humidity problems in 30% of problem cases.¹⁸⁷

2.2.2.3.8 Inadequate Lighting Quality. Lighting has been associated with “Sick Building Syndrome”.^{188,189} In areas with tinted glazing, occupants reported more health problems than in areas with clear glazing.¹⁹⁰

Glare from a constellation of low ceilings, luminaires in the line of occupant sight, and low levels of background illumination were also associated with reports of adverse health effects.¹⁹¹ The influence of glare on complaints of headache, eye irritation, and muscle, neck and shoulder pains has been partly attributed to a change in body position to avoid glare at visual display terminals.¹⁹²

2.2.2.3.9 Inadequate Noise Control. Noise has been associated with general discomfort and odor problems. In one study, reports of cold, drafty air in association with noise were attributed to renovation during occupancy.¹⁹³

2.2.2.3.10 Inaccessibility of System Components. Failure to maintain building systems and their components can be caused or supported by failure to provide for removable panels and crawl spaces at design. Inaccessible HVAC components reportedly prevented or complicated system maintenance, and contributed to contaminant build-up during building occupancy.^{194,195,196}

2.2.2.3.11 Absence of System Description. System descriptions in the design phase are usually available in the form of specifications and plans. As-built drawings reflect the design of the system including changes during the construction phase. Maintenance and record keeping operations, as well as problem investigations become complicated, when a system description is not available.¹⁹⁷ Incomplete building documents and documentation formats that cannot easily be updated must therefore be considered as a second order design deficiency.

¹⁸⁶ Bayer CW, Downing CC. 1992. *ibid.*

¹⁸⁷ Woods, JE. 1988. *ibid.*

¹⁸⁸ Robertson AS, McInnes M, Glass D, Dalton G, Burge PS. 1989. Building sickness; are symptoms related to the office lighting? *Ann. Occup. Hyg.*: 47-59.

¹⁸⁹ Hedge A, Burge PS, Robertson AS, Wilson S, Harris-Bass J. 1989. Work related illness in offices: a proposed model of the sick building syndrome. *Environment International*, 15: 143-158.

¹⁹⁰ Burge PS, Robertson A. 1993. Surveillance of office buildings using the workforce to measure the building symptom index (BSI). A measure of the sick building syndrome. *Proceedings of Indoor Air '93*: 569-574.

¹⁹¹ Burge PS, Robertson A. 1993. *ibid.*

¹⁹² Wallace LA, Nelson CJ, Dunteman G. 1991. Workplace Characteristics Associated with Health and Comfort Concerns in Three Office Buildings in Washington, DC. *Proceedings of IAQ '91*. 56-60.

¹⁹³ Wallace LA, Nelson CJ, Dunteman G. 1991. *ibid.*

¹⁹⁴ Morey PR, Jones WG, Clere JL, Sorenson WG, et al. 1986. *ibid.*

¹⁹⁵ Woods JE, Janssen JE, Morey PR, Rask DR. 1987. Resolution of the “Sick” Building Syndrome. *ibid.*

¹⁹⁶ Robertson G. 1988. *ibid.*

¹⁹⁷ Burge PS, Jones P, Robertson AS. 1990. Sick Building Syndrome. *Proceedings of Indoor Air '90*: 479-483.

2.2.2.4 Omissions in the Specification of Building Materials

Building materials strongly influence the prevalence of occupant symptoms by emitting contaminants into the indoor air.¹⁹⁸ New materials act as sources of contamination in the installation and curing processes.¹⁹⁹ Non-emitting materials may become sinks and consequently secondary sources, when their properties enable them to absorb and release airborne contaminants.

2.2.2.4.1 Carpets. Carpets and insulation materials are frequently reported sources of contamination.^{200,201} Carpets may release volatile organic compounds (VOCs) and fibers. They may also serve as a reservoir for microbial contaminants.

The risk of indoor air contamination through carpets is influenced by the composition of the backing holding the fibers. In a school, a styrene-butadiene synthetic rubber carpet had caused complaints about odor discomfort and various health problems.²⁰²

A study on workplace characteristics associated with health and comfort problems showed few relationships between new carpets and health problems.²⁰³ However, carpet installation and frequency of cleaning were strongly associated with throat problems.

2.2.2.4.2 Insulation Materials. Insulation materials consist of man-made fibers that may cause exposure problems. When loose insulation is disturbed, fibers become airborne and can cause skin reactions and respiratory problems. Furthermore, porous interior duct insulation can be a sink for microbial contamination and debris.²⁰⁴

Prior to 1973, asbestos was extensively used in buildings for fire proofing and as insulation material. It can be found on ceilings and steel girders, in components of HVAC systems, in floor coverings and in roofing materials, as well as in some appliances. Through wear, abrasion, friability or water damage, asbestos fibers can become airborne and may cause lung damage and potentially cancer, when inhaled. It is estimated that about 20% of existing buildings in the U.S. still contain some form of asbestos.²⁰⁵

¹⁹⁸ Sundell J, Lindvall T, Stenberg B. 1992. *ibid.*

¹⁹⁹ Girman JR. 1989. *ibid.*

²⁰⁰ Fisk WJ, Mendell MJ, Daisey JM, Faulkner D, Hodgson AT, Nematollahi M, Macher JM. 1993. Phase 1 of the California Healthy Building Study: A Summary. *Indoor Air* 1993; 3: 246-254.

²⁰¹ Winfield M. 1987. A Case History. Odour and Health Problems in a Texas Public School Building. *Proceedings of IAQ '87*: 111-118.

²⁰² Winfield M. 1987. *ibid.*

²⁰³ Wallace LA, Nelson CJ, Dunteman G. 1991. *ibid.*

²⁰⁴ Morey PR, Jones WG, Clere JL, Sorenson WG, et al. 1986. *ibid.*

²⁰⁵ Robertson G. 1988. *ibid.*

2.3 Quality Assurance at Schematic Design

2.3.1 Quality Assurance per ISO 9000

In 1979, the Technical Committee ISO/TC 176 was formed in response to the growing interest for quality in products and services. First published in 1987, the ISO 9000 standards are a vehicle for national and international industries and trades, and cover all quality-related processes and parties.

There are three types of design controls: Design review, design verification and design validation. They are applicable to designs required to be described with performance parameters, or when confidence in product performance is established through assurance of supplier qualification.²⁰⁶

2.3.1.1 Design Review

The design review is defined as a “*documented, comprehensive, and systematic examination of a design to evaluate its capability to fulfill the requirements for quality (...), identify problems, if any, and propose the development of solutions.*”²⁰⁷ There is no prescribed date of implementation for design reviews during the design process. As a minimum, though, design reviews are recommended at design completion.

Design reviews are formal and documented. They involve representatives of all functions involved in the design of a product.²⁰⁸

2.3.1.2 Design Verification

Design verification is a method to ensure that the outputs of a design process meet the requirements at the input stage.²⁰⁹ During design verification, alternative calculations, comparisons to similar designs, tests and demonstrations may be used to collect evidence.

The personnel conducting the design verification should not have had prior involvement or responsibilities in the design under review. Participants are required to have professional knowledge of the subject under review.²¹⁰

²⁰⁶ ISO Standards Compendium. 1994. ISO 9001. Quality systems - Model for quality assurance in design, development, production, installation and servicing. Switzerland. 1: Scope.

²⁰⁷ ISO Standards Compendium. 1994. ISO 9000. Quality Management. Fifth Edition. Switzerland. ISO 8402-1994, 3.11.

²⁰⁸ ISO Standards Compendium. 1994. ISO 9001. 4.4.6

²⁰⁹ ISO Standards Compendium. 1994. ISO 9001. 4.4.7

²¹⁰ ISO Standards Compendium. 1993. ISO 9000-2. Quality management and quality assurance standards - Part 2: Generic guidelines for the application of ISO 9001, ISO 9002 and ISO 9003. 4.4.5: Design verification.

2.3.1.3 Design Validation

Design validations are conducted after design verification, and can be performed at any time until design completion. The objective of design validations is to ensure that a product conforms to defined user needs and requirements.²¹¹

2.3.2 Quality Assurance per AIA

Three procedures to control the quality of the architectural design can be identified: Program review, evaluation of concept alternatives, and owner approval.

2.3.2.1 Program Review

The design procedures recommended by the American Institute of Architects (AIA) are based on the assumption that a clear definition of the client's program is available at the start of the design process.²¹² The architect reviews the program, and performs a preliminary evaluation of the owner's program, schedule and construction budget requirements.²¹³

The objective of the program review is to arrive at a mutual agreement between the owner and the architect about the project requirements.²¹⁴

The scope of the program review typically includes the program, site analyses, zoning and code requirements, scheduling, cost, regional construction industry practices, and architectural precedents of the intended project.²¹⁵

2.3.2.2 Evaluation of Concept Alternatives

In the design process, the architect produces several alternative architectural solutions in response to the program requirements. The alternatives are reviewed with the owner.²¹⁶

In the architectural practice, architectural firms typically have developed firm-specific methods of selecting the "best" solution. Grading against project requirements or subjective evaluation are commonly used methods.²¹⁷

²¹¹ ISO Standards Compendium. 1994. ISO 9001. 4.4.8

²¹² Perkins B. 1987. Building Design. In: The Architect's Handbook of Professional Practice. American Institute of Architects. 11th Edition. Washington DC. 2.5:1

²¹³ The American Institute of Architects. 1987. Standard Form of Agreement Between Owner and Architect. AIA Document B141. Washington DC. Article 2: Scope of Architect's Basic Services. 2.2 Schematic Design Phase.

²¹⁴ The American Institute of Architects. 1987. Standard Form of Agreement Between Owner and Architect. AIA Document B141. Washington DC. 2.2.1

²¹⁵ Perkins B. 1987. *ibid.* 2.5:5

²¹⁶ The American Institute of Architects. 1987. Standard Form of Agreement Between Owner and Architect. AIA Document B141. Washington DC. 2.2.3

²¹⁷ Perkins B. 1987. *ibid.* 2.5:9

With the contractual responsibilities, participants formally acknowledge that the quality of the design is influenced by a team of contributors after the conceptual development. The extended design team includes architects, engineers, interior designers, specialist consultants, construction managers, public agencies, and clients.²¹⁸

2.3.2.3 Owner Approval

The schematic design documents showing the scale and the relationship of the project components are submitted to the owner for approval at the end of the schematic design phase.²¹⁹ After the owner has approved the schematic design, the architect continues the project planning with the design development.²²⁰

2.3.3 Assurance of Indoor Air Quality per ASHRAE

The following documents were selected to represent available engineering methods for assurance of indoor air quality at schematic design:

1. ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air Quality
2. ASHRAE Standard 55-1992: Thermal Environmental Conditions for Human Occupancy
3. ASHRAE Guideline 1-1989: Guideline for Commissioning of HVAC Systems
4. ASHRAE Guideline 4-1993: Preparation of Operating and Maintenance Documentation for Building Systems

2.3.3.1 Ventilation for Acceptable Indoor Air Quality

The objective of this standard is to minimize the potential for adverse health effects caused by deficiencies related to ventilation and air-conditioning in buildings.²²¹ The ventilation requirements of indoor or enclosed spaces for human occupancy are stated.²²² Two strategies of indoor air quality control are presented in this standard, one emphasizing provision of ventilation air of a specified quality and quantity to the occupied space (also known as ‘control by dilution’), and the other one emphasizing contaminant control.²²³ In order to comply with the standard, it is sufficient to use one of the two strategies.²²⁴

²¹⁸ Perkins B. 1987. *ibid.* 2.5:9

²¹⁹ The American Institute of Architects. 1987. Standard Form of Agreement Between Owner and Architect. AIA Document B141. Washington DC. 2.2.4

²²⁰ The American Institute of Architects. 1987. Standard Form of Agreement Between Owner and Architect. AIA Document B141. Washington DC. 2.3 Design Development, 2.3.1.

²²¹ American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1990. ANSI/ASHRAE Standard 62-1989. Ventilation for Acceptable Indoor Air Quality. Atlanta. 1. Purpose.

²²² ANSI/ASHRAE Standard 62-1989. *ibid.* 2. Scope.

²²³ ANSI/ASHRAE Standard 62-1989. 4. Classification.

²²⁴ ANSI/ASHRAE Standard 62-1989. 6. Procedures.

The provisions for acceptable indoor air are not specified for each building phase. For schematic design, where the objective is to select the major building systems and present the overall concept, the following provisions are likely to apply:

A. Requirements from the Ventilation Rate Procedure

*The outdoor air at the building site must be within acceptable limits.*²²⁵

Limits for the most common contaminants are shown in Table 1 of 62-89. The contaminant levels at the site can be estimated by reviewing monitoring data of the local government institutions or measured by air monitoring at the site for three consecutive months.

Furthermore, *the assumptions and criteria regarding occupancy and contamination levels must be documented.*²²⁶

B. Requirements from the Indoor Air Quality Procedure

*The concentration of contaminants indoors must meet acceptable levels.*²²⁷

Limits for the most common indoor contaminants are shown in Table 1 and Table 3 of 62-89. Acceptable concentrations are achieved by using adequate control measures.

*The assumptions and criteria regarding occupancy and contamination levels must be documented.*²²⁸

Furthermore, the following control measures apply in the design of the ventilation systems:

*When the requirements for ventilation air cannot be met through infiltration and natural ventilation alone, mechanical ventilation has to be provided.*²²⁹ *Assumptions regarding ventilation rates and air distribution must be documented.*²³⁰

*Reentrainment of exhausted contaminants or other forms of contamination of make-up air must be avoided.*²³¹ Contaminated make-up air may stem from parking garages, loading docks, or street traffic, and can be introduced through inadequate location of air inlets and outlets, and stack effects. In regions where radon is a natural resource, the respective gaseous contaminants can enter occupied spaces through crawlspaces, basements, and underground ductwork below atmospheric pressure.²³²

2.3.3.2 Thermal Environmental Conditions for Human Occupancy

The purpose of this standard is to specify acceptable thermal conditions for environments

²²⁵ ANSI/ASHRAE Standard 62-1989. 6.1.1.

²²⁶ ANSI/ASHRAE Standard 62-1989. 6.1.3.1.

²²⁷ ANSI/ASHRAE Standard 62-1989. 6.2.

²²⁸ ANSI/ASHRAE Standard 62-1989. 6.3

²²⁹ ANSI/ASHRAE Standard 62-1989. 5.1.

²³⁰ ANSI/ASHRAE Standard 62-1989. 5.2.

²³¹ ANSI/ASHRAE Standard 62-1989. 5.5

²³² ANSI/ASHRAE Standard 62-1989. 5.5

designed for human occupancy.²³³ The requirements for compliance to 55-92 are based on a combination of indoor environmental and personal factors. Environmental factors are temperature, thermal radiation, humidity and air velocity. Personal factors relate to activity and clothing of building occupants. In order to comply with 55-92, simultaneous fulfillment of all criteria is mandatory.²³⁴

The provisions for two potential problems at schematic design are:

A. Requirements for avoidance of general thermal discomfort

Natural ventilation is not effective, when the outdoor thermal conditions are outside the ranges shown in Figure 2 of 55-92.

B. Requirements for avoidance of local thermal discomfort

*Local discomfort is a human response to non-uniformity in the thermal environment.*²³⁵ The potential for local thermal discomfort is specifically given in areas near windows, corners and entrance areas.²³⁶

C. Other

*The temperature of building materials must be controlled to avoid condensation.*²³⁷ Condensation may cause microbial contamination and damage to the building fabric.

2.3.3.3 Commissioning of Building Systems

The purpose of this guideline is to document and verify HVAC system performance ‘as designed’.²³⁸ The goal of the recommended procedures is “...a fully functional, fine-tuned HVAC system”²³⁹.

The recommended evaluation procedures consist of functional performance testing, as well as documentation for HVAC system acceptance, and adjustments to actual occupancy needs. The documentation of the procedures includes occupancy requirements and design assumptions in the design of the HVAC systems, and a statement of the design intent for use by contractors, owners and operators. A methodology for identification of roles and responsibilities in the process is provided.

The provisions for commissioning of HVAC systems at schematic design can be identified from Section 5 of 55-89, Predesign.

²³³ American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1992. ANSI/ASHRAE Standard 55-1992. 1.

²³⁴ ANSI/ASHRAE Standard 55-1992. 2.2.

²³⁵ ANSI/ASHRAE Standard 55-1992. 5.1.6.(d)

²³⁶ ANSI/ASHRAE Standard 55-1992. 7.1.1.

²³⁷ ANSI/ASHRAE Standard 55-1992. 5.1.3.

²³⁸ American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1989. ANSI/ASHRAE Guideline 1-89. 1.1.1.

²³⁹ ANSI/ASHRAE Guideline 1-89. 2.2.

The predesign phase of the commissioning process consists of a documented review of the client program and the development of a conceptual design based on stated building environmental objectives.²⁴⁰

*The special review items are occupancy, functional activities and required equipment, special needs areas, thermal environmental requirements and budget constraints.*²⁴¹

*A formal documentation of the commissioning at predesign includes a statement of the design assumptions, performance standards, the recommended conceptual approach, and the spatial requirements of the intended system.*²⁴²

2.3.3.4 Preparation of Operating and Maintenance Documentation for Building Systems

The objective of this guideline is to operate buildings and building systems safely, reliably and efficiently. Guideline 4 provides detailed information about accurate, relevant and timely documentation during HVAC commissioning. It specifies format, content, delivery, and update of the HVAC building systems and related operation and maintenance procedures as to be provided by design and construction personnel.

*The O&M documentation at the conceptual design phase of an HVAC system is a detailed statement of the design intent, and also specifies the required skills of the building operators.*²⁴³

The design intent at conceptual design consists as a minimum of a description of the building function²⁴⁴ and the building itself²⁴⁵.

The description of the building functions includes type of occupancy, functional requirements of the building occupants, and utility information.

The building description includes an overview of the building systems in the form of single-lined schematics.

²⁴⁰ ANSI/ASHRAE Guideline 1-89. 5.2.3.1.

²⁴¹ ANSI/ASHRAE Guideline 1-89. 5.2.1.2.

²⁴² ANSI/ASHRAE Guideline 1-89. 5.2.4.2.

²⁴³ American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 1993. ANSI/ASHRAE Guideline 4-93. Table 1.

²⁴⁴ ANSI/ASHRAE Guideline 4-93. Appendix C, Section 1.

²⁴⁵ ANSI/ASHRAE Guideline 4-93. Appendix C, Section 2.

3.1 Development of the Hypothesis

In Chapter 2 of this thesis, evidence of design causes of health and building symptoms in investigated problem buildings was reviewed. Figure 3-1 shows the identified design omissions and the associated building symptoms in the operating phase as established through the literature review.

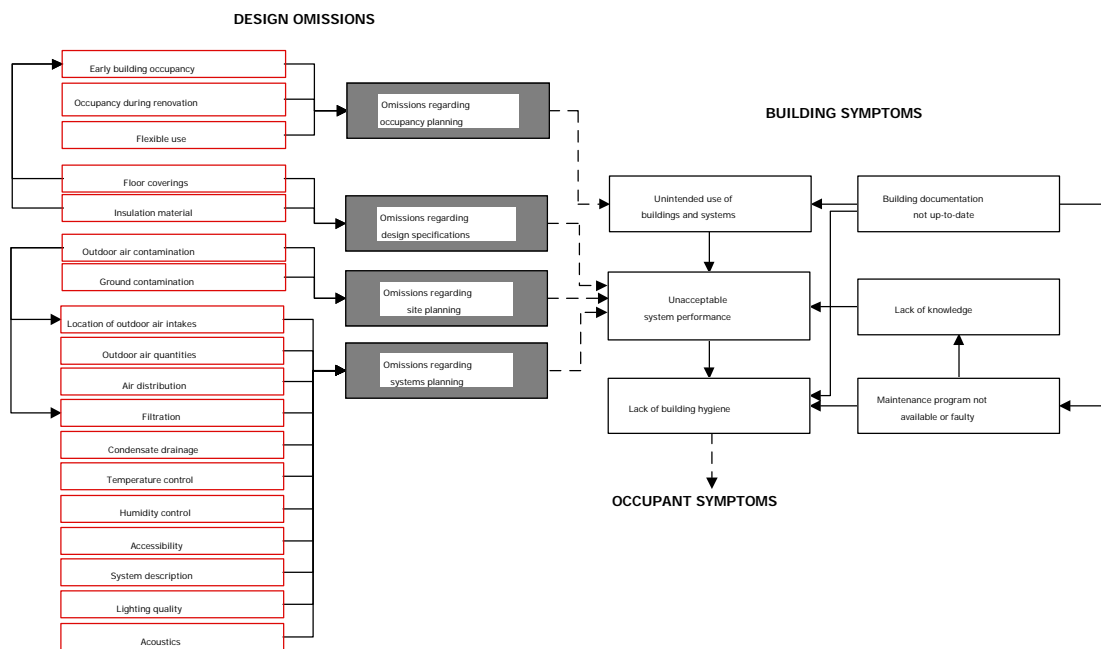


Figure 3-1
Building Symptoms in the Operation phase and their Design Causes
(per reported results of building investigations)

Two conclusions can be drawn from the findings of the literature review:

1. Occupant health was affected by exposure to environmental stressors from building deficiencies caused by design omissions. The design omissions were found in the design tasks of occupancy planning, design specification, site planning and building systems planning.
2. The design deficiencies passed the buildings' systems of quality inspection and control, and were only detected after occupant health in the operation phase had been affected.

In the constitution of the World Health Organization, ‘health’ is defined as “... a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity”²⁴⁶. From there, some have concluded that environmental conditions in buildings should promote occupant well-being in addition to minimizing the risks of adverse health effects.²⁴⁷ In operating buildings, actions to comply with occupant demands for well-being by eliminating the causes of malfunction or faults are of a reactive nature. The effectiveness of reactive measures is limited by a number of factors:

1. *Dependence on symptoms*

Faults in the operation of buildings are detected by screening for building or occupant symptoms of undesired performance. Under certain circumstances, multiple small deviations in individual performance factors may lead to adverse occupant responses without measurable building symptoms.²⁴⁸

2. *Limited number of options for corrective action*

The implementation of corrective actions requires integration of a physical solution into an existing building. The spectrum of available options for building system modifications depends on the installed building systems and components, and on time and budget constraints in each specific case.

3. *Restricted potential for improvement of perceived environmental quality*

Once occupant health has been affected, mitigation efforts are time and cost-consuming. In cases involving serious occupant health problems, the costs for corrective action exceeded the costs for planning and construction.²⁴⁹ In addition, return on investment is not always guaranteed, as occupant mistrust in the performance of mitigated buildings in some cases has led to on-going complaints about building environmental conditions that were actually within acceptable ranges.

4. *Dealing with symptoms of causes in earlier building phases*

The causes of the environmental problems may originate in faulty operation and maintenance procedures, in which case remedies can directly address the identified causes. However, symptoms of malperformance in the operating phase may be only indirectly linked to the existing systems, but originate in earlier building phases. Correcting omissions from previous phases during building operation means dealing with symptoms at a time when the original causes cannot be addressed any more. The result may be restricted effectiveness in mitigating the problems. If the identified omissions are systemic, a large number of buildings are likely to be affected ‘by default’.

²⁴⁶ World Health Organization. 1946. Constitution of the World Health Organization. Official Record of the World Health Organization. 2:100

²⁴⁷ Berglund B, Lindvall T, Samuelsson I, Sundell J. 1988. Prescriptions for Healthy Buildings. In: Berglund B, Lindvall T (eds): Proceedings of CIB Conference Healthy Buildings ‘88. Conclusions and Recommendations for Healthier Buildings. Swedish Council for Building Research, Stockholm. 5-14

²⁴⁸ World Health Organization. 1987. Air Quality Guidelines for Europe. WHO Regional Publications, European Series No. 23.

²⁴⁹ Woods JE, Boschi N. 1995. Evolving concepts of continuous degradation and continuous accountability. Proceedings of Healthy Buildings ‘95: 201-212

Traditionally, standards are developed and complied with to ensure that minimum requirements for quality are met. The published problems show, however, that environmental quality in buildings cannot be achieved with the current building procurement processes. The focus of some standards on prescribed system performance to control quality within acceptable ranges, when the basis of indoor environmental quality is actually occupant needs for well-being has been identified as a possible source of problems.²⁵⁰

The ineffectiveness of standards to comprehensively provide for indoor environmental quality may also lie in the scope of factors taken into consideration: ‘Quality control’ is defined as “...operational techniques and activities that are used to fulfill requirements for quality...”²⁵¹. It is used to monitor the performance of processes and to detect and resolve the causes of unwanted performance.²⁵² In that sense, standards function as a tool to comply with acceptable system performance in building phases where the specified system criteria can be controlled. However, when quality control is performed within individual building phases only, the potential to meet occupant needs in the operation phase may be limited.²⁵³

To address intended quality states in industrial and commercial processes more comprehensively, a concept called ‘quality assurance’ evolved. The definition of ‘quality assurance’ for international use is “all the planned and systematic activities implemented within the quality system (...), and demonstrated as needed, to provide adequate confidence that an entity (...) will fulfill requirements for quality (...)”²⁵⁴. Quality assurance is strictly based on user needs with respect to products and services, and exceeds the scope of quality control as it relates to all processes and products that are in any measurable relationship with the intended quality.²⁵⁵

It is suggested in this thesis that by implementing a method to control intended quality in individual processes and to assure quality on a comprehensive level, design omissions can be prevented and related problems in operating buildings can be minimized. Furthermore, transfer of building performance deficiencies from early planning phases into later phases could be avoided, and the use of potentially ineffective reactive strategies aimed at offsetting the faults of earlier building phases during building operation could be minimized.

As pointed out in the quality literature, the potential for avoidance of problems is greatest in the early planning phases, when changes can be made with only minor impact on time and budget.²⁵⁶ The engineering standards reviewed in [Chapter 2](#) refer largely to detailed design, when many planning decisions have already been finalized. There may be multiple, often conflicting

²⁵⁰ Woods JE, Arora S, Sensharma NP, Olesen BW. 1993. Rational Building Performance and Prescriptive Criteria for Improved Indoor Environmental Quality. *Proceedings of Indoor Air '93*. 3:471-476.

²⁵¹ International Organization for Standardization. 1994. ISO 8402:1994. ISO 9000 Quality Management. Fifth Edition. Switzerland.

²⁵² Juran JM, Gryna FM. 1993. *ibid.* Chapter 5: Control of Quality.

²⁵³ Woods JE. 1990. Continuous accountability: A means to assure acceptable indoor environmental quality. *Proceedings of Indoor Air Quality and Climate*. 5:85-94

²⁵⁴ International Organization for Standardization. 1994. *ibid.*

²⁵⁵ Gryna FM. 1988. Quality Assurance. In: Juran’s Quality Control Handbook. Juran JM, Gryna FM (eds), 1988. Fourth Edition. Mc-Graw-Hill.

²⁵⁶ Juran JM, Gryna FM. 1993. Quality Planning and Analysis. From Product Development through Use. Third Edition. McGraw-Hill. Economic Models of Quality of Conformance: 25

approaches in the assurance of quality, but there are no disagreements in the concepts related to quality planning that quality is a characteristic that has to be defined and planned for from early on.²⁵⁷

Theoretically, an early intervention to ensure occupant needs for indoor environmental quality is beneficial in several ways:

1. *Low cost of change*

Due to the relatively low information content at this stage, the expenses for incorporating the evaluation and possible modifications into the on-going design process are low.

2. *High effectiveness of input*

In early planning phases, several alternative concepts in response to the program requirements can be evaluated.²⁵⁸ Building diagnostics data could serve as additional source of information to point out potential sources of problems or strengthen designs aiming at optimizing indoor environmental quality.

3. *Early detection of preplanning faults*

There is evidence in the reviewed literature that decisions during the planning of buildings can impact building operation. By evaluating the owner program and project requirements, potential problems with indoor environmental quality can be identified for correction in current or later planning phases.

It is concluded from the above that a method for quality assurance in early planning phases should be pro-active and ensure occupant needs of indoor environmental conditions over an extended time frame.

In the operation phase, the causes of occupant health problems are detected by analysis of occupant symptoms, sources and systems.²⁵⁹ Through building diagnostic procedures, building data are analyzed and future building performance is predicted.²⁶⁰ The so developed data are the basis for recommendations of corrective measures, and for feedback to building operation. It has been indicated that similarly, building diagnostics can be used to diagnose building quality in phases prior to building occupancy.²⁶¹

The objective of building diagnostic processes is to predict building performance over time.²⁶² The prediction relies on a comparison between the measured data for specified parameters and the

²⁵⁷ Suarez JG. 1992. Three Experts on Quality Management: Philip B. Crosby, W. Edwards Deming, Joseph M. Juran. Department of the Navy, Office of the Under Secretary of the Navy, Total Quality Leadership Office. TQLO Publication No.92-02.

²⁵⁸ Perkins B. 1987. *ibid.* 2.5:9

²⁵⁹ Woods JE, Morey PR, Rask DR. 1989. Indoor air quality diagnostics: qualitative and quantitative procedures to improve environmental conditions. Special Technical Publication 1002 1989. American Society for Testing and Materials, Philadelphia, PA.

²⁶⁰ Woods JE. 1990. *ibid.*

²⁶¹ Woods JE. 1990. *ibid.*

²⁶² Building Research Board. 1985. Building Diagnostics: A Conceptual Framework. National Research Council. National Academy Press, Washington, DC.

predefined quality criteria. Building diagnostics is also a method to test compliance with building performance criteria in which case it is used to screen for inconsistencies (i.e. lack of compliance) between the intended quality criteria and actual (or simulated) building performance.^{263,264}

Should it be possible to develop a building diagnostic method for early planning phases, the following should be accomplished in response to the problem statement:

1. Problems that can be controlled within the specified planning phase can be detected.

In fulfilling this requirement, causes of problems with the expected indoor environmental conditions can be detected and resolved in the scope of quality control measures.

2. Occupant health problems through omissions in early planning phases can be prevented.

For this requirement, the overall concept of providing for indoor environmental quality has to be addressed. Evidence is needed that the developed method is an effective measure to avoid occupant health problems.

It is suggested to develop and test such a method in the course of a case study. The results of case studies are not statistically significant, however, they can produce valid results of a preliminary nature from which hypotheses for further testing can be developed. Due to the low statistical significance of case studies, hypotheses can only be rejected or not rejected. For acceptance of any hypotheses in respect to the method, a larger number of cases should be reviewed.

Furthermore, it is suggested to develop a building diagnostic method for application at schematic design, and to compare its results with the building performance at substantial completion to evaluate the effectiveness of reviews at schematic design, because these phases mark the start and the completion of a building as a tangible product: At the beginning of schematic design, information about the site, and the expected occupant and owner needs are turned over to the architect for development of a building design in compliance with the stated information. Substantial completion marks the date when the building project is completed and turned over to the owner and its occupants. Both phases represent unoccupied building states, with schematic design as the first step from written information to a three-dimensional representation of the building, and substantial completion as the last phase of the building construction process.

A comparison of the two phases may provide insight into the potential of provisions at schematic design and their effects on later building phases.

²⁶³ Building Research Board. 1985. *ibid.*

²⁶⁴ Woods JE, Morey PR, Rask DR. 1989. *ibid.*

3.2 Hypothesis

The following hypothesis was developed for testing:

The performance of a building at substantial completion can be predicted through a systematic evaluation of the schematic design.

4 Development of the Method

4.1 Development of the Process

4.1.1 Analysis of the Schematic Design Process

The schematic design phase is the first of three design phases in the planning of a building, which are schematic design, design development and preparation of construction documents. The schematic design follows the predesign phase, in which the project needs are identified and the site is analyzed.

There are two different types of schematic design processes, the schematic design process of private and the one of public projects. The schematic design activities of private projects are described in the ‘Architect’s Handbook of Professional Practice’ by the American Institute of Architects, and are recommended procedures for implementation in the architectural practice.²⁶⁵ The schematic design process of public projects is described in the Capital Outlay Manuals of the different states.

4.1.1.1 Private Projects

In the first step of the schematic design of private projects, the program developed at predesign is verified by the architect, and clarified in discussions with the owner. Then, a design concept is developed based on the identified program needs. Often, several alternative solutions are prepared which are evaluated with design criteria developed from project and architectural requirements. The so selected design concept is then documented in more detail, and presented to the owner. If the owner approves the proposed schematic design, it continues to design development. If the owner does not agree with the proposed schematic design, the design criteria are modified and the design documentation is updated.

Figure 4-1 shows an overview of the activities at schematic design of private projects as recommended by the American Institute of Architects.²⁶⁶

²⁶⁵ The Architect’s Handbook of Professional Practice. American Institute of Architects. New York.

²⁶⁶ Perkins B. 1987. Building Design. In: The Architect’s Handbook of Professional Practice. American Institute of Architects.

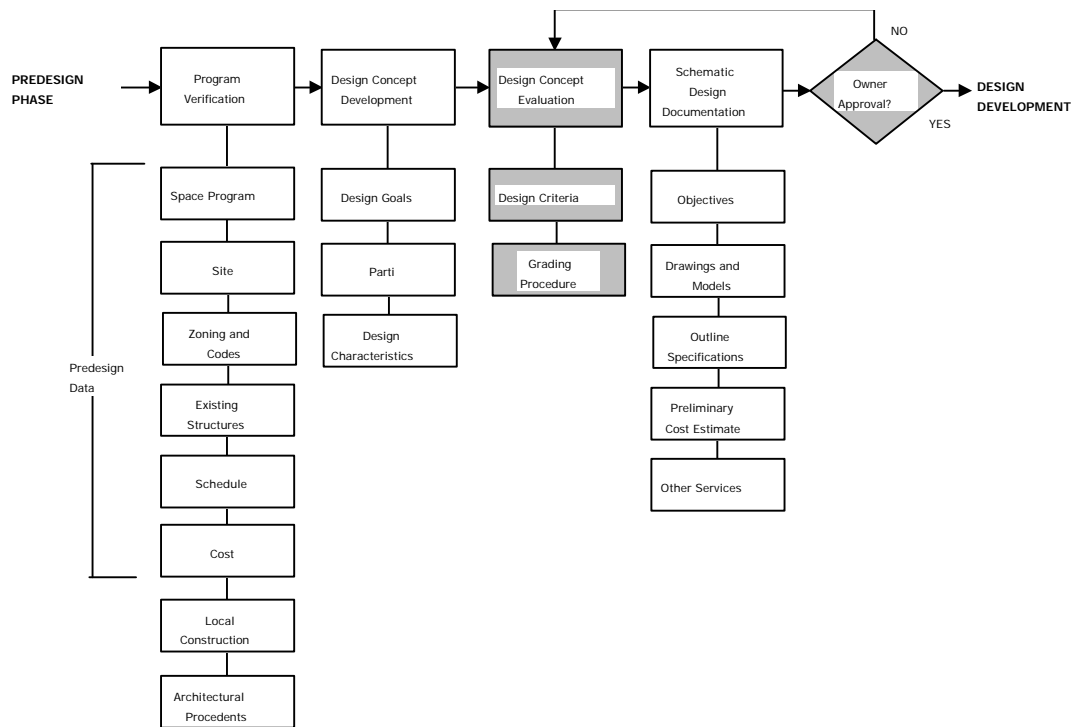


Figure 4-1
The Schematic Design Process of Private Projects

4.1.1.2 Public Projects

The first steps in schematic design of public projects are to identify preplanning information and to determine whether a submission meeting with the Art and Architecture Review Board is required. If there are no preplanning studies available, or if a submission meeting is required, the architect defines the project needs and submits it for verification to the owner before starting the preparation of the schematic design documents. If preplanning studies are available, or if there are no requirements for a submission meeting, the architect reviews and refines the program and prepares the schematic design drawings and specifications. The completed schematic design documents are submitted to the Art and Architecture Review Board for approval, if this has been determined as required before continuing to the next phase. If there are no requirements for submittal, the schematic design proceeds to the next stage.

Figure 4-2 shows the schematic design process of public buildings in Virginia.²⁶⁷

²⁶⁷ Commonwealth of Virginia Department of General Services. 1996. Construction and Professional Services Manual - For Agencies. Bureau of Capital Outlay Manual, Richmond, Virginia, USA, December 1996.

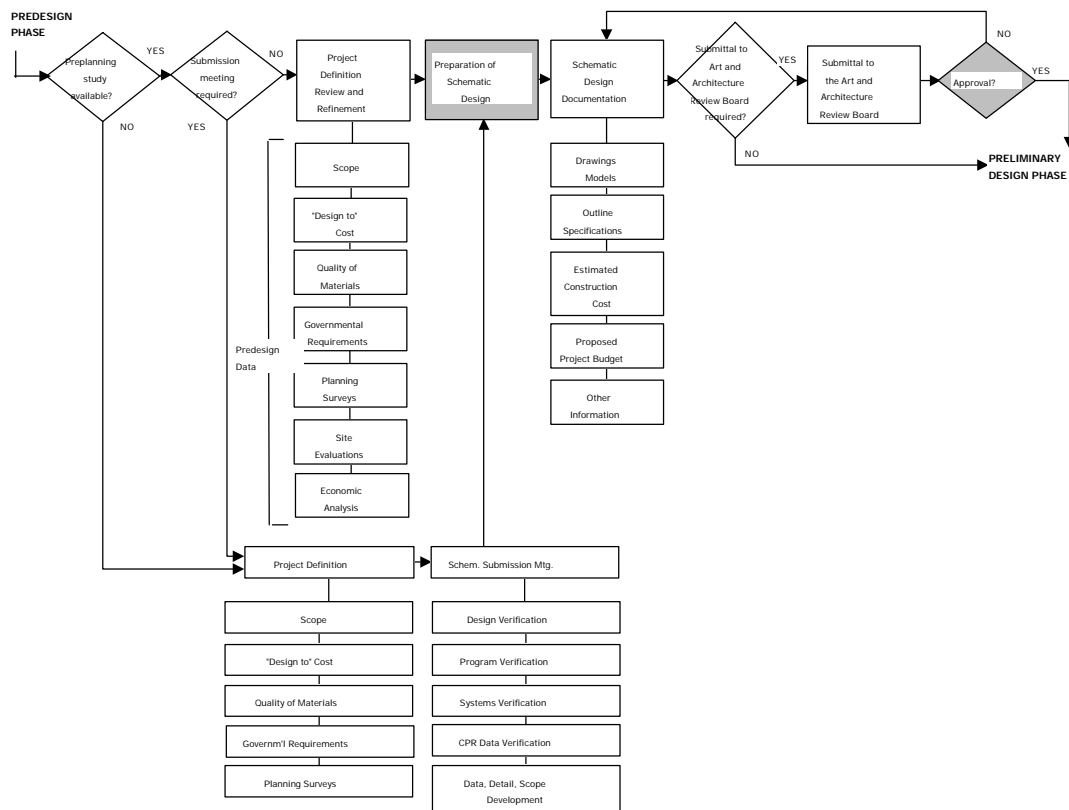


Figure 4-2
The Schematic Design Process of Public Projects

4.1.2 The Quality System at Schematic Design

4.1.2.1 Overview

The schematic design process can be viewed as a system, in which an architect uses professional expertise and expert knowledge to fulfill owner-defined project requirements for a specified building quality (see [Figure 4-3](#)).

Similar to the input/output analysis of industrial processes²⁶⁸, each component has a potential influence on the overall quality of a product or service. Therefore, the quality of the schematic design can be assessed by an evaluation of its process components.

Examples for performance evaluation of the schematic design process are presented in [Figure 4-3](#): At q1, the overall quality of the schematic design documents is influenced by the qualifications of the architectural firm supplying the professional services. At q2, the quality of the schematic design documents is influenced by the specific knowledge that is applied in a design project. This knowledge may come from internal (architectural) or external (consultant) sources. A third means of influencing the quality of schematic design documents is given through the process of

²⁶⁸ Koelling P, Torgerson P, Van Aken E. 1994. Quality Assurance. College of Industrial and Systems Engineering, Virginia Tech. Spring 1994.

preparing the schematic design documents, specifically through the activities of program verification and the preparation of schematic design and related documents. Fourth, the results of the schematic design process, i.e. the schematic design documents rely on the inspection of the achieved quality. Fifth, the owner who is the customer in the schematic design process, is involved in the achievement of quality at schematic design, as the building program is based on owner requirements for building use, and the schematic design documents need approval by the owner to proceed to design development.

When indoor environmental quality is a measure of compliance with occupant requirements for health and comfort, an inherent problem of the schematic design process (Figure 4-3) becomes obvious: If the building owner is not also the prospective building occupant, the priority of criteria in the development of a building may not be aimed at health and comfort, but at optimizing other owner requirements, such as economic criteria. If occupant requirements are not specifically addressed in a schematic design process, nor recommended by the planning team or specified through the owner program, alternative measures are needed to make sure that the minimum requirements for occupant health and comfort are fulfilled.

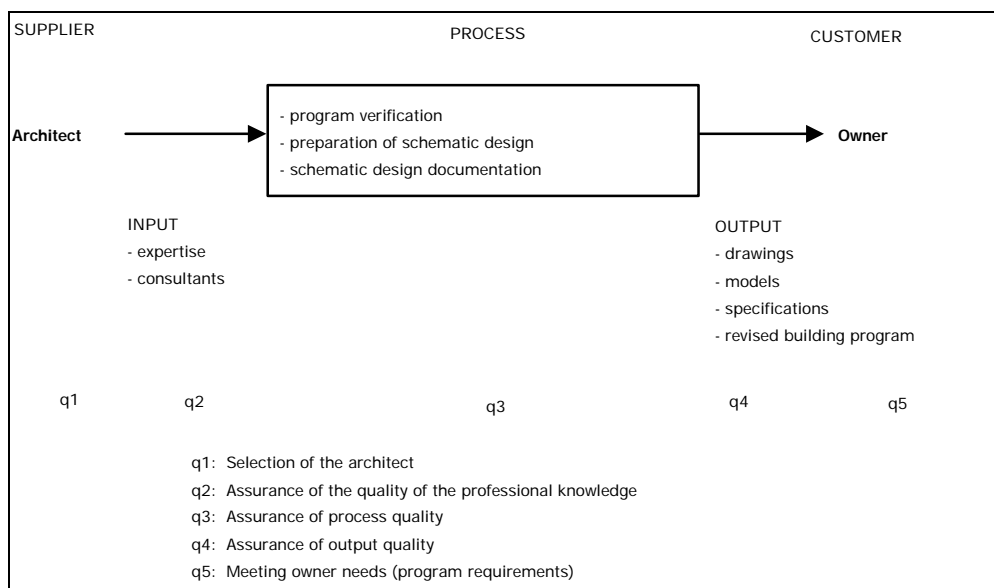


Figure 4-3
Input/Output Analysis of the Schematic Design Process

4.1.2.2 Opportunities for Review

There are two opportunities for a review of the schematic design to check for potential problems with indoor environmental quality:

In private projects, the schematic design can be reviewed during preparation of the documents (e.g. during concept evaluation) before submission to the owner for approval, or during owner approval before continuing to the next phase (see shaded areas in Figure 4-1). If the review takes

place during schematic design preparation, the architect can use the information from the evaluation for following up on the recommended improvements to the design. If the review occurs during owner approval, the owner can use the information for decisions about modifications of the design, and can request that the architect modifies the design documents to incorporate the necessary changes.

The same applies to schematic design processes of public projects where the information from a review of indoor environmental quality can be used by the architect during preparation of the schematic design or by the owner in the approval process (see shaded areas of [Figure 4-2](#)).

4.1.3 The Building Diagnostic Process

Building diagnostic processes consist of the tasks of design of measurements, selection of appropriate instrumentation, interpretation of the results, and prediction of building performance.²⁶⁹ These tasks are directed by occupant symptoms, sources and systems in indoor environments, and by the diagnostic objectives of the evaluation.²⁷⁰

4.1.3.1 Symptoms, Sources and Systems

Indoor environments can be viewed as a system of relationships between symptoms, sources and systems where occupant health symptoms are caused by exposure to environmental stressors outside of acceptable limits.²⁷¹ The stressors may stem from sources in or outside of a building. Prevention of occupant health problems can be avoided by controlling environmental stressors within acceptable ranges.

To use this concept at schematic design, it has to be adapted to the information content at this stage. [Table 4-1](#) shows an overview of typical documents at schematic design.²⁷² The indoor environment at schematic design is represented by conceptual drawings and specifications of the major systems and materials together with data on economics, construction cost, time, and energy consumption. Since there are no data on occupant symptoms available at this stage, the prediction of adverse health effects is based on the ability of the chosen building systems to manage environmental loads from the site and on requirements from the expected use and occupants.

²⁶⁹ Building Research Board. 1985. *Building Diagnostics: A Conceptual Framework*. National Research Council. National Academy Press, Washington, DC.

²⁷⁰ Lane CA, Woods JE, Bosman TA. 1989. Indoor Air Quality Diagnostic Procedures for Sick and Healthy Buildings. *Proceedings of IAQ '89*. 237-240

²⁷¹ Woods JE, Arora S, Sensharma NP, Olesen BW. 1993. Rational Building Performance and Prescriptive Criteria for Improved Indoor Environmental Quality. *Proceedings of Indoor Air '93*.

²⁷² Perkins B. 1987. *op. cit. supra*.

Table 4-1 Typical Products of the Schematic Design Process

Type of Documentation	Scale or Scope
Site plan Plans for each level All elevations Two or more sections	<ul style="list-style-type: none"> • 1/16" • 1/8"
Outline specification	<ul style="list-style-type: none"> • General description of the work, and major systems and materials
Statistical summary of the design area	<ul style="list-style-type: none"> • Comparable to the program
Preliminary construction cost estimate	<ul style="list-style-type: none"> • May be broken down by trades or systems • May include contingencies for design development, market contingencies and changes during design
Additional services	<ul style="list-style-type: none"> • Energy studies • Tenant-related design studies • Life cycle cost, or other economic studies • Renderings, models • Brochures, promotional material for owner

4.1.3.2 Diagnostic Objectives

In the absence of building and occupant symptoms, schematic design projects have to be treated like “buildings without known problems”, and performance evaluations are conducted on a whole building scale (diagnosis by inclusion).²⁷³

The objective in the diagnosis of “buildings without known problems”, typically, is aimed at maximizing true-negative outcomes, i.e. correct statements about the absence of problems.²⁷⁴ Furthermore, either false-negative or false-positive outcomes are minimized, although it is often difficult to decide in advance which of the two objectives to choose.²⁷⁵

False-negative outcomes at schematic design relate to incidents of not detecting existing problems. As a consequence, design omissions may remain undetected and enter the design development phase. False-positive outcomes at schematic design relate to an overprediction of problems, e.g. control measures may be rated ineffective, when in fact, they were correctly chosen. At schematic design, where the assessment of quality is mainly based on qualitative, lenient criteria, building diagnostic processes are only capable of minimizing false-positive outcomes, i.e. suppressing incorrect diagnoses of non-existing problems.²⁷⁶

²⁷³ Lane CA, Woods JE, Bosman TA. 1989. op. cit. supra.

²⁷⁴ Lane CA, Woods JE, Bosman TA. 1989. op. cit. supra.

²⁷⁵ Lane CA, Woods JE, Bosman TA. 1989. op. cit. supra.

²⁷⁶ Swets JA. 1988. Measuring the Accuracy of Diagnostic Systems. *Science*, June 1988. 240:1285-1293.

4.1.3.3 Design of measurements

The objective of the measurements at schematic design is to collect data on potential sources and on the specified systems. The scope of the review is the entire building including the site and its surroundings as presented in drawings, specifications and other available project information. The collected data are used to test compliance with the evaluation criteria.

4.1.3.4 Selection of instrumentation

There is no instrumentation required to collect the data. The evaluator must be able to read and understand schematic design and predesign documents.

4.1.3.5 Interpretation of the results

Potential sources of problems can be identified through omissions in the drawings and specifications. Data on building systems and loads are used to evaluate whether occupant health problems and building problems can be avoided with the specified control strategies. A design is acceptable, when the documentation is in compliance with the evaluation criteria.

4.1.3.6 Prediction of building performance

Building diagnostics at schematic design predicts the likelihood that a building ‘as-designed’ will perform acceptably. If all evaluation criteria are met by a schematic design, the risk that omissions from the schematic design phase will cause occupant health problems has been minimized.

4.1.3.7 Deriving the Building Diagnostics Process

It has been stated that building diagnostics can be performed in operating buildings as well as in buildings in the development phase.²⁷⁷ For the evaluation of indoor air quality in operating buildings, qualitative and quantitative procedures have been developed and proven valid, reliable, and accurate.^{278,279}

The procedures consist of three phases, a consultation phase, a qualitative phase, and a quantitative phase.²⁸⁰ The consultation phase is used to develop a preliminary hypothesis based on the reported problems and a cost estimate for the intended measurements. The qualitative phase is based on a walk-through procedure. The quantitative phase is used in problem buildings, when more evidence in support of the hypothesis is required.

²⁷⁷ Building Research Board. 1985. op. cit. supra. 3:13

²⁷⁸ Woods JE, Morey PR, Rask DR. 1989. op. cit. supra.

²⁷⁹ Lane CA, Woods JE, Bosman TA. 1989. op. cit. supra.

²⁸⁰ Woods JE, Morey PR, Rask DR. 1989. op. cit. supra.

Since the buildings at schematic design are treated like ‘buildings without known problems’, the method is developed from a qualitative evaluation of the schematic design. Similar to a walk-through in an operating ‘building without known problems’, all spaces of the building at schematic design are reviewed for potential problems that may hinder compliance with the environmental criteria.

Compared to the qualitative phase in operating buildings, the process at schematic design does not contain steps to evaluate medical conditions of occupants or to analyze loads quantitatively. The remainder of the qualitative phase for diagnostics of indoor air quality and thermal conditions consists of the following steps:

1. Set performance criteria
2. Define system boundaries and functional areas
3. Analyze control strategies
4. Formulate and test the hypothesis
5. Criteria compliance
6. Recommend modifications, if required
7. Submit report

If problems are found, predicted building performance is less than acceptable. For the purpose of quantification of the deviation from acceptable performance, a method exists to classify building performance in respect to expected health patterns.²⁸¹

Buildings are classified based on their compliance profile with criteria for human response, exposure, system performance and economic performance. If a building complies with the full set of predefined criteria, building performance in a defined time period is likely to be acceptable. Failure to comply with exposure criteria leads to classification as a ‘problematic’ building, failure to comply with system performance or economic performance criteria leads to classification as a ‘marginal’ building.

The three building classes are representative of the environmental population in operating buildings, where acceptable building performance leads to classification as ‘healthy’, ‘marginal’ performance compares to that of ‘buildings with undetected problems’, and ‘problematic’ performance to that of buildings with manifestations of “Sick Building Syndrome” or “Building-Related Illness”.²⁸² Application of the classification procedures at schematic design allows for a comparison of building performance at different stages of the building life cycle.²⁸³

²⁸¹ Woods JE, Arora S, Sensharma NP. 1994. Indoor Environmental Diagnostics: Evolution of a Systematic Approach. Indoor Environment ‘94, Washington DC. IAQ Publications.

²⁸² Woods JE, Arora S, Sensharma NP. 1994. op. cit. supra.

²⁸³ Woods JE, Boschi N, Sensharma NP, Wilman A. 1997. The Use of Classification Criteria in Building Diagnostics and Prognostics. Proceedings of Healthy Buildings ‘97, Washington, D.C. 483-488

4.2 Development of Evaluation Criteria

4.2.1 Conceptual Approach

The development of evaluation criteria is based on a transformation process relating human response to indoor environmental factors. With the transformation process, human response criteria are related to exposure, exposure criteria to system performance, and system performance criteria to environmental sources and loads, and each criteria category also relates to economic performance criteria.²⁸⁴ The criteria may vary with building function and geographical location, and should represent indoor conditions to which 80% or more building occupants will perceive acceptable.²⁸⁵

The findings of the literature review in Chapter 2 suggest that a high number of complaints in operating buildings relate to indoor air. It can therefore be assumed that by improving the controls for quality of indoor air and thermal properties in developing buildings, indoor environmental quality will be substantially improved. For the purpose of testing of the method, the criteria development in the following will focus on requirements for achievement of acceptable indoor air quality and thermal quality.

4.2.2 Requirements from Standards and Guidelines

The following requirements could be identified from a review of standards and guidelines in section 2.3.3 of this thesis:

Indoor air quality

1. The outdoor air at the building site must be within acceptable limits.²⁸⁶
2. The assumptions and criteria regarding occupancy and contamination levels must be documented.^{287,288}
3. The concentration of contaminants indoors must meet acceptable levels.²⁸⁹

Ventilation system design

1. When the requirements for ventilation air cannot be met through infiltration and natural ventilation alone, mechanical ventilation has to be provided.²⁹⁰
2. Assumptions regarding ventilation rates and air distribution must be documented.²⁹¹
3. Reentrainment of exhausted contaminants or other forms of contamination of make-up air must be avoided.²⁹²

²⁸⁴ Woods JE, Arora S, Sensharma NP, Olesen BW. 1993. op. cit. supra.

²⁸⁵ Woods JE, Morey PR, Rask DR. 1989. op. cit. supra.

²⁸⁶ ANSI/ASHRAE Standard 62-1989. 6.1.1.

²⁸⁷ ANSI/ASHRAE Standard 62-1989. 6.1.3.1.

²⁸⁸ ANSI/ASHRAE Standard 62-1989. 6.3

²⁸⁹ ANSI/ASHRAE Standard 62-1989. 6.2.

²⁹⁰ ANSI/ASHRAE Standard 62-1989. 5.1.

²⁹¹ ANSI/ASHRAE Standard 62-1989. 5.2.

²⁹² ANSI/ASHRAE Standard 62-1989. 5.5

4. In areas where radon is a natural resource, the related gaseous contaminants must be controlled.²⁹³

Thermal Quality

1. Local discomfort is a human response to non-uniformity in the thermal environment and must be avoided.²⁹⁴
2. The temperature of building materials must be controlled to avoid condensation.²⁹⁵

Documentation

1. Special review items are occupancy, functional activities and required equipment, special needs areas, thermal environmental requirements and budget constraints.²⁹⁶
2. A formal documentation of the commissioning at predesign includes a statement of the design assumptions, performance standards, the recommended conceptual approach, and the spatial requirements of the intended system.²⁹⁷
3. The O&M documentation at the conceptual design phase of an HVAC system is a detailed statement of the design intent, and also specifies the required skills of the building operators.²⁹⁸
 - 3.1 The design intent at conceptual design consists as a minimum of a description of the building function²⁹⁹ and the building itself³⁰⁰.
 - 3.2 The description of the building functions includes type of occupancy, functional requirements of the building occupants, and utility information.

4.2.3 Requirements from the Review of Reported Building Problems

In [Chapter 2](#), design omissions that caused problems in occupied buildings were reviewed. From the identified causes, related controls to avoid the experienced problems can be developed. A summary of the identified design causes and opportunities for control at schematic design are shown in [Table 4-2](#).

²⁹³ ANSI/ASHRAE Standard 62-1989. 5.5

²⁹⁴ ANSI/ASHRAE Standard 55-1992. 5.1.6.(d)

²⁹⁵ ANSI/ASHRAE Standard 55-1992. 5.1.3.

²⁹⁶ ANSI/ASHRAE Guideline 1-89. 5.2.1.2.

²⁹⁷ ANSI/ASHRAE Guideline 1-89. 5.2.4.2.

²⁹⁸ ANSI/ASHRAE Guideline 4-93. Table 1.

²⁹⁹ ANSI/ASHRAE Guideline 4-93. Appendix C, Section 1.

³⁰⁰ ANSI/ASHRAE Guideline 4-93. Appendix C, Section 2.

Table 4-2 Design Omissions and Control Principles at Schematic Design

Design Causes	Control Principles	Documentation
SITE PLANNING		
outdoor air contamination	control of sources of contamination at the site	site planning specifications
ground contamination		
OCCUPANCY & USE		
premature occupancy	emission control	specifications
occupancy during renovation	zoning concept	schematic design drawings
multiple use	definition of space function and specific requirements	specifications
BUILDING SYSTEMS DESIGN		
inadequate location of outdoor air intakes	immission control (entrainment control)	schematic design drawings
inadequate outdoor air quantities	documentation of room-specific needs	specifications
inadequate air distribution		
inadequate filtration		
inadequate drainage of condensate		
inadequate temperature control		
inadequate humidity control		
inadequate lighting quality		
inadequate noise control		
inaccessibility of system components		
absence of system description	documentation of system components and operation	
SPECIFICATION OF BUILDING MATERIALS		
carpets	emission control	specifications
insulation materials		

4.2.4 Minimum Criteria for Evaluation at Schematic Design

From the opportunities for control of the experienced problems in Table 4-2 and the criteria from the standards review, minimum criteria for review of the specific products at schematic design are developed. They are shown in Table 4-3.

If the program requirements of a reviewed project are more stringent than the criteria in Table 4-3, the list of criteria has to be corrected accordingly.

Also, the requirements in individual zones may vary. Therefore, parts of a project may have to be in compliance with the special criteria developed from the stringent program requirements, while other areas are reviewed regarding compliance with the minimum criteria in Table 4-3.

Table 4-3 Minimum Criteria for Evaluation of Indoor Air Quality and Thermal Comfort at Schematic Design

<p>SCHEMATIC DESIGN DRAWINGS</p> <p>1. Building Environmental Zoning <u>Indoor air quality</u> 1.1. The function of a space must be documented. 1.2. Acceptable contamination levels in special use areas must be documented. <u>Ventilation system design</u> 1.3. Intended ventilation rates and air distribution concepts must be documented.</p>	<p>2. Control of Supply Air Quality <u>Ventilation system design</u> 2.1. Reentrainment of exhausted contaminants or other forms of contamination of building supply air must have been prevented.</p>
<p>SPECIFICATIONS</p> <p>3. Control of Outdoor Sources of Contamination <u>Indoor air quality</u> 3.1. The acceptable levels of outdoor air contamination must be specified. 3.2. If the ground contains radon, the intended method of control must be stated.</p> <p>4. Control of Emissions from Building Materials <u>Indoor air quality</u> 4.1. The acceptable levels of indoor contaminants must be specified.</p> <p>5. Occupancy Planning <u>Indoor air quality</u> 5.1. The number of occupants, the space function, and acceptable contaminant levels must be stated. <u>Ventilation system design</u> 5.2. Intended ventilation rates and air distribution concepts must be specified. 5.3. The control methods for non-uniform thermal environments must be specified. 5.4. The control methods for condensation in building materials must be specified. <u>Documentation</u> 5.5. The number of occupants, space function, space equipment, special use areas, thermal environmental requirements and budget constraints must be stated.</p>	<p>6. Documentation of System Components and Operation <u>Ventilation system design</u> 6.1. The requirements for ventilation air and air distribution must be stated. 6.2. The intended method of building ventilation must be specified. 6.3. The control method against reentrainment of exhausted contaminants or other forms of contamination in the building supply air must be specified. 6.4. The methods to control non-uniform thermal environments must be stated. 6.5. Design assumptions, performance standards, the recommended conceptual approach, and the spatial requirements of the system must be stated. 6.6. The design intent, in particular the space function, functional needs of the building occupants, utility information, and building description, and the required skills of the building operators must be stated.</p> <p><u>Legend</u> ■ Exposure Criteria ■ System Performance Criteria ■ Economic Criteria</p>

4.3 Presentation of the Method

The presented method is used to predict building performance in private and public projects based on a review of provisions for indoor air quality and thermal conditions at schematic design. It is an information tool for evaluation of architectural design concepts and for owner approval.

The method is aimed at maximizing true-negative outcomes (i.e. maximizing the number of correct diagnoses stating the absence of problems), and at minimizing false-positive outcomes (i.e. minimizing the number of incorrect diagnoses stating non-existing problems).

Basis for the implementation of the method is the schematic design documentation, i.e. the schematic design plans and the specifications. Additionally, the building program and information about ground and site conditions should be available.

The method consists of the five steps shown in Figure 4-4, identification of project requirements, measurement of indoor environmental quality, compliance test, building classification and documentation.

4.3.1 Identification of Project Requirements

In Task 1 in Figure 4-4, activities related to the identification of project requirements are shown.

In the first step, the scope of the evaluation and the minimum criteria in respect to acceptable exposure, system performance and economics are defined. The presented method is aimed at evaluating the provisions for indoor air quality and thermal conditions at schematic design. The scope of the evaluation is the entire building. The minimum criteria are developed from research studies and standards, and are consistent with the scope of the schematic design. Should more stringent or additional criteria be specified in the building program, the minimum criteria are updated accordingly.

Table 4-3 shows the criteria for evaluation of indoor air quality and thermal conditions in the schematic design of projects in North America.

4.2.2 Measurement of Indoor Environmental Quality

In Task 2 of Figure 4-4, activities related to the measurement of indoor environmental quality at schematic design are shown.

The building systems related to the achievement of indoor air quality and thermal comfort are described, and the supported zones are defined and described. Expected environmental loads are determined and the selected methods for control are analyzed.

Based on the analysis of data on sources and building systems, a hypothesis is formulated. The hypothesis is a statement of predicted likelihood that the evaluated building will perform as intended.

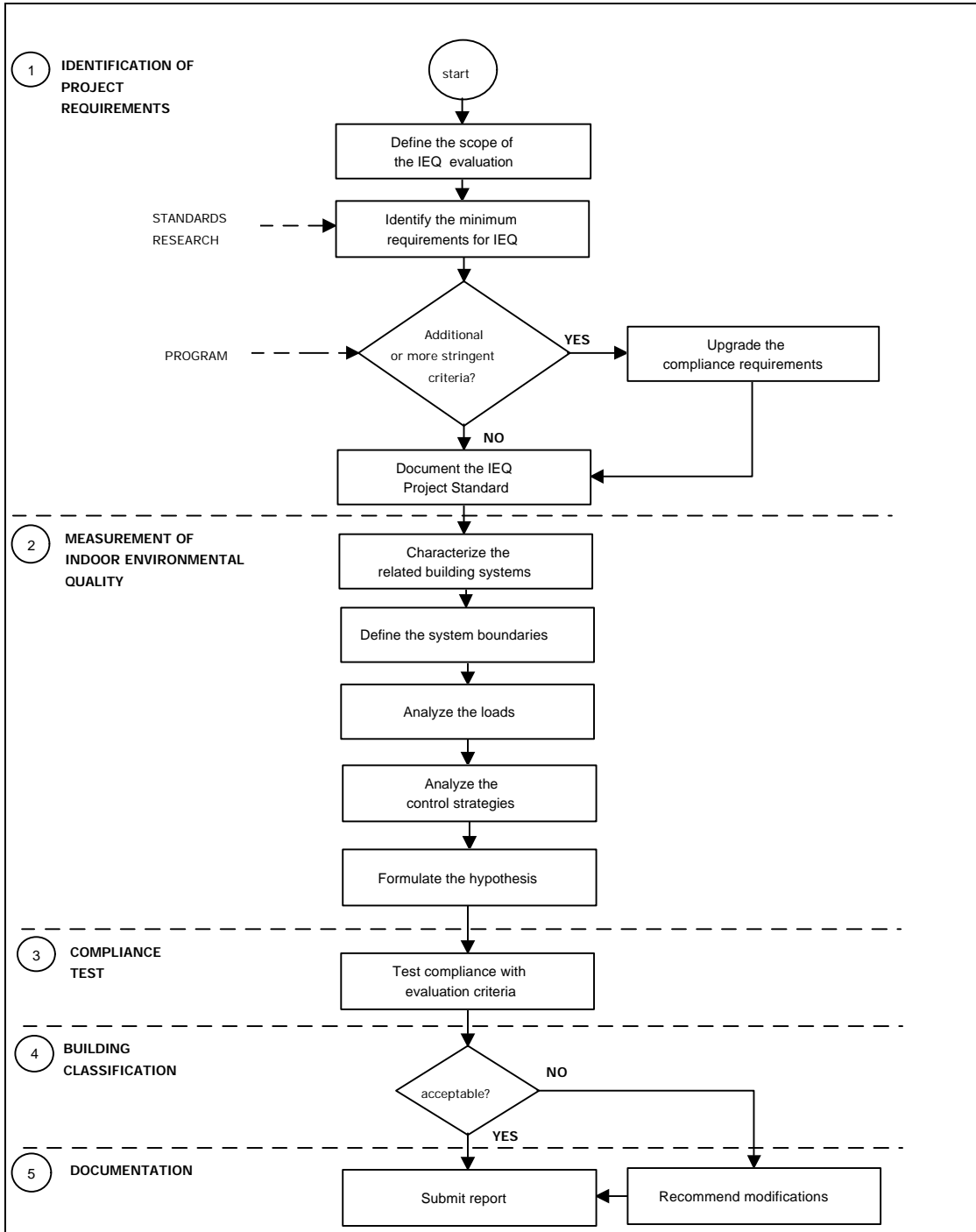


Figure 4-4
Building Diagnostics at Schematic Design

4.3.3 Compliance Test

In the compliance test, requirements that are not met in the evaluated schematic design are identified.

4.3.4 Building Classification

In Task 4, the building design is classified according to its compliance with the evaluation criteria. The classification process is used to describe four building conditions, buildings that are free from problems, buildings with undetected problems, buildings with “Sick Building Syndrome”, and those with “Building-Related Illness”.

If all specified criteria are met, there is evidence that the building design is free from problems, and that adverse occupant responses to the indoor environment through omissions at schematic design are avoided.

If one or more economic or system performance criteria are missed, a building design is rated ‘marginal’ indicating that problems exist that might compromise occupant health. If no economic criteria are specified, building designs pass by default.

If one or more exposure criteria are missed, the building is rated ‘problematic’. ‘Problematic’ buildings pose an actual health risk to occupants, and the identified problems should be resolved prior to the next building phase.

4.3.5 Documentation

In Task 5 of [Figure 4-4](#), activities related to the documentation of the evaluation process are shown.

If building performance is acceptable, the diagnostic procedures, results and findings are documented in a report and submitted to the architect or owner.

If building performance is less than acceptable, the diagnostic procedures, results, findings and recommended modifications are documented and submitted to the architect or owner.

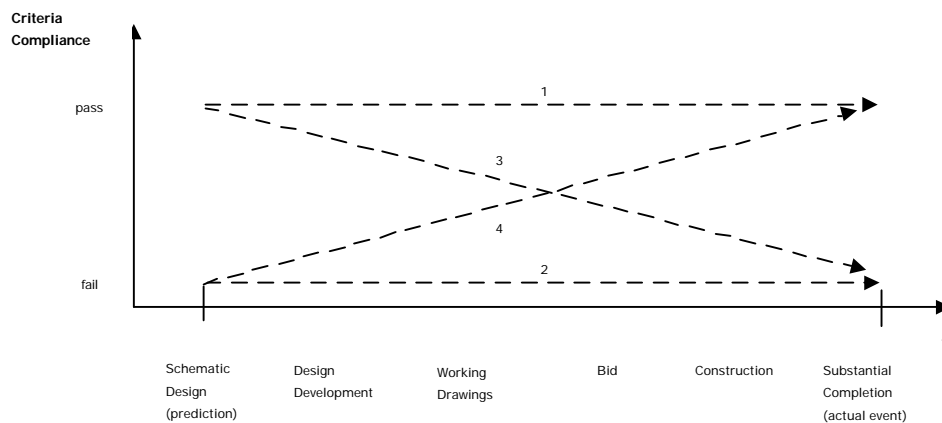
5.1 Objectives

The hypothesis developed in [Chapter 3](#) of this thesis is that building performance at substantial completion can be predicted by a review of the schematic design. It is the objective of this chapter to provide evidence that with the developed method, (a) problems with compliance to indoor environmental criteria can be detected, and (b) building performance at substantial completion can be accurately predicted.

For objective (a), the schematic design of a building will be reviewed and classified. Building performance may be rated ‘acceptable’, ‘marginal’ or ‘problematic’ depending on criteria compliance. Objective (a) is achieved, when at least one problem is detected in the course of implementation of the method. Further testing for effectiveness of the method is not part of this thesis. If building performance is rated ‘acceptable’, i.e. when no problems can be detected, other case studies are needed to test the method.

For objective (b), building performance at schematic design is compared with that at substantial completion. There are four ways in which the prediction and the actual event may agree or disagree(see [Figure 5-1](#)):

1. The method correctly predicts problems at Substantial Completion.
2. The method correctly predicts the absence of problems with building performance at Substantial Completion.
3. The method fails to predict acceptable performance at Substantial Completion.
4. The method fails to predict problems with building performance at Substantial Completion.



- | | |
|---|-----------------------------------------------------------------------------------------------------------|
| 1 | The method correctly predicts problems at Substantial Completion |
| 2 | The method correctly predicts the absence of problems with building performance at Substantial Completion |
| 3 | The method fails to predict acceptable performance at Substantial Completion |
| 4 | The method fails to predict problems with building performance at Substantial Completion |

Figure 5-1
Four Possible Outcomes of the Prediction

If the method can predict building performance at Substantial Completion, (1) or (2) will be supported by the results of the case study. If the outcome is (2), more tests with other schematic designs are required to test the reliability of the diagnostic method. If (1) is the result of the evaluation, the method cannot be tested, and a different case study should be selected for evaluation of the method.

If (3) or (4) occur, building performance at substantial completion cannot be predicted with the method, and possible causes of the failure should be identified.

5.2 Description of the Case Study

The case study is a public building, namely a county judicial and office facility in Wheaton, Illinois/USA, approximately 20 miles west of Chicago. At the time of the case study, the building is completed and operating.

The following is a description of the building at schematic design:

The site is located in a suburban area. A railway line is bordering to the north. Access to the site is provided through roads in the southwest and west of the site. The building is directly adjacent to an existing Sheriff's office and prison building, which it is connected to through a walkway on the second floor. Parking spaces are available north of the existing facility. Two office buildings are located directly off the access roads in the west. South of the planned building is a pond. The site slopes from east and west towards the center of the site in direction to the pond. The height of the building site above sea level is between 753 ft.(east/west) and 720 ft. (pond).

At schematic design, the planned gross area of the building is 300,000 sq.ft. for 34 courtrooms and support spaces. The projected number of occupants is 1,632 (603 persons and 1,029 visitors) in 1986, 1,837 in 1990 and 2,228 in 2020. In the north of the existing Sheriff's office is an existing parking area that is scheduled for expansion to hold 2,000 additional parking spaces. For anticipated needs beyond 1990, an addition of 65,000 sq.ft. for 6 more courtrooms and support spaces are planned. By 2020, 200 additional parking spaces will be added.

The building has a rectangular footprint of about 150 ft. by 440 ft. with the long sides facing east and west, and the short sides facing south and north. Main access to the building is through the entrances at the east and at the west on the first floor. For deliveries and garbage pick-up, trucks back up against a loading dock on the basement level at the north side. The building has 4 stories and one basement. The height of the stories vary from 16 ft. (typical office floor) to 20 ft. (basement and third floor). Total building height excluding roof-top equipment or roof structures is about 72 ft. above grade. The building has as a steel structure with face brick and inoperable windows at room height (9 ft.). The roof is flat.

On the first floor, probation, forensics, the office of the court clerk, and the jury commissions are located. The cafeteria on the south side of the first floor has outdoor dining directly at the lake. Escalators in the lobby lead to the upper floors.

On the second floor, the civil courts are located in the core surrounded by offices at the perimeter across a hallway. The law library is in the north of the second floor adjacent to the office of the public defender in the east and to the walkway leading to the prison building in the west.

On the third floor, the office of the state's attorney and the domestic relations courts can be found. Office spaces are organized along the perimeter on the east and south facades.

On the fourth floor are the criminal courts, the office of the court reporters, and the public administration. Office spaces are at the perimeter on the east, south and west facades. The court rooms are in the core and are connected with the prison building by a secure corridor between the third and the fourth floor in the center of the building.

For the basement, three alternative versions exist, one containing a large unexcavated portion in the west, and two fully excavated alternatives. In the partially excavated basement, a large mechanical equipment room and loading docks are located in the north at grade. The below grade portion of the basement contains storage facilities for office materials and electronic data and equipment. Alternative 1 has additional storage space in the west. Alternative 2 has a parking garage in the west accessed from the area near the mechanical room.

5.3 Validation Procedures

At schematic design as well as at substantial completion, building performance was evaluated based on available building documentation. At the time of the evaluation, the building was completed and operating.

5.3.1 Schematic Design Review

The schematic design evaluation was conducted according to the process outlined in [Figure 4-4](#). Available for review were the schematic design drawings, the specifications, the facility program, and the owner/architect agreement (see [Appendix A](#) for a detailed list of documents). The criteria shown in [Table 4-3](#) served as minimum criteria, and attempts were made to develop additional criteria from requirements in the facility program.

After review of the schematic design documents and the specifications, the building systems related to indoor air quality and thermal comfort were described, and the spatial zones served by these systems were defined. The expected environmental loads and the specified strategies for control of the loads were identified. From the collected data, a hypothesis with respect to existing sources and the potential for control was developed.

The collected data were compared with the evaluation criteria and needs for compliance were identified.

Then, the building design was classified, and recommendations for modification of the schematic design documents were developed.

5.3.2 Evaluation of Building Performance at Substantial Completion

Independent from this case study, building performance at substantial completion was evaluated by an expert panel based on available building documentation.

5.4 Results

5.4.1 Results of the Schematic Design Review

The facility program did not contain new requirements to upgrade the minimum criteria. In the Agreement between the Owner and the Architect, the owner had specified expectations, some of which did not show in the facility program or the specifications. From the expectations regarding the performance of the prospective building, one economic criterion could be developed. Contract documents are not typical schematic design documents and should not be considered for criteria development in the case study. However, to test the effect of hidden requirements on the diagnostic results, the criterion was added as desirable, i.e. non-compliance of the design to this criterion will not have an effect on building classification.

The project requirements as well as the list of evaluation criteria for the case study are shown in Appendix A (Case Study: Identification of Project Requirements (Step 1)).

From data on the envelope and ventilation systems, thermal zones, and thermal and air quality loads in drawings and specifications, the following information can be obtained:

1. Building

The building is a steel structure with a brick facade equipped with inoperable windows and tinted glazing. The metal roof has four skylights for natural light in the central hallway on the fourth floor. Transmission coefficients for various envelope elements are specified. The assumptions leading to the selection of the envelope systems, especially regarding the glazing are not stated. The effects of the tinted glazing on the neighboring building were not considered in the specifications.

2. Air Handling Systems

The air handling systems are to be planned in compliance with ASHRAE Standards 62-73, 55-74 and 90-80. The ground floor and the lobby areas are being served by constant air volume systems, whereas the other spaces are being served by variable air volume. In addition, hot water radiators are used to offset the heat loss in unheated areas. The general heating design criteria are $-10^{\circ}\text{F}/72^{\circ}\text{F}$, the ones for cooling are 95°F dB and 78°F wB/ $75^{\circ}\text{F}@50\%rh$. Special design criteria are stated for machine and mechanical rooms. Filtration systems are equipped with throw-away and 55% efficient filters. Outdoor air rates for the court rooms are either 15 cfm/p or code requirements, and 0.1 cfm/ft^2 for offices and lobby areas. The CAV systems operate at 100% outdoor air and have ducted return air plenums. The room air of areas served by VAV systems is returned over unducted ceiling plenums. The total supply air is estimated at 0.9 cfm/ft^2 for interior spaces, and 1.0 for exterior offices. The loading dock is ventilated at 6 ACH all year round. The mechanical equipment is specified to maintain 75°F dB in all seasons. The estimated

capacity of the systems is based on 1.1 cfm/ft² for the typical floors and 1.2 cfm/ft² for the top floor. The heating system is zone controlled, however, no thermal zones have been identified. Occupant control of temperature and ventilation is unavailable. All zones are served by the mechanical equipment located in the mechanical room in the north of the building.

Appendix B (Case Study: Data Collection (Step 2)) contains a detailed list of identified building characteristics.

After data collection, a qualitative analysis of cooling, heating and indoor air quality loads was conducted. In a separate step, the spaces with special requirements for temperature, humidity and ventilation control were reviewed regarding existing loads and load management. Various problems with the provisions for indoor air quality and thermal comfort were detected:

1. Problems with the Load Assessment

The assumed densities and loads are calculated on a building average, while three out of four floors above grade contain spaces with higher than average peak loads. The estimates in most areas are therefore unrepresentative of the actual loads. Some loads, such as caused by smoking or laboratory use in the Forensic DUI have not been addressed at all.

2. Problems with Provisions for System Control

Also, the controllability of the spaces is not addressed in the specifications, which would be required in the public and internal spaces with high intermittent loads.

3. Problems with the Concept of Air Distribution

Although the major building systems are described, the concept of how the systems deliver outdoor air to the occupants in the different zones is not specified. Outdoor air intakes and building exhausts are not identified.

4. Problems with the Location of Outdoor Air Intakes

Since no outdoor air intakes and building exhausts are identified, it cannot be excluded that air intakes are located in close vicinity to the mechanical room near the loading docks. There is a lack of evidence that contamination of supply air has been effectively prevented.

5. Omissions in the Specification of Outdoor Air Quantities

There are no provisions or specifications for the areas with special requirements for temperature and ventilation. The specified systems cannot provide the required outdoor air quantities in these spaces to meet the special needs.

6. Problems with Information Transfer

The information content of the drawings differs from that in the specifications. The specifications do not show any reference to the drawings as could be expected in the description of the building operation or the identification of building air intakes and exhausts.

7. Omissions regarding Effects of the Planned Building on the Surroundings

Outdoor loads and effects of the building on the existing site and neighboring buildings are not addressed.

8. Problems with Occupancy Planning

The stated needs and loads are based on spatial functions or energy saving measures, and the estimated loads are not representative of the expected occupant densities in the court rooms.

9. Problems with Owner-Specified Criteria

Furthermore, the special requirements for humidity, temperature and ventilation specified in the facility program have not been addressed. Owner expectations about the economic performance of the building were stated in contract documents, and not in the facility program.

10. Lack of Provisions for Operation and Maintenance

Requirements for operation and maintenance were not specified, nor were related costs taken into account in the preliminary cost estimate.

An overview of the problems is shown in Table 5-1 and Table 5-2. In Table 5-1, the omissions in the documentation of provisions for indoor air quality and thermal comfort are summarized. In Table 5-2, omissions in the specification of special needs are shown.

In Appendix B (B1: Analysis of Loads and Control Strategies, B2: Analysis of Spaces with Special Needs and B3: Analysis of Loads in Court Rooms), a more detailed analysis is presented.

Based on the analysis of loads and systems, the following hypothesis was developed:

Omissions regarding occupancy planning, specifications of building materials, site planning and building systems planning have resulted in a building that cannot be expected to perform according to owner and occupant requirements for indoor air quality and thermal comfort.

The schematic design documents fail to comply with exposure, system performance and economic criteria. An overview of the compliance results is shown in Appendix C (Case Study: Compliance Test (Step 3)). On the grounds of failure to comply with exposure criteria, the building design was rated 'problematic'. If the design omissions are not corrected and are transferred into building operation, occupant health will be at risk.

Table 5-1. Omissions In The Documentation Of Provisions For Indoor Air Quality And Thermal Comfort

SOURCES	PROBLEMS	CATEGORY
Cooling Loads		
Building Envelope	The assumptions leading to the estimated percentage of glazing in the building envelope are not stated.	Load Assessment
	The assumptions leading to the selection of the tinted glass and the envelope system are not stated.	Load Assessment
	The effects of the tinted glazing on the neighbor building are not stated.	Building Effects on Surroundings
Building Occupants	The estimated occupant density is too low.	Occupant Loads
	Spatial or time related variation was not considered.	Control of Temperature and Humidity
Lights, Appliances, Equipment	The assumed loads are too low.	Load Assessment
	Spatial or time related variation was not considered.	Control of Temperature and Humidity
Ventilation	Supply air quantities are based on floor space	Load Assessment
Heating Loads		
Building Envelope	The assumptions leading to the estimated percentage of glazing in the building envelope are not stated.	Load Assessment
	The assumptions leading to the selection of the tinted glass and the envelope system are not stated	Load Assessment
INDOOR AIR QUALITY		
External Loads	The location of the outdoor air intakes and exhausts are not identified.	Location of Air Intakes
	The garage air is controlled by natural ventilation.	Load Assessment
	Control of the exhaust fumes from vehicular traffic near the mechanical room is unclear.	Location of Air Intakes
Internal Loads	Control of emissions from building materials is not specified.	Building Materials
	In the following areas no methods have been stated to control microbial contamination: lined ductwork, kitchen exhaust, return air plenum.	Provisions for O&M
	No smoking policy is specified.	Load Assessment

Table 5-2 Omissions In The Specification Of Special Needs

SPACES	PROBLEMS	CATEGORY
CONTROL OF HUMIDITY, TEMPERATURE AND VENTILATION		
Computer Room	The assumed loads are too low.	Load Assessment
	No exposure ranges or specific control methods are specified.	Temperature and Humidity Control
Storage	Uncontrolled stormwater.	Humidity Control
	No exposure ranges are specified.	Temperature and Humidity Control
Coroner Rooms	There are no coroner rooms in the schematic design drawings.	Owner-specified Criteria
CONTROL OF HUMIDITY AND TEMPERATURE		
Data Processing	Uncontrolled stormwater.	Humidity Control
Record Vaults	No exposure ranges are specified.	
CONTROL OF HUMIDITY AND VENTILATION		
Library	For this two-story space, no specific control methods or exposure ranges are specified.	Humidity Control Air Distribution
CONTROL OF TEMPERATURE AND VENTILATION		
Jury Deliberation Rooms	The assumed loads are too low.	Load Assessment
	No exposure ranges or specific control methods are specified.	Temperature Control Outdoor Air Quantities
VENTILATION CONTROL		
Court Rooms	The assumed loads are too low.	Load Assessment
Conference Rooms	No exposure ranges or specific control methods are specified.	Outdoor Air Quantities
Mechanical Room	The location of the outdoor air intakes and exhausts are not identified.	Air Distribution
	Control of the exhaust fumes from vehicular traffic near the mechanical room is unclear.	Location of Outdoor Air Intakes
Holding Area	No exposure ranges or specific control methods are specified.	Outdoor Air Quantities
Cafeteria		
Copier Areas		

To comply with the requirements and to bring the building design up to the intended standard, the following modifications are necessary:

1. Integrate information about provisions for thermal and indoor air quality into the drawings.

The drawings should be updated to give an overview of the air flow in the building with indication of the number of occupants in a zone, thermal zoning, building air intakes and exhausts, and internal and external loads.

2. Revisit the load assumptions.

The assumptions for internal and the external environmental loads should be revisited and updated. A statement regarding existing loads on the site can be obtained from the site analysis. This review may also yield information on regionally typical control methods for site specific loads. Precise climate and air quality data representative for the location should be obtained at the nearest weather station. For an assessment of internal loads, the planned number of occupants in a zone, the thermal zoning, and expected contamination sources such as building materials, interiors and activities (incl. smoking) should be

identified. All assumptions should be documented with reference to the relevant thermal zones.

3. Update the specification of control methods.

All assumptions leading to the proposed systems should be documented. Provisions to minimize the potential for contamination of supply air should be referenced. The planned environmental conditions in each zone should be specified.

4. Document the provisions for the special needs identified in the facility program.

Specific requirements for ventilation, humidity and temperature control for various spaces are listed in the facility program and should be addressed separately in the drawings and the specifications.

5. State additional requirements to achieve the indoor environmental objectives.

The requirements for operation and maintenance of the environmental conditions through the specified systems and the operational schedule of the building should be considered in the preliminary cost estimates. Also, potential environmental effects of the building design on the surroundings should be evaluated and documented.

Notes regarding the development of the modifications are shown in Appendix D (Case Study: Identified Problems and Recommended Modifications (Step 5)).

5.4.2 Results of the Review at Substantial Completion

The expected building performance at substantial completion was classified as ‘acceptable’. Through stepwise improvements in the phases following schematic design, the problems had been detected and corrected, however, at an increased cost.

5.5 Hypothesis Testing

Based on the outcomes of the case study, the hypothesis that building performance at substantial completion can be predicted by a systematic review of the schematic design was rejected.

6.1 Building Diagnostics at Schematic Design

One requirement for the method was that it can detect design omissions known to produce unwanted building performance. The problems identified in the case study relate to the design tasks of occupancy planning, design specifications, site planning and building systems planning.

Some problems were similar to those reported in the literature review:

In the schematic design specifications, no provisions for control of the emissions from building materials and furniture were stated. Information about outdoor air quality and potential contamination sources on the site was not incorporated in the building documentation. With respect to building systems planning, the concept of the airflow and air distribution within each zone was not presented, and it was unclear, where the building's air intake and exhaust is located. Due to the unidentified location of the air intakes, the risk of supply air contamination through the vehicles from and to the garage, at the loading docks and from other unidentified sources on the site could not be excluded. Temperature and humidity control were not addressed at all, although requests for special consideration of these needs existed per owner program.

Furthermore, some problems were found that were not in the group of design omissions identified in the literature review:

The estimate of thermal and air quality loads was too low and the specified system capacity was therefore probably underestimated. One reason leading to the problems with the correct load assessment was that the system capacities were based on a typical building load per area, which may be not representative for the evaluated building that has spaces with special needs for temperature and humidity on three out of four floors above grade due to high occupant densities. Also, indoor sources were not specifically identified. The assumptions that led to the selection of the specified systems were not stated nor were they referred to. There is no evidence that the thermal effects of the glazing on the neighboring building were considered before specification. The operation and maintenance requirements of the specified systems were not addressed, nor were they taken into consideration in the preliminary cost estimate.

All of the problems above could be identified with either the load analysis in support of the preliminary hypothesis or by testing compliance with the evaluation criteria. The recommended modifications were developed on the basis of missed criteria, since the objective is that the expected building performance meets at least the minimum criteria.

However, some problems could not be detected and addressed through the compliance test, but were discovered in the course of construction of the preliminary hypothesis:

For one, there is a large difference in the depth of information in the drawings compared to the design specifications. Also, references between the two documentation formats are missing. As shown in Table 6-1, there is an overlap of information in some building and occupant factors while meeting the requirements for indoor air and thermal quality. A reason for the different information contents could be that the information transfer was interrupted through a lack of coordination among the responsible parties caused by problems with team work or with completing the two documents simultaneously. Although a building with these symptoms will not be able to pass the evaluation, the causes cannot be detected by the mere test of criteria compliance.

Table 6-1 Overview of Building and Occupant Factors in Criteria Catalog

	Drawings	Specifications
EXPOSURE		
thermal	(none)	(none)
indoor air quality	<ul style="list-style-type: none"> • space function • indoor air contaminants 	<ul style="list-style-type: none"> • space function • indoor air contamination • outdoor air contamination • radon • number of occupants
SYSTEM PERFORMANCE		
thermal	(none)	<ul style="list-style-type: none"> • thermal asymmetry • condensation • thermal loads • special needs areas • design assumptions • performance standards • conceptual approach
indoor air quality	<ul style="list-style-type: none"> • ventilation rates • air distribution • supply air contamination 	<ul style="list-style-type: none"> • ventilation rates • air distribution • supply air contamination • number of occupants • space function • space equipment • budget constraints • special needs areas • ventilation concept • design assumptions • performance standards • conceptual approach • spatial requirements of the systems

Another problem that could only be detected via the initial data collection and analysis deals with the owner-specified criteria:

In the case study, a number of owner expectations with respect to the economic and overall performance of the building were stated in the contract between the architect and the owner. Typically, contract documents are not available in a review of building documents, and owner expectations for building quality that are stated in contracts - as in the case study - cannot be found and entered in the catalog of evaluation criteria. In the presented case, an economic criterion could be developed from the hidden information, and the building design failed to comply with this criterion. Non-compliance to this one criterion would have forced the design

into the ‘marginal’ class. In the recommended changes, issues such as the location of the mechanical room, the various effects of the tinted glazing and the use of duct lining in various areas with a high contaminant generation rate could have been discussed from the perspective of operation and maintenance and economics. Without the economic criterion, these issues could only be addressed by stating the need for updated documentation of existing loads and requirements for control and management of the loads.

It should be noted that the evaluation criteria do not contain economic requirements, because the basic architectural services at schematic design only contain preliminary cost estimates for construction, not for operation and maintenance. The latter are listed among additional services and are performed at request at additional cost to the owner. Unless documents through which operation and maintenance criteria can be controlled are required at schematic design, it is not useful to specify the respective criteria. (The consequences of this circumstance are discussed in Section 6.2 of this thesis.)

Finally, a finding should be discussed that relates to the development of criteria based on standards and guidelines:

Some indoor environmental parameters are addressed in several standards but different contexts depending on the purpose of the document. In order to reflect the original context, some criteria were developed in the form of clusters of requirements rather than individual requirements as this is often done in building evaluations. One advantage of this format was that a requirement now could be categorized as exposure, system performance or economic criterion. However, this process also produced repetitions among the requirements which - using the format with the individual criteria - would have been deleted.

Theoretically, several clusters of criteria with overlapping requirements but differing in some aspects should lead to a more precise evaluation of the relationships among the building factors, because several conditions must be fulfilled at the same time.³⁰¹ In terms of the diagnostic objectives at schematic design, this format should lead to improvements in maximizing the true-negative outcomes of reviews in this phase, i.e. to a greater level of confidence that all possible problems have been avoided. The case study building failed to comply with too many criteria as to support this theory further. Other case studies with less omissions should be more suitable to test a related hypothesis.

In the second diagnostic objective, the risk of prediction of non-existing problems (false-positive outcomes) is addressed. This risk exists when, for instance, potential causes for the findings developed in the data analysis are identified based on assumptions that cannot be supported by the collected data, but relate to processes outside the schematic design. In the evaluation of the case study, the differences in information content of the drawings compared to the specifications and the absence of owner-specified criteria for economic performance were discussed. One assumed cause of the difference in information was that there may have been a lack of team work, but in retrospective evaluations, it is difficult to support this thesis with evidence in the available documents. In the presented method, lack of coordination of information among the different

³⁰¹ Juran JM, Gryna FM. 1993. Quality Planning and Analysis. From Product Development through Use. McGraw-Hill. 255-256.

document by itself does not lead to classification of unacceptable performance, as long as the evaluation criteria are fulfilled. In real time evaluations, related false-positives can be avoided by collection of additional information regarding the team structure in the on-going process before recommendations are made.

In the retrospective evaluation, the problem in connection with owner demands stated in inaccessible documents could be detected, because the otherwise unavailable contract between the architect and the owner was available for review. In real time evaluations, false-positives could be further minimized by adding a requirement that ensures the completeness of the owner expectations stated in the facility program.

In addition to detecting omissions that might affect building performance, the method was found to be useful in the detection of deviations from original program requirements that might not influence expected building performance, but should still be documented. In the facility program, a large number of rooms for coroners' activities are specified. In the schematic design drawings, no coroner spaces are planned, nor are reasons given for this change. If deviations or changes to original requirements or assumptions are documented, the variations in the projected cost estimates can be better understood, and the effectiveness of individual measures to save resources can be stated more reliably.

In summary, the method performed as expected:

Through application of diagnostic procedures at schematic design, several problems with the intended building performance could be identified, and recommendations for modification of the schematic design could be developed. The method can therefore be used for the purpose of quality control at schematic design. In the case study, the quality of the output of the schematic design phase and compliance with the owner and occupant needs for indoor environmental quality could be controlled with the method.

6.2 Schematic Design Reviews as a Method to Prevent Problems with Indoor Environmental Quality

The second requirement for the method was that occupant health problems caused by design omissions can be avoided. Since building diagnostics is typically used to predict building performance, its potential for prevention at schematic design was evaluated by testing the predictive power of a building diagnostic method. Ideally, a design prediction at an early stage should enable to estimate expected performance of a building at completion. Building performance was therefore assessed at schematic design and compared with the performance at substantial completion, both in retrospective and using available building documentation.

In [Figure 6-1](#), the omissions at schematic design identified in the case study and the associated building symptoms in the operating phase are shown. The design omissions that have been identified in the case study, but not in the literature review are marked to indicate that their effects on the problems during building operation have not been validated. It was suggested in the hypothesis that problems with occupant well-being can be prevented by a systematic review of the schematic design.

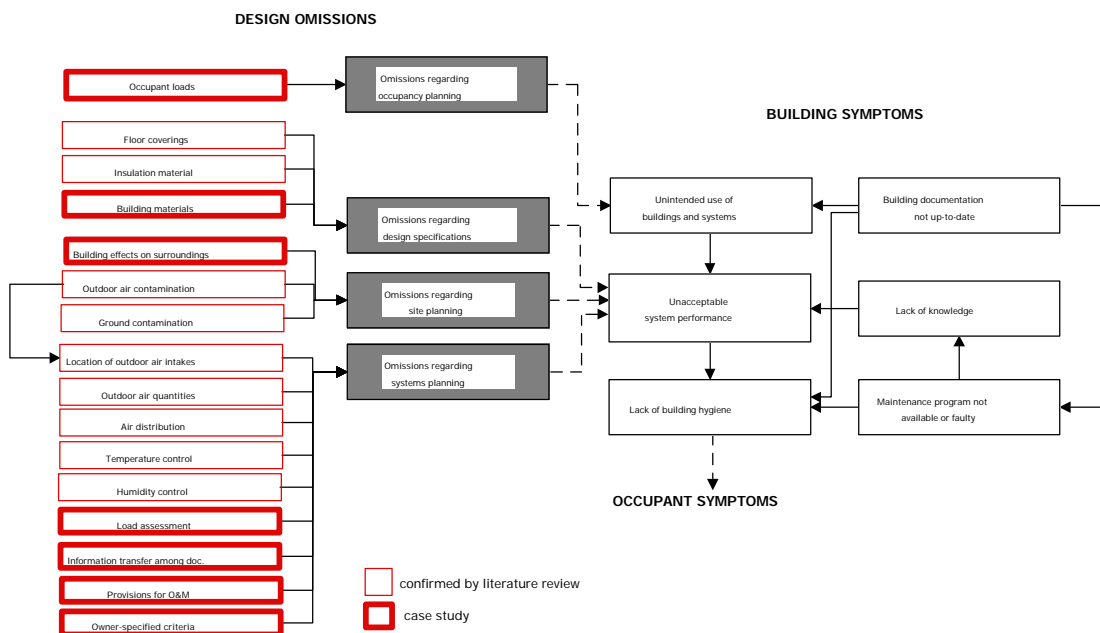
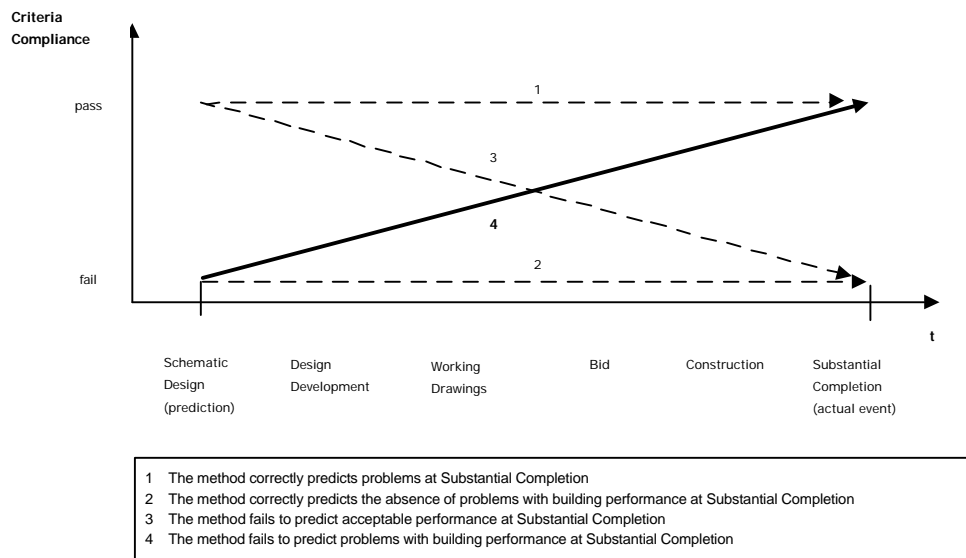


Figure 6-1
Schematic Design Omissions and Suspected Building Symptoms in the Operation Phase
(per case study)

The results of the case study showed that prediction at schematic design pointed to unacceptable building performance, but at substantial completion, building performance was acceptable (see [Figure 6-2](#)). It is further known that the design omissions were not corrected in the schematic design phase, but proceeded into the following phases where they were corrected before occupants were affected, however, at increased cost.

**Figure 6-2**

Performance of the Method in the Case Study

Since the method failed to predict the absence of problems at substantial completion, the hypothesis that building performance at substantial completion can be predicted through a systematic review of the schematic design was rejected.

One explanation for the deviation from the predicted performance would be that the diagnostic objective to minimize false-positives is not achieved, and the method overpredicts building problems. This explanation, however, cannot be maintained, because it is further known that the problems were detected and corrected in the phases following schematic design to the effect that at substantial completion, no measurable deviation from the expected indoor environmental quality could be determined. This fact leads to the conclusion that the stepwise corrections have introduced variation into the original building design data. The original prediction was therefore not representative for the later building states.

Two types of variation can be identified in the building procurement process, one is caused by the growing complexity of building factors from one phase to the next, the other one is caused by the need for meeting specified requirements:

It is generally assumed that a product undergoes continuous improvements during manufacturing and refinements in the operation and maintenance phase leading to improvements in product performance with time.³⁰² A similar idea can be found in a concept related to the performance of operating buildings: The concept of continuous degradation highlights the necessity of corrective actions to maintain specified performance, as it assumes that building performance degrades from 'healthy' to 'sick', if no measures are taken to maintain the specified conditions.³⁰³ The findings of the case study indicate that in the building procurement process, building performance

³⁰² Duane JT. 1964. Learning Curve Approach to Reliability Monitoring. IEEE Transactions on Aerospace. 2,2: 563-566.

³⁰³ Woods JE. 1990. Continuous accountability: A means to assure acceptable indoor environmental quality. Proceedings of Indoor Air Quality and Climate. 5:85-94

improves when measures are taken to fulfill the specified requirements, and that if the requirements are not fulfilled as early in the process as possible, the growth of building performance is delayed.

It is also known that variation in building performance can be a result of inconsistent criteria over time.³⁰⁴ If the set of criteria is not representative of the occupant and owner requirements that can be identified, measured and controlled in a building phase, even the strictest compliance with the specified criteria will not improve the expected building performance.

The objective of many improvements processes is to lower the cost of achieving acceptable performance. One way of affecting the cost of quality is to reduce the number and frequency of inspections in the process, a measure requiring the process to be in statistical control with both common and special causes of variation controlled.³⁰⁵

In [Table 6-1](#), building and occupant factors that are addressed when meeting the evaluation criteria are shown. These criteria can only be used to control common causes of variation, i.e. omissions related to schematic design. Since the effectiveness of the criteria varies with the effectiveness of control measures at each point in the building life, the achievement of indoor environmental quality must also include controls for the special causes of variation.

In [Figure 6-3](#), omissions that are special causes of variation are listed. They do not only relate to the schematic design phase, but may affect other phases as well:

The problems with the transfer of information of the schematic design documents can be caused by factors related to the structure of information in the specifications and drawings, the structure of the organization of participants in the building process, and the schedule of completion of both types of documents. All three causes of variation may not only apply at schematic design, but also at design development and during development of construction drawings. Therefore, problems with coordination of information can be indicators for future problems with the quality of the output of the phases following the schematic design phase.

When owner requirements for quality are hidden in inaccessible documents or program requirements are not considered in the development of building documents, the criteria for compliance, or the “project standard”, against which the developing building is evaluated at the end of each phase is incomplete. If not detected and corrected, incomplete criteria for building performance may lead to problems during occupancy, where the actual loads may exceed the potential of the installed building systems to control the loads within acceptable ranges.

Similarly, a lack of provisions for operation and maintenance will put acceptable system performance in the operation phase at risk, where measurements of building performance are conducted without prior planning for the evaluated parameters. If, in addition, the systems have been selected on the basis of economic criteria without consideration of the costs of maintenance

³⁰⁴ Woods JE, Arora S, Sensharma NP, Olesen BW. 1993. Rational Building Performance and Prescriptive Criteria for Improved Indoor Environmental Quality. *Proceedings of Indoor Air '93*. 3:471-476.

³⁰⁵ Juran JM, Gryna FM. 1993. *Quality Planning and Analysis*. From Product Development through Use. McGraw-Hill. *Companywide Assessment of Quality*.

and operation of these systems, correction of the likely problems may involve substantial changes to the existing systems.

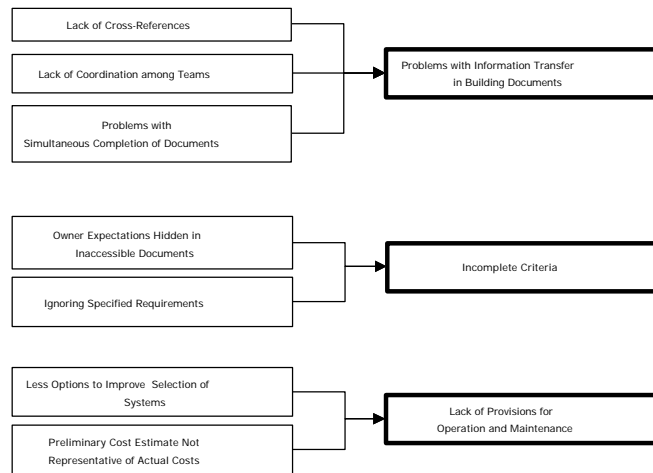


Figure 6-3

External Factors Promoting Omissions at Schematic Design

If the special causes of variation are not identified and controlled as early as possible, additional corrective actions are necessary in later phases, i.e. reactive strategies have to be applied already during the planning and construction of a building. The problems associated with reactive vs. proactive strategies (as discussed in the formulation of the hypothesis in [Chapter 3](#) of this thesis) are misinterpretation of symptoms or failure to detect symptoms, limited options in the specification of corrective actions, and reduced effectiveness of the implemented quality measures and the required quality improvements.

Another effect of reactive strategies is that the quality goals have to be met in less time than otherwise available. This may lead to unpredictable corrective actions of the responsible parties, and failure or faults in the prediction of building performance over time.

Quality assurance has been defined as "(...) *the activity of providing the evidence needed to establish confidence, among all concerned, that the quality-related activities are being performed effectively.*"³⁰⁶

The results of the case study show that building diagnostics at schematic design has a limited potential to assure the quality of a building at substantial completion:

Using the developed criteria for evaluation of indoor environmental quality at schematic design, omissions related to the schematic design phase can be detected, and if corrected, transfer of the faults into the following phases can be avoided. By controlling the omissions related to the design process and other external factors, quality assurance can be further improved.

³⁰⁶ Juran JM, Gryna FM. 1993. op. cit. supra.

For a comprehensive assurance of indoor environmental quality, specific evaluation criteria should be developed for each phase of the building process taking into consideration the growing potential for load management in a developing building.

7 *Conclusions*

Based on the findings of the case study, the following conclusions can be drawn:

- The presented method for building diagnostics at schematic design can detect omissions that may cause occupant health and building problems in operating buildings.
- If omissions at schematic design are not corrected immediately, the faults will be transferred to the following building phases.
- Delayed correction of the omissions at schematic design will promote reactive strategies in the planning and construction processes increasing the planning cost and delaying the process of completion.
- For a comprehensive assurance of indoor environmental quality, specific evaluation criteria should be developed for each phase of the building process taking into consideration the specific abilities for control of the criteria in each phase.

8 *Recommendations*

While omissions of design detail may be typical in the practice of planning buildings, the case study also shows the potential for improvement at schematic design. The achievement of indoor environmental quality requires a structured planning approach to fulfill occupant requirements for acceptable exposure while minimizing the number of unplanned changes in the building process. Independent of the media and methods used to accomplish the quality objectives, the following actions should always be taken:

1. *Define Intended Building Performance at Schematic Design*

Criteria for the achievement of indoor environmental quality should be defined from early on and should address requirements from the perspective of building occupants, owners and all factors affecting the building process. The design intent should be recorded.

2. *Measure Building Performance at Schematic Design*

In building processes where a formal schematic design phase is not mandatory, architects and owners may choose to proceed to design development in the hope of reduced planning cost. However, by conducting a formal review of indoor environmental quality at schematic design, omissions triggering costly reactive strategies and external factors influencing building performance in the following phases can be detected and controlled from early on.

3. *Pro-active Corrections*

The problems identified at schematic design should be corrected right away to avoid costs associated with reactive strategies in the planning process.

9 *Needs for Future Research*

The findings and conclusions of this thesis rely on the evaluation of a case study. To strengthen the statement of this thesis, additional studies must be conducted to gain more insight into the effectiveness of the presented method. Further studies should incorporate advanced mathematical and environmental modeling of the prospective building to evaluate the effects of early building performance information for building designers on their decision process. For that purpose, the influence of required subjective and objective judgments to determine criteria compliance must be examined in detail.

The quality requirements in this thesis were based on indoor air and thermal quality only in representation of the many requirements that need to be met to satisfy occupant demands in operating buildings. More aspects in indoor environments have to be included to improve the accuracy of predictions of occupant satisfaction in indoor environments.

Also, it has been acknowledged in the literature that building environmental quality can only be achieved by meeting several criteria simultaneously. More research should be conducted to examine the formats in which the quality criteria should be specified.

If external factors play a role in the achievement of acceptable building performance, the type of delivery method (i.e. design/build, design/bid, construction management, etc.) and the firm-specific design processes may also have an influence on the outcome of the method in various phases. The effectiveness of current project delivery methods to assure indoor environmental quality with the presented diagnostic procedures should therefore be further examined.

The effectiveness of the diagnostic method depends on the expertise of the building diagnostician. In order to make the method accessible to non-experts in the building process, the development of a user-friendly, computerized tool of information should be considered.

Case Study: Identification of Project Requirements (Step 1)

The following documents were available for evaluation of the schematic design:

1. Schematic Design Drawings

- Rendering
- Site Plan, Extent of Work Plan
- Levels 1 through 4, Roof Plan, Basement Plans
- Typical Courtrooms
- Building Elevations
- Building Sections, Typical Wall Section
- Typical Structural Framing
- Mechanical Flow Diagram
- Floor Plan and Systems Diagram
- Electrical Distribution Diagram

2. Specifications:

- Architectural outline specification and civil engineering criteria
- Structural criteria and system description
- Mechanical, electrical, plumbing, and fire protection criteria and systems description
- Security, communication and systems description
- Code analysis

3. Facility Program

4. Agreement between the Owner and the Architect

Since the case study was conducted in retrospective, and the project had been subject of criminal investigation, this file had to be opened. It cannot be assumed that during schematic design reviews, this type of information would be available for review to third parties.

No site analysis or other predesign data were available.

The evaluation focused on the review of indoor air and thermal quality. Based on available information, the schematic design corresponding to the first stage of the facility program (i.e. space needs until 1990) was reviewed. The review included all three basement alternatives.

The evaluation was based on the minimum criteria as shown in Table 4-3. In addition, special needs for control of humidity, temperature and ventilation are specified in the facility program for the following spaces:

- library (humidity, ventilation)
- computer room (humidity, temperature, ventilation)
- word processing (humidity, temperature)
- storage areas (humidity, temperature, ventilation)
- record vaults (humidity, temperature)
- jury deliberation room (temperature, ventilation)
- coroner rooms:
 - coroner x-ray room (humidity, ventilation)
 - coroner freezer room (temperature, ventilation)
 - coroner inquest room (temperature)
 - coroner refrigeration room (temperature, ventilation)
 - coroner autopsy room (temperature, ventilation)
 - coroner viewing room (ventilation)
 - coroner receiving (ventilation)
 - coroner family/meditation room (ventilation)
- court rooms (ventilation)
- cafeteria/kitchen (ventilation)
- copier areas (ventilation)
- conference rooms (ventilation)
- mechanical equipment room (ventilation)
- holding area (ventilation)

Since the special needs were not quantified in the facility program, additional evaluation criteria could not be developed. Compliance of the rooms with the special requirements was evaluated by comparing the environmental loads from specified materials and functions with the specified control methods.

In the Agreement between the Owner and the Architect, the following requirements for the development of economic criteria are mentioned:

- efficient, economical use of architectural, engineering and construction practices
- functionality without embellishment, while striving to achieve an optimum balance between aesthetic considerations, operation and maintenance costs, energy conservation issues, organizational issues and human factors
- incorporate modern construction techniques and architectural treatments to obtain quality and economy
- consider operation and maintenance costs in the initial selection of the equipment

Of these, only the last requirement could be translated into an economic criterion. It should be noted that as this contract document is usually not available for review, no economic criteria should have been specified in this case study. The economic criterion was included in the evaluation criteria for the purpose of testing effect of economic criteria on the results of the diagnostic process.

The criteria for evaluation of the case study are presented in Table A-1 below.

Tab. A-1 Criteria for Evaluation of Compliance with Requirements for Indoor Environmental Quality and Thermal Comfort in the Case Study

<p>SCHEMATIC DESIGN DRAWINGS</p> <p>1. Building Environmental Zoning <u>Indoor air quality</u> 1.1. The function of a space must be documented. 1.2. Acceptable contamination levels in special use areas must be documented. <u>Ventilation system design</u> 1.3. Intended ventilation rates and air distribution concepts must be documented.</p>	<p>2. Control of Supply Air Quality <u>Ventilation system design</u> 2.1. Reentrainment of exhausted contaminants or other forms of contamination of building supply air must have been prevented.</p>
<p>SPECIFICATIONS</p> <p>3. Control of Outdoor Sources of Contamination <u>Indoor air quality</u> 3.1. The acceptable levels of outdoor air contamination must be specified. 3.2. If the ground contains radon, the intended method of control must be stated.</p> <p>4. Control of Emissions from Building Materials <u>Indoor air quality</u> 4.1. The acceptable levels of indoor contaminants must be specified.</p> <p>5. Occupancy Planning <u>Indoor air quality</u> 5.1. The number of occupants, the space function, and acceptable contaminant levels must be stated. <u>Ventilation system design</u> 5.2. Intended ventilation rates and air distribution concepts must be specified. 5.3. The control methods for non-uniform thermal environments must be specified. 5.4. The control methods for condensation in building materials must be specified. <u>Documentation</u> 5.5. The number of occupants, space function, space equipment, special use areas, thermal environmental requirements and budget constraints must be stated.</p>	<p>6. Documentation of System Components and Operation <u>Ventilation system design</u> 6.1. The requirements for ventilation air and air distribution must be stated. 6.2. The intended method of building ventilation must be specified. 6.3. The control method against reentrainment of exhausted contaminants or other forms of contamination in the building supply air must be specified. 6.4. The methods to control non-uniform thermal environments must be stated. 6.5. Design assumptions, performance standards, the recommended conceptual approach, and the spatial requirements of the system must be stated. 6.6. The design intent, in particular the space function, functional needs of the building occupants, utility information, and building description, and the required skills of the building operators must be stated. 6.7. The estimated costs for operation and maintenance of the selected method for provision of indoor environmental and thermal quality must be documented.)*</p> <p><u>Legend</u> ■ Exposure Criteria ■ System Performance Criteria ■ Economic Criteria</p>

)*As of Agreement between Owner and Architect

Case Study: Data Collection (Step 2)

B.1 Characterization of Related Building Systems

B.1.1 Envelope System

- steel structure with face brick
- inoperable windows (max. infiltration 0.06 cfm/sq.ft.; $U_{\text{summer}}= 0.49$, $U_{\text{winter}}= 0.57$, tinted glazing, interior sunshades (i.e. blinds or draperies))
- metal roof ($U=0.06$)
- sky lights for top level rooms (double panes, exterior pane tinted)

B.1.2 Air Handling Systems

- Standard compliance with ASHRAE 62-1973, 55-1974, 90-1980
- design criteria
heating (OA/IA) -10°F/72°F (lobby: -10°F/70°F)
cooling (OA/IA) 95°F dB and 78°F wB/75°F@50%rh (lobby 78°F@50%rh)
telephone, equipment, and elevator machine rooms (htg./clg.) 65°F/78°F
mechanical room (htg./clg.) 65°F/ventilated
transformer and switchgear (htg./clg.) ventilated/ventilated
loading dock (htg./clg.) ventilated (infrared spot heating)/ventilated
- Constant Air Volume on ground floor and lobby areas (100% outdoor air, ducted return air in ceilings)
- Variable Air Volume (supply and return, ceiling return plenum, 2”-throw-away pre-filters, 55% efficiency filters)
- hot water radiators in “all areas with heat loss”
- outdoor air supply
court rooms 15 cfm/person or code
office 0.1 cfm/sq.ft.
lobby 0.1 cfm/sq.ft. and positive pressurization
- supply air
interior spaces 0.9 cfm/sq.ft. (based on 16°F temperature differential supply air)
exterior offices 1.0 cfm/sq.ft.
toilets supply and transfer 1.0 cfm/sq.ft. each
- exhaust air
public toilets 2 cfm/sq.ft.
loading dock 6 ACH
transformer 3 cfm/KVA

- capacity

equipment selected to maintain 75°F dB year round

additional capacity for fans, coils and filters (15%), chillers, cooling towers and pumps (10%),
boilers, heat exchangers and pumps (25%)

typical floors 1.1 cfm/sq.ft., top floor 1.2 cfm/sq.ft.

- controllability

no occupant control of temperature through space thermostats (“tamper-proof”)

no occupant control of space ventilation (inoperable windows)

zone controlled heating (no zones defined)

B.2 Definition of System Boundaries

- no zone definitions per mechanical equipment specification available
- all zones are served by the units in the mechanical room in the north of the building

B.3 Analysis of Loads and Control Strategies

B.3.1 Thermal Loads (Temperature, Humidity)

B.3.1.1 Cooling Loads

Sources/Loads	Specified Control Strategy	Comments
COOLING LOADS		
<u>Building Envelope</u> heat gain through solar radiation	<u>typical floors</u> max. 25% glazing, double panes, tinted <u>entrance lobby</u> max. 75% glazing, double panes, clear, no blinds <u>skylights</u> double panes, tinted, solar control <u>transmission coefficients</u> $U_{\text{roof}}=0.06$ $U_{\text{walls}}=0.08$ $U_{\text{typical window}}=0.57$ $U_{\text{lobby window}}=1.04$ $U_{\text{exposed soffits and floors over unheated space}}=0.10$ $U_{\text{sky lights}}=0.57$ <u>shading coefficients</u> <ul style="list-style-type: none"> typical windows: 0.55 without blinds, 0.44 with blinds entrance/lobby: 0.95 skylights: 0.55 	<ul style="list-style-type: none"> percentages indicate estimate was based on allowable rather than existing needs consider external shading devices or constructive solar control analyze solar load for adjacent building through reflections from tinted glazing
<u>Building Occupants</u> metabolic heat, humidity	<ul style="list-style-type: none"> offices 100 sq.ft./p lobbies 100 sq.ft./p courts 50 sq.ft./p cafeteria 15 sq.ft./p 	<ul style="list-style-type: none"> use head count identify thermal zones assumed densities are too low
<u>Lights</u> heat gain from artificial lighting	offices 2.0 W/sq.ft. other 1.0 to 4.0 W/sq.ft.	assumed loads are too low
<u>Appliances Equipment</u> heat gain from electric power operations	<ul style="list-style-type: none"> offices 0.5 W/sq.ft. computer rooms 3.0W/sq.ft. 	
<u>Lights and Appliances</u> heat gain from electric power operations	<ul style="list-style-type: none"> lobbies 5.0 W/sq.ft. court areas 5.0 W/sq.ft. cafeteria 3.0 W/sq.ft. kitchen 3.0 W/sq.ft. (excl. cooking equip.) 	
<u>Infiltration Air</u> latent and sensitive loads from outside	max. 0.06 cfm/sq.ft. through windows	
<u>Ventilation Air</u> outdoor air portion through the air systems	<ul style="list-style-type: none"> court rms. 15 cfm/p or code offices 0.1 cfm/sq.ft. lobby 0.1 cfm/sq.ft. 	<ul style="list-style-type: none"> per person minimum requirements as in 62

B.3.1.2 Heating Loads

Sources/Loads	Specified Control Strategy	Comments
HEATING LOADS		
<u>Building Envelope</u> heat loss through transmission	typical floors max. 25% glazing, double panes <u>entrance lobby</u> max. 75% glazing, double panes <u>skylights</u> double panes <u>transmission coefficients</u> $U_{\text{roof}}=0.06$ $U_{\text{walls}}=0.08$ $U_{\text{typical window}}=0.49$ $U_{\text{lobby window}}=1.13$ $U_{\text{exposed soffits and floors over unheated space}}=0.10$ $U_{\text{sky lights}}=0.49$	<ul style="list-style-type: none"> percentages indicate estimate was based on allowable rather than existing needs
<u>Building Occupants</u> latent and sensitive heat gain	<ul style="list-style-type: none"> offices 100 sq.ft./p lobbies 100 sq.ft./p courts 50 sq.ft./p cafeteria 15 sq.ft./p 	
<u>Infiltration Air</u> heat loss	max. 0.06 cfm/sq.ft. through windows	
<u>Ventilation Air</u> heat loss	<ul style="list-style-type: none"> court rms. 15 cfm/p or code offices 0.1 cfm/sq.ft. lobby 0.1 cfm/sq.ft. 	

B.3.2 Indoor Air Quality Loads (VOC, particulates):

B.3.2.1 External Sources

Sources/Loads	Specified Control Strategy	Comments
Combustion Engines		
cars to and from garage (basement alt. 2)		<ul style="list-style-type: none"> location of outdoor air intakes and exhausts not defined
garage (alt. 2)		<ul style="list-style-type: none"> positive pressurization of basement spaces required method of exhaust of garage air missing
trucks at the loading dock	<ul style="list-style-type: none"> exhausts “as required” ventilation rate 6 ACH 	<ul style="list-style-type: none"> location of outdoor air intakes and exhausts not defined control of exhaust fumes from trucks unclear
Pesticides, Herbicides		
landscaping along east and west facades		<ul style="list-style-type: none"> location of outdoor air intakes and exhausts not defined
Cross-Contamination		
air stream from building exhausts to air intakes?		<ul style="list-style-type: none"> building air intakes not specified
Site Contamination		
previous uses? soil gases? water contaminants (pond)?		<ul style="list-style-type: none"> site analysis not available during review

B.3.2.2 Internal Sources

Sources/Loads	Specified Control Strategy	Comments
Building Materials		
caulking inside acrylic base sealants horizontal planes: polyurethane based		specify min. time for curing of building products before occupancy
fireproofing on steel structure: MMF, porous		<ul style="list-style-type: none"> ensure effective filtration prior to recycling of indoor air
acoustic ceiling tiles: MMF		<ul style="list-style-type: none"> frequent inspections during occupancy for early detection of microbial contamination
Furniture, Interiors		
hardwood plywood particle board shelving plastic laminate cabinets natural finished woodwork wood paneling hardwood veneers on particle board wood trim wood doors (solid or particle board core with hardwood veneer) carpets and padding fabric wall covers wall paints (epoxy, alkyd enamel undercoat and finish, enamel, latex primer, latex finish, urethane primer) tiles in cement mortar with latex additive vinyl tiles and adhesives upholstery draperies cubicle walls: fabric and padding	<u>ventilation</u> <ul style="list-style-type: none"> Constant Air Volume on ground floor and lobby areas (100% outdoor air, ducted return air in ceilings) Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters) <u>outdoor air supply</u> <ul style="list-style-type: none"> court rooms 15 cfm/person or code office 0.1 cfm/sq.ft. lobby 0.1 cfm/sq.ft. and positive pressurization <u>supply air</u> <ul style="list-style-type: none"> interior spaces 0.9 cfm/sq.ft. (based on 16°F temperature differential supply air) exterior offices 1.0 cfm/sq.ft. toilets supply and transfer 1.0 cfm/sq.ft. each 	specify products free from emissions
Occupancy and Use		
Forensic DUI laboratory use?		define function
Courtrooms high predicted load of VOC and particulates through visitors	<u>ventilation</u> Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters) <u>outdoor air supply</u> 15 cfm/person or code <u>supply air</u> interior spaces 0.9 cfm/sq.ft. (based on 16°F temperature differential supply air)	<ul style="list-style-type: none"> capacity as indicated through assumed loads is not sufficient to control loads
Smoking		define requirements for smoking or specify smoking policy
Building Systems		
VAV: ceiling return plenum		<ul style="list-style-type: none"> ensure effective filtration prior to recycling of indoor air
ductwork: glass fiber insulation or sound lining		<ul style="list-style-type: none"> frequent inspections during occupancy for early detection of microbial contamination

kitchen exhaust with mineral wool insulation (floor to roof)		<ul style="list-style-type: none">• frequent inspections during occupancy for early detection of microbial contamination
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B.4 Analysis of Spaces with Special Needs

Requirements and Loads	Specified Control Strategy	Missing Items Comments
Library		
<u>humidity control</u> occupants outdoor air		<ul style="list-style-type: none"> specify methods of de-/humidification specify sensor location and method of measurement
<u>ventilation control</u> books occupants	Variable Air Volume (supply and return, ceiling return plenum, 2”-throw-away pre-filters, 55% efficiency filters)	specify ventilation criteria and assumptions based on function and occupancy as indicated in facility program
Computer Room		
<u>humidity control</u> occupants, outdoor air		<ul style="list-style-type: none"> specify methods of de-/humidification specify sensor location and method of measurement
<u>temperat. control</u> heatgain from occupants, electronic equipment, lights		<ul style="list-style-type: none"> specify temperature range and assumptions specify sensor location
<u>ventilation control</u> occupants, outdoor air, VOC from equipment, building materials and furniture	Variable Air Volume (supply and return, ceiling return plenum, 2”-throw-away pre-filters, 55% efficiency filters)	specify ventilation criteria and assumptions based on function and occupancy as indicated in facility program
Data Processing		
<u>humidity control</u> occupants, outdoor air		<ul style="list-style-type: none"> specify methods of de-/humidification specify sensor location and method of measurement
potential humidity from rainwater drainage from parking	<ul style="list-style-type: none"> rubberized asphalt sheet membrane primers, sealers and protection board rigid insulation 	specify drainage system
<u>temperat. control</u> heatgain from occupants, electronic equipment, lights		<ul style="list-style-type: none"> specify temperature range and assumptions based on function and occupancy as indicated in facility program specify sensor location
Storage Areas		
<u>humidity control</u> outdoor air		<ul style="list-style-type: none"> specify methods of de-/humidification specify sensor location and method of measurement
potential humidity from rainwater drainage from parking	<ul style="list-style-type: none"> rubberized asphalt sheet membrane primers, sealers and protection board rigid insulation 	specify drainage system
<u>temperat. control</u> seasonal thermal variations		<ul style="list-style-type: none"> specify temperature range and assumptions based on function and occupancy as indicated in facility program specify sensor location
<u>ventilation control</u> stored goods		<ul style="list-style-type: none"> specify ventilation criteria and assumptions based on function and occupancy as indicated in facility program define stored goods
Record Vaults		

<u>humidity control</u> outdoor air		<ul style="list-style-type: none"> specify methods of de-/humidification specify sensor location and method of measurement
potential humidity from rainwater drainage from parking	<ul style="list-style-type: none"> rubberized asphalt sheet membrane primers, sealers and protection board rigid insulation 	specify drainage system
<u>temperat. control</u> seasonal thermal variations		<ul style="list-style-type: none"> specify temperature range and assumptions based on function and occupancy as indicated in facility program specify sensor location
Jury Deliberation Room		
<u>temperat. control</u> west sun, west wind, temperature	inoperable windows (max. infiltration 0.06 cfm/sq.ft.; $U_{summer}= 0.49$, $U_{winter}= 0.57$, tinted glazing, interior sunshades (i.e. blinds or draperies))	<ul style="list-style-type: none"> specify temperature range and assumptions based on function and occupancy as indicated in facility program specify sensor location
<u>ventilation control</u> occupants, outdoor air	Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters)	specify ventilation criteria and assumptions based on function and occupancy as indicated in facility program
Coroner Rooms: NO CORONER ROOMS IN SCHEMATIC DESIGN		
Court Rooms		
<u>ventilation control</u> occupants, outdoor air, VOC from interiors and occupants	Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters)	
Cafeteria		
<u>ventilation control</u> occupants, outdoor air	Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters)	
Copier Areas		
<u>ventilation control</u> occupants, outdoor air	Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters)	specify ventilation criteria and assumptions based on function and occupancy as indicated in facility program
Conference Rooms		
<u>ventilation control</u> occupants, outdoor air	Variable Air Volume (supply and return, ceiling return plenum, 2"-throw-away pre-filters, 55% efficiency filters)	
Mechanical Equipment Room		
<u>ventilation control</u>		
Holding Area		
<u>ventilation control</u> occupants		

B.5 Analysis of Loads in Courtrooms

area (ft ²)	max. no. of seated persons	assumed density (ft ² /p)	actual density (ft ² /p)	total supply air 0.9 cfm/ft ²	outdoor air alone (15 cfm/p)	capacity 1.1 cfm/ft ²
CEREMONIAL COURTS						
1,840	161	50	11	1,656	2,415	2,024
CRIMINAL COURTS						
1,472	115	50	13	1,325	1,725	1,619
1,395	77	50	18	1,256	1,155	1,535
JUVENILE COURTS						
682	37	50	18	614	555	750
NON-JURY COURTS						
928	41	50	23	835	615	1,021

Appendix C

Case Study: Compliance Test (Step 3)

SCHEMATIC DESIGN DRAWINGS

	P	F
1. Building Environmental Zoning		
1.1. The function of a space must be documented.	x	
1.2. Acceptable contamination levels in special use areas must be documented.		x
1.3. Intended ventilation rates and air distribution concepts must be documented.		x
2. Control of Supply Air Quality		
2.1. Reentrainment of exhausted contaminants or other forms of contamination of building supply air must have been prevented.		x

SPECIFICATIONS

	P	F
3. Control of Outdoor Sources of Contamination		
3.1. The acceptable levels of outdoor air contamination must be specified.		x
3.2. If the ground contains radon, the intended method of control must be stated.		x
4. Control of Emissions from Building Materials		
4.1. The acceptable levels of indoor contaminants must be specified.		x
5. Occupancy Planning		
5.1. The number of occupants, the space function, and acceptable contaminant levels must be stated.		x
5.2. Intended ventilation rates and air distribution concepts must be specified.		x
5.3. The control methods for non-uniform thermal environments must be specified.	x	
5.4. The control methods for condensation in building materials must be specified.	x	
5.5. The number of occupants, space function, space equipment, special needs areas, thermal environmental requirements and budget constraints must be stated.		x
6. Documentation of System Components and Operation		
6.1. The requirements for ventilation air and air distribution must be stated.		x
6.2. The intended method of building ventilation must be specified.	x	
6.3. The control method against reentrainment of exhausted contaminants or other forms of contamination in the building supply air must be specified.		x
6.4. The methods to control non-uniform thermal environments must be stated.	x	
6.5. Design assumptions, performance standards, the recommended conceptual approach, and the spatial requirements of the system must be stated.		x
6.6. The design intent, in particular the space function, functional needs of the building occupants, utility information, and building description, and the required skills of the building operators must be stated.		x
6.7. The estimated costs for operation and maintenance of the selected method for provision of indoor environmental and thermal quality must be documented.)*		x
<p><u>Legend</u></p> <p>■ Exposure Criteria</p> <p>■ System Performance Criteria</p> <p>■ Economic Criteria</p>		

*as of Agreement between Owner and Architect

Case Study: Identified Problems and Recommended Modifications (Step 5)

D.1 General Requirements

SCHEMATIC DESIGN DRAWINGS

REQUIREMENTS	PROBLEMS	RECOMMENDED ACTIONS
1. Building Environmental Zoning		
1.1. The function of a space must be documented.		
1.2. Acceptable contamination levels in special use areas must be documented.	<ul style="list-style-type: none"> special use areas not identified 	develop an overview of the overall building ventilation system with planned occupants, ventilation rates, controlled contaminant levels, thermal zones, building air intakes and exhausts, and identification of external and internal loads
1.3. Intended ventilation rates and air distribution concepts must be documented.	<ul style="list-style-type: none"> thermal zones not identified outdoor air intakes and building air exhausts not identified garage air exhaust unclear control of exhaust fumes from trucks at loading dock unclear 	
2. Control of Supply Air Quality		
2.1. Reentrainment of exhausted contaminants or other forms of contamination of building supply air must have been prevented.	<ul style="list-style-type: none"> outdoor air intakes and building air exhausts not identified garage air exhaust unclear control of exhaust fumes from trucks at loading dock unclear 	

SPECIFICATIONS

3. Control of Outdoor Sources of Contamination		
3.1. The acceptable levels of outdoor air contamination must be specified.	<ul style="list-style-type: none"> site analysis not considered 	review site analysis for existing and acceptable levels of contamination
3.2. If the ground contains radon, the intended method of control must be stated.		
4. Control of Emissions from Building Materials		
4.1. The acceptable levels of indoor contaminants must be specified.	<ul style="list-style-type: none"> control of emissions from building materials unclear 	specify acceptable levels of indoor contaminants to be maintained during occupied hours

5. Occupancy Planning		
5.1. The number of occupants, the space function, and acceptable contaminant levels must be stated.	<ul style="list-style-type: none"> head count not used densities underestimated loads underestimated 	<ul style="list-style-type: none"> identify the number of occupants in each thermal zone as intended per facility program
5.2. Intended ventilation rates and air distribution concepts must be specified.	<ul style="list-style-type: none"> estimates not based on occupants, but on “allowable” needs air distribution from mechanical room unclear 	<ul style="list-style-type: none"> update the loads from building internal sources identify likely sources of contamination and their methods for control statement regarding smoking required
5.3. The control methods for non-uniform thermal environments must be specified.		
5.4. The control methods for condensation in building materials must be specified.		
5.5 Number of occupants, space function, space equipment, special needs areas, thermal environmental requirements and budget constraints must be stated.	<ul style="list-style-type: none"> effects of garage on building air quality not considered head count not used loads and densities underestimated attempts to minimize ventilation requirements 	<ul style="list-style-type: none"> state assumptions leading to building system selection (especially HVAC, fenestration) state requirements for operation and maintenance of the selected methods of control of indoor environmental loads evaluate the effect of the reflected light from the tinted glazing on the neighboring building
6. Documentation of System Components and Operation		
6.1. The requirements for ventilation air and air distribution must be stated.	<ul style="list-style-type: none"> requirements not based on occupants thermal and air quality loads underestimated 	<ul style="list-style-type: none"> develop a catalog of needs for ventilation air from information about the occupants in a zone, the expected environmental loads based on the intended uses, and potential methods for control
6.2. The intended method of building ventilation must be specified.		
6.3. The control method against reentrainment of exhausted contaminants or other forms of contamination in the building supply air must be specified.	<ul style="list-style-type: none"> building air intakes and exhausts not identified control of vehicle exhaust at loading dock and in garage unclear 	<ul style="list-style-type: none"> evaluate the potential for contamination of building supply air
6.4. The methods to control non-uniform thermal environments must be stated.		

<p>6.5. Design assumptions, performance standards, the recommended conceptual approach, and the spatial requirements of the system must be stated.</p>	<ul style="list-style-type: none"> assumptions leading to systems selection not stated 	<ul style="list-style-type: none"> state all assumptions leading to system selection
<p>6.6. The design intent, in particular the space function, functional needs of the building occupants, utility information, and building description, and the required skills of the building operators must be stated.</p>	<ul style="list-style-type: none"> operation and maintenance requirements not considered occupant needs for outdoor air not identified 	<ul style="list-style-type: none"> include requirements for operation and maintenance including activities of the building operators state the building environmental quality based on occupant needs
<p>6.7 The estimated costs for operation and maintenance of the selected method for provision of indoor environmental and thermal quality must be documented.)*</p>	<ul style="list-style-type: none"> operation and maintenance costs in respect to provision of occupant well-being not estimated 	<ul style="list-style-type: none"> develop a cost estimate for operation and maintenance of the selected systems for control of indoor environmental quality

D.2 Specific Requirements

Specific needs for thermal and indoor air quality as stated in the facility program existed for the library, computer rooms, data processing areas, record vaults, jury deliberation room, coroner rooms, court rooms, cafeteria, copier areas, conference rooms, mechanical equipment room, and the holding area.

These rooms should be addressed separately and the requirements and options for control should be stated in compliance with the evaluation criteria.

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Curriculum Vitae

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Publications

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