An Integrated Condition Assessment Model for Educational Buildings Using BIM

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Abstract

An Integrated Condition Assessment Model for Educational Buildings using BIM.

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Building facilities compose a major part of any urban infrastructure. Despite their considerable economic, cultural and/or historic importance, several studies have shown that many buildings are sick, deteriorating and a major source of pollution. Maintaining a building is essential to keep it performing and functioning for a longer period of time as well as providing better quality of life for building occupants. Despite the importance of the condition assessment (CA) stage in the asset management process, literature review reveals that there is no building condition assessment framework that considers both physical and environmental conditions. Schools and educational facilities in Canada, which comprise a major component of the non-residential buildings sector, has passed 51% of their useful service life

The primary objective of this research is to develop an Integrated Condition Assessment Model for Educational Buildings that considers both building physical and environmental conditions. This model will assist owners and facility managers in the condition assessment phase during the asset management process. As buildings are composed of spaces; this proposed model uses "space" as the principal element of evaluation. The Multi Attribute Utility Theory (MAUT) is used to calculate the physical and environmental conditions of each space, and the K-mean clustering is conducted to calculate the integrated condition of each one. Data are collected from experts via questionnaires to assign relative weights to models' attributes using both the Analytical Network Process (ANP) and the Analytical Hierarchy Process (AHP) techniques. The

proposed methodology upgrades the use of an object-oriented Building Information Model (BIM) so that it can be used as a platform and an advanced tool for storing, exchanging, and transferring assessment data inputs as well as serving in the assessment process. Integrated Condition Assessment model for Buildings (ICAB) is the developed automated tool that integrates with Revit© 2011. This integration allows the BIM model to be used as the data source and to provide any required graphical representation.

The model is implemented and tested using data collected from experts and from field measurements taken from an educational building in Montreal. Finally, the model was validated by experts working in the facilities management field and they acknowledged having good potentials.

To my Parents; Dr. Mohamed Eweda, Dr. Laila Moharram

and

my family; Mariam Wifi, Kenzy and Saja

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$A(SP_i)$	Space area in unite area
$A(SPt_u)$	Total are of all spaces having the same space type
ABC	Airborne bacteria count
ACMV	Air-conditioning and mechanical ventilation
AEC/FM	Architecture, Engineering, Construction & Facilities Management
AFC	Airborne fungi count
AHP	Analytical hierarchy process
ANP	Analytical Network Process
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BIM	Building information modelling
BMI	Body Mass Index
BPH	Building project hierarchy
C (SPi)	Integrated condition of a space
CA	Condition assessment
CAD	Computer Aided Design
Cat_I	Building Categories
CFU/m3	Colony-Forming Units per Cubic Meter
CI	Condition index
CI_j =	Condition index for the j^{th} (component or section)
CIS	Subcomponent condition index
CIS_u	Condition index for the future u^{th} subcomponent
CO	Carbon monoxide
CO_2	Carbon dioxide
CPWA	Canadian Public Works Association
CSCE	Canadian Society for Civil Engineering
Cα	Cronbach's alpha
dBA	Decibels
D_{ij}	Distress density
EC (SPi)	Environmental condition inside the space
EPA	Environmental Protection Agency
F(t,d) =	Adjusted factor for the multiple distress types
fc	Foot candle
FHWA	Federal Highway Administration
IAI	International Alliance for Interoperability
IAQ	Indoor Air Quality
ICAB	Integrated Condition Assessment Model
IEQ	Indoor Environmental Quality

IEQFs	Indoor Environmental Quality Factors
IFMA	International Facility management Association
Leq	Equivalent noise level
Lux	Illumination level
MAM	Method Adoption Model
MAUT	Multi Attribute Utility Theory
MEM	Method Evaluation Model
mi	Number of severity levels for the ith distress type
NC	Noise Criterion
NO2	Nitrogen dioxide
NRC	National Research Council
O3	Ozone
OBS	Organizational Breakdown Structure
PC (SPi)	Physical condition inside the space
PCA	Property Condition Assessments
PCI	Parent Condition Index
Ppm	Parts per million
PSAB	Public Sector Accounting Board
PWCs	Pair-wise-comparisons
QOL	Quality of life concept
$QSPt_u$	space type calculated from the questionnaire
ROI	Return on Investment
RW	Relative Weight
SBS	Sick building syndrome
S_j	Severity level
SO2	Sulfur dioxide
SOM	Self-organizing-map
SPi	Spaces inside a building
SPt_u	Space type
TAM	Technology Acceptance Model
TCA	Tangible Capital Assets
TDSB	Toronto District School Board
T_j	Distress type
TVOC	Total volatile organic compounds
$U.\ EQF_{Ki}$	Utility value of each environmental quality factor inside the space
$U.Cat_{ji}$	Utility value of the whole category
V-CAP	Visual Condition Assessment Program
VOC	Volatile Organic Compounds
$W.\ EQF_{Ki}$	Relative weight of the environmental quality factor
$W.Cat_{ji}$	Weight of each building category

WHO	World Health Organization
W_i	Weight for deficiency (i)

Chapter 1: Introduction

1.1 Overview

Building facilities play a major role in the urban infrastructure, as they provide physical support services, shelter, and accommodation for human activity. Despite the great historical, cultural and economic importance of these buildings, there is mounting evidence that they are deteriorating and are in an unsatisfactory situation due to lack of funds and poor or mismanagement (Hudson et al. 1997). The estimated maintenance and repair expenditure requirements, when added to the capital renewal budget in Canada, are close to CDN$ 196.5 billion per year, which is almost double the current value of new construction at approximately CDN$ 100 billion (Vanier, 2000). Canadian cities currently spend almost CDN$12 to 15 billion every year on maintaining and renewing their infrastructure, but this has been insufficient and the accumulated shortfall was estimated to be CDN$ 57 billion to return these assets to an acceptable condition as stated by the Canadian Society for Civil Engineering (CSCE), the National Research Council (NRC) and the Canadian Public Works Association (CPWA) (Mirza, 2007). Moreover, according to TD Economics (2002), that shortfall accumulation increases by about CDN$ 2 billion per year. Mirza (2007) also stated that the revised 2007 estimate of the municipal infrastructure deficit is calculated to be $123.6 billion for upgrading requirements which should be alarming for the need of an urgent and immediate action. In addition a survey of the conditions of higher education facilities in the U.S. issued by the Association of Higher Education Facilities Officers (APPA) concluded that there was a backlog in deferred maintenance in USA (Kaiser and Davis, 1996). In Canada, the equivalent figure has been reported at CDN$3.6 billion (CAUBO 2000) of which more than CDN$1 billion has been considered urgent.

Many studies have shown that infrastructure facilities in North America are deteriorating dramatically as most infrastructures are approaching their projected service life (Vanier, 2000). According to Statistics Canada (2010), the average age of Canada's education infrastructure (elementary and secondary schools, colleges, and universities) in 2008 was estimated to be 20.1 years old, slightly below the peak of 21.3 years in 2000, this decline was attributed to the large investments in university buildings, mainly in Ontario and Quebec. Educational buildings were at their youngest in 1969 when the average age was about 11.0 years, following huge investments in new facilities to accommodate the large inflow of baby boomers (Gaudreault et al., 2009). The average age increased rapidly until the mid-1980s, followed by a slower increase until the turn of the millennium, as new investments were required to accommodate the children of baby boomers. According to the same report, on average, the service life of an educational building is estimated at about 40 years. The average of 20.1 years in 2008 implies that educational physical infrastructure had passed 51% of their useful service lives as shown in Figure 1.1. In 2008, the gross stock of educational facilities amounted to $115.5 billion, nearly half of the nation's total institutional infrastructure. Infrastructures cost Canadian municipalities CAD$15 billion per year, of which 80% is spent on the repair and renewal of aging infrastructures.

Schools and other educational facilities represent the major component of the non-residential buildings sector, itself the sector represents the highest expenditure among all infrastructure spending in Canada and the United states. Non-residential buildings represent 40% and 63% of infrastructure expenditures in Canada and in the United States, respectively (Statistics Canada, 1995 and U.S. Census Bureau, 1999).

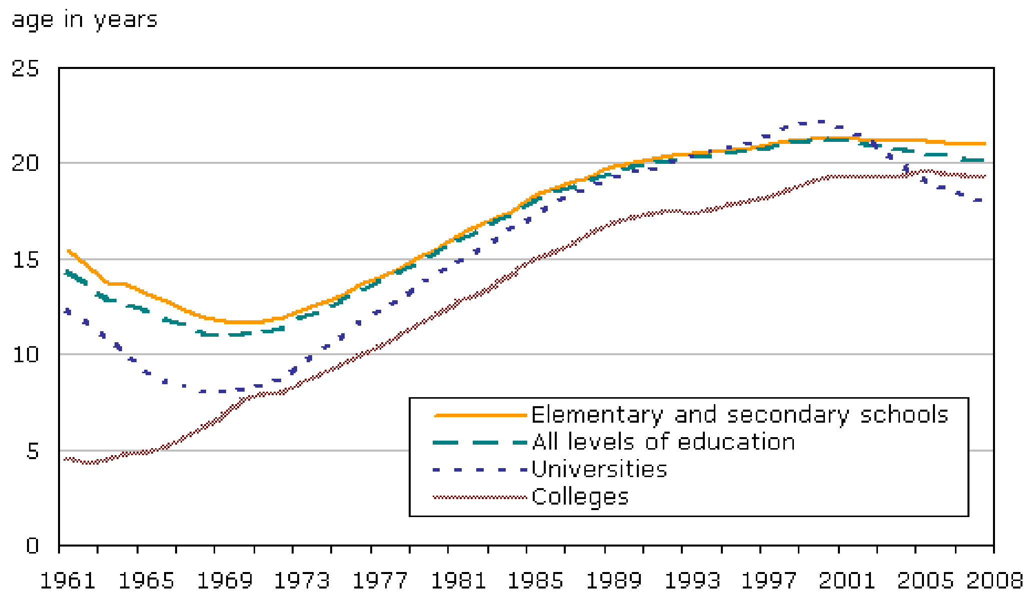


Figure 1.1 The average age of education infrastructure in Canada 1961-2008 (Gaudreault et al., 2009)

In the United States, the ASCE infrastructure report card published in 2009 shows that the Schools Sector grade is [D] as shown in Figure 1.2, with no improvements since 2001, and that the total investment needed is $160 billion, which represents a shortfall of $35 billion compared to the estimated spending of $125 billion.

The grade will not remain static for long, as spending on schools in the U.S. grew from $17 billion in 1998 to a peak of $29 billion in 2004; this growth made some real difference and kept the condition level stable. However, by 2007 spending fell to $20.28 billion; this decrease of course affected the condition of schools, and an improved maintenance plans are required (ASCE report card, 2009).

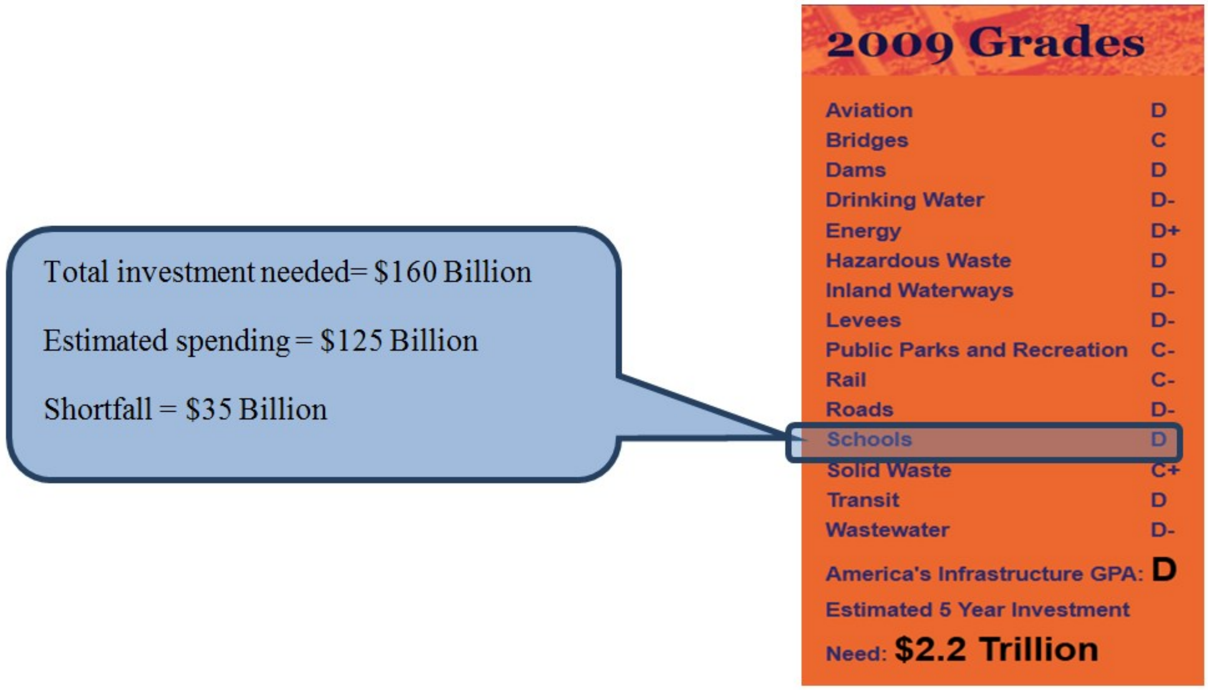


Figure 1.2: ASCE Report Card for US infrastructure

1.2 Problem Statement and Research Motivations

Over the past three decades, emphasis has been placed more and more on new construction, without adequate attention to the cost of proper maintenance and operation of existing buildings (Johnson and Clayton, 1998). As a result, many organizations will have more facilities than they can afford to maintain. Existing buildings should provide high-quality and comfortable indoor environments to fulfill their occupant's needs. Furthermore, a building's indoor environmental quality (IEQ), which includes thermal, light, acoustics, and air qualities as the most common factors reported in literature, is considered to be one of the most important building aspects affecting occupant's assessment of their quality of life. Indoor air quality has been ranked among the top four environmental risks posing a significant threat to public health in the United States. It has been reported that indoor environments are more critical on human health than outdoor, even in the most industrial areas (Godish, 1995). Poor Indoor Air Quality (IAQ) costs tens of billions of dollars every year, a situation linked to the evidence that people spend most of their time in indoor environments (Levin, 1999). The cost of absenteeism in the workplace is estimated to be $12.4 to 24.8 billion/year in the U.S., while the cost of the reduced productivity of the non-absent workers at work is estimated to be $1.5 to 3.1 billion/year (Levin, 1999). Wright et al. (2002) stated that clinical psychologists have documented the role of positive or negative emotions on various individual outcomes including productivity. They added that feeling "sad" or "depressed" and/or having low self-esteem would exhibit in reduced motivation and slowed thought processes. In addition to the fact that approximately 20% of all Americans spend time in a school building as students, teachers, administrators, and staff (Schneider, 2002; Wilson, 2002). In a study conducted by Evans and Stecker (2004), it was determined that both severe and constant exposure to uncontrollable environmental stressors, such as noise, crowding, traffic congestion, or air pollution, can produce "learned helplessness" in adults as well as in children. Fisher (2001) stated that indoor environmental quality factors represented in individual factors such as lighting levels, air quality, temperature, and acoustics have an effect on student behavior and outcomes. Thus, it can be said that there are several factors that clearly affect occupant performance and well-being. These include, but are not limited to, indoor air quality (IAQ), noise and background sound level, lighting, thermal comfort, and ventilation effectiveness.

Facility managers, in their day-to-day management and operation of buildings, contribute significantly to the creation of a healthy working and living environment for building users. Lack of funds and mismanagement are from the main reasons causing unsatisfactory performance of building facilities. Maintaining a building is essential to keep it performing and functioning for a longer period of time, and condition assessment is the most important stage during the asset management process. It is the starting point for the other stages – determining where and when it is necessary to repair, rehabilitate or replace any component in the building.

Based on literature review there were no much research has been reported in the area of building condition assessment. Moreover, none of previous condition assessment models or frameworks has integrated the physical and the environmental factors. Thus a comprehensive model that considers both the physical and environmental aspects of buildings is needed in this field. This model should also be rapid, cost effective, objective, as well as integrates with other phases of the life cycle of the building, starting from the design process to the facilities management phase. The scope of the present research is to investigate the various building systems and components, as well as the different indoor environmental quality factors, and to integrate them into one flexible comprehensive model. The purpose of this research is to develop an integrated condition assessment model that considers buildings' physical and environmental aspects; thus improving the asset management process for buildings and specifically the educational buildings, which is one of the largest infrastructure sectors.

1.3 Research Objectives

The primary objective of this research is to develop an Integrated Condition Assessment Model for Educational Buildings that considers both physical and environmental aspects. This model will assist owners and facilities managers in the condition assessment phase during the asset management process by applying several tools and techniques to provide integrated condition assessment model in the final outputs.

With the primary objective in mind, the following sub-objectives are formulated:

1. Identify and study the factors that affect the physical and environmental conditions of the building;
2. Design an evaluation scheme for both physical components and environmental conditions inside buildings;
3. Develop an integrated condition assessment framework for educational buildings integrating the physical and environmental conditions;
4. Develop an automated system for integrating the physical and environmental criteria through the Condition Assessment Process.

1.4 Research Methodology

The research is designed to develop an integrated condition assessment model for educational buildings that considers buildings' physical and environmental aspects. In order to fulfill the previous stated objectives, the research proceeds with the following steps, explained in four main phases as shown in figure Figure 1.3:

1.4.1 Literature Review

a. An extensive literature review was conducted to examine existing condition assessment and rating systems. This review is extended to cover the different indoor environmental quality assessment methods and approaches

b. Review of some of the available research and scientific software packages for asset management systems, combined with study of how the assessment of asset conditions is performed.

c. Investigate the use of the new and advanced tools and systems for data recording, storing, sharing, and transferring. For example, Building Information Modeling is an emerging tool that helps project teams work together to increase productivity and improve outcomes for all stakeholders

1.4.2 Model Development

Develop the Integrative Building Rating Framework, which will require the following points, first, identify the different space types inside an educational building and study the relative importance of each space among others; second, identify the selected asset hierarchy and set the upper and lower levels. Propose an evaluation mechanism for physical assessment; third, identify the main evaluation criteria for indoor environmental quality evaluation and set the benchmarks required to properly assess each factor, and study and assess the relative importance of each indoor environmental quality factor among others in each space type. After finalizing the previous preparation points the following steps are conducted

a. Develop a space physical condition assessment model.

b. Develop a space environmental condition assessment model,

c. Integrated the physical and environmental models in one integrated condition assessment model for each space and,

d. Develop an integrate condition assessment model for the entire building.

1.4.3 Model Implementation

This phase in the research methodology deals with implementing the developed model and it is composed of the following steps:

a. Data collection through different phases: 1) data on physical and environmental evaluation criteria is collected from various literature sources; 2) the relative importance of each building category and its families in each space type is assessed though questionnaires and interviews; 3) the relative importance of each indoor environmental quality factor is determined through questionnaires and interviews; and 4) the operational as well as the field indoor physical and environmental is collected in a complete case study to prove the concept.
b. Develop a BIM model, modify it to accommodate the new input parameters and attributes;
c. Develop an integrated data model using multi-paradigm programming language to develop the data model, which will be needed for both the assessment model and the user-friendly tool to automate the whole process; and
d. Develop an evaluation scheme in order to explain and analyze the results of the complete assessment process for the next steps, such as diagnosing and decision making.
e. The final step is to implement the model on a case study and validate the model.

1.4.4 Conclusions and Recommendations

The final part of the research methodology is to present the research conclusions, contributions to the body of knowledge and finally the research recommendations and future work.

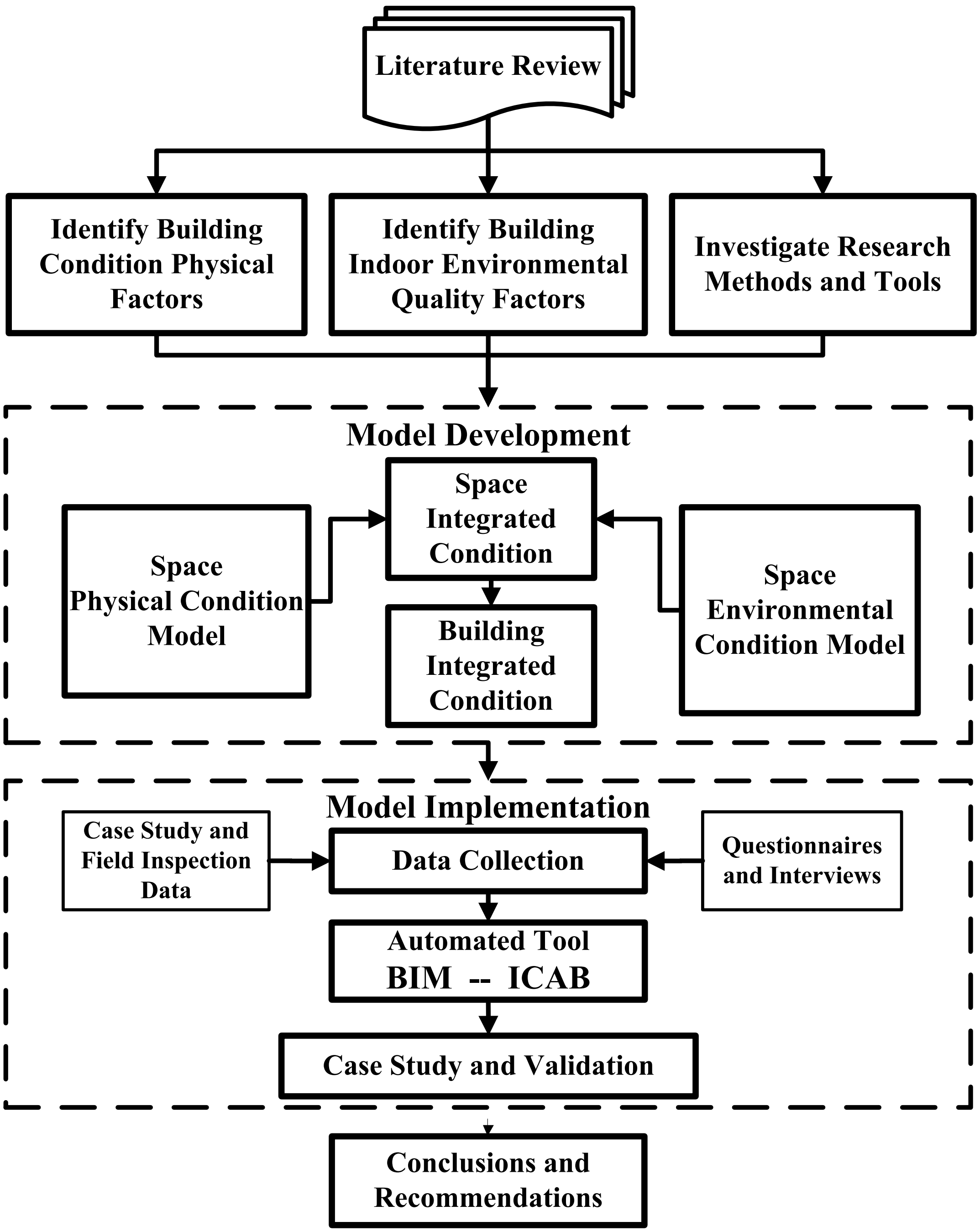


Figure 1.3: Research methodology

1.5 Dissertation Organization

The dissertation is organized as follows:

Chapter One:

This chapter includes the introduction, the state of the Educational buildings infrastructure in Canada, the problem statement and research motivations, research objectives, research methodology, and the dissertation organization.

Chapter Two:

This chapter provides a detailed literature review required to locate and summarize the related studies. The chapter is divided into 3 parts: The first focuses on the previous work done on buildings' physical assessments; the second part is about the previous work done on indoor environmental assessments; and the third part covers the tools and techniques used for model implementations which are: (1) definition of Building Information Modeling, its importance and benefits and (2) the applied techniques for modeling.

Chapter Three:

This chapter covers the detailed research methodology for the Integrated Building Condition Assessment Framework through several steps, starting with assessing building internal spaces physically, environmental and integrating them together; and ending with assessing the entire building.

Chapter Four:

This chapter covers the data collected for the case study used in the model testing. It also presents the research surveys types held in this research, and finally the data collected for all the space priorities, physical, and environmental building attributes in order to calculate the contribution of each attribute to the building condition.

Chapter Five:

This chapter covers the BIM model development and implementation. The first part presents the analysis of the collected data. The second part is the model development in which all assessment attributes are identified in the Building Information Modeling (BIM) data model. The proposed model methodology is implemented through the BIM technology.

Chapter six:

This chapter represents the automated tool for the developed model. Tool development is explained in this chapter in which graphical user interface as well as general description of the operational function, along with some software snap-shots for the tool. In this chapter also the tool is tested in which a case study is demonstrated, processed and implemented as a proof of concept. A step by step procedure of assessing an entire building through its internal spaces is explained and discussed. Validating the model by comparing the results of the model with results calculated but the building facilities management team. Moreover the model and the automated tool were validated as a methodology of building condition assessment by experts working in these fields.

Chapter Seven:

This chapter includes the research summary, conclusions, limitations, in addition to the future work and recommendations.

Chapter 2: Literature Review

2.1 Educational Buildings

An educational building is an institute designed and built for teaching students. It is a term that refers to many educational facility types such as child development centers, elementary schools, secondary, schools, college, and higher education. Certainly, clean, quiet, safe, and comfortable environments are important for teaching and learning to take place in the educational building (Schneider, 2002). Thus when school facilities fail in providing the students and teachers comfortable, healthy, neat, it is certainly affecting the educational process. People spend 90% of their lifetime inside buildings (Pennsylvania Governor's Green Government Council, 2002). Moreover, 20% of all American's spend time in a school building as students, teachers, administrators, and stuff (Schneider, 2002; Wilson, 2002). Thus, it is very important to consider a facilities management research that considers the occupants as a prior to its evaluation. Researches have been conducted to examine the relation between the students' health and ability to perform academically as well as the teachers and employees, by the effect of lighting, indoor air quality, thermal quality and acoustics. An educational building such as the secondary school educational facility type is mostly composed of the following spaces' types: (1) Administrative Offices, (2) Auditorium/Performing Arts, (3) Art Facilities, (4) Cafeteria—In secondary schools, the cafeteria often doubles as the auditorium, (5) Classroom, (6) Common areas/courtyards, (7) Gymnasium, (8) Health Services, (9) Lobby, (10)Media Center, (11) Multipurpose Rooms, (12)Music Education, (13) Restrooms, (14)Science Facilities, (15) Swimming Facilities.

Schools building type is one of the most important Public infrastructure. Despite this event, the ASCE report card gave the schools a grade “D”. The National Education Association’s best estimate to bring the nation’s schools into good repair is $322 billion.

2.2 Physical Assessment

This part will present a comprehensive review of the state-of-the-art, explained in several areas that are related to the present research. It will include topics such as building deterioration and asset service life, asset management systems, condition assessment and rating systems.

2.2.1 The Nature and Cause of Building Deterioration

In order to assess the condition of a building and its components, the characteristics of the deterioration found in the building systems and components must be understood. The factors affecting the deterioration of any building can be divided into three categories: physical, chemical, and biological factors (Lee, 1996).

i. Physical Factors

Moisture, heat and frost, ultraviolet solar radiation, and particulate emissions are the most important destructive physical factors affecting building materials, and this destruction is worse when moisture combines with temperature. These factors can damage the internal and external walls of a building causing cracks due to expansion; they can also affect timber structures promoting fungi and leading to rot and thus causing weakening. Repeated freezing and thawing cycles change the physical dimensions of materials such as concrete and weakens them. Building cladding becomes distorted or cracked due to different movements resulting from moisture and temperature changes, and many other problems affect different building systems (Knöfel, 1978; Maness, 1999; Robson, 1991).

ii. **Biological Factors**

Timber and hardwood used for building structures are damaged by biological agents such as fungi, worms, and insects. However, steel, concrete, bricks and stone are not susceptible to biological factors (Knofel, 1978).

iii. **Chemical factors**

Chemical factors such as acids, alkalis, bird excrement, deicing salts, and flue gases attack building materials. Some chemical reactions with moisture may cause strong chemicals to form that can cause serious damage to building materials such as concrete structures, steel reinforcement and carbonate stone (Bell, 1993; Michael, 1987).

2.2.2 Infrastructure Service Life

The Building Research Board publication "Pay Now or Pay Later" (1991) defined service life as "The period in years over which a building, component, or subsystem provides adequate performance; a technical parameter that depends on design, construction quality, operations and maintenance practices, use, and environmental factors." They also defined building performance as "The degree to which a building or rather facility serves its user and fulfills the purposes for which it was built or acquired." The service life of any facility depends on design and construction methods, usage, environment, as well as in-service maintenance and operation practices.

The public and users think and expect that an infrastructure is there to provide a particular service forever, unless something happens like a catastrophic failure. However, from the design and analysis point of view, a finite number of years of design life/analysis period is associated with each component of an infrastructure (Langevine, 2006). Managers of an infrastructure facility know that there is a time beyond which the infrastructure cannot provide adequate service because of one or more of the following reasons:

1. Becomes structurally unsafe
2. Becomes functionally obsolete
3. Causes delay and inconvenience to users due to overuse and over-demand
4. Becomes too costly to maintain and preserve
5. Becomes unsafe or inhospitable due to poor maintenance practices.

The prediction of effective service life is very complex for buildings. This is primarily because the structural integrity of a building depends upon many factors in addition to the construction materials and the performance of the various functional subsystems (NRC 1998, Hudson et al. 1997).

2.2.3 Asset Management

According to the Federal Highway Administration (FHWA) "Asset Management is a systematic process of maintaining, upgrading and operating physical assets cost effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both shortand long-range planning” (FHWA 1999). Managing building assets is not a simple task and it is more challenging than other systems with a limited number of components (Elhakeem, 2005). Urquhart et al. (2005) conducted a study and they stated that proper asset management is based on a condition assessment that can reflect assets’ current serviceability and failure risk, as well as quantify their current value. Thus, an accurate and well-developed condition assessment can provide a powerful tool to develop proactive maintenance and balanced plans.

2.2.4 Asset Management System

Asset management systems are tools that support owner organizations to better manage their assets (Elhakeem, 2005). Hudson et al. (1997) described an asset management system as an operation package. This package consists of the methods, procedures, data, software, policies, decisions, etc., and it enables the carrying out of all the activities involved in asset management. According to Vanier (2000), asset management systems include six implementation levels that he referred to as the six ‘what’s’ asset management levels:

1. What do you own?
2. What is it worth?
3. What is its condition?
4. What is the deferred maintenance?
5. What is the asset’s remaining service life?
6. What to fix first?

The main functions of an asset management system as shown in Figure 2.1 cover the following aspects (Elhakeem, 2005; Ahluwalia, 2008):

1. Assessment of the current condition;
2. Prediction of the future deterioration;
3. Selection of maintenance and repair strategies;
4. After repair condition improvement; and
5. Asset prioritization and repair fund allocation.

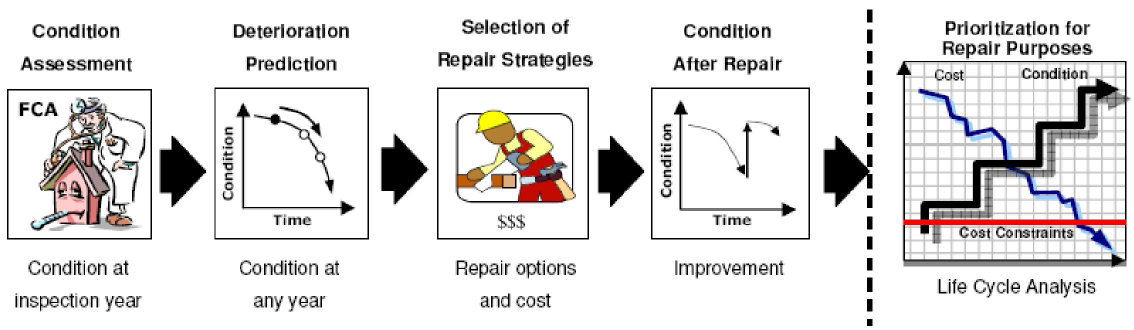


Figure 2.1:Main Functions of an Asset Management System (Elhakeem, 2005)

Based on various sources in the literature, Condition Assessment (CA) is the most important function throughout the Whole Asset Management System; this is because the results of this stage represent the starting point for the other functions. Defining the condition of an asset can be associated with different thresholds which can be used to decide what, when, and how to maintain first. Knowing the condition of an asset will affect maintenance decisions and this will help in predicting the consequences of maintenance delays.

2.2.5 Condition Assessment (CA)

In order to determine the level of the preventive maintenance required for a building's system and components, Condition Assessment should be performed (NCES, 2003). CA has been defined in different ways in the literature. Rugless, (1993) defined CA as "a process of systematically evaluating an organization's capital assets in order to project repair, renewal, or replacement needs that will preserve their ability to support the mission or activities they were assigned to serve". Telcholz, (1995) defined it as "A service provided by design professionals which included the performance of building audits, primarily for reports of building deficiencies, to raise a building's performance to its original (new) potential". It is better to perform building assessment on a regular basis, because the longer the period between inspections, the more extensive the inspection becomes (Lewis and Payant 2000; NCES 2003; DfES 2003).

It was found that condition assessment systems have been developed for each type of infrastructure asset, with that asset's particularities. For example, PAVER was developed for pavement management (Shahin 1992), RAILER for railroads, ROOFER for roofs (Bailey et al. 1989), and BUILDER for buildings (Uzarski and Burley 1997); which were all developed by the U.S. Army corps of Engineers - Engineer Research and Development Center. There are other condition assessment software systems such as RECAPP, MAXIMO, and TOBUS, whose applications are also on buildings.

1. BUILDER, version 3, developed by the US Army Construction Engineering Research Laboratories in Champaign, IL (www.cecer.army.mil). BUILDER provides capabilities for inventory collection, condition assessment information collection on buildings and maintenance/repair analysis (BUILDER, 2007).

2. RECAPP, version 2001.0.0, is the Re-Engineering the Capital Asset Priority Plan. It was developed using physical planning technologies (www.recapp.com), and it includes an inventory for buildings' major components, checklist-style inspection, and condition indexes.
3. MAXIMO Enterprise (MAXIMO 2001), version 4.03, developed by MRO Software, Inc. (www.mro.cam). MAXIMO provides capabilities for inventory collection, condition monitoring, maintenance planning and scheduling, and procurement of machinery and components in plant facilities. In the condition-monitoring module, there is a limited capability to determine the existing condition of an asset relative to pre-set performance requirements (PPTI 2006). It lacks data on civil works.
4. TOBUS, developed by the European Commission (D.G. XII) in the JOULE II program. The condition assessment stage in this software covers the degree and extent of physical degradation and the work required to renovate a building (Brandt and Rasmussen, 2002).

According to Elhakeem (2005), the four main aspects that are needed to develop a condition assessment for any asset are: asset hierarchy, evaluation mechanism, field inspection, and condition analysis. These four aspects are the steps followed when making a detailed condition assessment, as shown in Figure 2.2.

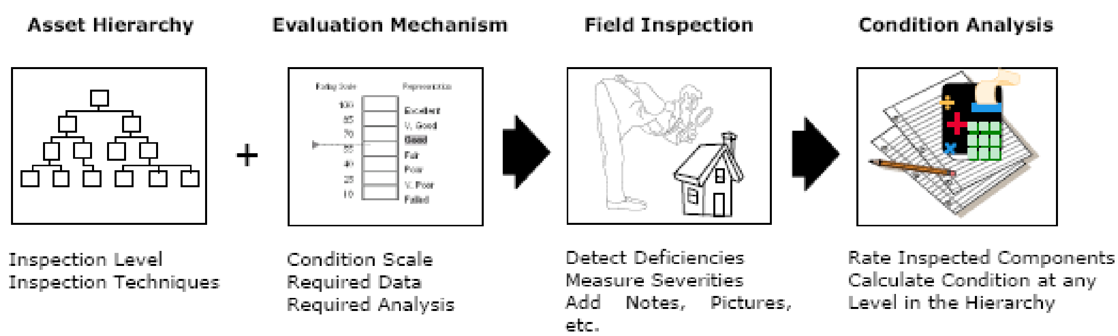


Figure 2.2: Main Steps of the Condition Assessment Process (Alhuwalia, 2008)

2.2.5.1 Asset Hierarchy

Asset Hierarchy is an essential step for condition assessment. Its purpose is to classify and cluster building components under different categories--like dividing a building into different disciplines such as mechanical, electrical, and structural, and which in turn can be further divided into more detailed component levels (exterior doors, windows, ceilings, floor surfaces, etc.). These groupings of different components into one branch can be done to reflect similar characteristics or similar inspection needs (Uzarski and Burely, 1997).

According to Ahluwalia, (2008), there are five main elemental classification systems used for data exchange around the world:

- The American UNIFORMAT classification (ASTM 1997),
- The Canadian CIQS classification (CIQS 1990),
- The United Kingdom RICS classification (RICS 1987),
- The unified UNICLASS classification (Dawood et al. 2003), and
- The European CEEC classification (Charette and Marshall 1999).

All hierarchies start with the whole building at the upper level, and they end up with almost the same components in the lowest level.

Elhakeem (2005) combined the benefits of the existing hierarchies and suggested a five-level (system, subsystem, component, type/element, and instance) building hierarchy to correspond to the Organizational Breakdown Structure (OBS) of educational organizations. This was done to facilitate the process of revising assessed components, to evaluate the performance of each department at keeping its components in a safe satisfactory condition, and to help organizations allocate funds among various systems according to their preferences and options.

Hegazy et al. (2001) proposed another hierarchy within the domain of building information modeling. Their hierarchy involves the creation of a building project hierarchy (BPH) from a central library of building components. This hierarchy has proven useful in representing multidisciplinary design data within each building space.

The asset hierarchy used by BUILDER divides a building into 12 systems and then into 150 components, ending at the 4^{th} level, which is the subcomponents' level (BUILDER, 2002). Each subcomponent is assigned an importance factor (called a value factor) from 0 to 1 to facilitate the calculation of the condition at the higher component level. The asset hierarchy developed by RECAPP has four main levels which divide the building into its components and further into the instance level (level 5). Rather than generic deficiencies, RECAPP lists component-specific deficiencies that can be used to evaluate the condition of a component at any instance. RECAPP's hierarchy does not have standardized lists of components for all building types. Furthermore, the number of instances per component is not fixed (Elhakeem, 2005). The latest system developed is TOBUS, which has a checklist of databases with 70 objects, such as roofing, façade and fire protection. These objects are then divided into 12 types (maximum) due to the differences in the material or design of the object (Ahluwalia, 2008).

From the previous proposed asset hierarchies, it was found that allocating the problems in a specific space or zone or part if the building is a hard process because they deal with the building as different systems; without allocating the building components or elements inside the whole building.

2.2.5.2 Condition Evaluation Mechanism

There are two approaches that can be followed to evaluate the condition of any component inside a building; a distress survey and a direct-condition rating survey. Either one or both of these approaches can be used (Uzarski, 2002). The decision about which approach to use requires knowledge of the purpose of the assessment. If the purpose of the assessment is merely to identify the condition of the component the direct condition rating is sufficient, as it is less accurate but much faster. Direct-condition rating involves a visual inspection of each component and evaluation of that item against a set of criteria. However, if the purpose is to identify current problems and failures in a system or a component, then the distress survey approach is more suitable since it is more accurate and reproducible. A distress survey provides a record of what is needed to be repaired in the inspected instance (Uzarski, 2002). In a recent study, Uzarski et al, (2007) reported that a distress survey can be divided into two groups, with or without sampling. He also added that either of the two approaches may better-suited for a particular stage in a components' life span, as shown in Figure 2.3.

Both BUILDER and RECAPP provide possible deficiency lists that are well-suited to the distress survey approach. Every component has its own deficiencies list and their weights that reflect their relative impact on the component condition. The inspector should judge the severity of each possible deficiency and then RECAPP calculates the condition index.

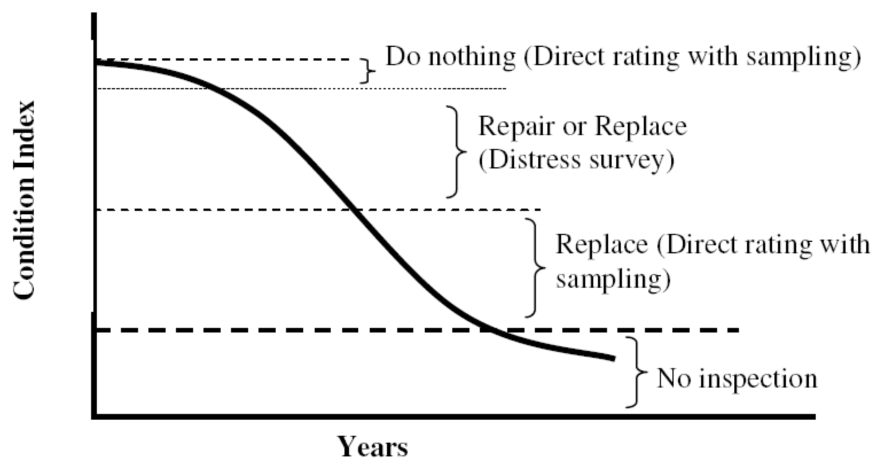


Figure 2.3: Component life cycle with repair versus replacement needs (Uzarski et al, 2007)

While BUILDER uses its 20 generic distress types in the evaluation process; the inspector evaluates each subcomponent against these 20 distress types. He/she should provide judgment on two measurements (density and extent) for each distress. The two approaches provide indexes for the condition of the building systems and components; these condition indexes (CIs) are used for comparing the condition of various components. The CI can be described as a condition-based measurement of performance based on observations and/or measurements at a specific time. In the literature, different researchers used different condition index scales and the corresponding linguistic representations. Ahluwalia (2008) listed some of the available condition indices, shown in Table 2.1.

Table 2.1: Rating Scales and Representations (Ahluwalia, 2008)

Reference	Asset Type	Condition Scale	Linguistic Representation
Lee and Aktan 1997	Buildings	1 – 4	Deterioration: (1 = no, 2 = slight, 3 = moderate, and 4 = severe)
Elhakeem and Hegazy 2005	Buildings	0 - 100	Deterioration: (0 - 20) = no, (20 - 40) = slight, (40 - 60) = moderate, (60 - 80) = severe, and (80 - 100) = critical
Greimann et al. 1997	Locks and Dams	0 - 100	Maintenance need [(0 - 39) = only after further investigation, (40 - 69) = only if economically feasible, and (70 - 100) = no action is required]
Pontis 1995	Bridges	1 – 5	Deterioration process (1 = protected, 2 = exposed, 3 = vulnerable, 4 = attacked, and 5 = damaged)
Lounis et al. 1998	Any Asset	1-7	Condition category (1 = failed, 2 = very poor, 3 = poor, 4 = fair, 5 = good, 6 = very good, and 7 = excellent)
NCES 2003 b	Buildings	1-8	Condition category (1 = excellent, 2 = good, 3 = adequate, 4 = fair, 5 = poor, 6 = non operable, 7 = urgent building condition, 8 = emergency condition)
ADOE 1997	Buildings	1-4	Condition category (1 = good, 2 = fair, 3 = poor, 4 = unsatisfactory)
WSDOT 2000	Buildings	1-5	Condition category (1 -2 = meets current standards, 3 – 4 = adequate, 4 – 5 = poor)
DfES 2003	Buildings	A-D	Condition category (grade A = good, grade B = satisfactory, grade C = poor, grade D = bad)

2.2.5.3 Inspection Process and Data Collection

In order to evaluate the condition of a building and its systems and components, full knowledge of all the deficiencies that the components can suffer from is required. To detect these distresses and measure their severity, the inspection should follow a systematic approach to obtain the required data. These data are used to calculate the performance or to evaluate the condition of the building involved. The inspection program is conducted by technically qualified and trained personnel who are familiar with the facilities and equipment to be assessed.

The inspection process is the first step of the assessment process, and thus it should be as accurate, consistent, and as un-subjective as possible. The deficiencies lists developed by previous researches such as BUILDER and RECAPP are either in a paper or in an electronic form (Elhakeem, 2005). Some other researchers have tried to automate the process by using robots, images, satellite technology, automated devices, and smart sensors. Elhakeem (2005) categorized the programs and techniques developed thus far into four groups: (1) visual inspection, (2) Photographic and optical methods, (3) Non-destructive evaluation methods, and (4) smart sensors. Lewis and Payant (2000) reported that among the various techniques and technologies that can be used for the condition assessment of facilities, only visual inspection is appropriate for the nature of building assets, because of its multiple diverse components and different requirements. Visual inspections can be defined as organized and planned visual examinations conducted by technically proficient personnel. However, Hammad et al. (2003) have mentioned that visual inspection is expensive and time consuming.

2.2.5.4 Analysis of Inspection Data

The inspection process provides data in the form of measurements of severity for each deficiency of a component. In order to translate these data into condition values, some analysis should be done. Once the condition value has been calculated for a component, that value can be used to calculate the condition at any level in the asset hierarchy -- a procedure called condition aggregation (Ahluwalia, 2008).

Based on the evaluation approach, whether it is by direct-condition rating or distress survey, the condition data is analyzed. If the direct condition rating approach is used at the system level, an index can be calculated for the whole facility. This is done simply to give an idea about the condition of the whole building in order to know whether it is worthwhile to fully modernize an existing building or to replace it (NCES 2003b). However, if the distress survey approach is used, it is more detailed and gives an analysis result for each component. This approach provides a more accurate idea about the complete situation; it helps to identify the specific defects and their severity for all building components and then combines them, since the building components contribute to the overall performance of the building system. The same relationship exists between the building systems and the whole building. This contribution value is determined by the relative importance of each component to the overall system performance. Using the Roll-Up Algorithm, the overall facility CI is computed using the bottom-up or roll-up process (Uzarski and Burely, 1997). In BUILDER, the section level identifies components by age, materials, floor, etc. In each section, samples are selected to be inspected. Finally, the calculation takes all of the subcomponents of each sample into consideration. Using the weighted-deduction density model developed by Uzarski and Burely (1997), the subcomponent condition index (CIS) can be calculated. When the CIS values for each of the sample subcomponents are calculated, the program calculates the component's condition index using the relative weight factor among subcomponents. Using the rolling-up process, the condition at any level in the hierarchy, including the system level and the overall building level, can be calculated using the assigned weights. This process is referred to as calculating the Parent Condition Index (PCI) using the weight average of its Children Condition Index.

$$CIS_u = 100 - \sum_{i=1}^{p} \sum_{j=1}^{m_i} a\left(T_{j1} S_{j1} D_{ij}\right) F\,(t, d)$$

Equation 2-1

Where:

CIS_u = the condition index for the future u^th^ subcomponent, Su

a = the deduct weighting value depending on the distress type T_j, the severity level S_j, and the distress density D_{ij}

i = the counter for the distress types

j = the counter for the severity levels

p = the total number of distress types for the subcomponent group under consideration,

$\mathbf{m_i}$ = the number of severity levels for the i^{th} distress type

F(t,d) = the adjusted factor for the multiple distress types

On the other hand, RECAPP calculates the building condition in a much easier process, because the asset hierarchy in RECAPP uses a pre-specified list of deficiencies for each component. Thus, only the deficiencies' severities should be checked and evaluated, and then weighted according to the pre-specified weight for each defect. These weights are normalized and the summation of weights equals 100%

$$CI_j = 100 - \frac{\sum_{i=1}^{d} W_i S_i}{100}$$

Equation 2-2

Where:

$\mathbf{CI_j}$ = condition index for the j^{th} (component or section);

$\mathbf{W_i}$ = Weight for deficiency (i);

$\mathbf{S_i}$ = Severity extent for deficiency (i);

i = Counter for possible deficiencies of component (j)

According to Elhakeem (2005), both BUILDER and RECAPP use weights to calculate the condition of the component and then use the Roll-up algorithm so that the condition can be calculated at higher levels in the hierarchy. However, the weights are explained without reference to how they were conducted and assumed. Also the two approaches have neglected the task held inside each space and they dealt with the components and its distress importances equally without considering that a distress that might occur in a space without a real importance might affect the human safety in another one.

Brandt and Rasmussen (2002) reported that in TOBUS, the system operates differently than BUILDER or RECAPP. The nature of the work required for retrofitting a building object has four codes, as shown below in Table 2-2. Each object has its own nature of work which is defined by a work code. This code corresponds to the degradation code. The inspector selects the work codes independently without considering the degradation codes; because either he/she may wish to select more (or less) extensive work or to select not to repair at all, or conditions other than physical degradation may influence the selection of the nature of the work (Brandt and Rasmussen 2002).

Table 2-2: Representative Work Codes Associated with the TOBUS Diagnosis (Ahluwalia, 2008)

Code	Type Exists
1	No works
2	Some refurbishment including maintenance
3	Extensive refurbishment including maintenance
4	Replacement or extensive repair

2.2.6 Condition Assessment and Rating Models

Elhakeem and Hegazy (2005) developed a system to enhance the process of the visual inspection of buildings. They reported that this system is easy to use by less-experienced individuals, thus making it possible for local personnel at facilities' sites to conduct a condition assessment simultaneously to save time and cost. Past condition assessment reports as well as past pictures captured for school buildings of the Toronto District School Board were analyzed to create a visual database of asset pictures at various condition states. These pictures were used to build a visual guidance system for the rapid assessment of components, thus implementing the Visual Condition Assessment Program (V-CAP). In addition, Langevine (2006) developed an approach to assess the condition of building components. He reported that the system allows for consistent evaluation from year to year and from inspector to another. He used it to determine the weights of components through a process of comparing the relative importance of the elements within each individual level in the hierarchy. His process utilizes the detailed inspections performed at the lowest level of the building hierarchy, and employs a roll-up procedure to determine a building's condition rating. Langevine also developed a strategy for dealing with the unique situation that is applicable to building facilities which have a level of interdependency among building systems. However this approach also neglected the different nature of the buildings and their spaces.

On the other hand Grussing et al. (2006) used the Weibull probability distribution function with the data collected during component section inspections to predict lifecycle condition and reliability over time. The model is self-correcting using attribute information collected during both current and historical inspections to accurately project the unique lifecycle degradation trend for an individual component section in a building. Finally, Alhuwalia (2008) developed an integrated framework for inspection and condition assessment that can overcome the drawbacks of traditional practices for inspecting and assessing the condition of building infrastructures. This framework was designed to overcome the high level of subjectivity and dependence on adequate resources of time, money and (qualified) manpower. The framework consists of three main components: (1) condition prediction and inspection planning (based on the available maintenance records) in order to highlight the components that most need to be inspected by experienced assessors; (2) a visual guidance system in which a pictorial database supports the visual inspection of building components; and (3) location-based inspection with a standardized building hierarchy. She analyzed two years of reactive-maintenance data for a sample of 88 schools from the Toronto District School Board (TDSB). The system consists of two stages: a survey conducted among TDSB professionals, and management/interpretation of the data collected. Stage one, the survey, was to provide an understanding of the important concerns related to building components. Stage two involved collecting, sorting, rearranging, and verifying pictures of components at different condition states. However researches that utilized the visual guidance in their inspection process trying to remove the subjectivity and fasten the process could not make it for all the building components; this is because the building facilities are composed of thousands of components and each component can occur in many different shapes, materials and location. Each time it might be required to assign distresses on a picture and train an inspector to assess according to it. It was reported in the literature and by discussing this issue with experts in this domain that so far the human expertise using his/her visual inspection is the most reliable way to recognize the distresses and deficiencies in the components. The way to enhance this issue is to provide him/her with reasonable and accurate evaluation criteria checklists.

2.3 Environmental Assessment

2.3.1 Environmental Quality Concept

The concept of environmental quality involves both human and physical factors, which operate at different spatial scales (Yoon, 2008). The human-environment interaction is complex and affects many aspects of our daily activities. Different means of environmental condition interpretations have led to the development of different concepts, such as the "sick building syndrome" as well as to various studies undertaken in the field of indoor environmental quality (IEQ). Environmental quality has been defined in different ways; one definition is that it is an essential part of the broader concept of the "quality of life" the basic qualities such as health and safety in combination with aspects such as coziness and attractiveness (RIVM, 2002). Table 2-3 shows various definitions of environmental quality reported in the literature.

Table 2-3: Some Definitions of Environmental Quality in literature

Researcher	Definition
Porteous (1971)	"… environmental quality is a complex issue involving subjective perceptions, attitudes and values which vary among groups and individuals"
Marans, R.W. Couper M. (2000)	"A high-quality environment conveys a sense of well-being and satisfaction to its population through characteristics that may be physical, social, and

	symbolic."
RMB (1996)	"Environmental quality is the resultant of the quality of composing parts of a given region but yet more than the sum of parts, it is the perception of a location as a whole. The composing parts (nature, open space, infrastructure, built environment, physical environment amenities and natural resources) each have their own characteristics and partial quality."

2.3.2 Environmental Quality inside buildings

The environmental quality of buildings refers to "the provision of comfortable lighting, acoustics, thermal and indoor air quality for occupants, and improving the residential quality for building occupants" (Davis, 1986). People now pay more attention to whether their living space is comfortable and healthy, to its 'greenness' and its environmental impact, especially working and living spaces' indoor environments (Chen et al. 2008). The concept of indoor environmental quality refers to all the factors in the built environment that impact the health and/or comfort of building occupants. The concept of acceptable indoor environmental quality (IEQ) as an integral part of the total performance of a building is still not fully valued (Chen et al. 2008).

2.3.3 Indoor Environmental quality factors (IEQFs)

According to Rapoport (1988), qualities of environment in general are grouped into three levels; these are: (1) the lower-level instrumental meanings, which groups all the utilitarian qualities of the environment, (2) the middle-level latent meanings, which represents value function qualities of the environment, and (3) the higher-level symbolic meanings that are related to symbolic qualities of cosmologies, world views, and religion. The first level (instrumental) hosts the physical-ecological qualities attributes that can be measured using instruments or devices. Yoon (2008) stated that environmental quality is mostly broken down into relevant performance criteria within the categories of lighting, acoustics, thermal, and indoor air quality. These factors should be considered as integrated components because the quality of one factor significantly affects the others.

2.3.3.1 Lighting Quality

Lighting plays an important role in building design; architects have always recognized the great importance of the visual environment in a space context (Ahmed 1994). The natural light daily rhythm sets the human biological clock; moreover, human mood is influenced by its seasonal rhythm and thus its presence is necessary for a number of health-sustaining biological processes (Yoon, 2008). Since people spend most of their time in indoor spaces, buildings should provide daylight to as many occupants as possible. Various studies have shown that people require daily doses of light and dark in order to be healthy. Daylight is controlled by building openings, glazing types, and the configuration of reflecting surfaces. It offers a rich spectrum that improves visual acuity. Its dynamic changes through the day provide visual stimulation and connect people with the outside world (Yoon, 2008). The quantity of light in space is usually the main consideration in designing a lighting system. This quantity is specified by illuminance measured in lux; and this amount various according to the activity held inside this space type. The amount of light needed (intensity and brightness), distribution, types, direction, its source concentration, and color must be appropriate with the function of the space, tasks, and activities (Lam, 1977). If the daylight is not adequate according to the standards of a space type, artificial light should complement it in order to achieve the amount of light needed. On the other hand, it is important not to provide more illumination than necessary, and to prevent glare which may cause adverse health effects such as headache frequency, stress and high blood pressure and decrease work efficiency (DiLouie, Craig, 2006). Thus it is important to provide the convenient amount of light intensity and color spectrum for each task.

2.3.3.2 Acoustics Quality

Acoustic quality in buildings is an important attribute for occupant satisfaction and comfort. Poor acoustic quality inside buildings results in increased stress and fatigue and also hinders verbal communication. Good acoustic designs aim to enhance wanted sounds and control unwanted ones, which are the 'noise' (Reffat and Harkness, 2001). Noise is now considered to be among the most important social concerns due to its health and the behavior effects. It can damage physiological and psychological health. Furthermore, it can cause annoyance and aggression, hypertension, high stress levels, tinnitus, hearing loss, sleep disturbances, and other harmful effects (Field, 1993). In order to have a good acoustical environment, noise should be kept at levels that do not interfere with activities within the programmed space of a building. People in offices need to communicate easily (Yoon, 2008). People should be able to communicate easily inside the space, without the strain of shouting to be heard or the stress of feeling that all conversation is overhead. According to Vischer (1989), different office tasks and activities vary in their acoustical requirements; however, most offices are designed to standard acoustical specifications that do not fulfill this wide range of requirements.

There are three aspects that should be considered in building design: sound isolation, control of noise and vibration caused by building services, noise and vibration control, and room acoustics (Yoon, 2008). The main sources causing noise inside a space can be classified into indoor sources and outdoor sources. Indoor sources can be the result of the occupants themselves with their loud conversations; building services that may contribute to excessive noise and vibration include HVAC systems, plumbing and electrical systems. Outdoor sources can be the result of aircraft, normal traffic, sirens and ambulances, car alarms, etc... In order to have a comfortable office space from an acoustics point of view, locate sensitive spaces (i.e. conference rooms) away from noise-generating factors. Sound-attenuating barriers and absorptive space surfaces must be used to control noise transmission through a building's internal spaces.

2.3.3.3 Indoor Air Quality

Over the past several years indoor air quality (IAQ) has become a major global issue due to its impact on human health, and it has been earning more and more attention. IAQ is a term that refers to the quality of air within a building's indoor environment. After the energy crises in 1973, it became more essential to search for alternative ways to conserve energy (Stellman, 1998). This led to the design of more airtight constructions and the closing off of the outside as much as possible in order to be efficient in terms of energy conservation (heat and/or air-conditioning loss). As a result of insufficient air intake and the accumulation of pollutants such as excess dust, bacteria and chemicals, indoor air lost it freshness and became problematic. Acceptable IAQ is defined as air in which there are no contaminants at harmful concentrations and which satisfies a substantial majority of people. People believe that outdoor air pollution can damage their health, while U.S. Environmental Protection Agency (EPA) studies of human exposure to air pollutants indicate that indoor air pollution may be 25 times, and occasionally 100 times, higher than outdoor levels. These indoor air pollutants are of particular concern because it is estimated that most people spend 90% of their time indoors (Steiber, 1995). Indoor environmental pollution has been ranked by the EPA as one of the top four environmental risks posing a significant threat to public health. During the past few decades, various symptoms and illnesses have increasingly been attributed to non-industrial indoor environments. The problems of poor indoor environments are a common environmental health issue faced by doctors and health practitioners. The sick building syndrome (SBS) has been reported more and more often over the years. It is defined by the World Health Organization (WHO 1983) as situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but include non-specific symptoms such as eye, nose, and throat irritation, mental fatigue, headaches, nausea, dizziness, and skin irritation. In addition to the previously mentioned heath issues, there is a financial aspect of poor IAQ which is estimated at tens of billions of U.S. dollars per year. The cost of absenteeism in the workplace in the U.S. is estimated to be $12.4 to 24.8 billion/year, while the cost of the reduced productivity of the non-absent workers at work is estimated to be $1.5 to 3.1 billion/year (Levin, 1999). Obviously, sick buildings cost societies more than what is saved through energy saving. It is impossible to cover all indoor pollutants and their sources within the scope of this study. However, the common indoor air pollutants are carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO2), Volatile Organic Compounds (VOC), radon, Legionella, formaldehyde, asbestos fibers, molds and other allergens, etc. Building location/orientation and air intake; building design, building materials and finishing; and indoor activities are all contributing factors to indoor air pollution. Poorly maintained and operated air-conditioning and mechanical ventilation (ACMV) system are a common source of indoor air problems. Building materials can be the source of VOC, radon, asbestos, etc. Environmental pollutants are currently regulated according to their potential to cause cancer or adverse health effects other than cancer, determined through the health risk assessment process. Finally, there are ways to improve IAQ in order to have a healthy and comfortable indoor environment as the main goal for all occupied spaces, so that good IAQ can enhance indoor activities and the well-being of occupants.

2.3.3.4 Thermal Quality

Thermal quality in this research means the physical environmental conditions which are related to the concept of thermal comfort; it is defined as "the condition of mind that expresses satisfaction with the thermal environment and it requires subjective evaluation" (ASHRAE standard 55-2004). Thermal quality in buildings is considered to be one of the most important evaluation factors for assessing indoor environmental quality. Fanger (2000) stated that thermally comfortable micro-environments in offices lead to higher employee productivity, greater satisfaction, and lower operating costs. Thermal quality is achieved by the balance of heat exchange between the occupants themselves and the surrounding environment, and it is a function of the occupant's level of activity. This heat exchange is called thermal balancing. Comfort level is also affected by the individual capability to control the local environment (Bauman et al., 1995). The International Facility management Association (IFMA) announced a survey that identifies the fact that the most predominant complaints of office occupants are “it is too hot and too cold, simultaneously” (IFMA, 2003). It is difficult for a human being is to be thermally comfortable when he or she cannot say whether they are cooler or wormer than the surrounding environment. There are six primary factors that influence thermal comfort:

- Air temperature
- Mean radiant temperature
- Relative humidity
- Air movement
- Activity level
- Clothing insulation

The first four factors are categorized under the “Environmental factors” that define the condition of the surrounding environment, while the latter two are categorized under the “Personal” factors that vary from one to another within the same environmental conditions (ASHRAE Handbook fundamentals, 2009).

Thermal comfort variables include conductive, radiative, and evaporative balances between the occupants and the environment and the rate of air movement over the skin (Fisk, 1981)

2.3.4 IEQ Evaluation Approaches for Buildings

The environmental crisis in the mid-1960’s and 70’s increased awareness of the environmental problems that face society. With the appearance of these environmental problems, environmental quality was recognized as part of the overall quality of life concept (QOL). The QOL concept was supposed to reflect all the aspects of a person's sense of well-being, and all the factors that contribute to human satisfaction. The assessment of environmental quality is usually based on the measurement of exposure to environmental conditions, such as indoor temperature and sound level. However, another method of assessment is effect-based measurement of environmental quality.

Various studies have discussed the concept of environmental quality from different perspectives. These different ways of interpreting environmental quality lead to a variety of means of evaluation. Reviewing these theories and methods for the analysis of environmental quality leads to better understanding and new research frameworks and methodologies for evaluation.

2.3.4.1 IAQ Evaluations

Kuo et al. (2007) aimed to establish a comprehensive IAQ audit approach for hotel buildings with portable equipment, and one five-star international hotel in Taiwan was selected to exam this integrated approach. They identified four major problems in their research: low room temperature (21.8°C), insufficient air exchange rate ($<1.5\ h^{-1}$), formaldehyde contamination (>0.02 ppm), and microbial pollution (total bacteria: 2,624–3,799 CFU/m3).

Farajollahi (2009) developed an experimental method to help measure the diffusion coefficient of different VOCs within building materials with different physical/chemical properties as a potential source of poor indoor air quality (IAQ). He also investigated the impact of environmental parameters, such as temperature and humidity, on effective diffusion coefficients. According to Farajollahi (2009), source control was determined to be the most effective approach to improve IAQ. Based on the twin-chamber method, he developed an experimental set-up to determine the diffusion coefficients of five VOC materials used in the ceiling tiles of buildings and linked them to their physiochemical properties. He found that among different physicochemical properties, the diffusion coefficient is positively related to vapor pressure as well as to the minor effect of the temperature and humidity on them.

Cheong and Chong (1999) developed an IAQ audit methodology to establish the IAQ profile of a building. They performed a case study in an administration office of a hospital building in Singapore to demonstrate the application of an IAQ audit and to evaluate its comprehensiveness and usefulness to both the owners and facilities managers. The audit is composed of examination of the air exchange rate, the ventilation effectiveness and the age of the air. They also monitored the thermal comfort parameters, microbial counts, dust particles and the concentrations of carbon dioxide (CO2), carbon monoxide (CO), formaldehyde (HCHO) and total volatile organic compounds (TVOC). In addition, their study also provided a subjective indoor air quality assessment using a questionnaire distributed to the staff. Their analysis concluded with some results, but the overall results obtained from the objective measurements and subjective assessment in this indoor air quality audit is that fresh air provision and air change effectiveness of a system is sufficient for diluting and removing pollutants in the office premises.

Mui et al. (2007) evaluated the contribution of airborne fungi to an unsatisfactory IAQ in the environment through their IAQ assessment of 474 air-conditioned offices in Hong Kong. Among a list of 13 common IAQ assessment parameters for air-conditioned offices in Hong Kong (eg. air temperature, relative humidity, air velocity, carbon dioxide, carbon monoxide, respirable suspended particulates, nitrogen dioxide, ozone), it was reported that the top three contributors were total volatile organic compounds (TVOC), the airborne fungi count (AFC) and the airborne bacteria count (ABC). The unsatisfactory rates regarding the assessment parameters were evaluated using the Monte Carlo simulations with data measured in Hong Kong offices.

Mui et al. (2009) examined the lifetime exposure risk of Formaldehyde HCHO in air-conditioned offices in Hong Kong under various indoor environmental conditions. 511 Hong Kong offices were assessed along with and their records from 1996 to 2005, together with the mathematical correlations among HCHO exposure concentration, ventilation and thermal environments were verified at 43 other local air-conditioned offices. The exposure risk in terms of loss of life expectancy (USEPA standard) was predicted for an office environment preset at certain air temperature and atmospheric carbon dioxide (CO_2) levels. Their study concluded that the average increment of HCHO exposure risk was 2% for every 18C increment in the air temperature range of 22.5–25.58C, or 2.5% for every 10 ppm increment in the CO_2 concentration range of 800–1000 ppm.

2.3.4.2 Acoustic Evaluation

Ayr et al. (2002) conducted a broad acoustic environment survey to measure sound pressure in a group of offices. Noise measurements and questionnaires were carried out during normal business hours. The research investigated the performance of the measured noise indices at describing subjective responses to noise. The performance of the noise indices was studied by means of linear regression analysis. The correlations between the noise indices and the subjective auditory ratings have been discussed, and statistical analysis shows that an A-weighted equivalent sound pressure level best correlates with the subjective ratings of annoyance, loudness and dissatisfaction.

Mui and Wong (2006) examined the acceptable noise level in an office environment by interviewing 422 occupants about the aural environment perceived in 61 air-conditioned offices in Hong Kong. The measured equivalent continuous noise level "Leq" in the offices was chosen as an indicator and correlated with the subjective responses from occupants on a visual analogue assessment scale and a dichotomous assessment scale. The results of their research showed that this acceptability was significantly influenced by office noise. Using a logistic regression model this influence could be correlated, and they proposed a mathematical expression for the overall acceptability of a noise level.

2.3.4.3 Thermal Evaluation

Various studies have followed the field measurement approach for evaluating indoor environmental quality. Benton et al. (1990), of the Center for Environmental Design Research, University of California, Berkley, performed a field survey on thermal environments and comfort in San Francisco office buildings located in two different Bay-area climates. Physical measurements as well as occupants' responses were assessed. 304 people participated in their study over two seasons, collecting a full set of physical measurements and subjective responses at each visit. They examined thermal sensation and thermal acceptability by comparing occupants' responses, and they reported that ventilation and temperature were more strongly related to comfort than light and humidity.

Dear and Fountain (1994) performed another survey similar to Benton's in San Francisco, where they investigated indoor climates and occupants' comfort in 12 air-conditioned office buildings in Townsville, located in the tropical northern part of Australia. 836 subjects provided 1,234 sets of questionnaire responses, which were accompanied, by a full set of physical indoor climatic measurements from laboratory-grade instruments. Thermal environmental results were compared with the ASHRAE standard 55-1992 prescription. Their results were compared with laboratory-based models and standards related to thermal neutrality, preference, and acceptability. Dear and Fountain observed that genders and seasons affected the responses, and they explained many of their data's differences from Benton's research data in terms of different clothing patterns.

Donnini et al. (1997) performed a field study of occupant comfort and office thermal environments in a cold climate. This report was published in Quebec Canada and was based on thermal office environments in 12 mechanically ventilated office buildings in southern Quebec. 877 surveys were conducted in hot and cold months. Each interview provided a set of responses to a questionnaire and a set of physical indoor climatic measurements. The standards referred to were ASHRAE 55 81 and ISO 7730. Their study concluded that there was little difference between the sexes in terms of thermal sensation, although there were significantly more frequent expressions of thermal dissatisfaction from the females in the sample, given the same thermal environments.

Gan and Croome (1994) performed research on thermal comfort models using field measurements in the UK. Experiments were carried out in five naturally ventilated offices to measure the indoor environmental parameters such as air velocity, turbulence intensity, and air temperature. Subjective assessment was made to evaluate the thermal comfort and air quality in the offices. The research showed that the thermal sensation in a work environment differs from that evaluated under laboratory conditions. Finally, they reported that indoor air temperature was the predominant factor affecting the responses of the occupants in questions related to thermal comfort and air freshness.

Aggelakoudis and Athanasiou (2005) showed that thermal comfort and sensation are different between males and females, and among overweight, normal and underweight people. Their study concluded that it is difficult to design offices that will satisfy all people, especially in groups with big differences in Body Mass Index (BMI). It is sometimes advisable to use local thermal or air-conditioning units to improve the health and comfort levels of occupants.

Wang (2006) performed another field study of indoor climate in residential buildings in China. The survey was conducted on the occupants of 66 residential buildings located in Harbin, in northeastern China. 120 sets of questionnaire responses were provided from 120 subjects during the winter, each accompanied by a full set of physical indoor climatic measurements taken with an indoor climate analyzer and a thermal comfort meter. This research study found that male occupants were less sensitive to temperature than female occupants.

2.3.4.4 Lighting Evaluation

Chung and Burnett (1999) mentioned that credits related to lighting are concerned with both energy consumption and indoor lighting quality. They added that energy efficiency and lighting quality are equally important: therefore indoor lighting quality should not be compromised simply to reduce energy consumption. They developed a model for this calculation and it showed that the scale used to assess installed lighting load is indeed practical, so that buildings with higher credits can contribute significantly to energy savings.

Chung and Burnett (2000) reviewed and described two office lighting quality surveys. The briefly reviewed the lighting quality index, or the CSP index, in which data from a large-scale lighting quality survey showed a very poor correlation between the CSP index and the occupants' subjective assessment of the lighting quality. The Surveys before and after lighting retrofit project, which consisted of two stages, showed that the occupants preferred the higher light levels after the retrofit. However, the data also revealed that a higher percentage of occupants reported that they suffered from headache or eyestrain after the retrofit.

2.3.4.5 Integrative Evaluation Approach

Wittchen and Brandt (2002) developed the TOBUS methodology for upgrading office buildings, after studying 15 European offices. TOBUS is a decision making tool used for selecting building upgrading solutions. It was developed through the European research project for IEQ in office buildings. It is a part of a new family of methodologies and multimedia tools for architects and engineers that can be used in the overall assessment and diagnosis of the existing condition of office buildings, in the evaluation of different refurbishment and retrofit scenarios, and to evaluate the cost of induced works in the preliminary stages of a project. The TOBUS survey is divided into four categories: degradation, functional obsolescence, energy, and IEQ. The corresponding analysis and calculations for each category are done by collecting the inputs from checklists, questionnaires, and audits. Researchers can then produce an integrative evaluation of an office building, after the entire investigation for all elements has been completed.

Bluyssen and Cox (2002) conducted a field investigation in 12 European buildings and analyzed the results focusing on the IEQ. They measure the IEQ performance using three different indices: the comfort index, the building symptoms index, and the number of building objects related to IEQ. The comfort index was calculated by averaging the percentage of complaints related to thermal comfort, light quality, IAQ, and noise. The building symptoms index was drawn from the mean number of symptoms reported by occupants. The building objects related to IEQ indicate the specific building objects that were possible causes of complaints or symptoms. It functions as an occupant's satisfaction measurement tool and it obtains object information about IEQ in buildings; however, that approach did not weight different aspects while calculating a percentage of complaints for an issue.

The Center for Built Environment (CBE) at Lawrence Berkeley National Laboratory developed a web-based occupant's indoor environmental quality (IEQ) survey in 2003 to measure occupants' perception of their workplace environment quality. Questions are used to assess occupant satisfaction and comfort with respect to many issues related to green building objectives, including indoor air quality, thermal comfort, lighting and acoustics. Surveys assessing other aspects of building quality are also used including an operation and maintenance staff survey, and a design and construction process survey. These three sets of surveys provide a complete picture of the quality of the building process, from the planning phase through the occupancy phase, to create a process that provides this feedback to the building industry so it can learn how various building features affect occupant comfort, satisfaction and productivity, as well as how the building performs from an operations and maintenance standpoint, and how the building process met the needs of the design and construction teams. However, this study evaluated the IEQ in buildings without considering weighted averages.

Reffat and Harkness (2001) proposed an integration method for evaluating environmental quality in office buildings based on a series of interviews with 50 experts in the field of environmental quality in the built environment. They determined the weighting factors for integration. The categories of environmental quality considered in this evaluation include lighting, acoustic and thermal comfort, and acceptable indoor air quality. Each category has a set of performance criteria, for a total of 65 criterions that cover the evaluation of environmental quality in office buildings. The experts' inputs were used to calculate the raw score, assigned weight, and rank for each environmental quality category, using a paired-wise scoring matrix.

Wong et al. (2007) examined indoor environmental quality (IEQ) from the prospect of an occupant's acceptance in four aspects: thermal comfort, indoor air quality, noise level and illumination level. 293 occupants completed an evaluation of the IEQ in offices in Honk Kong; empirical expressions were proposed to approximate an overall IEQ acceptance of an office environment at certain operative temperature (To), carbon dioxide concentration (CO2), equivalent noise level (Leq) and illumination level (lux). A multivariate logistic regression model was used to calculate the overall IEQ acceptance. The results of their research showed that the operative temperature, carbon dioxide concentration, equivalent noise level and illumination level all had important effects on the overall IEQ acceptance. Their relative significances, from the most important to the least important, were the indoor thermal environment, the air quality, noise level and the illumination level.

Malmqvist (2008) discussed and tested the different approaches for selecting environmental aspects in a method used in the development of a comprehensive Swedish environmental rating for buildings. The results showed that depending on the chosen approach, different numbers of aspects may turn out to be significant

Lai et al. (2009) proposed an empirical expression to approximate overall IEQ acceptance with respect to four contributors: operative temperature, carbon dioxide concentration, equivalent noise level, and illumination level. 125 occupants living in 32 typical residential apartments in Hong Kong were individually interviewed to evaluate their indoor environmental conditions. Mathematical expressions were proposed for overall IEQ acceptance using a multivariate logistic regression model. The results of their research showed that the operative temperature, CO_2 concentration, equivalent noise level and illumination level all had important effects on the overall IEQ acceptance. According to their results, thermal and aural environmental qualities were deemed the most important contributors, while indoor air quality was considered to be perceived as the least. They stated that occupants would accept a thermal environment by adjusting his/her clothing for an operative temperature up to 29 ºC. This thermal acceptance would decrease at any operative temperature higher than 29 ºC and the thermal environment would become unacceptable at an operative temperature above 32 ºC. IEQ acceptance becomes very sensitive to an operative temperature higher than 28 ºC, but not to the CO_2 concentration. A significant drop in the acceptance was also found when the noise level exceeded 70 dBA, while the visual acceptance would increase gradually starting from an illumination level of 10 lx and remain relatively steady at 50 lx or above.

Yoon (2008) proposed an integrative evaluation model for improving the environmental quality of residential buildings. He conducted field physical measurements as well as an occupant survey in residential buildings. He examined the relationship between indoor physical conditions and occupant responses in buildings with all four different orientations, and in two seasons (i.e., winter and summer); because of the different environmental conditions of each space within the same building. The environmental assessment covered the four main IEQ factors: the thermal, lighting, acoustic, and indoor air qualities. The research suggested the weighting values for EQ priority for each space type. The results of his EQ field measurement data and occupant surveys pointed out that occupants' satisfaction and their responses to the physical residential environment are strongly related to thermal, acoustic, lighting, and indoor air conditions inside the building. The research reported many results that showed the different correlations among the physical measurements, occupants' satisfaction and subjective responses, and the occupants' health effects during the winter and summer seasons and in the four different building orientations.

All the previous comprehensive approaches were trying to correlate and find the relationship between the different building indoor environmental quality factors and the occupants acceptances. Almost all followed the same methodology; the procedures were to conduct field measurements to physically measure all the attributes and on the other hand conducting occupants survey or recording occupants complaints. Finally correlating them to develop a correlation between each attribute value and occupants acceptance.

There was a lack of models that assess the building according to its indoor environmental quality. However those results can be analyzed and used along with the codes and guide lines in order to be used during the building environmental assessment.

2.4 Building Information Model (BIM)

2.4.1 Introduction

Building Information Model (BIM) is a new term coined by Autodesk in 2002 to describe an innovative approach to building design and construction (Rundell and Stowe, 2005). It is defined as the creation and use of coordinated, consistent, computable information about a building project; these data are parametric and used for design decision making, the production of high-quality construction documents, prediction of building performance, cost estimation, and construction planning (Krygiel et al., 2008). Furthermore, the project information in the model can be material quantities, installation dates, subcontractor responsibilities, and alternative materials. A BIM has a very important feature – it has a three-dimensional capacity. A major benefit of the 3D model is that no training for one’s imagination or prior experience is required to visualize a structure from lines and dimensions. Instead, the structure, along with a multitude of building spaces, such as rooms, hallway and entrances, can be easily viewed and even examined, because the BIM elements are actually simulations of building components. This is a great jump from data to information (Bedrick, 2005). BIM provides the construction community a complete 3D database that significantly aids in estimating, scheduling, detailing, advance bill production, automated shop drawing, and construction planning for all of the trades (Ruby, 2008). This concept was recently extended to the facilities management phases to provide continuity in the flow of information in a coordinated and comprehensive manner from the design and construction of a building to its occupation and operation.

2.4.2 Importance

"BIM represents a paradigm change that will have far-reaching impacts and benefits, not only for those in the construction industry but for society at-large, as better buildings are built that consume fewer materials and require less labor and capital resources and that operate more efficiently" (Eastman et al., 2008).

The nature of the design and building industry has changed dramatically over the past 100 years. Buildings have become more complex, with many interrelated and integrated systems. For example, there are elements that have been added to or expanded in office buildings, such as data and telecommunications services, air conditioning, security, underground parking,, and enhancements to building envelopes. With this complexity, architects, engineers, contractors, and facilities managers all have had to adapt (John et al., 2005).

On the other hand, the NIST (2004) conducted a study to estimate the efficiency losses in U.S. capital-intensive facilities industry such as commercial and institutional buildings, and industrial facilities. The study reported that the annual cost associated with inadequate interoperability among computer-aided design, engineering, and software systems was $15.8B in 2002. The same study added that owners and operators shoulder almost two-thirds of that cost as a result of their ongoing facility operation and maintenance programs. Manual updating of occupancy reports; calculating the area for space charge-backs by counting ceiling tiles; digging through stacks of building documentation to find the maintenance manual for a water heater; searching in vain for an as-built floor plan, only to find they never received it in the first place are all examples of inefficient use of resources and manpower. BIM can enhance the lifecycle operations stage. The International Alliance for Interoperability (IAI) is an organization promoting effective means of exchanging information across all software platforms by adopting a single building information model. When using BIM, a greater initial investment will have to be made during the design phase, but applying the BIM will be significantly cost-effective, as it saves money during the construction stage and even more money during the operation of a building. Thus, owners and facilities managers can mitigate their portion of the cost associated with their current lack of interoperability by using the BIM during the maintenance and operation phase of a building's lifecycle.

2.4.3 BIM Benefits

The main goal of applying a BIM is to give an overview of the building or project by including all its documents such as drawings, specifications, details, material descriptions, etc. in one single-source model. When any of the project stockholders makes any change in any object in that single model, it allows the system to propagate these changes for those objects throughout all the views in the set of deliverables (Krygiel et al., 2008). An integrated building information model should also include information about the construction and maintenance activities linked to the relevant physical building components. These activities should also be described by the phases of building construction and management (Fu et al., 2006). The BIM database contains the physical functional characteristics of a structure composed of intelligent objects rather than lines, arcs, and text (McGraw, 2008). All of these characteristics are primarily due to BIM's ability to virtually realize the building through all of the stages of the design process, in the form of a database. Krygiel et al., (2008) summarized the basic benefits of BIM as the following:

i. 3D Simulation vs. 2D Representation: A two dimensional (2D) drawing is merely a representation of the final project, composed of abstract plans, sections, and elevations. while BIM allows three dimensional (3D) simulation of the building and its components, This simulation goes beyond demonstrating how different building assemblies can be combined in the project. It can predict conflicts, show the construction variables of different building designs, and calculate material and time quantities.

ii. Accuracy vs. Estimation: BIM gives the possibility to build the whole project virtually before the beginning of any physical construction. It gives a level of accuracy to both building quantities and quality that supersedes the traditional design and documentation processes. Building materials, environmental variables, as well as cost-estimations can be done in real time rather than manually estimated.

iii. Efficiency vs. Redundancy: BIM provides a level of efficiency to the project. By drawing the building elements for a project in a plan view, the projections of all elevations and sections are generated automatically and rapidly. This enables the design team to focus on other design issues without wasting their time on drawings (Krygiel et al., 2008).

"Building Information Modeling (BIM): Transforming design and Construction to Achieve Greater Industry Productivity" is a report published by McGraw Hill

Construction on December 2008 (McGraw, 2008), It presents the impact of using BIM in the construction industry in the US. The report is produced in collaboration with 23 construction industry organizations; including 15 associations and the U.S. Army Corps of Engineers. It is based on extensive interviews with hundreds of owners, architects, civil, structural, and MEP engineers, construction managers, general contractors and trade contractors who are currently using BIM (McGraw, 2008). They came up with some findings which are listed here and presented in Figure 2.4:

- 62% of BIM users will use BIM in more than 30% of their projects in 2009.
- 82% of BIM experts believe that BIM has a very positive impact on their company's productivity.
- 72% of BIM users say that BIM has had an impact on their internal project processes.

The same report added that by measuring the value of BIM, it indicates that 48% of respondents are tracking BIM Return on Investment (ROI) at a moderate level or above. Results from companies who are actively tracking BIM return on investment (ROI) are showing initial BIM ROIs of 300 to 500% on projects where BIM was used (McGraw, 2008).

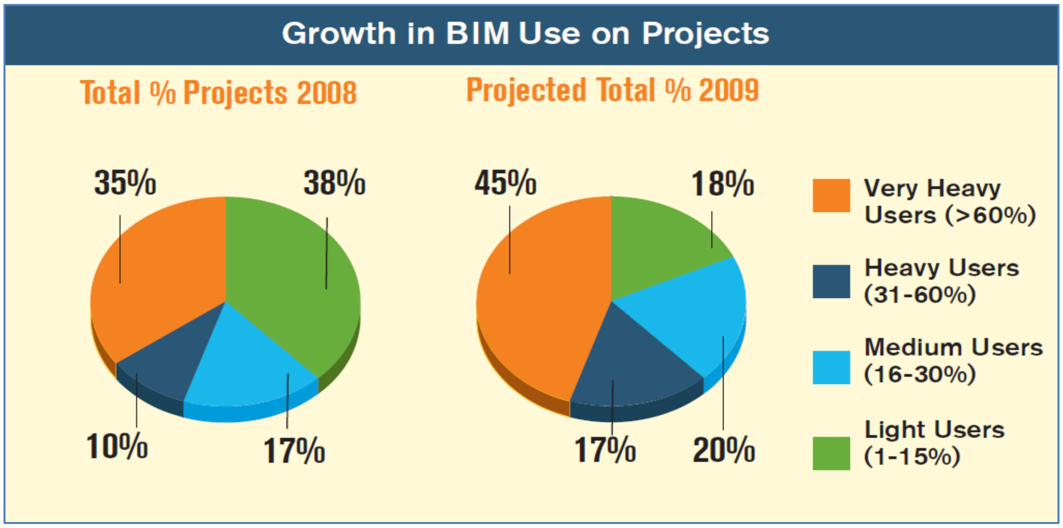


Figure 2.4: Growth in BIM Use on Projects (McGraw, 2008)

On the other hand, Bentley published a report recording the results of a survey conducted in 2007 to evaluate the use of BIM solutions. Architecture was the predominant discipline that was represented; there were also a sizable proportion of respondents practicing from engineering, construction, and facilities management and operations backgrounds. The number of respondents from large, multi-firm offices was almost the same as those from smaller, single-office firms. Results of the survey are (Bentley, 2007):

20% project cost savings

25% faster delivery

35% improved safety record

30% increased productivity

Much improved quality

Competitive Advantage

2.4.4 Parametric Modeling

Parametric modeling is a fundamental component of BIM. The BIM uses a parametric change engine to automatically coordinate changes and revisions across the project deliverables (Rundell and Stowe, 2005). In comparison to earlier Computer Aided Design (CAD) systems, BIM-based CAD systems are building object-oriented systems where the basic component of the 3D drawings are the building elements, such as walls, floors, doors, windows and so on, rather than geometric elements as in earlier CAD systems (dots, lines, and polygons) (Fu et al., 2006). Traditional 2D and 3D CAD programs do not represent spaces because they do not exist as distinct physical entities. Nevertheless, space entities will be fundamental parts of a building model, and they will include the suitable relationships to walls, ceilings, floors, and so on (Khemlani, 2004). Thus the information needed during the operational phase can be extracted from an application using a building data model as shown below, whereas several complex calculations will be required to derive the same information from an application using a geometric data model

Parametric modeling is not an entirely new idea. The manufacturing and mechanical engineering industry has been using Pro/Engineer, a software program with parametric modeling, to design mechanical pieces and components since 1989 (Tse, Wong, and Wong, 2005). The software also has the 3D ability to review a product from all angles. 2D AutoCAD, for all of its proven use-history, does not have the ability to represent the relationship between objects being drawn, and thus it demands time and money to update drawings. Indeed, CAD has been beneficial, yet it has not fully reaped the benefits of technology because it placed the engineer/drafter in front of a computer instead of a drafting table. In addition, the BIM has the ability to integrate all building component drawings, such as recognizing that wall sections form an enclosed structure, as shown in Figure 2.5.

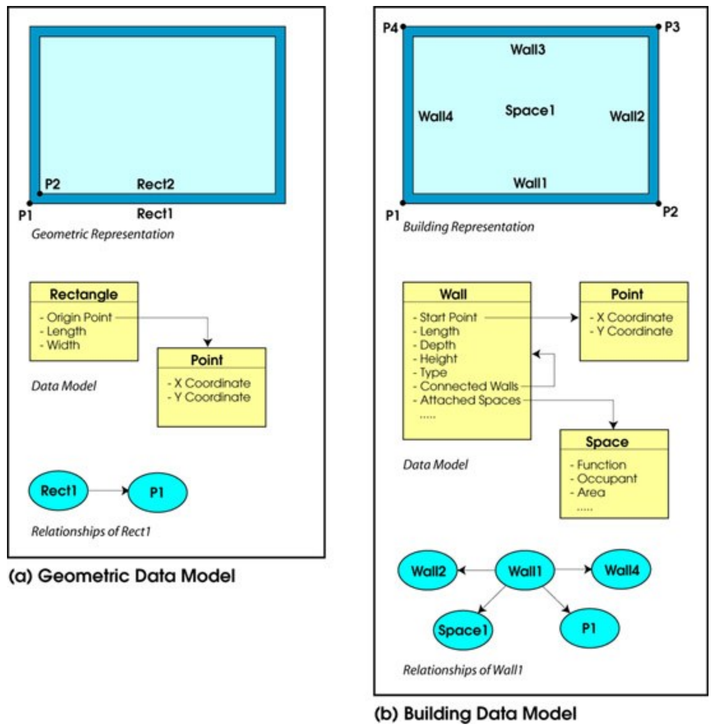


Figure 2.5: Geometric Model vs. Data Model (Khemlani, 2004)

2.4.5 BIM in facility management

The benefits of BIM are not only realized during the design and construction stage of buildings, but also owners and facilities managers can realize a significant benefits by using BIM processes and tools to streamline the delivery of better performing and higher quality of buildings (Eastman et al., 2008). Facility managers can optimize facility management and maintenance processes by exporting relevant as-built building and equipment information in order to start the systems that will be used over the lifecycle of the building. BIM can be implemented in several areas during the project, starting with the feasibility study till the operation phase. In the facilities management phase, benefits such as better management of facilities with BIM asset management tools; in which MEP systems across a project can be managed and maintained in a more efficient way. Also 4D financial model that associates each building object or objects with a condition assessment over time; the "assessed" condition of facilities, ranging from good (green) to fair to poor (red) as indicated by different colors, changes over time. (Eastman et al, 2008). The owner can view the facilities periodically to get a "big picture" view of their condition assessment. Mitchell and Schevers, 2005 show another example for a rapid evaluation of the impact of the maintenance work on the facility; by using the visual and intelligent models to help facility managers assess the impact of maintenance work. BIM-based FM system was applied during the maintenance work of Opera house of Sydney. They used the model to visually assess which areas would be affected when power cuts in a specific room.

Existing facility management tools either rely on polygonal 2D information to present the building spaces or numerical data entered in a spreadsheet. Most of the tools do not require 3D information in managing spaces and their related equipment and facility assets. However, 3D, component-based models can add value to facility management functions (Eastman et al., 2008). By using BIM, owners can utilize "space" components that define space boundaries in 3D, thus they can reduce the time needed to create the facility's database, since the traditional method involves manual space creation once the project is complete. In a case study conducted by Eastman et al., (2008) about a UNITED STATES COAST GUARD BIM IMPLEMENTATION; three projects demonstrate the United States Coast Guard's effort to implement BIM to support tactical and strategic business missions using Web-based services and open standards enabled by

BIM and accessible to a wide range of users. They recorded a 98 % reduction in time and effort to produce and update the facility management database by using a building information model. Nowadays, few existing tools accept the input of BIM space components or other facility component representing fixed assets. Tools currently available as facility management modules in BIM solutions developed in house or by third party developers. These includes but not limited to: FM:Interact for FM:Systems, “ArchiFM” for Graphisoft’s ArchiCAD, “Bentley Facilities” for Bentley, ONUMA Planning System, Vizelia suite of FACILITY management products, ActiveFacility, EcoDomus, etc. (Eastman et al., 2008; Khemlani, 2011). Some of these modules lack the building environmental aspects completely, some others considers the sustainability from the energy perspective. All modules manage the buildings according to its internal building systems while consider the spaces only in the space management process.

2.5 Overview of Applied Research Techniques

2.5.1 K-means Clustering technique

The K-mean was first used by James MacQueen in 1967 (MacQueen, 1967). However it was first introduced as an idea by Hugo Steinhaus (1956). It is one of the most popular unsupervised learning algorithms that solve the clustering problems. It is a partitioning method in which it aims to divide and isolate subsets of objects in different partitions. Its procedures follow a simple and easy way to classify a given data set through a certain number of clusters (K clusters) fixed a priori. The main idea is to set and define K centroids, one of each cluster. These centroids should be located in a cunning way; this is because a different location will cause a different result. Thus placing them as far as possible from each other is a better choice. Each observation belongs to the cluster with the nearest mean by taking each point belonging to a given data set and associates it to the nearest centroid. . When no point is pending, the first step is completed and an early groupage is completed. The next step is to re-calculate k new centroids as barycenters of the clusters resulting from the previous step. After getting these k new centroids, a new binding has to be done between the same data set points and the nearest new centroid. . A loop has been generated. As a result of this loop k centroids change their location step by step until no more changes are done as centroids do not move any more. K-mean algorithm aims a minimizing an objective functions as shown in Equation 2-3, in this case a squared error function (MacQueen, 1967).

$$J = \sum_{j=1}^{k} \sum_{i=1}^{n} \left\| x_i^{(j)} - c_j \right\|^2$$

Equation 2-3

Where $\left\| x_i^{(j)} - c_j \right\|^2$ is a chosen distance measure between a data point $x_i^{(j)}$ and the cluster center c_j , is an indicator of the distance of the *n* data points from their respective cluster centers.

The basic steps of k-means clustering are simple. In the beginning it is required to determine number of cluster K and assume the centroid or center of these clusters. Then take any random objects as the initial centroids or the first K objects in sequence can also serve as the initial centroids. Then the K means algorithm will do the three steps shown in Figure 2.6 until convergence. Iterate until *stable* (= no object move group):

- Determine the centroid coordinate
- Determine the distance of each object to the centroids
- Group the object based on minimum distance

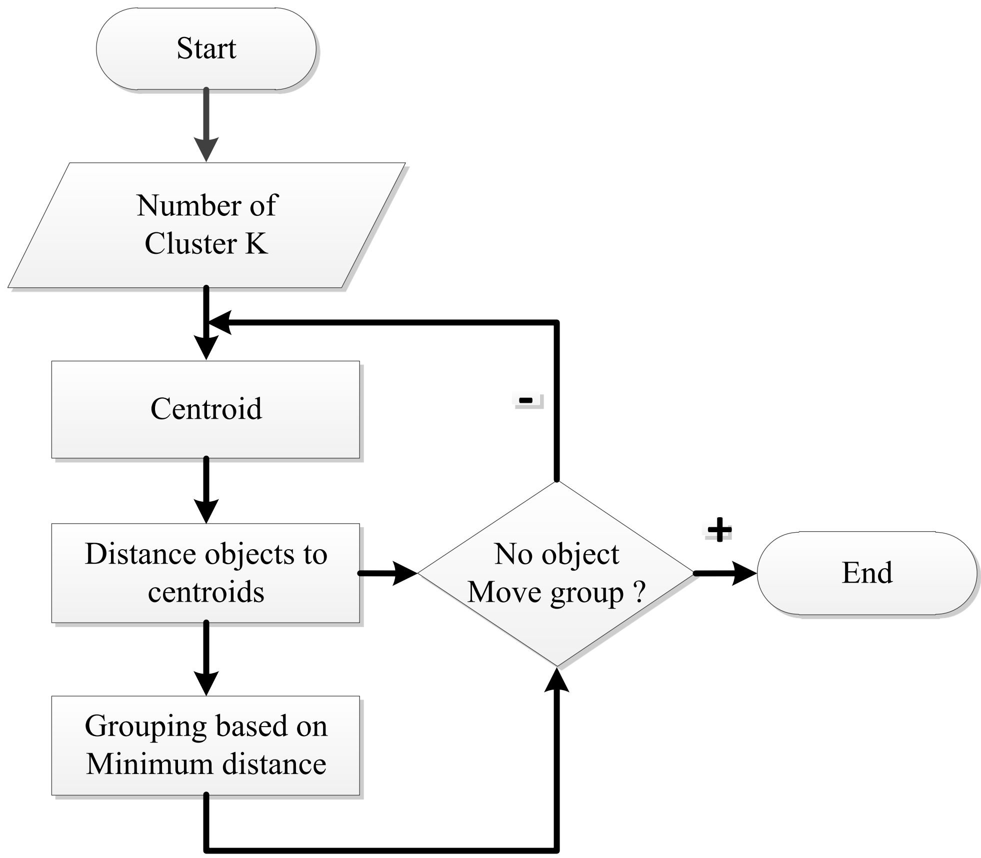


Figure 2.6: K-mean algorithm

K-means is easy to implement and works with any of the standard norms, it also allows straight forward parallelization, and finally it is insensitive with respect to data ordering. However it is not obvious what a good number of K is in each case and thus it needs some engineering sense and trial and error until a good number of clusters is obtained.

2.5.2 Analytic Hierarchical Process (AHP)

Thomas Saaty developed the AHP in 1971 as a methodology for prioritizing alternatives based on the relative rank amongst them. It has achieved widespread use in the management community, and is most commonly used in the software solution Expert Choice. The ability to connect various levels of a hierarchy and to relate lower level items to higher level ones is one of AHP's most dominant features. The first step in an AHP is to create the hierarchy that will define the levels of the analysis to be performed. Once this has been accomplished, pair-wise comparison matrices are made among all the alternatives. With the matrix completed for each of the criteria, calculations can be performed to elicit the rankings of the alternatives. The eigenvector of each of the criteria matrix is computed -- which then indicates the relative importance of each alternative. The impact of the alternatives across all of the criteria is determined by weighting the eigenvectors according to their importance to the decision maker, and summing them. A single value for each of 29 alternatives is the result, and the larger the value the higher the ranking relative to the rest of the field (Wind & Saaty, 1980).

2.5.3 Analytical Network Process (ANP)

The "Analytical Network Process (ANP) is a general theory of relative measurement used to derive composite priority ratio scales from individual ratio scales that represent relative measurements of the influence of elements that interact with respect to control criteria" (Saaty, 1999). The ANP provides a general framework to deal with decisions without making assumptions about independencies or interdependences between the higher and lower level elements, nor about the independence of the elements in the same level. The ANP does not need to specify levels in a hierarchy, as in the

Analytical Hierarchy Process (AHP), but rather it uses a network. In other words, the ANP provides a solution for problems that cannot be structured in a hierarchy (Saaty 1996). Therefore, the term cluster in the ANP replaces the term level in the AHP. ANP is thus a useful tool for prediction and represents a variety of competitors or factors with their surmised interactions and their relative strengths in order to manipulate their influence in making a decision. Figure 2.7 represents the feedback network diagram, which models many potential problems during the process of determining the importance of each criterion.

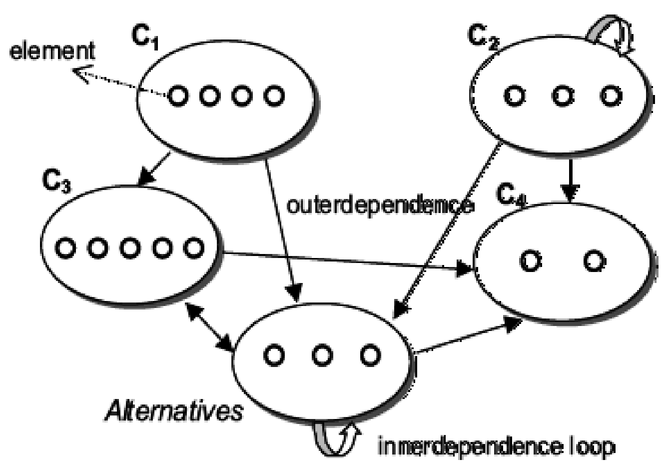


Figure 2.7: Feedback Network (Saaty 1996)

ANP and AHP are similar in their comparative judgment phase, but they are different in the synthesizing phase. In the ANP, ratio-scale priority vectors derived from pair-wise comparison matrices are not linearly synthesized as in AHP. Saaty has an improved the “supermatrix" technique to synthesize ratio scales. Each ratio scale is appropriately introduced as a column in a matrix to represent the impact of elements in a cluster on an element in another cluster (outer-dependence) or on elements of the cluster itself (inner-dependence). In that case, the supermatrix is composed of several sub-matrices, each of whose columns is a principal eigenvector that represents the impact of all elements in a cluster on each of the elements in another (or the same) cluster. The resulting priorities of the clusters are then used to weight column vector clusters on the left with respect to the corresponding cluster on the top. Thus, the supermatrix is column stochastic.

2.5.4 Multi Attribute Utility Theory (MAUT)

MAUT approach is an attempt to apply objective measurement to decision making. The basic hypothesis of MAUT is that in any decision problem, there exists a real valued function or utility (U), defined by the set of feasible alternatives that the decision-maker seeks to maximize (Olson, 1996). Each alternative results in an outcome, which may have a value on a number of different dimensions. MAUT seeks to measure these values, one dimension at a time, followed by an aggregation of these values across the dimensions through a weighting procedure. The simplest and most widely used aggregation rule is to take the weighted linear average. In this case, each weight is used in conjunction with each criterion value to produce the final utilities (Zietsman et al., 2006).

2.6 Summary of the Previous Research Limitations

Based on the review conducted on physical and environmental building assessments and evaluation approaches as well as Building Information Modeling as an advanced tool, the following limitations were derived:

- The method of assessing the condition of the building systems and components is time-consuming and costly, this is because the mechanism itself is subjective, un-automated, and requires expertise.
- The mechanisms of the condition assessments in literature are very generic and it is very difficult to locate the problem(s) inside the whole building, which consists of many building systems and components.
- The inspection processes in all of the condition assessment mechanisms are done using either the "direct condition rating" or the "deficiencies lists", and there is a lack of one single flexible mechanism that can be adapted for both methods easily.
- All the previous condition assessment systems assess a building using the building systems as the highest hierarchy level; however, using space as the highest level in the building asset hierarchy will facilitate the facilities management process for managers.
- Previous research works in literature do not consider the difference in tasks held inside spaces, in which the different effect(s) of all building systems on the nature of the task are completely ignored.
- Lack of research works that consider the physical aspects that deals with the building economic, cultural and historical importance and environmental aspects that deal

with the occupants comfort and quality of life in one integrated model has been reported in the literature.

- Previous models that dealt with the physical elements did not consider the inter-relationships between the different components and the effect of one component's deterioration on others' deterioration.
- Most of the environmental assessment approaches for buildings and specifically educational ones do not allow for a comprehensive assessment of all of the environmental factors; furthermore, the weighting factors were dependent on occupants' surveys which have not been statistically verified.
- Lack of an integrated platform that considers facility management's aspects throughout the entire building life cycle.
- Previous asset management models were a kind of some automation of the paper based ordinary work. They implement the asset management phase as a separate entity without integrating it with other phases in the building lifecycle such as the design, construction, etc.; the way it results to a lot of rework, inaccuracy and mistakes. By using BIM, owners and facilities managers can mitigate their portion of the cost associated with their current lack of interoperability.

Chapter 3: Research Methodology

3.1 Overview of the Proposed Methodology

Buildings in North America are aging and need extra attention. The required expenditures for building maintenance and repair in Canada are nearly CDN$ 110 billion per year, whereas the capital renewal figures are close to CDN$ 86.5 billion per year. At the same time, considering the evidence that people spend most of their time in indoor environments, poor Indoor Air Quality (IAQ) costs tens of billions of dollars every year due to absenteeism in the workplace and the reduced productivity of the non-absent workers at work. Thus, improving the condition assessment process by integrating both disciplines (physical and environmental conditions) is expected to provide substantial benefits for the economy as a whole.

The proposed model methodology of this research is based on developing an integrated condition assessment model that considers the physical and environmental aspects of buildings. The model will assist facility managers and owner's organizations in their administration of buildings.

3.2 The main Concept of Proposed Methodology

The integrated building condition assessment model considers both physical and environmental conditions. To develop this model, the research methodology is divided into four main parts which are incorporated to give a final integrated model for the entire building. The methodology is based on managing a building according to its spaces; where space is the principal evaluated element, according to its internal physical elements as well as its indoor environmental quality. The integrated condition assessment process will be implemented and automated through Building Information Modeling (BIM) technology.

Figure 3.1 illustrates the model methodology's concept and shows the main components, as highlighted below (Eweda et al., 2010):

1. Spaces inside the building and their ranking
2. Space Physical Assessment
3. Space Environmental Assessment
4. Integrated Condition for spaces and the entire building

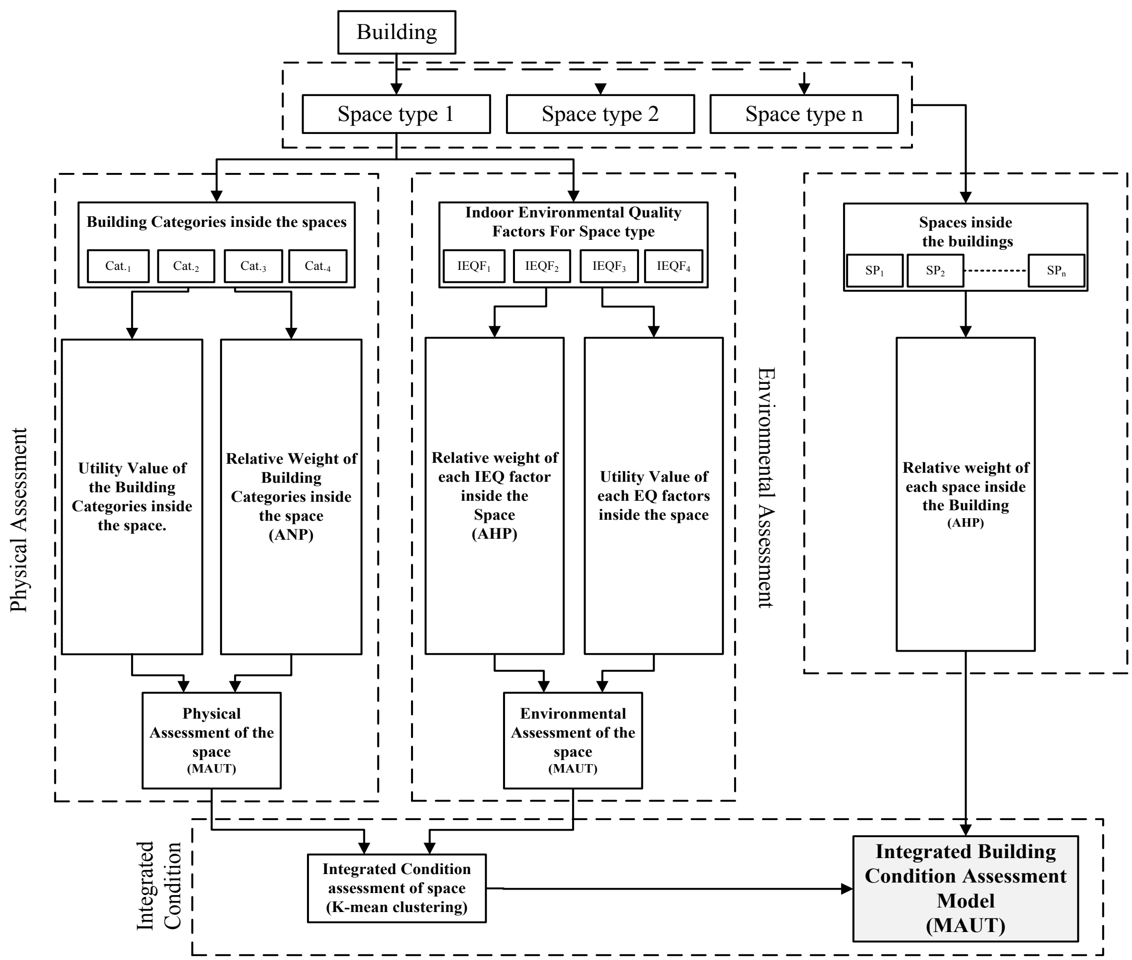


Figure 3.1: Model Methodology

3.2.1 Spaces inside the building

Spaces are determined horizontally by floor and ceiling, and vertically by walls. They form an internal environment to man which enables him to live in an appropriate way and offers privacy, shelter, and other needs (WBDG 2008). Each building type consists of a certain number of spaces which represents the different functions conducted inside the building, as shown in Figure 3.2: $B = \{SP_1, SP_2 \ldots SP_n\}$. Each space type has its own characteristics and requirements; moreover, each space has its own relative importance compared to others in a specific building type and based on many factors; for example, the function of the space, the number of occupants, the frequency and the duration of usage.

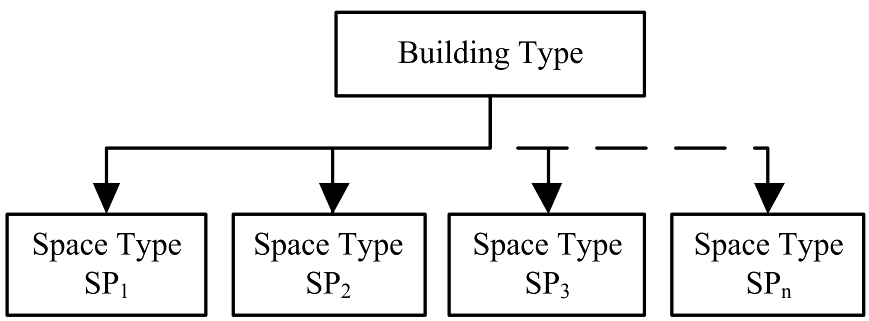


Figure 3.2: Building is composed of different space types

3.2.2 Physical assessment

The definition of physical assessment, within this research, is the inspection and evaluation of the physical elements inside each space (SP), represented by the different building categories as shown in Figure 3.3: $SPi = \{Cat_1, Cat_2 \ldots Cat_m\}$. Assessing the physical condition of each system in a way that can evaluate building components can provide very useful information to an asset manager. Since the condition assessment is the most important stage in the asset management process, it should be consistent and reliable.

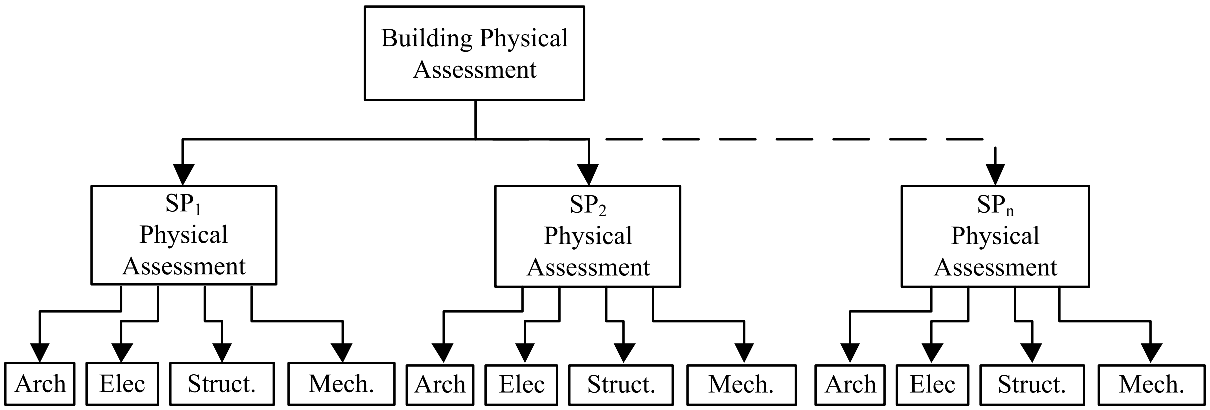


Figure 3.3: Building Physical Assessment

3.2.3 Environmental assessment

The environmental assessment as performed within this research is to measure and inspect the indoor environmental quality of a building. The Indoor Environmental Quality (IEQ) of a building is divided into four main categories, each of which is an indoor environmental quality factor (IEQF): (1) indoor air quality, (2) thermal quality, (3) lighting quality, and (4) acoustics quality, as shown in Figure 3.4. In other words, each space has four different Indoor Environmental Quality factors (IEQFs) to be measured, represented as follows: SPi = $\{IEQF_1, IEQF_2 \ldots . IEQF_l\}$.

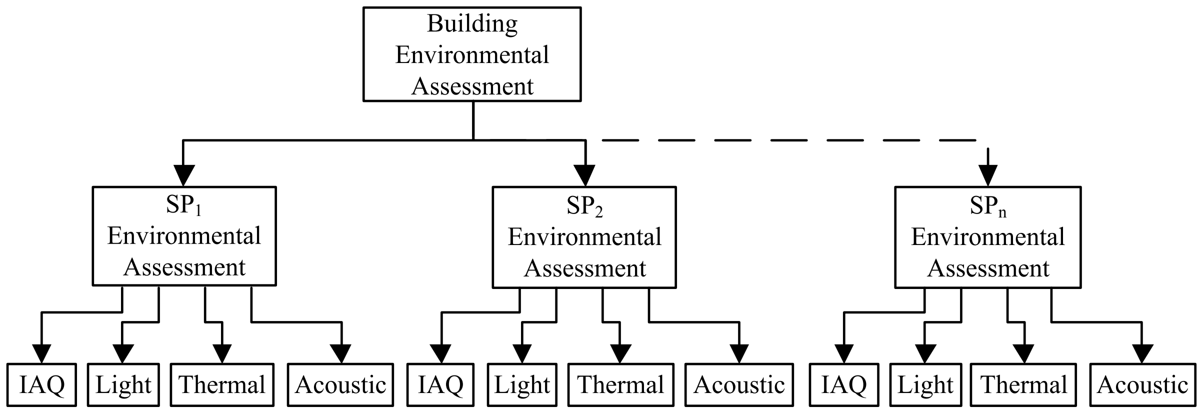


Figure 3.4: Building Environmental Assessment

3.3 Ranking Spaces inside a Building

3.3.1 Identifying the various space types inside a building

Buildings are composed of different space types; each space type has its own characteristics and requirements associated with the activities held in it. The activities held inside the space lead to the functional needs of the occupants; these needs are related to space requirements in a specific way. This in turn leads to a listing of the so-called spaces (rooms) that are required, along with the approximate square foot areas that each will require. The interrelationship of these spaces is studied to determine which need to be near each other and which can be further apart. For example, an educational building is mostly composed of the following spaces:

1. Offices
2. Laboratories
3. Auditoriums
4. Classrooms
5. Cafeterias
6. Circulation areas (lobby and corridors)
7. Wet areas

3.3.2 Identifying the relative importance of each space type inside a building

Each space has its own relative importance compared to the other spaces in a specific building type according to many factors; for example, the function of the space, the number of occupants, the frequency and the duration of usage, etc. This study will identify the relative importance of each space type inside a building. Information about space priorities helps ensure the validity of the space-weighting factor. The data is collected in the form of a survey sent to experts, and is then analyzed using the AHP technique, in which the relative importance weight of each space type is calculated using the Eigenvector approach. Figure 3.5 shows the process of prioritizing spaces and of having a relative importance for each space with respect to the others within a building type using AHP. The number of spaces and the surface area are also contributing factors affecting the relative weight of each space inside the entire building, for example an office with a bigger surface area than another office will certainly have a higher relative weight in such a building type. Equation 3-1 illustrates how the process of calculating the relative weight of each space type per unit area. While Equation 3-2 illustrates how to calculate the relative weight of each single space in an entire building knowing the relative weights per unit area of the space type it belongs to and the space surface area.

$$\boldsymbol{RW\ (SPt_u)/m^2} = \frac{\boldsymbol{RW\ (QSPt_u)}}{[\sum_{\boldsymbol{u=1}}^{\boldsymbol{z}} \boldsymbol{RW\ (QSPt_u) X\ A\ (SPt_u)}\ ]}$$

Equation 3-1

where:

$\boldsymbol{RW\ (SPt_u)/m^2}$: is the relative weight of a space type per unit area,

$\boldsymbol{RW\ (QSPt_u)}$ **:** is the relative weight of the space type calculated from the questionnaire,

$\boldsymbol{A\ (SPt_u)}$: is the total are of all spaces having the same space type.

The relative weight of each space will be simply the multiplication of its area in sq. meters by the relative importance of the space type per unit area:

$$\boldsymbol{W\ (SP_i) = RW\ (SPt_u)/m^2\ X\ A\ (SP_i)}$$

Equation 3-2

where:

$\boldsymbol{A\ (SP_i)}$: is the space area in unite area.

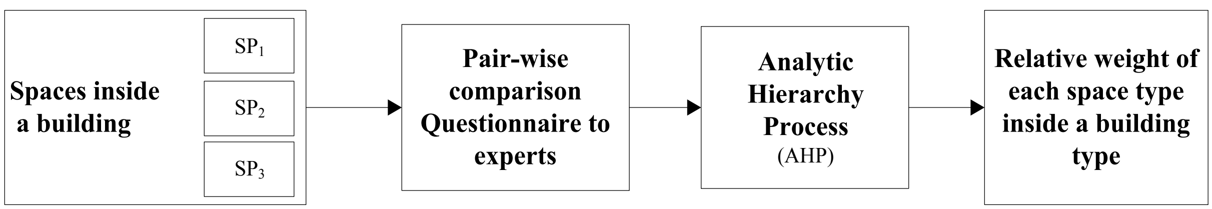


Figure 3.5: The process of prioritizing spaces inside a building using AHP

3.4 Development of Physical Assessment Model for Spaces

3.4.1 Proposing a new asset hierarchy for buildings

In order to assess the physical condition of a building space, both the identification of the different building categories in each space and the asset hierarchy must be determined at the outset. As discussed in chapter 2, there are some drawbacks in the existing asset hierarchies. Based on their pros and cons a new asset hierarchy that considers their benefits along with the building information modeling procedures is proposed. The new asset hierarchy is structured on six levels -- starting with the building at the upper level and ending with the instance level. Figure 3.6 illustrates the proposed asset hierarchy:

i. **Building Level:** the top level of the asset hierarchy -- represents the building type where it is different from one building type to another;
ii. **Space Level:** includes all the spaces inside the building such as offices, wet areas, auditoriums, etc.;
iii. **Category Level:** includes the four main building disciplines represented inside the space -- architectural, mechanical, electrical, and structural;
iv. **Family Level:** includes all the components in the same category that have similar characteristics, such as the "columns" under the "Structural" Category;
v. **Family Type Level:** includes the different component types in the family level, such as "fixed aluminum" or "aluminum sliding window" in the "windows" family; and
vi. **Instance Level:** includes components properties such as "white paint exterior wall 14 inch thickness" inside the "exterior wall" family type.

3.4.2 Proposed Evaluation Mechanisms

As discussed in chapter 2, there are two methods for evaluating the condition of any building component during the inspection process: the direct condition rating, which is faster but less accurate, and the distress survey, which is more detailed and more accurate. The two methods will be used in this research, inspector will have the option to use either of the two methods and the model can be adapted to utilize both of them.

i. **The Direct condition Rating**

In case of using the direct condition rating method, inspector will be asked to evaluate give a grade to the physical components out of "100" with "0" represents the worst case which is failure. He will be provided with an index as shown in Figure 3.7, this index has been developed after several discussions with experts working in the field of condition assessment and building inspections. This index is flexible and can be adjusted according to the facilities management company or the facility manager himself in order to be standard for the entire managed buildings.

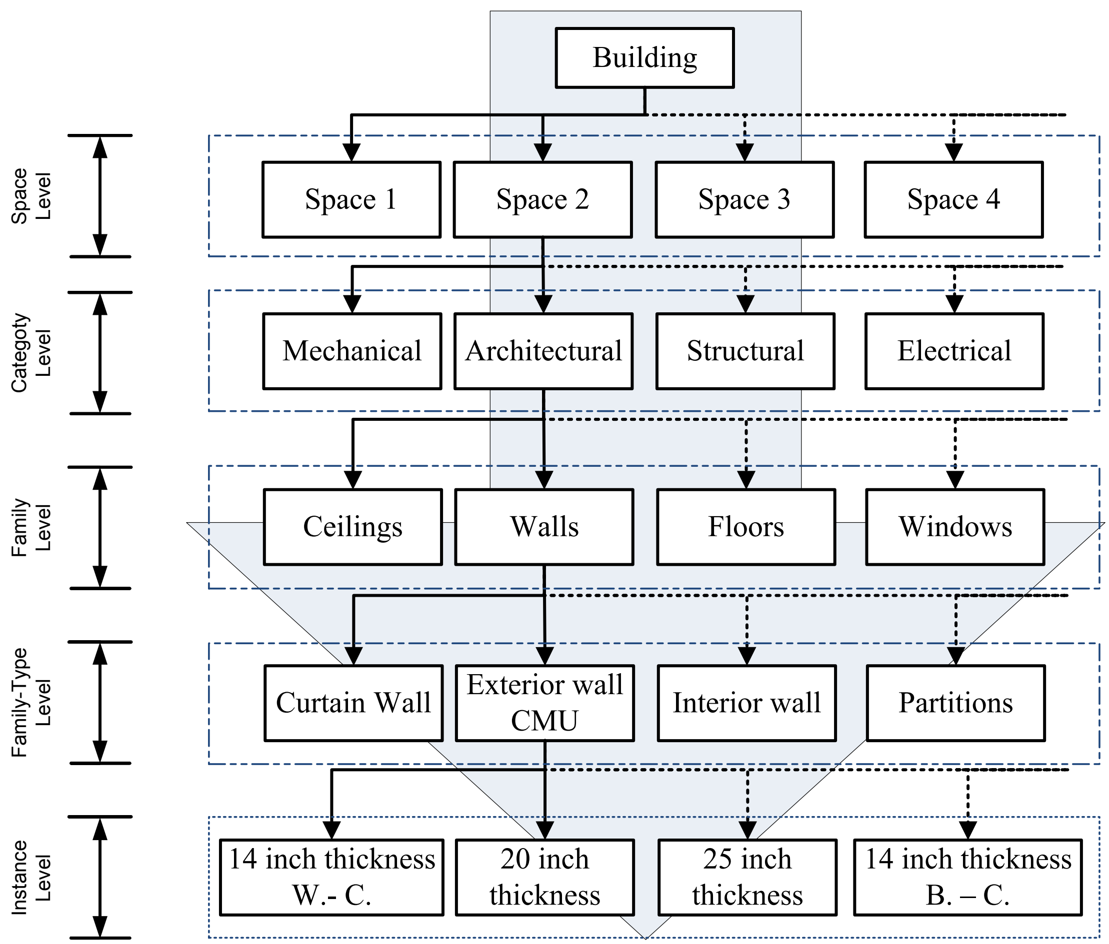


Figure 3.6: Proposed Asset Hierarchy

A guide line in order to assign the grade that reflects the condition of the physical element. Based on visual observation, the inspector is asked to determine the condition of the element based on the comparison of the current situation and the desired condition or performance of that specific element. In that case inspector having enough experience is required during the inspection process inside building, and certified inspector is preferred.

ii. Identifying a list of deficiencies

The other method is the distress method in which the inspector is asked to evaluate the physical components according to a list of evaluation criteria. This method may be more suitable because it gives a better understanding of the exact problem, it is more suitable in cases where more details are required, and finally it is more accurate and less subjective. Another capability of the distress survey method is to give an idea about the location of the problem; hence, it will be used in the other phases of managing the asset. Since the "family" or the "family-type" levels are the levels of the assessment in the proposed hierarchy; there will be a generic list of evaluation criteria for all the building components.

3.4.3 Condition Index Scale

The next step is to set a condition index scale which is used to assign a value that represents the category condition. This scale is used to represent the numeric values related to the linguistic representation. The proposed condition index (CI) scale as presented in Figure 3.7 extends from "0" to "100", with "0" representing the critical condition (complete failure) and "100" representing the perfect condition (excellent condition). The scale is divided into six levels and adapted from several scales that were used by Mckay, (1999) and Elhakeem. (2005) and it is finalized after several discussions with facility managers and experts in building condition assessment. In Figure 3.7, definition of each grade is explained in the description text as a general guide line for all physical elements inside building; and the inspector is responsible to adapt those definitions to all different physical elements.

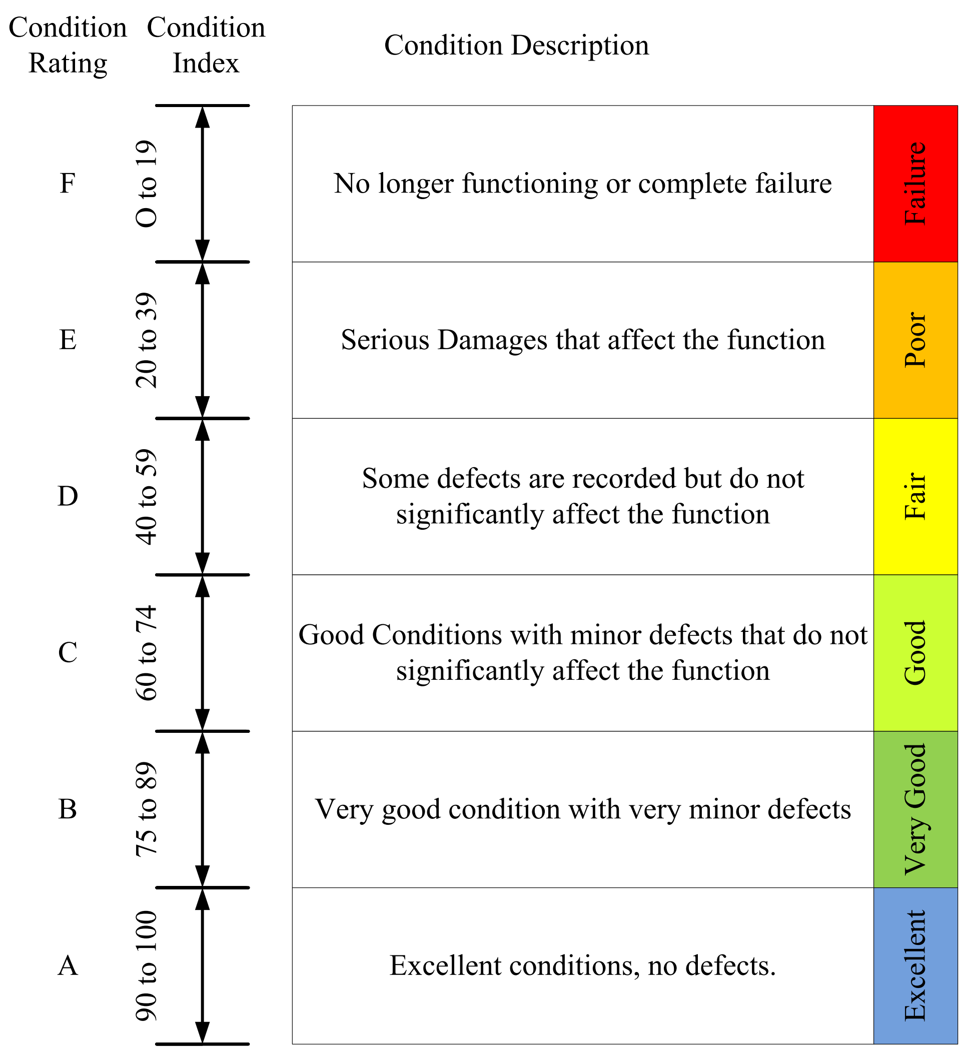


Figure 3.7: Proposed Condition Index Scale

As mentioned before that BUILDER uses its 23 generic distress types in the evaluation process; the inspector evaluates each subcomponent against these 23 distress types. He/she should provide judgment on two measurements (density and extent) for each distress. It was found that using these 23 distress type requires a lot of time and may not be also cost effective. This is because the inspector is asked to answer 23 questions and give his judgment on two measurements (density and extent) for each element inside the building. A better and more effective method is required and there is a requirement of maintaining the aim of reducing subjectivity and saving time. The 23 published distress types in the BUILDER condition assessment manual were analyzed and grouped to only three evaluation criteria in order to evaluate physical elements with. Table 3-1 shows the process of grouping the distress types into the three main criteria with option of recommending extra and more detailed evaluation for a specific element that may require that.

Damage, Performance, and Appearance are the main three evaluation criteria. Expert will be asked to assign a relative weight for each criterion for its contribution on the entire condition of the physical element using a survey questionnaire. The inspector is asked to evaluate the condition of the physical element according to them and using the relative weight of each one, an overall condition for the element is calculated. This overall condition is similar to that of the direct condition rating where expert is asked to provide it using his engineering sense.

Using either of the two methods, an evaluation for the physical elements will be calculated out of “100” with “0” represents failure. The second step is to calculate the condition at any level using the roll-up method. Finally, the utility value of the whole category ($U.Cat_{ji}$) in a specific space can be calculated in order to be used in the MAUT calculations.

Table 3-1: The process of grouping the distress types into the three main criteria

No.	Distress Type	Category
1	Animal/Insect Damaged	Damage
2	Blistered	Damage
3	Broken	Damage
4	Capability/Capacity Deficient	Performance
5	Clogged	Performance
6	Corroded	Damage
7	Cracked	Damage
8	Damaged	Damage
9	Deteriorated	Damage
10	Displaced	Appearance
11	Efflorescence	Damage
12	Electrical Ground Inadequate or Unintentional	Performance
13	Holes	Damage
14	Leaks	Performance
15	Loose	Damage
16	Missing	Appearance
17	Moisture/Debris/Mold Contaminated	Damage
18	Noise/Vibration Excessive	Performance
19	Operationally Impaired	Performance
20	Overheated	Performance
21	Patched	Appearance
22	Rotten	Damage
23	Stained/Dirty	Appearance

3.4.4 Identifying the relative weight of each building category inside a space type

Several research efforts have acknowledged the presence of complex relationships between the different building categories: (Elhakeem, 2005; Langevine, 2006; and Ahluwalia, 2008). Each of these studies have acknowledged this complexity and determined the relative weights for the categories throughout the building hierarchy, but none of them has determined the relative importance of these categories inside a space and how these importance levels are changed from one space type to another. For example, the HVAC relative importance in an auditorium space is different than its relative importance in a space like a storage space or a wet area, and this is the case with all of the different categories inside the different space types. Hence, in this step, the research will identify the relative weight of each building category inside each particular space type; in other words, all the spaces with the same type will have the same categories' relative weights. To proceed, first, a pair-wise comparison as a questionnaire will be made, because the human mind is much better at establishing differences than it is at estimating absolute values; experts should identify the weight of each building category with respect to another inside of a particular space type.

The Analytical Network Process (ANP) will then be applied to obtain the relative importance weight of each building category inside a space type ($W.Cat_{ji}$) and their families $\boldsymbol{W.fam_{nj}}$ using the ANP Super-matrix. Figure 3.8 shows the hierarchy of four building categories as well as their families. The categories and their families will be clustered into eight different clusters. In Figure 3.9, the connections between the clusters indicate the flow of influence between the elements. For example, the connection between any two clusters indicates that there is at least one relationship between two elements in those two clusters.

3.4.5 Calculating the physical condition of each space

The utility value of the building category inside each space will be determined by multiplying the utility value calculated for each family using an average of all the components that belong to this family inside this particular space represented in the family types and instance that compose it, multiplied by the weight determined using the ANP from the expert questionnaires using the Multi Attribute Utility Theory (MAUT) as shown in equation 3-1

$$\boldsymbol{U.Cat_{ji}} = \sum_{\boldsymbol{n=1}}^{\boldsymbol{t}} \boldsymbol{U.Fam_{nj}} \times \boldsymbol{W.Fam_{nj}}$$

Equation 3-3

where:

$U.\ Cat_{ji}$ is the utility value of each building category inside the space,

$U.\ Fam_{nj}$ is the relative weight of the families inside each category, and

$W.\ Fam_{nj}$ is the relative weight of the families inside each category.

Having the utility value of each building category inside a space as well as their relative importance inside that space, the physical condition assessment of the space can be calculated by simply multiplying the utility value of the category inside the space by its weight using the (MAUT) as shown in equation 3.1. The structural elements category as it has some safety issue will be dealt in a different way using if-then condition to proceed with running the model.

$$PC\ (SP_i) = \sum_{j=1}^{m} U.Cat_{ji} \times W.Cat_{ji}$$

Equation 3-4

where:

PC (SPi) is the physical condition inside the space, and

W. Cat_{ji} is the relative weight of the building category inside the space.

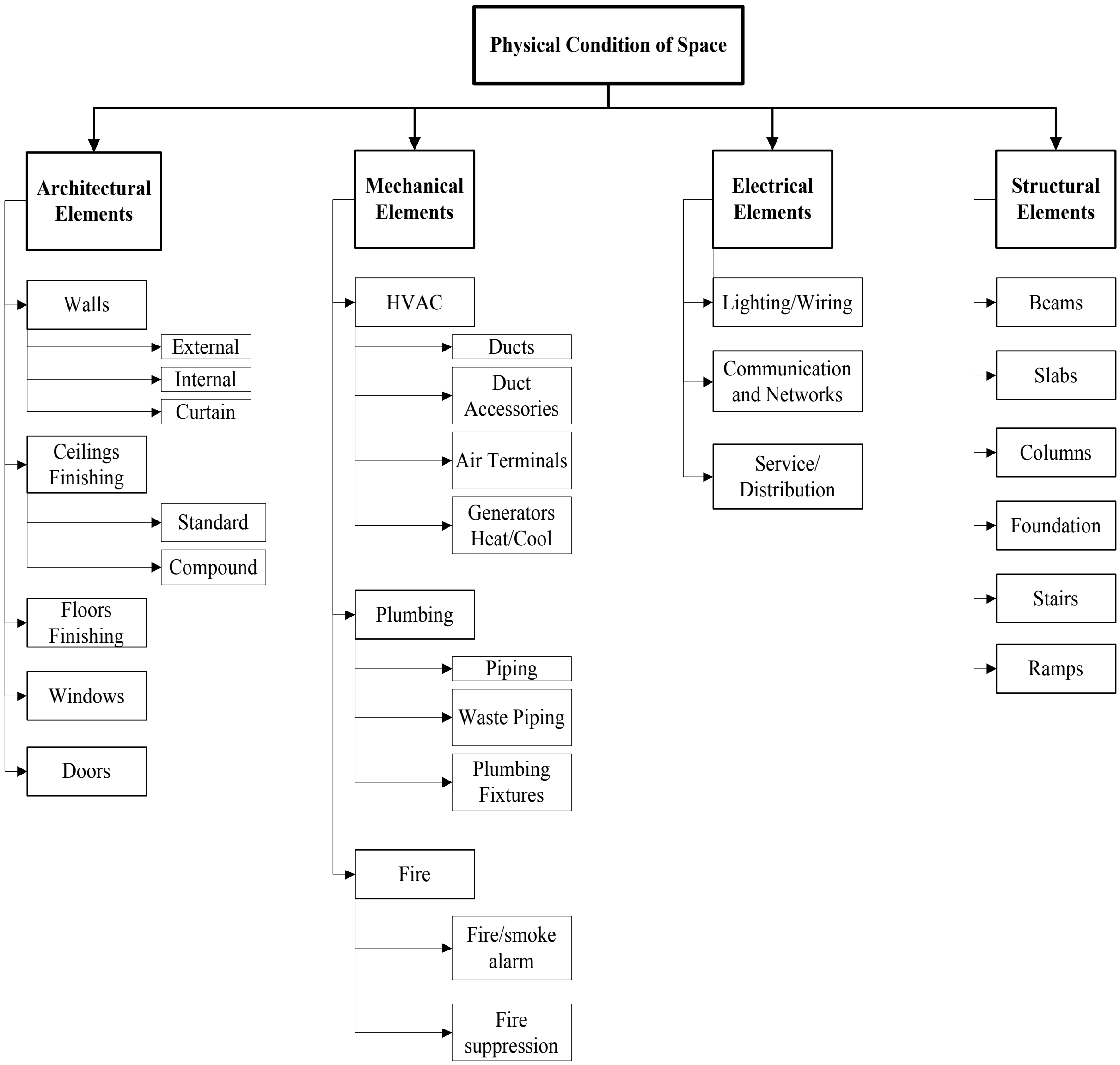


Figure 3.8: The building categories and their sub-criteria

Figure 3.10 explains the complete process of determining the physical condition assessment of a space inside a building. The graphical representation of the building categories conditions inside a space can be represented in a radar chart as shown in Figure 3.11.

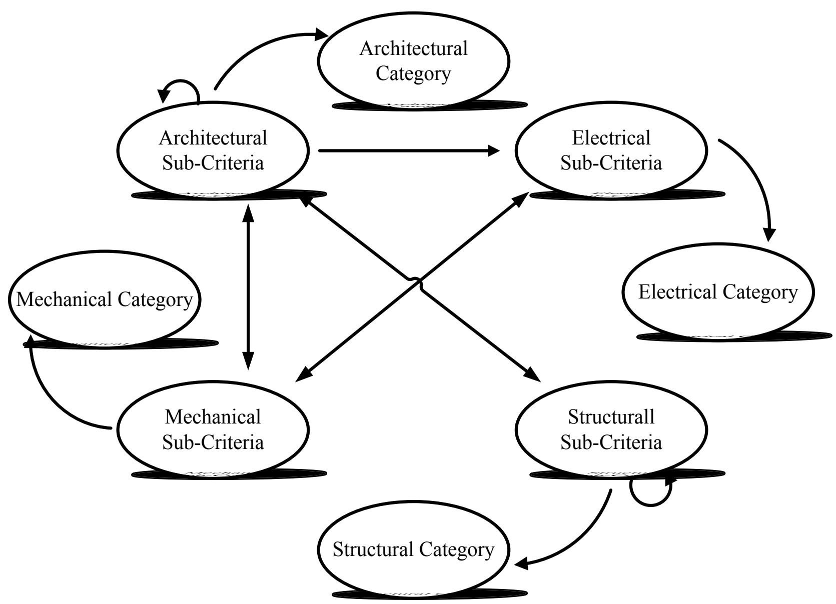


Figure 3.9: Representation of physical clusters in the ANP network

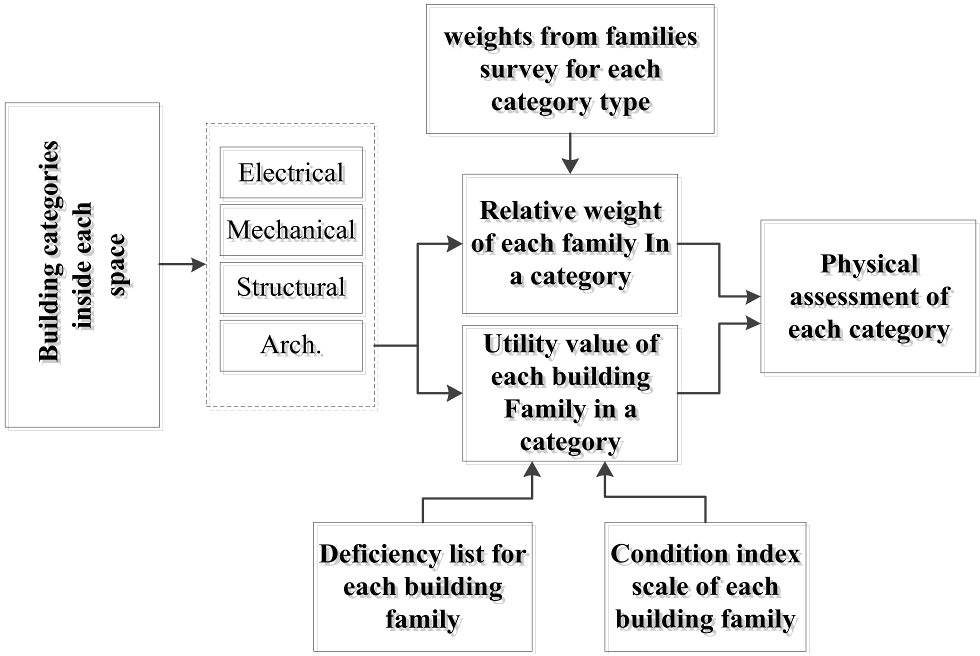


Figure 3.10: The process of assessing the physical elements inside a space

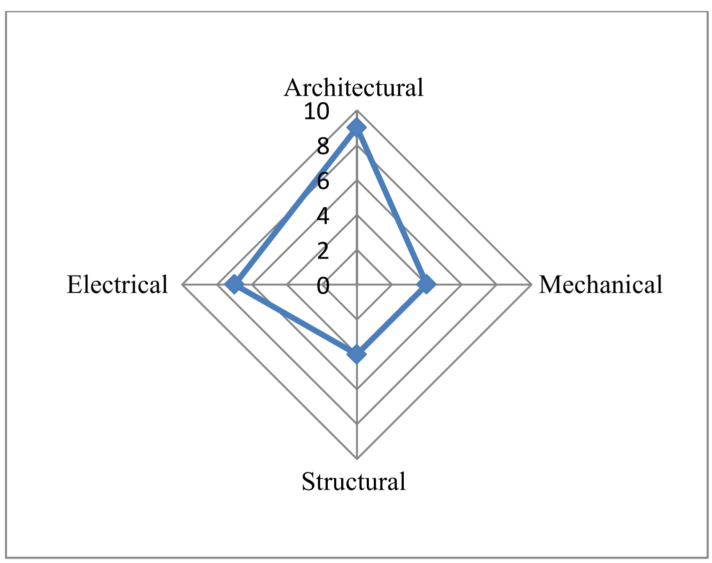


Figure 3.11: The graphical representation of building categories inside space

3.5 Environmental Assessment Model Development for Spaces

3.5.1 Identifying the various measurements of each IEQF inside a space type

To assess the environmental condition of a building space, the indoor environmental quality evaluation criteria should first be identified. As discussed earlier, the indoor environmental quality factors in this research are the indoor air quality, light quality, acoustic quality, and the thermal quality. Each has its own set of evaluation criteria on which it will be assessed.

i. **Indoor Air Quality (IAQ):** In order to measure the air quality inside a space, air pollutants should be identified and set as measurement variables. Figure 3.12 shows the major air pollutants as determined by the World Health Organization, Health Canada, ASHRAE, etc.,: carbon dioxide (CO_2), carbon monoxide (CO), ozone (O_3), formaldehyde, nitrogen dioxide (NO_2), Volatile Organic Compounds (VOCs), radon and dust.

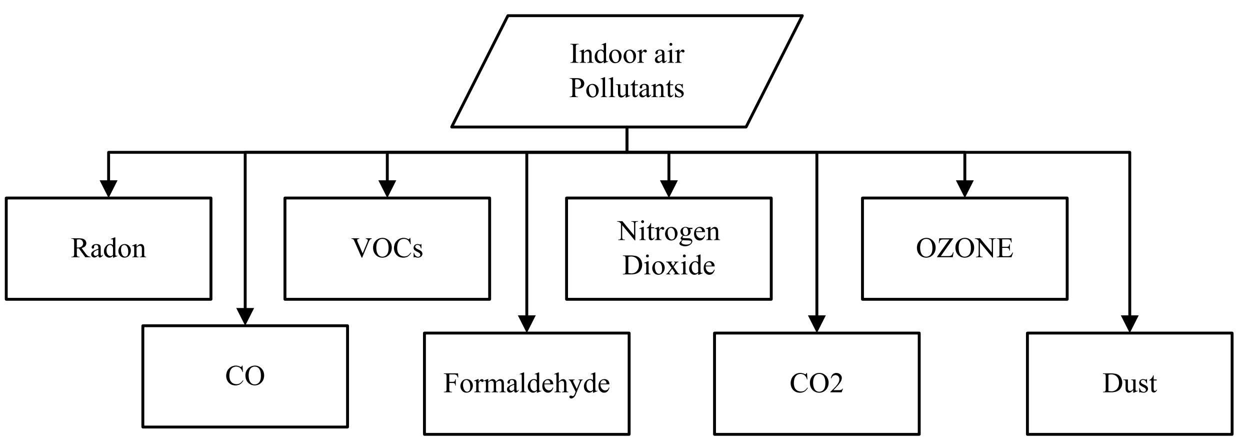


Figure 3.12: Indoor air pollutants

ii. **Thermal Quality:** Measuring the thermal quality inside a space requires measuring the indoor temperature as well as the humidity. These two variables have a significant effect on human comfort, as there is a relation between the levels of each to achieve a comfort zone for human beings.

iii. **Light Quality:** According to the Illumination Engineering Society of North America (IESNA, 2000), measuring the light quality variable means measuring the light intensity and then comparing it with the design standards.

iv. **Acoustics Quality:** Measuring the acoustics quality inside a space requires measuring the noise, which is the unwanted sound(s) that interferes with the desired one(s). Therefore, it is important to measure the sound level and compare it with the acceptable measurements in each space type.

3.5.2 Setting the benchmarks and measurement variables of each IEQF

In this step, it is important to review the standards of the different indoor environmental quality factors and set their measurement variables and benchmarks. Those standards, guidelines, and codes are targeting average values for each attribute which are designed to provide comfortable indoor environment to most of the building occupants in each specific building type by depending on real life experiments on thousands of people.

Thermal Quality

- ASHRAE standard 55, Section 6

Indoor Air Quality

- ASHARE Standard 62 (pollutant concentration)
- Environment Canada

Acoustics Quality

- Acoustic Standard: The Acoustical Society of America

Light Quality

- The Illuminating Engineering Society of North America

Utility Curves

These standards and codes for the different indoor environmental quality factors will be used to develop the utility curves in order to draw the relation between the field measurements for each evaluation criterion and the utility value to be used in the MAUT. Recommended, maximum desirable and maximum acceptable values for all IEQFs sub-criteria will be assigned according to the suitable codes. This part of the analysis will be presented in chapter 4 which is the chapter of data collection and analysis. Figure 3.13 shows the process of developing the utility curves for IEQFs sub-criteria. According to these factors, a utility value will be given for each criterion field measurement; and finally can be used as an input value in the MAUT.

i. Thermal Quality

The temperature in a space is the most noticeable element of thermal comfort; it is also controllable by the users via a thermostat. According to Dear et al., (1991), even though climates, living conditions, and cultures differ widely throughout the world, the temperature that people choose for comfort under similar conditions of clothing, activity, humidity, and air movement has been found to be very similar.

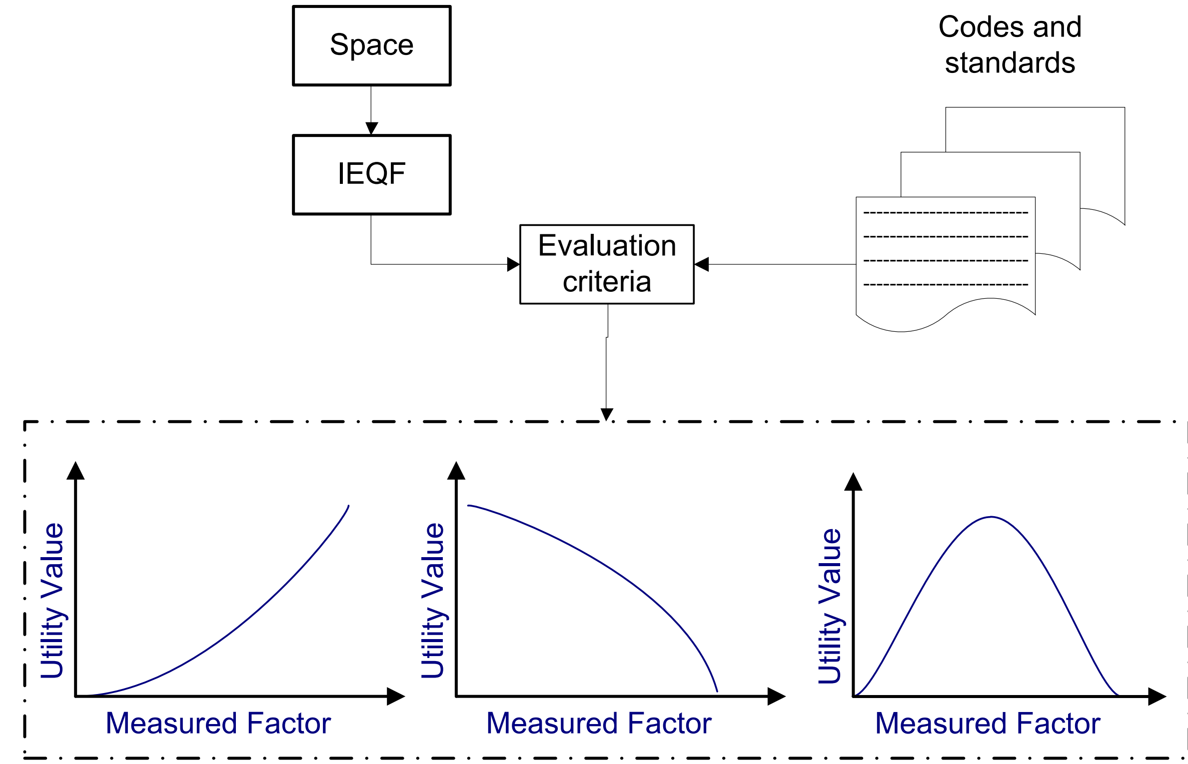


Figure 3.13: The process of developing the utility curves for environmental assessment

ASHRAE standard 55-2004 reported that the average person who is wearing seasonally appropriate clothing and performing a primarily sedentary activity is most comfortable when the surrounding temperature is between 69° F and 81° F (20.5 to 27.2). The second criterion is the relative humidity (%RH), which is a function of temperature -- when the air worms it becomes capable of holding more moisture. According to the ASHRAE standard 55-2004, most occupants become comfortable when the relative humidity is between 30 and 60%. Air temperature and the relative humidity both contribute to occupant comfort. Figure 3.14 shows a graph that represents the comfort zone as a function of the temperature and humidity, according to the ASHRAE.

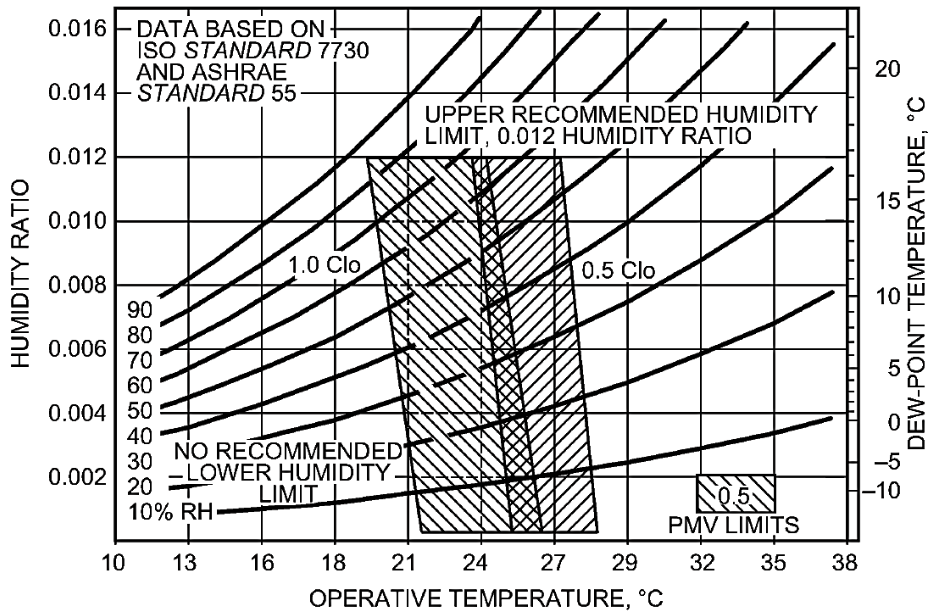


Figure 3.14: ASHRAE summer and winter comfort zones

ii. Indoor Air Quality

As stated earlier, the selected air pollutants are the most common indoor air pollutants for people who spend most of their time in residential, work, and educational spaces. There are some other pollutants common in industrial places, repair shops, etc. Table 3-2 summarizes a comparison of regulations and guidelines pertinent to indoor environments (ASHRAE standards 62.1, 2004). For example, carbon monoxide (CO) is a colorless, odorless, poisonous gas produced during incomplete combustion. Exposure limits for CO are 35 ppm for one hour for exposure once a year, or it can be 9 ppm for a limit of an 8 hour period. With carbon dioxide (CO_2), ASHRAE standard 62 recommends that the indoor level of carbon dioxide may not exceed ~700 ppm above outdoor ambient levels, and the Canadian standard limits it to 3500 ppm. Ozone (O_3) concentration is limited by the Canadian standard to 0.12 ppm for only one hour.

Table 3-2: Comparison of regulations and guidelines pertinent to indoor environments (ASHRAE standard 62.1, 2004)

	Canadian[c]	WHO/Europe	NAAQS/EPA[f]	NIOSH REL (TWA)[h]	OSHA (TWA)[h]	ACGIH (TWA)[h]	MAK[g] (TWA)[h]
Acrolein	0.02 ppm[a]			0.1 ppm 0.3 ppm (15 min)	0.1 ppm	C 0.1 ppm, A4	
Acetaldehyde	5.0 ppm			Ca: ALARA[b]	200 ppm	C 25 ppm	50 ppm 100 ppm (5 min)
Formaldehyde	0.1 ppm (1 h) 0.04 ppm (8 h)	0.081 ppm (30 min)		0.016 ppm 0.1 ppm (15 min) Ca	0.75 ppm 2 ppm (15 min) Ca	C 0.3 ppm, A2	0.3 ppm 1.0 ppm (5 min)
Carbon dioxide	3500 ppm			5000 ppm 30 000 ppm (15 min)	5000 ppm	5000 ppm 30 000 ppm (15 min)	5000 ppm 10 000 ppm (60 min)
Carbon monoxide	11 ppm (8 h) 25 ppm (1 h)	8.6 ppm (8 h) 25 ppm (1 h) 51 ppm (30 min) 86 ppm (15 min)	9 ppm (8 h) 35 ppm (1 h)	35 ppm C 200 ppm	50 ppm	25 ppm	30 ppm 60 ppm (30 min)
Nitrogen dioxide	0.05 ppm 0.25 ppm (1 h)	0.02 ppm (1 yr) 0.1 ppm (1 h)	0.053 ppm (1 yr)	1 ppm (15 min)	C 5 ppm	3 ppm 5 ppm (15 min), A4	5 ppm 10 ppm (5 min)
Ozone	0.12 ppm (1 h); Insufficient data for long-term level	0.06 ppm (8 h)	0.12 ppm (1 h) 0.085 ppm (8 h)	C 0.1 ppm	0.1 ppm	0.05 ppm, A4 (for heavy work) 0.2 ppm (2 h) (light, moderate, or heavy work)	
Particles <2.5 MMAD[d]	40 μg/m³ (8 h) 100 μg/m³ (1 h)		15 μg/m³ (1 yr) 35 μg/m³ (24 h)		5 mg/m³ (respirable fraction)	3 mg/m³ (8 h) (no asbestos, <1% crystalline silica, with median cut point of 4.0 μm)	1.5 mg/m³ (for less than 4 μm)
Sulfur dioxide	0.019 ppm 0.38 ppm (5 min)	0.047 ppm (24 h) 0.019 ppm (1 yr)	0.03 ppm (1 yr) 0.14 ppm (24 h)	2 ppm (8 h) 5 ppm (15 min)	5 ppm	2 ppm 5 ppm (15 min)	0.5 ppm 1.0 ppm (5 min)
Radon	800 Bq/m³[e]		4 pCi/1				

( ) Numbers in parentheses represent averaging periods
C = ceiling limit
Ca = carcinogen
A4 = not classifiable as human carcinogen per ACGIH
[a] Parts per million (10^6)
[b] As low as reasonably achievable
[c] Health Canada *Exposure Guidelines for Residential Indoor Air Quality*
[d] Mass median aerodynamic diameter
[e] Mean in normal living areas
[f] U.S. EPA National Ambient Air Quality Standards
[g] German Maximale Arbeitsplatz Konzentrationen
[h] Value for 8-h TWA, unless otherwise noted
[i] WHO Air Quality Guidelines for Europe

iii. Acoustics Quality

The acceptable amount of noise level is different from one space type to another, as shown in

Table 3-3.

Table 3-4 shows that the Noise Criterion (NC) for a conference room is between "NC-25" and "NC-30"0; which is equivalent to 35 dBA. to 40 dBA. Figure 3.15 shows the Noise Criteria curve as given by Beranek (1960).

Table 3-3: Types of Rooms and Noise Criteria (Moris, 2009)

Type of Room - Occupancy		Noise Criterion - NC -	Noise Rating - NR -	db(A)
Very quiet	Concert and opera halls, recording studios, theaters, etc.	10 - 20	20	25 - 30
	Private bedrooms, live theaters, television and radio studios, conference and lecture rooms, cathedrals and large churches, libraries, etc.	20 - 25	25	25 - 30
	Private living rooms, board rooms, conference and lecture rooms, hotel bedrooms	30 - 40	30	30 - 35
Quiet	Public rooms in hotels, small offices classrooms, courtrooms	30 - 40	35	40 - 45
Moderate noisy	Drawing offices, toilets, bathrooms, reception areas, lobbies, corridors, department stores, etc.	35 - 45	40	45 - 55
Noisy	Kitchens in hospitals and hotels, laundry rooms, computer rooms, canteens, supermarkets, office landscape, etc.	40 - 50	45	45 - 55

Table 3-4: Recommended Noise Criterion - NC (ASHRAE, 2007)

Space	RC(N)	NC
Private residences, apartments, condominiums	25-35	25-35
Hotels/Motels		
Individual rooms or suites	25-35	25-35
Meeting/banquet rooms	25-35	25-35
Halls, corridors, lobbies	35-45	35-45
Service, support areas	35-45	35-45
Office Buildings		
Executive and private offices	25-35	25-35
Conference rooms	25-35	25-35
Teleconference rooms	25 max	25 max
Open plan offices	30-40	30-40
Circulation and public lobbies	40-45	40-45
Hospitals and Clinics		
Private rooms	25-35	25-35
Wards	30-40	30-40
Operating Rooms	25-35	25-35
Corridors	30-40	30-40
Public areas	30-40	30-40
Performing Arts		
Drama theaters	25 max	25 max
Concert and recital halls	A	A
Music teaching studios	25 max	25 max
Music practice rooms	25 max	25 max
Laboratories		
Testing/Research, minimal speech communication	45-55	45-55
Research, extensive phone use, speech communication	40-50	40-50
Group teaching	35-45	35-45
Churches, Mosques, Synagogues	25-35	25-35
With critical music programs	A	A
Schools		
Classrooms up to 750 ft²	40 max	40 max
Classrooms over 750 ft²	35 max	35 max
Lecture rooms for than 50	35 max	35 max
Libraries	30-40	30-40
Courtrooms		
Unamplified speech	25-35	25-35
Amplified speech	30-40	30-40
Indoor Stadiums and gymnasiums		
School and College gymnasiums and natatoriums	40-50	40-50
Large seating capacity spaces	45-55	45-55

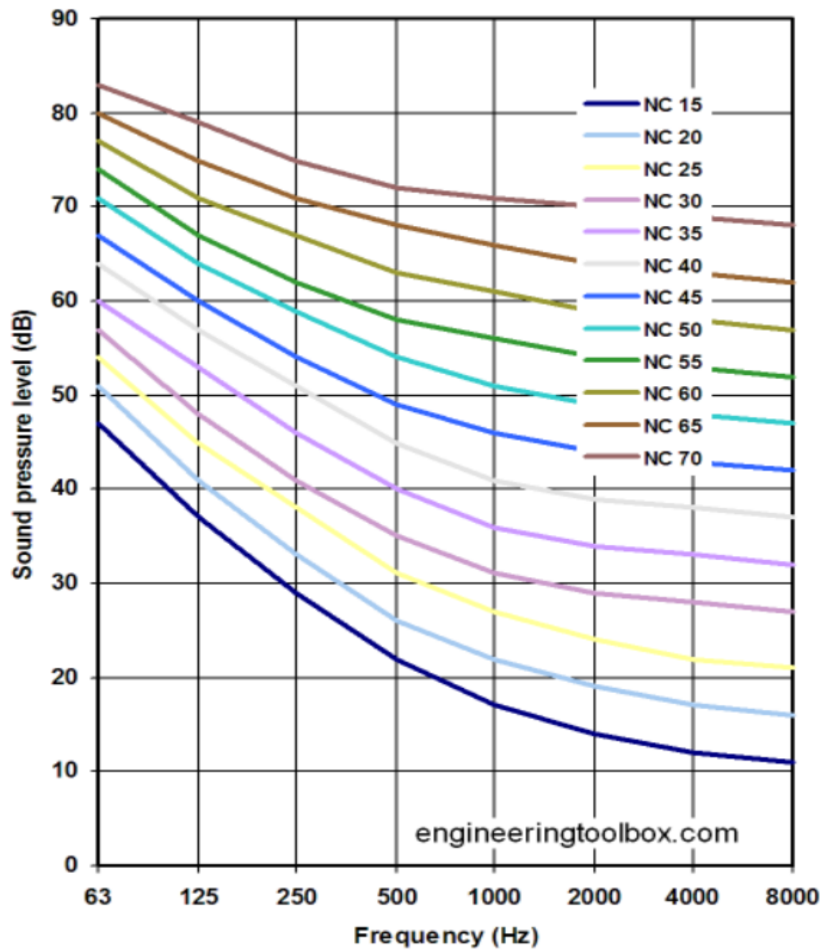


Figure 3.15: Noise Criteria curve (Beranek, 1960)

iv. <u>Light Quality</u>

Each space is designed to house a specific activity and so the design process should plan for sufficient light intensity to fulfill such activity. For example, if the work space is an office designed to house people engaged in thought and in a number of forms of communication (written, visual, telephone, computer, and face to face). Office lighting should enable workers to perform these tasks effectively. Ambient illuminance throughout the office space should not exceed 500 lx (50 fc) as stated by the IESNA (2000).

3.5.3 Identifying the relative weight of each IEQF inside the space type

In this step the relative importance of each environmental quality factor (IEQF) among others in each space type inside a building will be identified. To identify the relative importance, a pair-wise comparison structured as a questionnaire will be sent to experts. These experts will identify the weight of each IEQF with respect to another IEQF inside a particular space type. The second step is to apply the analytical network process (AHP) to obtain the relative weight of each IEQF inside a space type. Figure 3.16 shows the hierarchy of four indoor environmental quality factors (IEQFs) as well as their sub-criteria. The IEQFs and their sub-criteria will be divided into eight different clusters.

3.5.4 Calculating the environmental condition of each space

Having the utility value of each indoor environmental quality factor inside a space as well as their relative importance (weight) inside that space, the environmental assessment of this space is calculated using the MAUT by multiplying the relative weight of each indoor environmental quality factor by its own weight, as shown in equation 3.2.

$$\boldsymbol{EC\ (SP_i) = \sum_{K=1}^{l} U.EQF_{Ki} \times W.EQF_{Ki}}$$

Equation 3-5

where:

EC (SPi) is the environmental condition inside the space,

$\boldsymbol{U.\ EQF_{Ki}}$ is the Utility value of each environmental quality factor inside the space, and

$\boldsymbol{W.\ EQF_{Ki}}$ is the relative weight of the environmental quality factor inside the space.

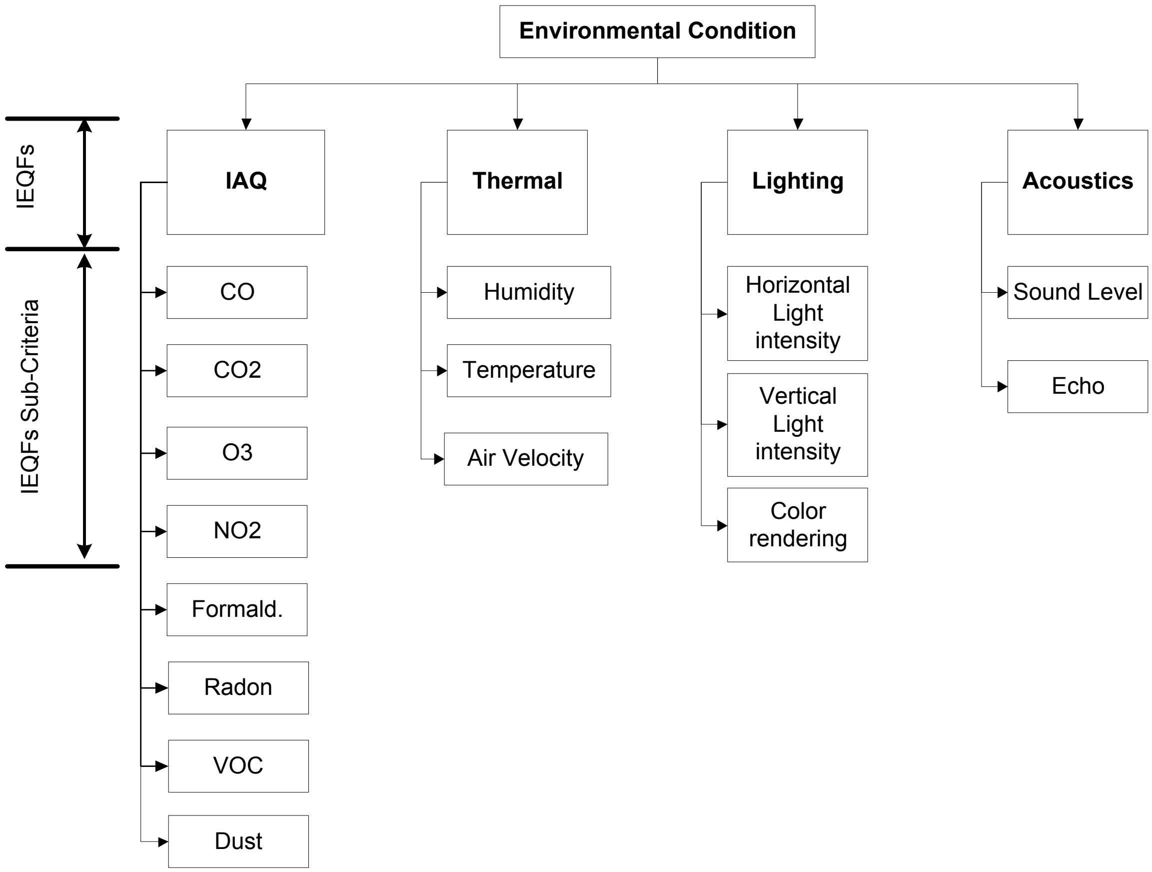


Figure 3.16: The IEQFs and their sub-criteria

Figure 3.17 illustrates the complete process of determining the environmental condition assessment of a space inside a building.

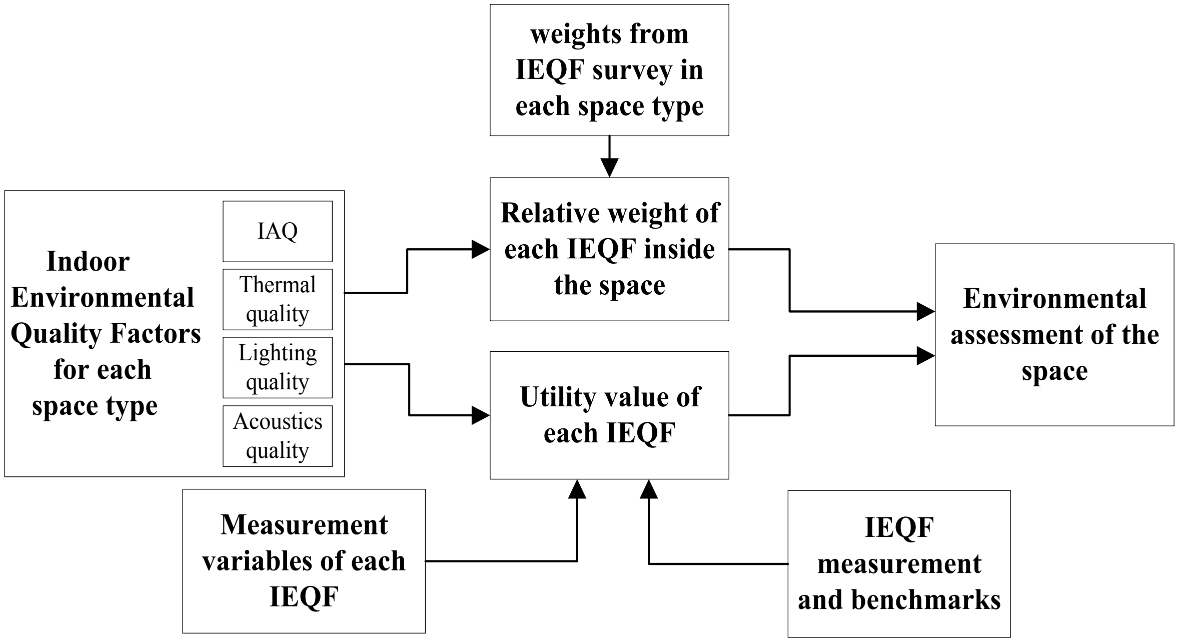


Figure 3.17: The process of assessing the environmental condition inside a space

The graphical representation of the indoor environmental quality factors conditions inside a space can be represented in a radar chart as shown in Figure 3.18

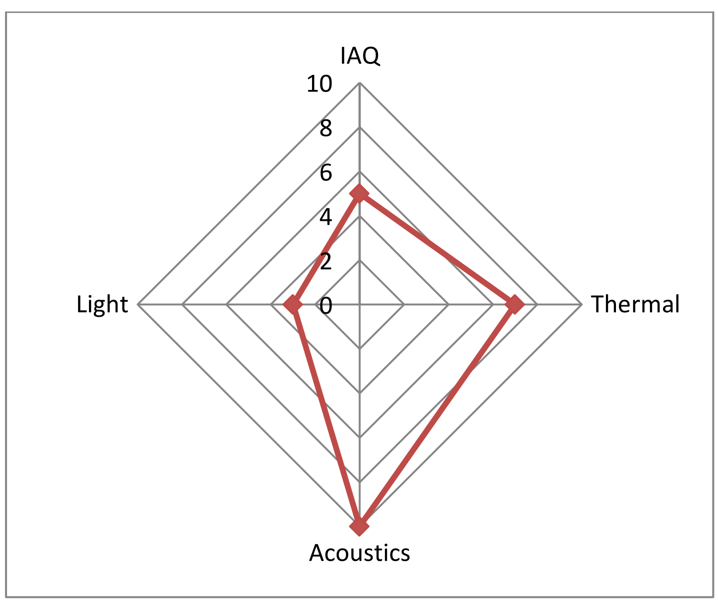


Figure 3.18: The IEQFs graphical representation inside space

3.6 Integrated Condition Assessment Model of the Space

The integrated condition of a space [C (SPi)] is composed of both the physical [PC (SPi)] and the environmental [EC (SPi] conditions inside a space. Those two conditions are represented in 36 possible scenarios for an integrated condition assessment of a space. The 36 possible scenarios will be clustered into six categories of condition classes. Self-organizing maps can be developed for clustering the physical and environmental conditions K-mean clustering technique. Computer software such as Minitab® can be used for this purpose.

3.7 Integrated Condition Assessment Model for the Building

The condition assessment of a building is the integration of the condition assessment of its spaces. Each space has an integrated condition assessment, calculated using the K-mean clustering technique. In addition, the relative weights of each space can be calculated from the space-ranking questionnaire using the analytical network process, as shown in equation 3.3.

$$\boldsymbol{C}\ (\boldsymbol{B}) = \sum_{\boldsymbol{i}=\boldsymbol{1}}^{\boldsymbol{n}} \boldsymbol{C}(\boldsymbol{SP_i}) \times \boldsymbol{W}.(\boldsymbol{SP_i})$$

Equation 3-6

where:

is the integrated condition of the whole building, and

is the weight of each space inside the building.

3.8 Summary

This chapter presented the proposed research methodology. The methodology involved the development of an integrated condition assessment model which considers the physical and the environmental aspects of buildings. It is based on managing a building according to its spaces; where space is the principal element to be evaluated, according to its internal physical elements as well as the quality of its indoor environment. To develop this model, the research methodology was divided into four main interrelated parts which were incorporated to produce a final integrated model for the entire building. The first part was to study the spaces interrelationships and determine their relative importance in a specific building type. Analytical Hierarchy Process (AHP) technique was used to assign those weights using the Eigenvector approach. The second part was to study the physical conditions of the building and its spaces. Several steps were followed in order to calculate this physical condition: identifying the physical categories; proposing a new asset hierarchy; setting a condition index scale; identifying the relative weight of each physical category and family using the Analytical Network Process (ANP); and finally applying the Multi Attribute Utility Theory (MAUT) to calculate the physical condition. The third part in this chapter was to study the environmental condition of the building and its spaces. Several steps were followed in order to calculate it: identifying the Indoor Environmental Quality factors (IEQFs); setting the benchmarks and measurement variables for each one using the codes and standards; identifying the relative weight of each IEQF in each space using the Analytical Network Process (ANP); and finally applying the Multi Attribute Utility Theory (MAUT) to calculate the environmental condition. The fourth and final part was to integrate the physical and the environmental conditions for each space using a clustering technique such as K-mean. Finally, the integrated condition assessment of the entire building was calculated using the MAUT. The model will assist facility managers and owner's organizations in the management of their buildings.

Chapter 4: Data Collection

4.1 Data collected for the Case Study

A case study of an educational building project was set up to be evaluated and assessed using the integrated condition assessment model for educational buildings. The objective is to use the model to assess a project in terms of its physical and environmental condition. The Integrated Engineering, Computer Science and Visual Arts Complex (EV Complex), located in Montreal, Canada and part of Concordia University SGW campus was selected for this research. The EV Complex a 17-storey, two-tower (linked on every floor) building that hosts research and graduate teaching labs, administrative offices, various studios, an art gallery, specialized amphitheatres and two Dean's Offices, as well as other unique facilities. The third floor of both towers has been selected for the research case study as it hosts different space types and is a good example for the proof of concept. The Architectural and Structural plans provided by Concordia University were in the form of 2D drawings saved in an Adobe Acrobat© format (pdf). Other mechanical, electrical and materials selection, installed units or building components were either assumed or set according to the field visit inspection. Figure 4.1 shows the building's 3rd floor; it is about 5100 square meters and hosts seven space types with their numbers and areas as shown in Table 4-1.

Table 4-1: Space types, and their total area

Space Type	Numbers of spaces	Total Floor Area (Sq. mt)
Classroom	5	500
Offices	102	1050
Laboratories	17	2000
Restrooms	6	150
Lunch rooms	2	1280
Lobby/Corridors	--	1000
Auditoriums	**1**	120
Total Area	**5100 (Sq. mt)**	

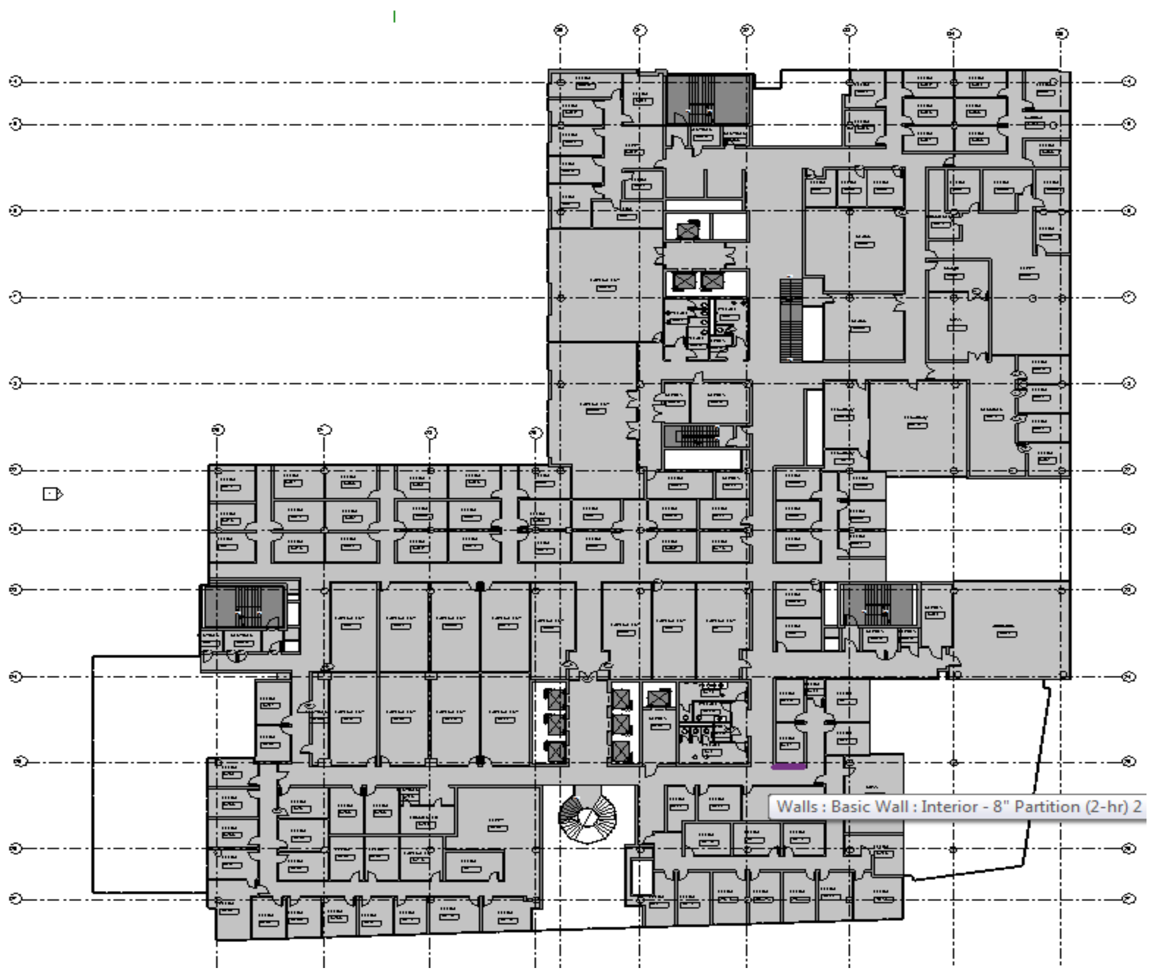


Figure 4.1: The 3rd floor of the Integrated Engineering, Computer Science and Visual Arts Complex

4.2 Research Surveys

The research survey passed through three steps to collect the data required for the proposed model: (1) unstructured interviews, (2) semi-structured interviews, and (3) structured interviews. These three types of data collection were conducted over two and half years of research.

4.2.1 Unstructured interviews

This type of interview was utilized at the very beginning of the research project and at the stage of identifying the problem statement. Interviews were undertaken with facilities manager, building asset management consultant, BIM coordinator, and finally condition assessment consultant. There was no pre-set order and no script in these interview; they were not limited to a particular protocol but more like a conversation. During these unstructured interviews, a considerable amount of information about current practices in the facilities management process, as well as current practices in the building condition assessment process was gathered. For example discussing the ASTM-E-2018-01 (Property Condition Assessments PCA) standard guidelines, and how they follow them in practice. These unstructured interviews were held five times with four different experts, as the condition assessment expert was interviewed twice.

4.2.2 Semi-structured interviews

This stage came after identifying the research problem statement and determining the research objective; it was carried out during the research methodology. Four experts were interviewed using a semi-structured interview format. Questions and checklists were prepared in advance. Additional information was obtained in a friendly and sociable discussion as part of the interview. Important attributes were considered or reconsidered after being neglected. The research scope was more clearly identified so that it would be in accord with the current practices of building condition assessment. Semi-structured interviews were held with four experts (a facility manager, a condition assessment consultant, a BIM specialist, and an asset management consultant).

4.2.3 Structured interviews

Structured interviews in the form of questionnaires were developed during the data collection process for the purpose of model development. Aspects such as the relative "weights" of the spaces inside the educational buildings, the IEQFs' relative "weight" inside each space, and the relative "weights" of each building category and their respective families inside each space type, were collected using a questionnaire that was discussed with each expert in an interview. This type of data collection is selected as the relationships between building physical components as well as buildings indoor environmental quality factors are not reported in literature and it is hypothesized that is highly dependent on the building type. Experts such as facilities managers, asset management consultants, and health and safety departments will be asked to provide the model with data from the facilities management point of view.

<u>Pilot Survey</u>

At the beginning, a pilot study was held with four experts (architects and facilities managers) in order to identify:

- If the questions were clear, understandable and measured what was intended to be measured;
- Any missing information;

- If the questionnaire was too long, and to determine approximately how long it should take to complete; and
- If all the questions were likely to be interpreted in a similar way by different respondents.

Questionnaire

After the pilot study, the questionnaires samples were revised as the duration of the questionnaire was too long and had to be adjusted to take only 15 to 18minutes to complete. Some unclear questions were clarified and new information was added to the top of each table, as well as some minor modifications. The Survey-questionnaire was conducted in a way to insure, as much as possible, its reliability, accuracy, and seriousness. Sixty two experts were contacted by e-mail and requested to participate in an interview, either by phone or in person. The response rate was about 35.5%, providing the research project 22 respondents, which is good as a proof of concept for the current study. The experts contacted were selected so that all aspects of the building could be covered. The model's parameters cover the physical and environmental aspects of educational buildings. Accordingly, facilities managers, architects, health and safety practitioners, condition assessment consultants, and asset management consultants were contacted. The 22 respondents include: nine facilities managers in educational buildings, six architects, four health and safety practitioners specializing in educational buildings and three asset management consultant. Figure 4.2 displays the questionnaire's experts' distribution. Thirteen experts were interviewed in person and eleven were interviewed by telephone to record their responses to the questionnaire. All of the experts were in

Canada; 15 in Quebec and seven located in Ontario. During the interviews, the questions were asked without any personal deviation and facial expression, to ensure an adequate level of consistency across all interviews.

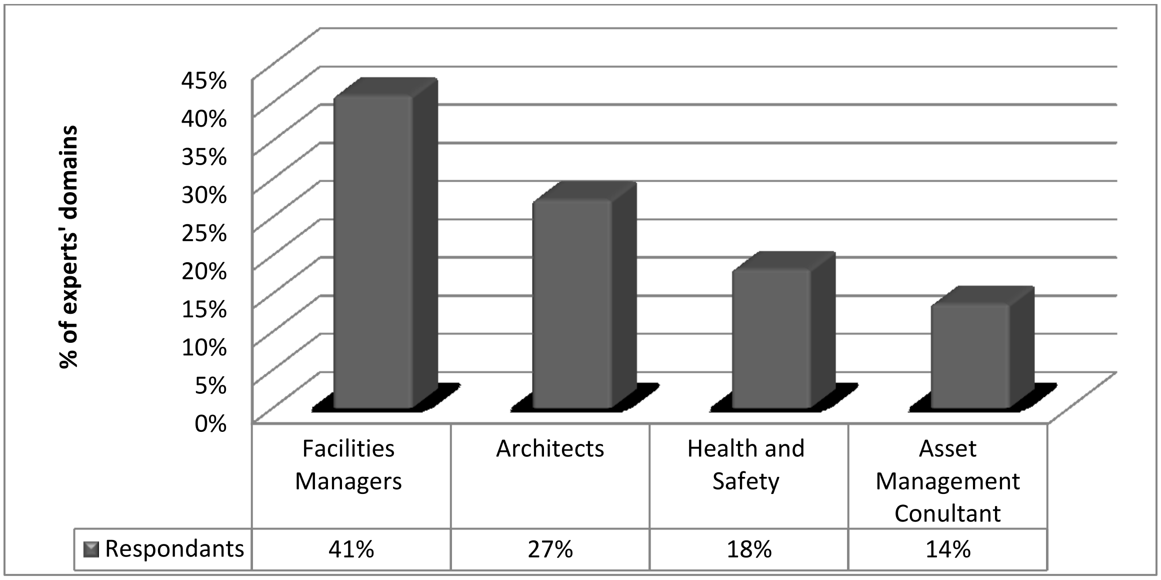


Figure 4.2: Categorization of survey respondents

4.3 List of the questionnaire sections

4.3.1 Space Priorities

In order to assess the condition of the entire building based on its internal spaces, it was necessary to examine the priorities of the building spaces inside this particular building type. As mentioned earlier, the case study was composed of seven spaces types, shown in Figure 4.3. In this methodology, individual spaces' levels of priority are defined as their relative importance from the facilities management point of view. Previously-identified spaces were weighted relatively, using the AHP technique and based on the responses gathered from a Canadian questionnaire described below.

This 'weighting' of space priorities questionnaire; a portion of which is given in Figure 4.4, was sent to 62 experts (facilities managers. consultants, and architects). Feedback was received from only 22, giving a response of 35.5%. The responses are answers to the question of "What is the importance of each space in contributing to building condition assessment?" The questionnaire asked participants to perform a pair-wise comparison for each space identified compared to others inside this particular building type. They were provided with a 9-point scale that ranges from "Equally important" to "Extremely important" proposed by Saaty (1994). The questionnaire form was designed to be very simple.

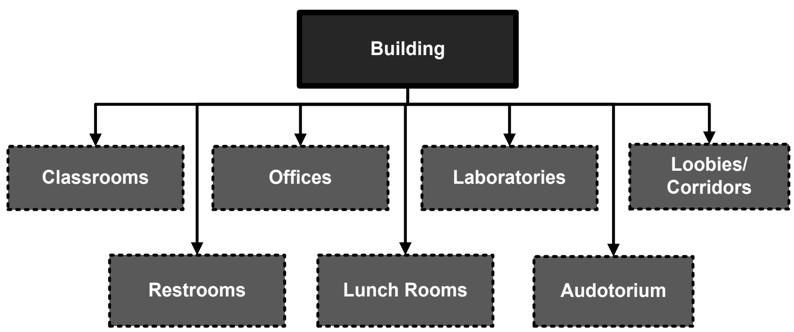


Figure 4.3: Selected space types for the case study

Spaces Priorities in an Educational Building											
Criterion (X)	**Degree of Importance or Preference**									**Criterion (Y)**	**Remarks**
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Classroom										**Laboratory**	
										Office	
										Lobby/corridor	
										Restroom	

										Lunch Room	
										Auditorium	

Figure 4.4: Sample question format of the space priorities questionnaire

4.3.2 Physical Assessment Data

As stated earlier, each building is composed of several spaces; each space is composed physically of four categories (Architectural, Mechanical, Electrical, and Structural). Those categories represent the first level in the physical condition hierarchy. Building categories are composed of sub-criteria "families" that represent the second level. The third level represents the "families’ types" which are sub-criteria of the family level (Level #2). The first and second levels will be used to develop the physical condition model of the study building. The structural category will not be incorporated in the condition assessment because it deals with safety issues. Instead, it will be considered as a filter in the pre-assessment process; the building structure will be assessed, if there are no symptoms that show that there are problems with the structure a further assessment will be conducted that considers all the other building categories in the assessment process. If any indications of structural problems are found, further structure investigation will be done (destructive or un-destructive tests).

4.3.3 Building category interdependencies

Due to the complexity of the building environment and the interconnections of its building categories, the deterioration of one building category might have an impact not only on itself but also on other categories. In other words, the interdependencies between the different categories of a building cause mutual influences between categories wherever this interaction exists. Building categories and their families are designed to function and operate both independently and in conjunction with others. This means that if any kind of failure occurs in one category or family it may or may not cause the failure of some others. For example, the leakage of a tube in the plumbing system inside a toilet may cause a problem to the adjacent walls or floors in this space or the adjacent ones. Being able to consider these interdependencies will provide facility managers with a better assessment of the relative weight of each category and family inside a building and to clearly identify which entities should have more influence on a building's condition. The AHP technique has the capability of addressing this relative importance of building categories, assuming that there is no mutual influence on deterioration between these categories. Saaty (1999) developed the Analytical Network Process "ANP" that provides a general framework to deal with decisions without making this assumption. The ANP is a useful tool that can predict the relative weight of all the different criteria on different levels inside the network, along with their surmised interactions; it considers the interdependencies as well as their strengths to wield influence in calculating the relative importance of each criterion inside a building. As stated earlier, the ANP is not considered to be an asset hierarchy but it deals with clusters. Those clusters form a complete network for the entire physical elements inside each space; a network of influences among the elements and clusters can then be clearly represented.

4.3.4 Calculating Relative Weights using ANP

ANP was used to calculate the relative weight of the building categories and families inside a building to assess its physical condition. To use the ANP, a network for the principal evaluated element inside the building, - the space, was established from the start. This network includes the three different categories (architectural, mechanical, and electrical) and their families, as shown in Figure 4.5. Twenty two experts (those who had responded to the weighting study) were asked to perform a pair-wise comparison for each category and family under each level in the form of a questionnaire survey. They were provided with a 9 point scale from "Equally Preferred" to "Extremely Preferred", as proposed by Saaty (1994).

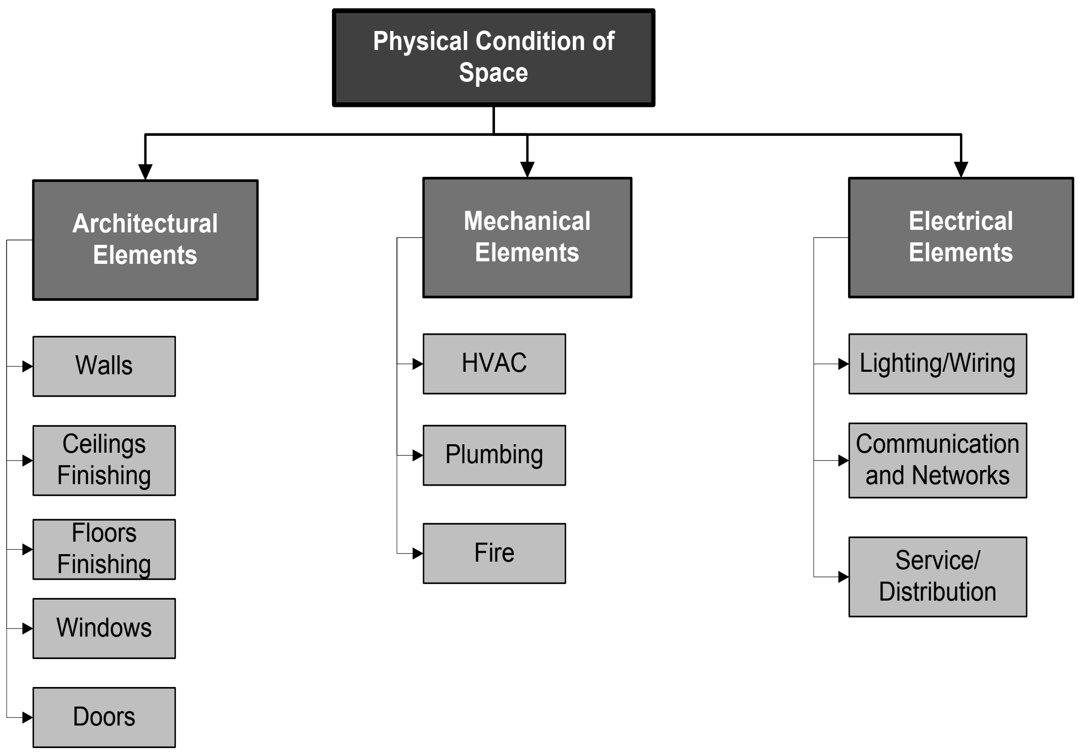


Figure 4.5: Selected physical categories and family types for the case study

The questionnaire was designed to be used in the ANP analysis and calculations. These experts were asked to provide a pair-wise comparison for the different categories in each different space type inside the building of the case study, as shown in Figure 4.6. They were also asked to provide a pair-wise comparison as to the degree of contribution of each family, when compared to the other, to physical condition in each space type. Figure

4.7 shows the pair-wise comparison of one of the spaces of the building case study; this was conducted for each of the different spaces inside the building.

Importance of each building category inside each space type											
Space Type	**Criterion (X)**	**Degree of Importance or Preference** (9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	**Criterion (Y)**
Classrooms	Architectural										Mechanical
											Electrical
Offices	Architectural										Mechanical
											Electrical
Laboratories	Architectural										Mechanical
											Electrical
Restrooms	Architectural										Mechanical
											Electrical
Cafeteria	Architectural										Mechanical
											Electrical
Lobby/ Corridors	Architectural										Mechanical
											Electrical
Auditoriums	Architectural										Mechanical
											Electrical

Figure 4.6: Sample question format of the physical categories pair-wise comparison questionnaire for every building space

A section about the interdependencies between the different categories was added to the questionnaire. It asks the experts to indicate the contribution of each criterion's deterioration on each other criterion's physical condition in each space type with respect to each category in the form of a pair-wise comparison. Figure 4.7shows a sample of what was developed for each space type.

With respect to each category, how much is the contribution of each criterion on physical condition when compared to each other criterion?											
Category	Criterion (X)	Degree of Importance or Preference									Criterion (Y)
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Architecture Elements	Walls										Ceilings
											Floors
											Windows
											Doors
Mechanical Elements	HVAC										Plumbing
											Fire System
Electrical Elements	Lighting/Wiring										Communication
											Services / Distribution

With respect to each category, what is the contribution of each category, compared to the others, to the overall condition?											
With respect to:	Criterion (X)	Degree of Importance or Preference									Criterion (Y)
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Architecture Category	Mechanical Category										Electrical Category
Mechanical Category	Architectural Category										Electrical Category
Electrical Category	Architecture Category										Mechanical Category

Figure 4.7: Sample Question format of the physical families' pair-wise comparison questionnaire for one space type

Assessing the physical conditions of spaces throughout an entire building requires knowing the relative weights of each of the building categories and families. With the direct inspection method, an inspector will be asked to give an overall grade for each component, with "0" representing a failure condition and "100" representing excellent condition. While with the distress survey method, an inspector will be expected to give a grade for the three general evaluation criteria (Damage-Performance-Appearance). It is important to assign weights to each of the evaluation criteria by asking the experts in a survey questionnaire in order to calculate the weighted average for all three so that they will be transformed into one number as an input for the condition assessment model . Experts were asked to complete a pair-wise comparison between the three criteria, and AHP was used to calculate the relative weight of each. A sample of the questionnaire sent to the experts is shown in Figure 4.8

4.3.5 Threshold Calculations for a Building's Physical Components

As mentioned earlier, each building is composed of four categories. The structural elements category will be used in the first step as a filter to help facility managers decide whether they should continue with further analysis of a building's condition assessment using the other three categories or not. Experts were asked to provide a critical threshold to indicate the value at which the deterioration of each structural element would be considered to have become dangerous for occupants' safety, in the format shown in Figure 4.8. From analysis, it was calculated that the minimum threshold of structural elements is 80%; this means that the preliminary assessment for the structural elements will be used to decide whether or not the analysis will go further.

The critical threshold of all the other physical elements (families) in the three building categories (Architectural, Mechanical, Electrical) will be also assigned using a survey questionnaire. The critical threshold will indicate a series problem if the condition of any component has dropped below, since it affects the occupants' safety. At that moment it raises a flag and should interrupt the process of condition assessment and it may stop the system unless the facility manager requested to proceed with the process.

Categories	Criteria	If affects Safety Check (√)	Minimum condition threshold On a scale of 0 to 100	Degree of contribution of component condition										
				Criterion (X)	**(9)Absolute**	**(7)V. Strong**	**(5) Strong**	**(3)Moderate**	**(1) Equal**	**(3)Moderate**	**(5) Strong**	**(7)V. Strong**	**(9)Absolute**	***Criterion (Y)***
Architectural Elements	Walls			*Performance*										*Damage*
														Appearance
	Ceilings finishing			*Performance*										*Damage*
														Appearance
	Floors finishing			*Performance*										*Damage*
														Appearance
	Windows			*Performance*										*Damage*
														Appearance
	Doors			*Performance*										*Damage*
														Appearance
Mechanical Elements	HVAC			*Performance*										*Damage*
														Appearance
	Plumbing			*Performance*										*Damage*
														Appearance
	Fire System			*Performance*										*Damage*
														Appearance
Electrical Elements	Lighting/ Wiring			*Performance*										*Damage*
														Appearance
	Comm. & Networks			*Performance*										*Damage*
														Appearance
	Service/ Distribution			*Performance*										*Damage*
														Appearance
Structural Elements														

Figure 4.8: Sample question format for assigning components critical threshold and the evaluation criteria pair-wise comparison

4.3.6 Environmental Assessment Data

The environmental assessment of the building in this research requires the assessment of the four IEQFs, as shown in Figure 4.9. These factors represent the first assessment level of the environmental conditions inside the building. Each IEQF is to be assessed according to its own sub-criteria. For example, Indoor Air Quality (IAQ) is to be assessed by measuring certain air contaminants such as carbon dioxide, carbon monoxide, etc. and then calculating the average grade of all the sub-criteria inside IAQ factor.

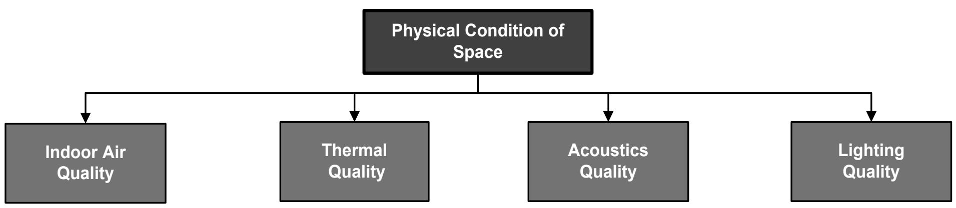


Figure 4.9: Selected IEQFs for the case study

4.3.7 IEQFs relative weights

Assessing the overall environmental quality of a space and thus of an entire building requires assessment of all the IEQFs inside this space. To calculate the overall assessment, it is important to know the contribution of each IEQF in the overall environmental condition of the space. Experts were asked through a survey questionnaire about the relative weights of each IEQF inside each space type, with the understanding that these relative levels of importance differ from one space type to another. A sample question format of the IEQFs pair-wise comparison questionnaire for all of the building spaces is shown in Figure 4.10.

Importance of each Indoor Environmental quality factor inside each space type											
Space Type	**Criterion (X)**	**Degree of Importance or Preference**									**Criterion (Y)**
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Classrooms	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality
Offices	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality
Laboratories	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality
Restrooms	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality
Cafeteria	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality
Lobby/ Corridors	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality
Auditoriums	Indoor Air Quality										Acoustics Quality
											Light Quality
											Thermal Quality

Figure 4.10: Sample Question format of the IEQFs pair-wise comparison questionnaire for all spaces

4.4 Summary

This chapter covered the methods of collecting data for both the model development and the case study. First, selecting the building for the case study and identifying the different properties, engineering plans and details, areas, and the hosted spaces. The second part in this chapter covered the research surveys held during the research project. Unstructured, semi-structured, and structured interviews were conducted. The responses from the questionnaires were analyzed and used to calculate the relative weights of space types inside a building, relative weight of physical elements (categories level and families' level) inside each space, relative weights of indoor environmental quality factors (IEQFs) inside each space, and of the physical elements evaluation criteria were all illustrated in this chapter. Preliminary statistical analysis were included showing a response rate of 35.5% for the sent questionnaires, the number of respondents and their profession and location in Canada.

Chapter 5: BIM Model Development and Implementation

5.1 Collected Data Analysis

5.1.1 Data Reliability

Several methods were applied to assess the reliability of the survey data collected. Cronbach's Alpha was used to measure the data's internal consistency and reliability (Cronbach 1951). Using a set of variables that measure a single, uni-dimensional latent aspect of individuals, it is considered as one of the most frequently applied methods to estimate reliability. This method utilizes the ratio of the true variance to the total variance of a measurement and a function of the number of observations, including variance and covariance. Cronbach's alpha can be calculated using more than one equation, but the one most commonly used is the following:

$$\boldsymbol{C\alpha = \frac{n}{n-1}\left(1 - \frac{\Sigma Vi}{\overline{V}}\right)} \qquad \text{Equation 5-1}$$

where:

n = Number of points;

Vi = Variance of scores for each point; and

$\overline{V}$ = Total variance of overall points.

The value of alpha (α) may lie between negative infinity and 1. Since only the positive values of α make sense, the alpha coefficient generally ranges in value from 0 to 1 and may be used to describe the reliability. Table 5-1 summarizes Cronbach's alpha values and their interpretations (Pison and Aelst 2004).

Table 5-1: Cronbach's Alpha and its Interpretation (Pison and Aelst 2004)

Cronbach's Alpha	Interpretation
0.9 and greater	High reliability
0.80 – 0.89	Good reliability
0.70 – 0.79	Acceptable reliability
0.65 – 0.69	Marginal reliability
0.50 – 0.64	Minimal reliability

However, a high alpha value does not imply that the measure is uni-dimensional. If, in addition to measuring internal consistency, it is desired to provide evidence that the scale in question is uni-dimensional, additional analyses can be performed. Mean, median, and mode values were compared, in addition to a verification of the standard deviation.

Table 5-2 to

Table 5-6 illustrates the mean median, mode and standard deviation, the trimmed mean of the data collected as well as Cronbach's alpha values. As indicated, in general the data proved to be acceptable and internally consistent when monitoring the Cronbach's alpha where it showed acceptable data ranges from minimal to highly reliable. Also, when comparing the mean to the trimmed mean (trimming upper and lower 10% of the data), there are no significant differences. The data was thus proved to be reliable, consistent, and robust and so appropriate to be used in the model development phase.

Table 5-2: Statistical analysis of space priorities and IEQF's relative weight data

Questionnaire	Elements	Mean	Trimmed Mean	Median	Mode	Standard Deviation	Crombach's Alpha
Space Priorities	Classroom	0.24	0.24	0.22	0.39	0.1354	**0.789**
	Laboratories	0.20	0.16	0.14	N/A	0.1521	
	Office	0.09	0.07	0.08	0.08	0.0763	
	Lobby/Corridors	0.10	0.09	0.09	0.13	0.0856	
	Restrooms	0.10	0.09	0.07	0.13	0.0882	
	Lunch Room	0.09	0.07	0.07	N/A	0.0956	
	Auditoriums	0.18	0.16	0.13	0.25	0.1531	
IEQFs relative weight in Classes	IAQ	0.29	0.29	0.25	0.22	0.1567	**0.430**
	Acoustics Quality	0.22	0.20	0.13	0.25	0.1931	
	Light Quality	0.18	0.18	0.13	0.13	0.1191	
	Thermal Quality	0.30	0.30	0.30	0.38	0.1965	
IEQFs relative weight in Labs	IAQ	0.42	0.43	0.43	0.58	0.1798	**0.925**
	Acoustics Quality	0.11	0.10	0.08	0.12	0.0756	
	Light Quality	0.19	0.18	0.17	0.19	0.1254	
	Thermal Quality	0.28	0.28	0.31	0.12	0.1553	
IEQFs relative weight in Offices	IAQ	0.26	0.25	0.19	0.25	0.1705	**0.425**
	Acoustics Quality	0.24	0.24	0.13	0.56	0.2018	
	Light Quality	0.22	0.22	0.20	0.13	0.1419	
	Thermal Quality	0.28	0.26	0.19	0.13	0.2091	
IEQFs relative weight in Restrooms	IAQ	0.59	0.60	0.61	0.70	0.1271	**0.988**
	Acoustics Quality	0.10	0.10	0.09	0.10	0.0557	
	Light Quality	0.14	0.13	0.12	0.10	0.0901	
	Thermal Quality	0.16	0.16	0.14	0.10	0.0894	

IEQFs relative weight in Lunchrooms	IAQ	0.34	0.35	0.32	0.54	0.1668	**0.738**
	Acoustics Quality	0.20	0.18	0.13	0.13	0.1923	
	Light Quality	0.16	0.15	0.17	0.13	0.1118	
	Thermal Quality	0.30	0.29	0.30	0.18	0.1788	
IEQFs relative weight in Lobs/corr.	IAQ	0.29	0.29	0.25	0.50	0.1699	**0.652**
	Acoustics Quality	0.20	0.19	0.17	0.17	0.1948	
	Light Quality	0.28	0.27	0.19	0.17	0.2108	
	Thermal Quality	0.23	0.22	0.17	0.17	0.1297	
IEQFs relative weight in Auditor.	IAQ	0.25	0.23	0.19	0.19	0.1780	**0.583**
	Acoustics Quality	0.32	0.31	0.25	0.13	0.2318	
	Light Quality	0.22	0.22	0.17	0.38	0.1662	
	Thermal Quality	0.21	0.19	0.14	0.13	0.1847	

Table 5-3: Statistical analysis of building categories' relative weight data

Questionnaire	**Elements**	**Mean**	**Trimmed Mean**	**Median**	**Mode**	**Standard Deviation**	**Crombach's Alpha**
Physical Cat. RW in Classes	Architectural	0.34	0.32	0.33	0.333	0.205260	**0.409**
	Mechanical	0.34	0.34	0.33	0.333	0.185864	
	Electrical	0.32	0.30	0.33	0.333	0.184520	
Physical Cat. RW in Labs	Architectural	0.15	0.11	0.09	0.090	0.180607	**0.939**
	Mechanical	0.46	0.47	0.46	0.454	0.117216	
	Electrical	0.39	0.41	0.44	0.454	0.098352	
Physical Cat. RW in Offices	Architectural	0.30	0.29	0.33	0.333	0.149093	**0.815**
	Mechanical	0.36	0.36	0.33	0.333	0.158458	
	Electrical	0.34	0.33	0.33	0.333	0.145894	
Physical Cat. RW in Restrooms	Architectural	0.30	0.29	0.20	0.333	0.252503	**0.833**
	Mechanical	0.52	0.52	0.51	0.333	0.289131	
	Electrical	0.18	0.17	0.13	0.333	0.15703	
Physical Cat. RW in Lunchrooms	Architectural	0.37	0.36	0.33	0.333	0.23257	**0.739**
	Mechanical	0.36	0.35	0.33	0.333	0.243426	

	Electrical	0.27	0.26	0.27	0.333	0.180916	
Physical Cat. RW in Lobs/Cor.	Architectural	0.51	0.51	0.60	0.714	0.255226	**0.851**
	Mechanical	0.20	0.18	0.14	0.142	0.133312	
	Electrical	0.30	0.27	0.21	0.142	0.214724	
Physical Cat. RW in Auditor.	Architectural	0.38	0.38	0.33	0.333	0.237658	**0.679**
	Mechanical	0.32	0.31	0.33	0.333	0.189538	
	Electrical	0.30	0.28	0.33	0.333	0.162851	

Table 5-4: Statistical analysis of architectural families' relative weight data

Questionnaire	Elements	Mean	Trimmed Mean	Median	Mode	Standard Deviation	Crombach's Alpha
Architectural Families. RW in Classes	Walls	0.16	0.16	0.15	0.272	0.082311	**0.487**
	Ceilings	0.19	0.18	0.18	0.272	0.169928	
	Floors	0.26	0.24	0.24	0.238	0.187619	
	Windows	0.26	0.24	0.26	0.090	0.183334	
	Doors	0.13	0.12	0.09	0.090	0.103673	
Architectural Families. RW in offices	Walls	0.15	0.15	0.12	0.272	0.083839	**0.648**
	Ceilings	0.18	0.16	0.13	0.027	0.174716	
	Floors	0.26	0.23	0.24	0.238	0.192621	
	Windows	0.27	0.26	0.28	0.405	0.186299	
	Doors	0.14	0.13	0.09	0.090	0.123837	
Architectural Families. RW in labs	Walls	0.16	0.16	0.15	0.157	0.081626	**0.753**
	Ceilings	0.21	0.20	0.20	0.272	0.184132	
	Floors	0.26	0.24	0.24	0.157	0.18887	
	Windows	0.25	0.23	0.26	0.090	0.189932	
	Doors	0.13	0.12	0.09	0.090	0.102269	
Architectural Families. RW in Restrooms	Walls	0.16	0.15	0.13	0.272	0.081863	**0.571**
	Ceilings	0.18	0.17	0.13	0.272	0.173764	
	Floors	0.29	0.28	0.26	0.238	0.211353	
	Windows	0.25	0.23	0.26	0.090	0.191815	
	Doors	0.12	0.12	0.09	0.090	0.101942	
Architectural Families. RW in Lunchrooms	Walls	0.15	0.15	0.12	0.272	0.082974	**0.650**
	Ceilings	0.18	0.17	0.13	0.272	0.171452	
	Floors	0.28	0.26	0.26	0.238	0.194883	
	Windows	0.24	0.23	0.26	0.090	0.19235	

	Doors	0.13	0.13	0.09	0.090	0.110433	
Architectural Families. RW in Lobby/Corridor	Walls	0.16	0.16	0.15	0.272	0.083649	**0.436**
	Ceilings	0.19	0.18	0.19	0.272	0.170217	
	Floors	0.27	0.25	0.24	0.238	0.187073	
	Windows	0.25	0.23	0.26	0.090	0.188365	
	Doors	0.13	0.12	0.09	0.090	0.105354	
Architectural Families. RW in Auditoriums	Walls	0.16	0.16	0.15	0.272	0.081637	**0.409**
	Ceilings	0.21	0.20	0.20	0.272	0.185578	
	Floors	0.26	0.24	0.24	0.238	0.188695	
	Windows	0.25	0.23	0.26	0.090	0.192067	
	Doors	0.13	0.12	0.09	0.090	0.102378	

Table 5-5: Statistical analysis of mechanical families' relative weight data

Questionnaire	Elements	Mean	Trimmed Mean	Median	Mode	Standard Deviation	Crombach's Alpha
Mechanical Families. RW in Classes	HVAC	0.35	0.35	0.33	0.333	0.205917	**0.589**
	Plumbing	0.23	0.20	0.14	0.333	0.23900	
	Fire system	0.41	0.41	0.33	0.333	0.269787	
Mechanical Families. RW in offices	HVAC	0.43	0.44	0.45	0.454	0.205195	**0.837**
	Plumbing	0.17	0.15	0.09	0.090	0.134288	
	Fire system	0.40	0.39	0.44	0.454	0.238591	
Mechanical Families. RW in labs	HVAC	0.34	0.33	0.33	0.333	0.234545	**0.316**
	Plumbing	0.25	0.25	0.28	0.333	0.138509	
	Fire system	0.41	0.40	0.33	0.333	0.245493	
Mechanical Families. RW in restrooms	HVAC	0.31	0.30	0.33	0.333	0.198167	**0.334**
	Plumbing	0.43	0.43	0.38	0.333	0.23763	
	Fire system	0.27	0.24	0.22	0.333	0.22539	
Mechanical Families. RW in Lunchrooms	HVAC	0.31	0.30	0.33	0.333	0.211196	**0.756**
	Plumbing	0.23	0.23	0.28	0.333	0.137572	
	Fire system	0.46	0.46	0.38	0.333	0.243657	
Mechanical Families. RW in lobbies/corri dors	HVAC	0.40	0.40	0.45	0.454	0.233289	**0.799**
	Plumbing	0.16	0.15	0.10	0.090	0.14742	
	Fire system	0.44	0.44	0.45	0.454	0.278383	
Mechanical Families. RW in Auditoriums	HVAC	0.46	0.46	0.46	0.454	0.259904	**0.874**
	Plumbing	0.12	0.11	0.09	0.090	0.092751	
	Fire system	0.42	0.41	0.45	0.454	0.265346	

Table 5-6: Statistical analysis of electrical families' relative weight data

Questionnaire	Elements	Mean	Trimmed Mean	Median	Mode	Standard Deviation	Crombach's Alpha
Electrical Families. RW in Classes	Lighting/Wiring	0.47	0.47	0.44	0.428	0.196401	**0.844**
	Communication	0.21	0.19	0.14	0.142	0.160015	
	Service/distribution	0.32	0.31	0.33	0.428	0.152981	
Electrical Families. RW in offices	Lighting/Wiring	0.42	0.41	0.43	0.333	0.167821	**0.608**
	Communication	0.28	0.26	0.24	0.333	0.21696	
	Service/distribution	0.30	0.31	0.33	0.333	0.149008	
Electrical Families. RW in labs	Lighting/Wiring	0.45	0.44	0.43	0.333	0.189915	**0.839**
	Communication	0.19	0.19	0.13	0.333	0.129718	
	Service/distribution	0.36	0.35	0.33	0.333	0.187898	
Electrical Families. RW in restrooms	Lighting/Wiring	0.57	0.57	0.56	0.333	0.188817	**0.967**
	Communication	0.20	0.19	0.14	0.333	0.122868	
	Service/distribution	0.23	0.23	0.18	0.333	0.148041	
Electrical Families. RW in Lunchrooms	Lighting/Wiring	0.54	0.54	0.45	0.454	0.156485	**0.956**
	Communication	0.18	0.17	0.14	0.090	0.108088	
	Service/distribution	0.28	0.28	0.27	0.454	0.153943	
Electrical Families. RW in lobbies/corridors	Lighting/Wiring	0.52	0.52	0.45	0.333	0.208377	**0.911**
	Communication	0.23	0.22	0.18	0.090	0.146634	
	Service/distribution	0.26	0.26	0.28	0.333	0.149971	
Electrical Families. RW in Auditoriums	Lighting/Wiring	0.55	0.56	0.60	0.6	0.206419	**0.949**
	Communication	0.23	0.23	0.20	0.2	0.128331	
	Service/distribution	0.22	0.21	0.20	0.2	0.120804	

5.1.2 Spaces' relative weights Calculations Process

The relative weights of different spaces inside building are determined using the Eigen-vector technique. It is summarized in and illustrated in Figure 5.1. The "Classroom" space type had the highest relative weight among other spaces inside this particular building type, while the "office" type had the lowest. The relative weights assigned using AHP from the survey questionnaire are given according to the space type, while in the research methodology the number of spaces and the surface area are also contributing factors affecting the relative weight of each space inside the entire building.

Figure 5.2 shows the relative weights of each space type inside the case study building. As shown the relative weights are completely different than those calculated using the Eigen vector approach using the AHP from the data of the survey; this is because the total areas of space types are different and not equal. For example the relative weight the “laboratories” space type became the highest after it was the second highest one due to the large number of laboratories inside the floor as well as the large total surface area covered by this particular space type. Another example is the auditorium which was the third highest relative weight with a value of 18%, felt down to be the second lowest with a value of 3%,; this is because there is only one auditorium in the floor with no large relatively area compared to the total are of the floor. Table 5-7 summarizes the process of calculating the relative weight of each space type per unit area (sq. mt). For example, office space with area of 10 sq. m will be 10 X 0.0002689549 = 0.002689549, which represents about 0.2% of the entire floor. This percentage is relatively low due to the large number of spaces as well as the representation of this small area compared to the area of the entire floor, which is 5100 sq. m. Figure 5.3 shows the relative weights of space types per square meter.

As a conclusion from the previous survey questionnaire, it was proved that each space type has its own relative weight. This weight depends on the function of the space and importance of the task held inside in a particular building. As indicated that the classroom space type which is the main element that hosts most of the education processes had the highest relative weight followed by the laboratories. The office space type relative weight was the least among all the space types; and it can be concluded that all other space types are occupied by the students and teachers while the offices the only spaces that are occupied by the teachers only.

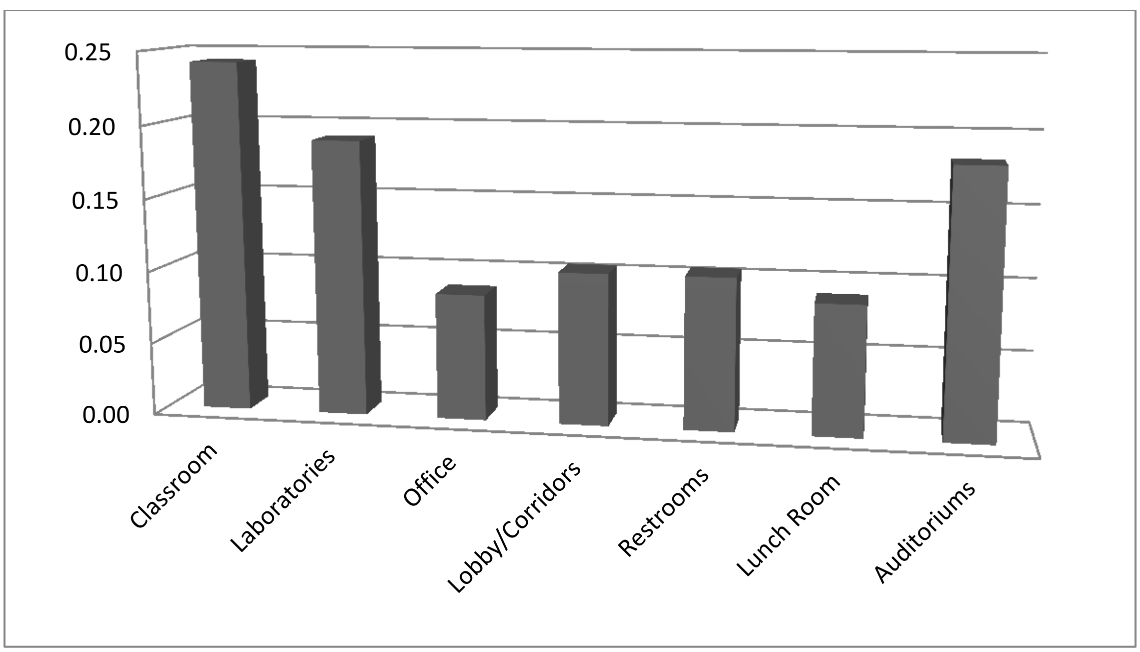


Figure 5.1: Relative weights of spaces determined using the Eigen-vector technique

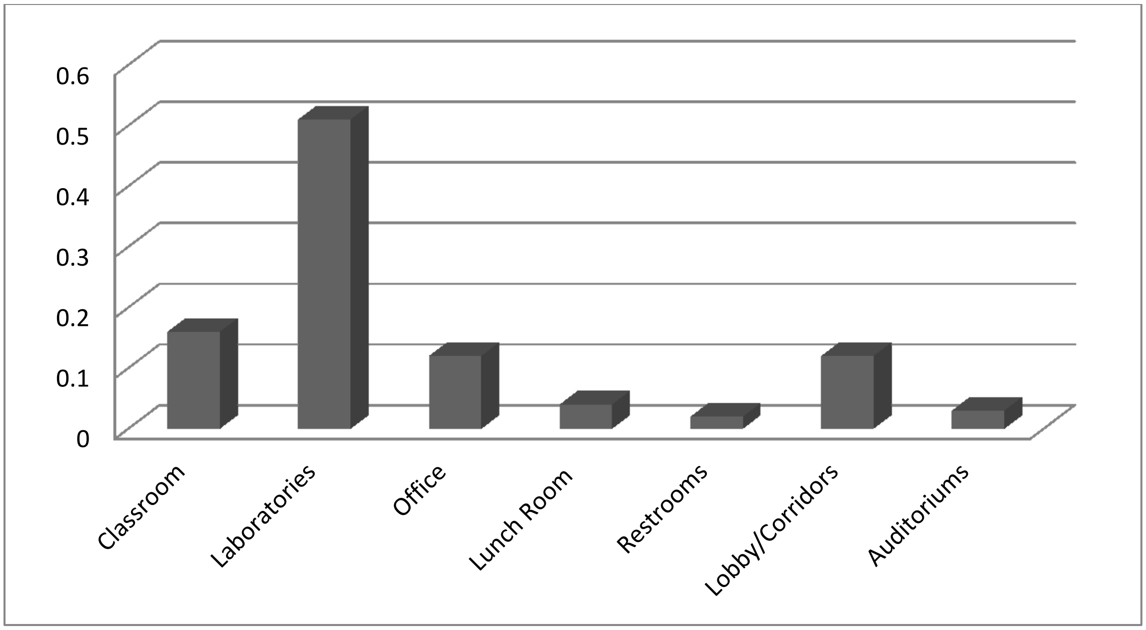


Figure 5.2: Relative weights of spaces types for the case study

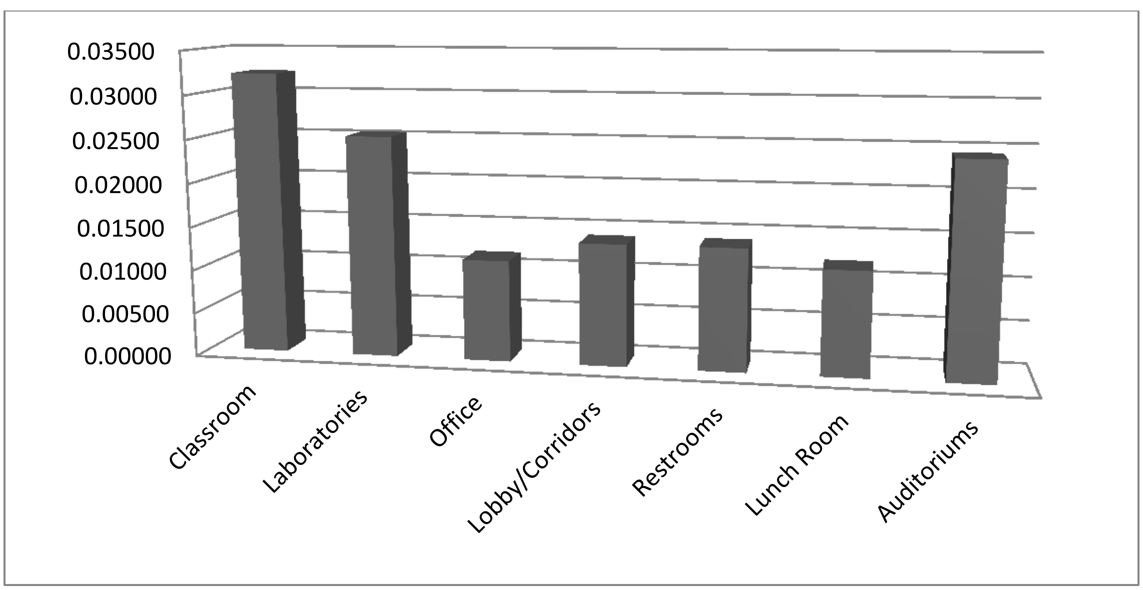


Figure 5.3: Relative weights of space types per square meter

Table 5-7: The process of calculating the relative weight of each space type per unit area (sq. m)

Space Type	$RW\ (QSPt_u)$	$A\ (SPt_u)$	$RW\ (QSPt_u)$ X $A\ (SPt_u)$	$RW\ (QSPt_u)$ X $A\ (SPt_u)/\sum_{u=1}^{z} RW\ (QSPt_u) X\ A\ (SPt_u)$	$RW\ (SPt_u)/m^2$ **(X100)**
Classroom	0.24	500	120.99	0.16	0.03232
Laboratories	0.19	2000	379.98	0.51	0.02537
Office	0.09	1050	91.22	0.12	0.01160
Lunch Room	0.10	280	29.25	0.04	0.01395
Restrooms	0.10	150	15.71	0.02	0.01399
Lobby/Corridors	0.09	1000	89.71	0.12	0.01198
Auditoriums	0.18	120	21.87	0.03	0.02434
Total	1.00	5100.00	748.73	1.00	

5.1.3 Physical Elements relative weights Calculation Process

Super Decisions software, developed by the Creative Decisions Foundation, implemented the ANP (analytic network process) that was used to calculate the relative weights of each building category and family inside each space type. Figure 5.4 shows the physical categories clusters for the ANP analysis. As indicated, the three building categories belong to the "Building Categories" cluster, while the building families are distributed on three different clusters; families that belong to a category are grouped in one cluster.

Figure 5.5 shows the process of data input in the software required to calculate the relative weights of each physical component. The process was repeated for each space type times in order to calculate the weights of each family and category inside each space type. The part of the mutual interrelationship between the categories is addressed in this analysis using the super-matrix approach in the ANP technique.

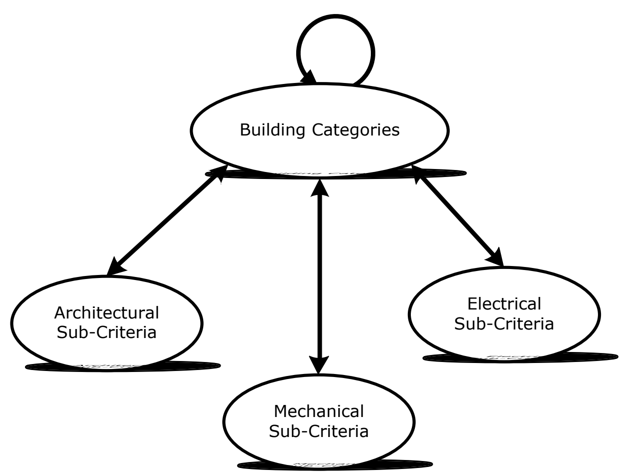


Figure 5.4 Physical categories and families clusters for the ANP analysis

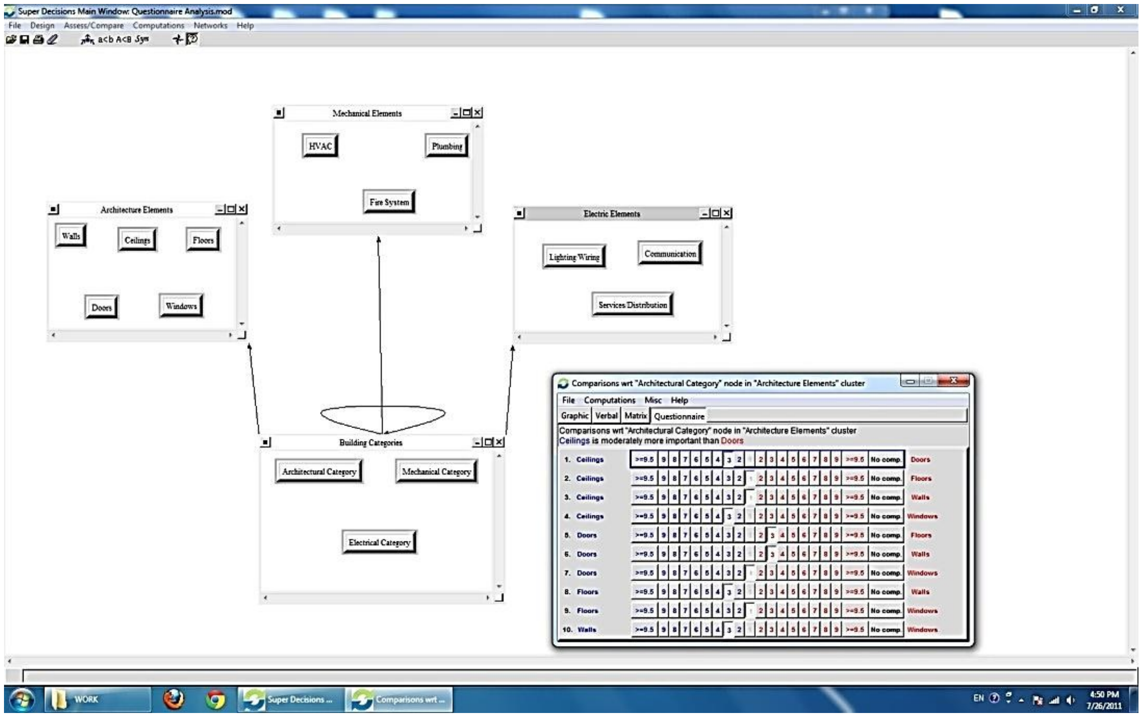


Figure 5.5 Snap Shot from the Super Decision software used for the ANP

Table 5-8 summarizes the relative weight values for all the categories and families in all the space types inside the studied building. As shown and according to the responses of the experts, the relative weights varies from a space to another that proves the assumption of the effect of the nature of the space type on the importances of all families that are inside it. There is no one single expert who neglected the space type and reported that a system is equally important in all spaces types inside a building. As represented, the relative weight of the mechanical system in a space such as a "laboratory" is higher than if it was in a "class", this can be interpreted as it is so critical to have any problems in the mechanical system in a laboratory that is hosting activities such as chemical reactions that causes poisoning gases, steams, smokes, etc.

The decomposed weights for all the families are also calculated; adjusted according to the weight of their categories and the spaces that host them. This adjustment is calculated by multiplying the space type weight by the category weight by the family weight. Table 5-8 and Figure 5.6 show the decomposed weight of each family in a space with the percentage of condition contribution of each calculated using equation 5-2.

$$\text{Family decomposed weight in each space} = W.(SP_i) \times W.Cat_j \times W.fam_n$$

Equation 5-2

Table 5-8: Summary of the relative weight values for all categories and families in all the space types inside the building

Space type	Weight	Category	Weight	Family	Weight	**Decomposed Weight of families**
Classrooms	**0.24**	Architectural	**0.34**	Walls	0.16	0.013056
				Ceilings	0.19	0.015504
				Floors	0.26	0.021216
				Windows	0.26	0.021216
				Doors	0.13	0.010608
		Mechanical	**0.34**	HVAC	0.35	0.02856
				Plumbing	0.23	0.018768
				Fire system	0.41	0.033456
		Electrical	**0.32**	Lighting/wiring	0.47	0.036096
				Communication	0.21	0.016128
				Services/Distribution	0.32	0.024576
Laboratories	**0.19**	Architectural	**0.15**	Walls	0.16	0.00456
				Ceilings	0.21	0.005985

				Floors	0.26	0.00741
				Windows	0.25	0.007125
				Doors	0.13	0.003705
		Mechanical	**0.46**	HVAC	0.34	0.029716
				Plumbing	0.25	0.02185
				Fire system	0.41	0.035834
		Electrical	**0.39**	Lighting/wiring	0.45	0.033345
				Communication	0.19	0.014079
				Services/Distribution	0.36	0.026676
Office	**0.09**	Architectural	**0.30**	Walls	0.15	0.00405
				Ceilings	0.18	0.00486
				Floors	0.26	0.00702
				Windows	0.27	0.00729
				Doors	0.14	0.00378
		Mechanical	**0.36**	HVAC	0.43	0.013932
				Plumbing	0.17	0.005508
				Fire system	0.40	0.01296
		Electrical	**0.34**	Lighting/wiring	0.42	0.012852
				Communication	0.28	0.008568
				Services/Distribution	0.30	0.00918
Lobby/Corridors	**0.10**	Architectural	**0.51**	Walls	0.16	0.008
				Ceilings	0.19	0.0095
				Floors	0.27	0.0135
				Windows	0.25	0.0125
				Doors	0.13	0.0065
		Mechanical	**0.20**	HVAC	0.40	0.008
				Plumbing	0.16	0.0032
				Fire system	0.44	0.0088

		Electrical	**0.30**	Lighting/wiring	0.52	0.0156
				Communication	0.23	0.0069
				Services/Distribution	0.26	0.0078
Restrooms	**0.10**	Architectural	**0.30**	Walls	0.16	0.0048
				Ceilings	0.18	0.0054
				Floors	0.29	0.0087
				Windows	0.25	0.0075
				Doors	0.12	0.0036
		Mechanical	**0.52**	HVAC	0.31	0.01612
				Plumbing	0.43	0.02236
				Fire system	0.27	0.01404
		Electrical	**0.18**	Lighting/wiring	0.57	0.01026
				Communication	0.20	0.0036
				Services/Distribution	0.23	0.00414
Lunch Room	**0.09**	Architectural	**0.37**	Walls	0.15	0.004995
				Ceilings	0.18	0.005994
				Floors	0.28	0.009324
				Windows	0.24	0.007992
				Doors	0.13	0.004329
		Mechanical	**0.36**	HVAC	0.31	0.010044
				Plumbing	0.23	0.007452
				Fire system	0.46	0.014904
		Electrical	**0.27**	Lighting/wiring	0.54	0.013122
				Communication	0.18	0.004374
				Services/Distribution	0.28	0.006804
Auditoriums	**0.18**	Architectural	**0.38**	Walls	0.16	0.010944
				Ceilings	0.21	0.014364
				Floors	0.26	0.017784

				Windows	0.25	0.0171
				Doors	0.13	0.008892
		Mechanical	**0.32**	HVAC	0.46	0.026496
				Plumbing	0.12	0.006912
				Fire system	0.42	0.024192
		Electrical	**0.30**	Lighting/wiring	0.55	0.0297
				Communication	0.23	0.01242
				Services/Distribution	0.22	0.01188

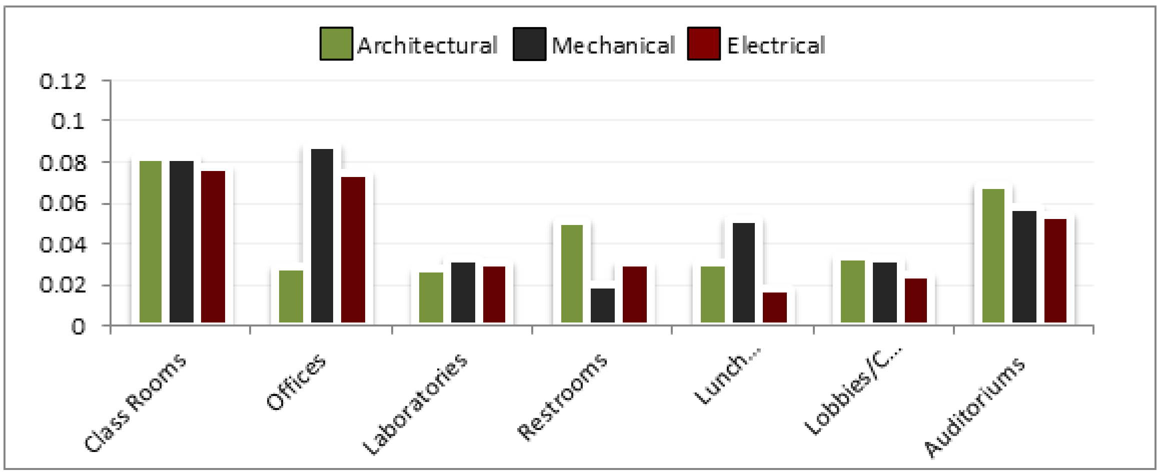


Figure 5.6 The decomposed weight of building category inside all space types

The aim of the analysis in Table 5-8 and types is to clarify how the importance of each category and family in each space type is reflected on the overall physical condition of the building. As shown the effect of the high relative weight of a space type such as the "classroom" is significant, it results to a high relative weight for all the decomposed relative weights of the categories and families inside it.

Figure 5.7 shows a comparison between the building's physical categories inside the building spaces. This figure reveals that the relative weights differ from one space type to another inside the building according to the function of each space type and the corresponding level of importance of each category.

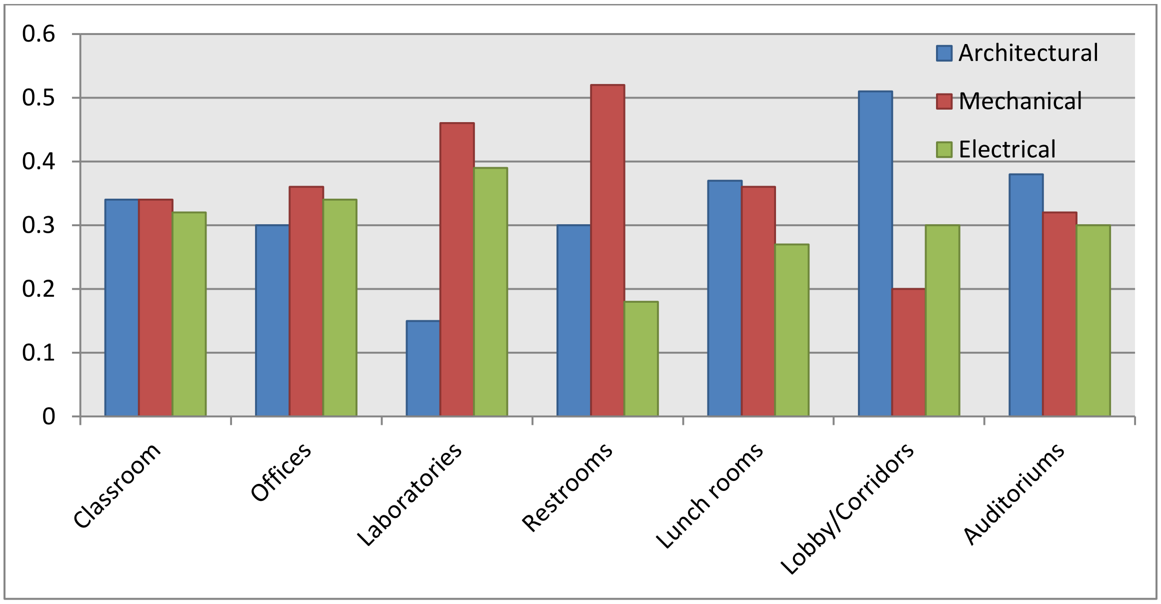


Figure 5.7 Comparison of building's physical categories' relative weights inside spaces

Table 5-9: Relative weight of each family inside the space types

	Class.	Off.	Lab.	Restrooms	Lunch rooms	Lobby/ Corridors	Aud.
Walls	0.0544	0.045	0.024	0.048	0.0555	0.08	0.0608
Ceilings	0.0646	0.054	0.0315	0.054	0.0666	0.095	0.0798
Floors	0.0884	0.078	0.039	0.087	0.1036	0.135	0.0988
Windows	0.0884	0.081	0.0375	0.075	0.0888	0.125	0.095
Doors	0.0442	0.042	0.0195	0.036	0.0481	0.065	0.0494
HVAC	0.119	0.1548	0.1564	0.1612	0.1116	0.08	0.1472
Plumbing	0.0782	0.0612	0.115	0.2236	0.0828	0.032	0.0384
Fire system	0.1394	0.144	0.1886	0.1404	0.1656	0.088	0.1344
Lighting/wiring	0.1504	0.1428	0.1755	0.1026	0.1458	0.156	0.165
Communication	0.0672	0.0952	0.0741	0.036	0.0486	0.069	0.069
Services/Distribution	0.1024	0.102	0.1404	0.0414	0.0756	0.078	0.066

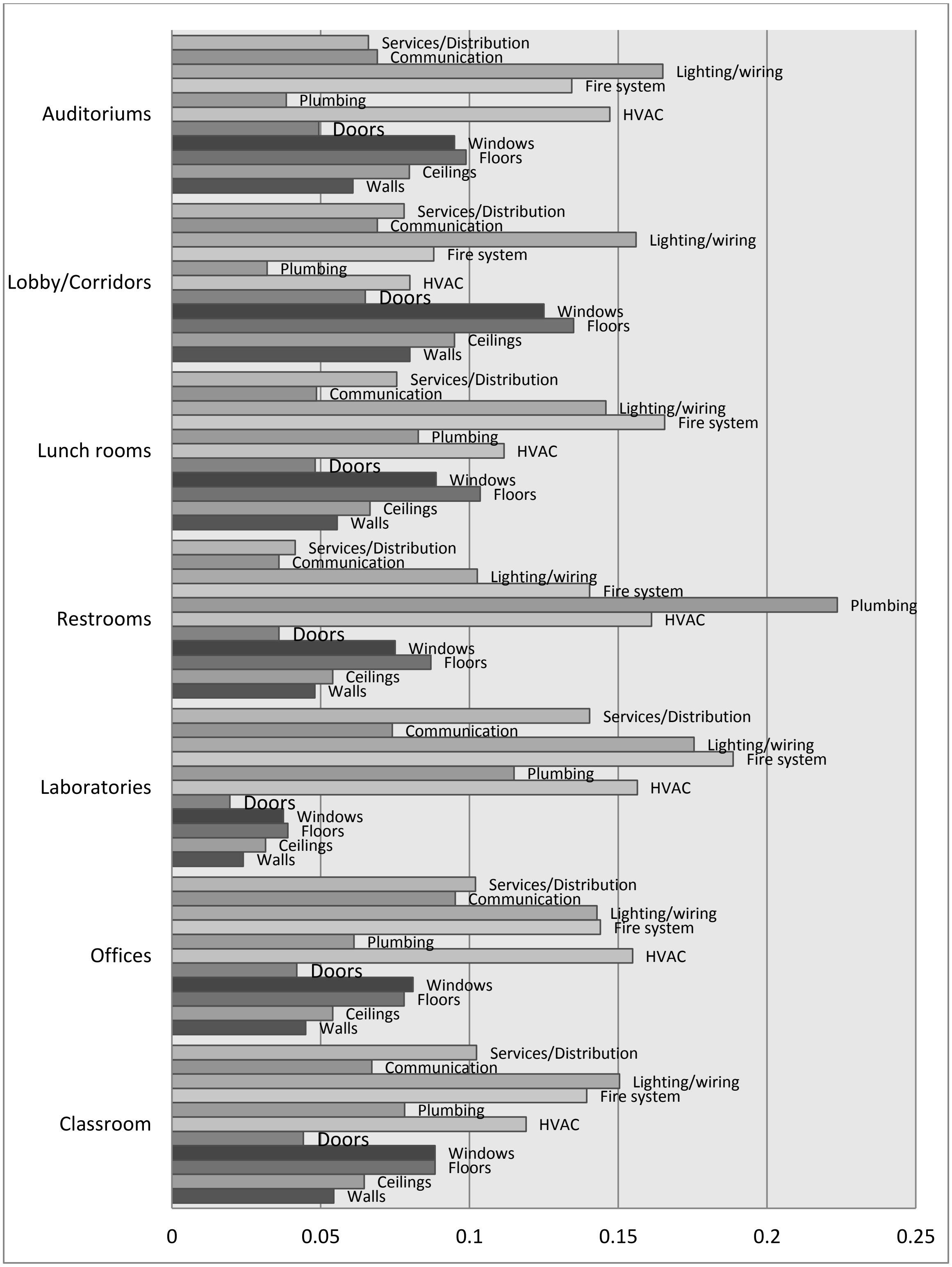


Figure 5.8 Comparison of all building's families' relative weights inside building's spaces

5.1.4 Evaluation criteria -- relative weight calculations

The relative weight of each physical component evaluation criterion was calculated using the AHP. Figure 5.9 shows a comparison of their relative weights which was different according to the component type. Some component has the "***Performance"*** with the highest weight of 78%, some others have the "***Appearance"*** with the highest weight of 54% and some others have the "***Damage"*** with the highest weight of 54%.

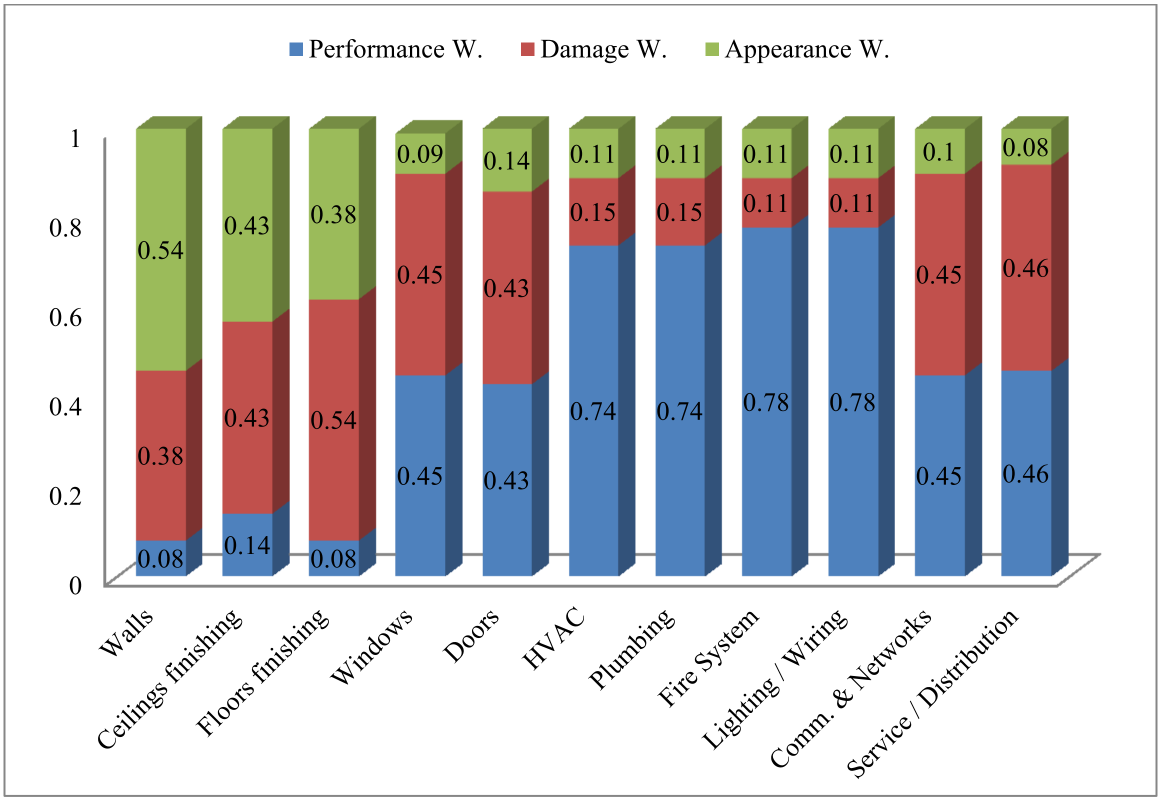


Figure 5.9 Comparison of components' evaluation criteria's relative weights

It is observed that the appearance of the architectural elements was higher than those of the electrical and mechanical due to the function of the architectural elements which are mainly used as the final finish covering a lot of pipes, connections, cables etc. and their appearance is an important role. There is an exception here which is the “window” which is considered as an architectural element however its performance of sealing the building from the outer climate is the most important. On the other hand it is observed that the performances of the mechanical elements are the most important when compared to the other criteria, because it is mostly hidden behind the walls and ceilings while the performance is the most important in which it controls the indoor temperature, humidity and fresh air.

5.1.5 Building’s physical components’ condition threshold calculations

According to the experts contacted, it was found that the fire-prevention system, Structural System, and windows are the elements whose deterioration addresses safety issues towards building’s occupants more than the other components and so are not allowed to have condition ratings less than 100%, 90%, and 70%, respectively. On the other hand other building families were calculated to be about 50% for all of them This means that if any of those elements have a condition that is below its threshold level, the process of the condition assessment will continue; however, a critical alarm will occur, indicating a critical problem in that specific element. Those thresholds are calculated from the data collected via a questionnaire interview with experts. “Mean”, “median”, and “mode” were calculated and it was found that the “mode” was the best to describe the final threshold as most of the experts agreed about specific values, for example about 95% of the experts agreed that the threshold of the fire-system is to be 100% and the others agreed to be about 90% thus it was considered to be %100. This will help facility managers to make decisions and to put repair, rehabilitation, or replacement plans into action. Table 5-10 shows the critical thresholds of these safety-related physical elements.

Table 5-10: Critical thresholds

Physical Element	Critical Threshold
Structural Elements	90%
Walls	50%
Ceilings finishing	50%
Floors finishing	50%
Windows	70%
Doors	50%
HVAC	50%
Plumbing	50%
Fire System	100%
Lighting / Wiring	50%
Comm. & Networks	50%
Service / Distribution	50%

5.1.6 IEQFs' relative weights' calculations process

The AHP was used to calculate the relative weights of these factors. Table 5-11 shows the relative weight of each IEQF inside each space type and it is illustrated in Figure 5.10. Results proved to be logic and are easily comprehended; for example the Acoustics quality in an auditorium was proven to be the most important due to the criticality and complexity of the acoustics design in an auditorium. On the other hand "Restrooms", "Laboratories", and "Lunchrooms" had the IAQ as the most important and have the highest relative weight; those spaces have functions held inside that may produce gases and smokes where it is required to give much attention to the quality of indoor air more than the other IEQFs. Finally, Acoustics in a "restrooms" or a "laboratory" was the least due to the low importance of controlling the background noise in those spaces.

Table 5-11: Relative weight of each IEQF inside space types

	Classroom	Offices	Laboratories	Restrooms	Lunch rooms	Lobby/ Corridors	Auditoriums
IAQ	0.295	0.259	0.422	0.587	0.344	0.290	0.248
Acoustics Quality	0.217	0.242	0.105	0.104	0.196	0.204	0.318
Light Quality	0.183	0.222	0.191	0.144	0.161	0.281	0.224
Thermal Quality	0.305	0.277	0.282	0.164	0.298	0.225	0.210

According to the previous results calculated using the data collected from the survey questionnaires, it is observed that the relative weights of each IEQF is different from a space type to another proving the assumption of the different importance of each factor in different space type. As represented the importance of IAQ in a space such as the "restroom" is much higher than if it was considered in a "corridor".

5.1.7 Development of IEQFs utility curves

Standards, codes, and previous models were used to develop the different indoor environmental quality factors' utility curves. Relations between the field measurements and the utility values were formulated to be used in the MAUT. A preference utility value of "1.0" indicates the highest preference score, and a preference utility value of "0" reflects the lowest. The following sub-sections show how these standards were used to develop utility curves for factors and/or sub-criteria.

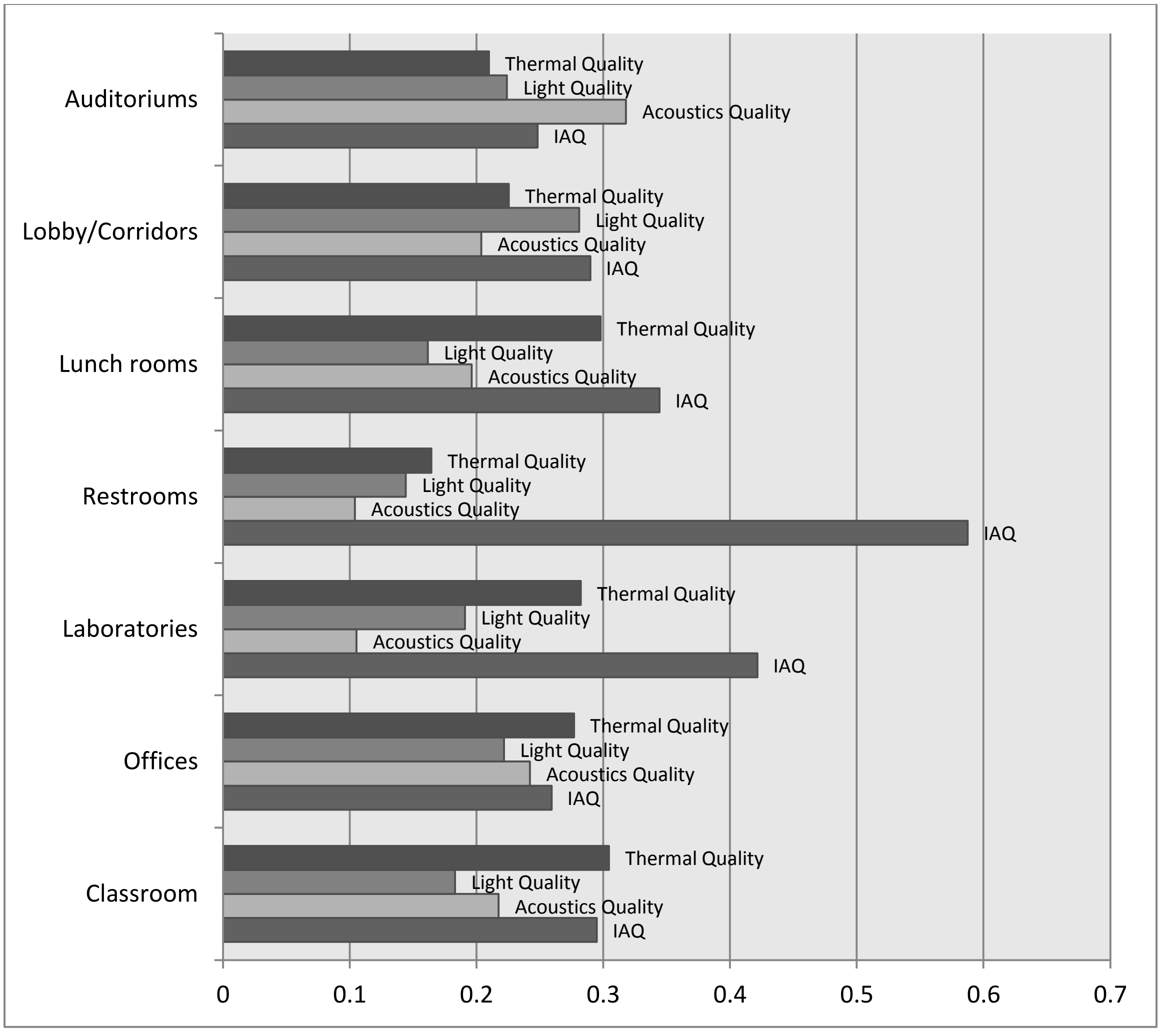


Figure 5.10 Comparison of the building's IEQFs' relative weights inside the building spaces

i. <u>Indoor Air Quality</u>

Indoor air quality has become a major global issue due to its impact on human health and productivity. As stated earlier, many indoor air pollutants are the result of problems in air intake, building design, building materials and finishing, etc. The three most common indoor air pollutants are carbon dioxide (CO_2), carbon monoxide (CO), and ozone (O_3), and so these three are the pollutants measured and assessed for indoor air quality inside the selected building.

Carbon Dioxide (CO_2) is considered to be an indicator for the proper ventilation of indoor air. It is a normal result of human respiration -- taking in oxygen (O_2) and giving out CO_2. It is also a result of combustion and other processes outside buildings. High indoor CO_2 indicates that there is poor air exchange and a lack in the fresh air supply; thus indicating a problem with the HVAC system. At levels above 1000 parts per million (ppm), occupants experience a lower level of satisfaction, perceive poor air quality, and show increased physical symptoms (Charles et al.,2005). The normal outdoor levels are in the range of 350-450 (ppm), while the acceptable level of CO2 is less than 600 (ppm), according to ASHRAE 62 (which recommends not to exceed 700 (ppm)). According to the Charles et al. (2005), more people were satisfied than were dissatisfied when CO2 concentrations were less than 650 ppm, as illustrated in Figure 5.11. These results indicate that there may be some benefits to exceeding ASHRAE's ventilation recommendations. ASHARE 62.1 (2004), states that the Canadian guidelines for the maximum CO_2 inside a building over an 8-hour work period should not exceed 3500 (ppm). These standards, guidelines, and the associated research have helped to establish the relation between occupants' comfort and CO_2 concentration inside buildings. Table 5-12 summarizes the previous results and assigns a utility value to the different concentrations. Figure 5.11 shows the percentage of satisfied dissatisfied occupants with the ventilation at levels of CO_2 concentration from 450 to 825 ppm.

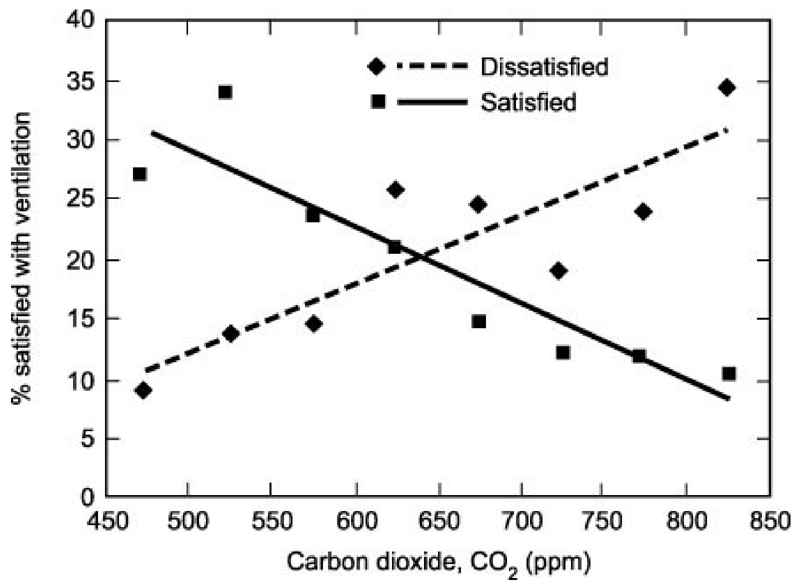


Figure 5.11 Comparison of the percentages of occupants indicating their satisfaction or dissatisfaction with the ventilation at each level of CO_2 concentration

Table 5-12: Utility Values' Equivalent to Carbon Dioxide concentrations

CO_2 levels (ppm)	**Description**	**Utility Value**
350-500	Outdoor concentration	1.00
600	Acceptable level	0.85
700	Some complaints	0.75
1000	Recommended maximum	0.50
3500	Canadian regulation upper limit	0.00

Figure 5.12 shows the utility curve developed using the values in the previous table which draw the relation between the utility value and the CO_2 levels inside buildings.

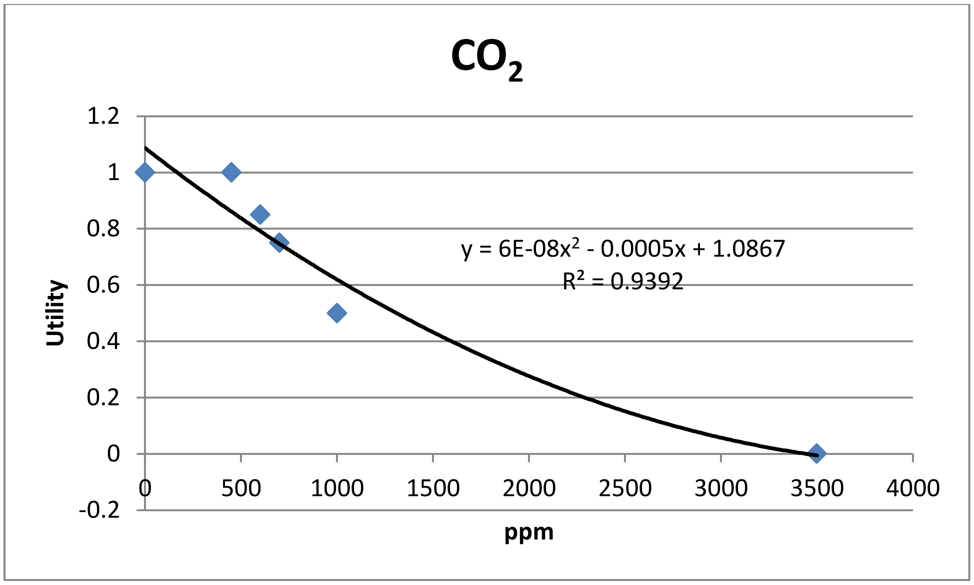


Figure 5.12 Carbon dioxide utility curves

Carbon Monoxide (CO) is an odorless, colorless, tasteless and very poisonous gas. It inhibits blood's ability to carry oxygen, and thus can quickly affect vital organs such as the brain and heart. Excessive exposure to CO can lead to death; according to the U.S Consumer Product Safety Commission, 170 people in the United States die every year from carbon monoxide produced by non-automotive consumer products. Guidelines, codes, and standards contain different regulations for the maximum allowed carbon monoxide exposure. According to OSHA, the maximum workplace exposure allowed for one hour is 35 ppm, and over an eight-hour period the maximum average exposure should be not more than 9 ppm. The Health Canada (1994) recommended national ambient air quality objectives for CO are summarized in Table 5-13.

Table 5-13: Health Canada (1994) recommended national ambient air quality objectives for carbon monoxide

Recommended National Ambient Air Quality Objectives for Carbon Monoxide, ppm (mg/m^3) [a]			
Averaging Times	**Maximum Desirable Level**	**Maximum Acceptable Level**	**Maximum Tolerable Level**
1 hour	13 (15)	30 (35)	n/a
8 hours[b]	5 (b)	13 (15)	17.4 (20)
[a] 1 ppm = 1.146 mg CO/m^3 [b] rolling average			

The utility curve used here to convert the value of the amount of CO concentration to a utility value is based on the Canadian regulations from Health Canada. Figure 5.13 shows the utility curve developed using the values in Table 5-14, which draw the relation between the utility value and the CO levels inside buildings.

Table 5-14: Utility Values Equivalent to Carbon monoxide concentrations

CO levels (ppm)	**Description**	**Utility Value**
0-2	Best Case	1.00
5	Maximum Desirable Level	0.5
13	Maximum Acceptable Level	0.0

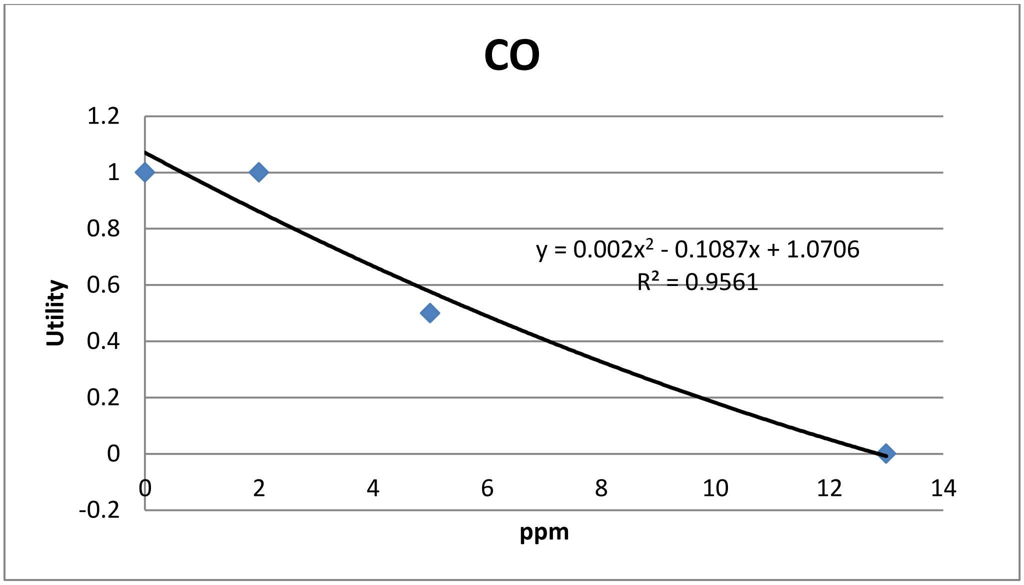


Figure 5.13 Carbon monoxide utility curves

Ozone (O_3) is created by high concentrations of pollution and daylight UV rays at the earth's surface, and can harm lung function and irritate the respiratory system (WHO, 2003). According to a study by Wilson (2009), people living in cities with high ozone levels such as Houston or Los Angeles have an over 30% increased risk of dying from lung disease. Another study on 450,000 people living in United States cities showed a significant correlation between ozone levels and respiratory illness over the 18-year follow-up period (Jerret et al., 2009). Health Canada's Regulations Related to Health and Air Quality set guidelines for the maximum desirable and acceptable levels of O3 concentration over a 24-hour period. Table 5-15 summarizes these guidelines.

Table 5-15: Health Canada: Regulations Related to Health and Air Quality guidelines for Ozone concentrations

Averaging Times	Maximum Desirable Level	Maximum Acceptable Level
24 hour	0.015	0.025
1 hour	0.051	0.082

The utility curve for converting the value of the amount of O_3 concentration to a utility value is based on the Canadian regulations from Health Canada. Figure 5.14 is the utility curve developed using the values in Table 5-16 and shows the relation between the utility value and the O_3 levels inside buildings.

Table 5-16: Utility Values Equivalent to Ozone concentrations

O_3 levels (ppm)	**Description**	**Utility Value**
0	Perfect Condition	1.00
0.015	Maximum Desirable Level	0.5
0.025	Maximum Acceptable Level	0.0

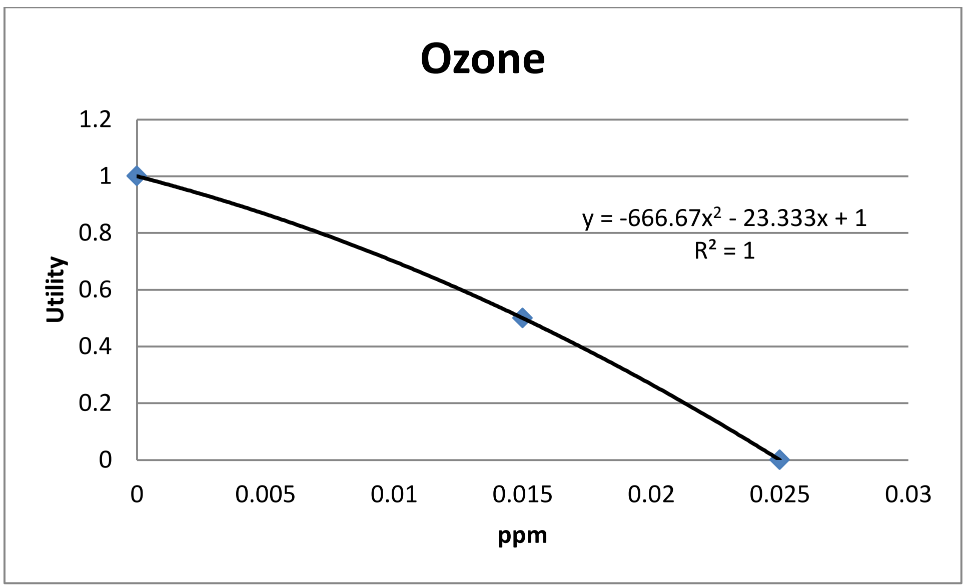


Figure 5.14 Ozone utility curves

ii. <u>Thermal Quality</u>

In this research, thermal quality means the physical environmental conditions related to the concept of thermal comfort; it is defined as "the condition of mind that expresses satisfaction with the thermal environment and it requires subjective evaluation"

(ASHRAE standard 55-2004). Only air temperature and relative humidity will be considered here, both during field measurements and in the assessment of the building spaces' indoor thermal quality.

High relative humidity causes problems such as molds, mildew, the growth of biological contaminants, and condensations on cold surfaces such as windows and the inside of exterior walls; it therefore causes problems to building materials, indoor air quality and occupants' health and comfort. On the other hand, humidity levels that are too low can contribute to irritated mucous membranes, dry eyes, sinus discomfort and a host of other problems for building occupants. According to ASHRAE standard-55-2004, the acceptable recommended range of indoor relative humidity is from 30% to 60%.

Low or high indoor temperature contributes significantly to occupants' thermal comfort and accordingly to the indoor thermal quality. Temperature is also the only element that occupants can control, thanks to thermostats. According to the ASHRAE standard-55-2004, an average person wearing seasonally appropriate clothing and performing a primarily sedentary activity is most comfortable when the dry bulb temperature is between 69^{o} F (20.5°C) and 81^{o} F (27.2°C).

By combining the effects of temperature and humidity, researchers have developed different relations that describe how occupants feel thermal comfort when experiencing different values of both temperature and relative humidity. Humidex is an index used by Canadian meteorologists to describe how hot the weather feels to the average person, by combining the effect of heat and humidity (Masterton and Richardson, 1979). It is a function of both air temperature and dew point in Kelvin. Dew point is the temperature to which a given parcel of humid air should be cooled, at a constant barometric pressure, for water vapor to condense into water. This condensed water is called dew. It is a saturation temperature. It is associated with the relative humidity -- where a relative humidity of 100% gives a dew point equal to the normal air temperature. The formula used to calculate the Humidex is shown in the equation below, while the formula for calculating the dew point is shown in the subsequent equation.

$$Humidex = Air\ temperature + 0.5555 \times (6.11 \times e^{5417.7530 \times \left(\frac{1}{273.16} - \frac{1}{dewpoint\ in\ Kelvins}\right)} - 10)$$

Equation 5-3

$$Dew\ point = \frac{b \times \left[\frac{aT}{b+T} + \ln\left(\frac{RH}{100}\right)\right]}{a - \left[\frac{aT}{b+T} + \ln\left(\frac{RH}{100}\right)\right]}$$

Equation 5-4

Where:

a : is equal to 17.271;

b : is equal to 237.7 °C;

T : is the temperatures in degrees Celsius; and

RH : is the relative humidity.

Using the above equations,

Table 5-18 was developed for calculating the Humidex value using both air temperature and relative humidity. The Canadian Center for Occupational Health and

Safety developed a table that describes the degree of comfort from Humidex ranges; while Environment Canada describes the degree of comfort from Humidex ranges slightly differently. Those two ranges were combined and integrated to form Table 5-17.

As stated above, the Humidex describes the degree of thermal comfort as a function of air temperature and humidity, but according to the Canadian Center for Occupational Health and Safety, little or no discomfort occurs when the Humidex value is less than 29, without specifying the lowest temperature accepted inside buildings. However, many Canadian occupational health and safety regulations as well as the federal guidelines specify lower temperature limits for work performed inside buildings. These lower limits vary from one Canadian province to another and according to the type of work involved. The most common lower limit for such type of work conducted inside office buildings is 18^{o}C, the temperature indicated by the Ontario, New Brunswick and Federal regulations. Figure 5.15 shows the utility curve that describes the relation between the utility value as a factor of the thermal quality and the Humidex.

Table 5-17: Utility Values equivalent to Humidex ranges

Humidex Range	**Degree of Comfort**	**Utility Value**	**Color**
Less than 29	Little or no discomfort	1.00	
30 to 34	Noticeable discomfort	0.75	
35 to 39	Evident discomfort	5.00	
40 to 44	Intense discomfort; avoid exertion	0.25	
45 to 52	Dangerous discomfort	0.00	
Above 53	Heat stroke	0.00	

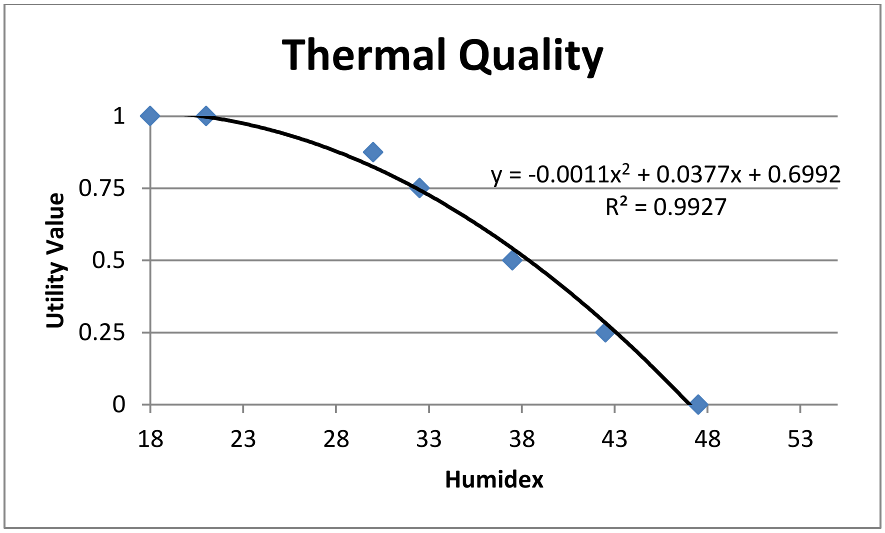


Figure 5.15 Thermal Quality utility curves

iii. Acoustics Quality

As stated earlier, acoustic quality in buildings is an important attribute for occupants' satisfaction, efficiency and comfort; whereas poor acoustics quality inside buildings increases stress and fatigue and hinders verbal communication. Noise, which is unwanted and disagreeable sounds that interfere with desired sound(s), should be controlled in order to provide a comfortable indoor environment. According to ASHRAE (2007), acceptable noise levels are different from one space to another. ASHRAE recommended acceptable noise levels for each space type and developed a noise criterion (NC) for each type of space. These noise criteria contain a recommended range for each space type; for example, in a private office space the NC range is from 30 to 35, which is 40 to 45 dBA.

Table 5-18: Humidex values equivalent to both temperature and relative humidity

R.H. / Temp	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
100	24	26	28	29	31	33	35	37	39	42	44	46	49	51	54	56	59	62	65	68	71	74	77	81	84	88
95	23	25	27	29	31	32	34	36	38	41	43	45	47	50	52	55	57	60	63	66	69	72	75	78	82	85
90	23	25	26	28	30	32	34	36	38	40	42	44	46	48	51	53	56	58	61	64	67	70	73	76	79	83
85	22	24	26	27	29	31	33	35	37	39	41	43	45	47	49	52	54	57	59	62	65	68	71	74	77	80
80	22	23	25	27	28	30	32	34	36	38	40	42	44	46	48	50	53	55	58	60	63	66	68	71	74	77
75	21	23	24	26	28	29	31	33	35	36	38	40	42	45	47	49	51	53	56	58	61	63	66	69	72	75
70	20	22	24	25	27	28	30	32	34	35	37	39	41	43	45	47	50	52	54	56	59	61	64	67	69	72
65	20	21	23	24	26	28	29	31	33	34	36	38	40	42	44	46	48	50	52	55	57	59	62	64	67	70
60	19	21	22	24	25	27	28	30	32	33	35	37	39	41	43	44	46	49	51	53	55	57	60	62	65	67
55	19	20	22	23	25	26	28	29	31	32	34	36	38	39	41	43	45	47	49	51	53	55	57	60	62	65
50	18	20	21	22	24	25	27	28	30	31	33	35	36	38	40	42	43	45	47	49	51	53	55	58	60	62
45	18	19	20	22	23	24	26	27	29	30	32	34	35	37	38	40	42	44	45	47	49	51	53	55	57	60
40	17	18	20	21	22	24	25	26	28	29	31	32	34	35	37	39	40	42	44	46	47	49	51	53	55	57
35	16	18	19	20	22	23	24	26	27	28	30	31	33	34	36	37	39	40	42	44	45	47	49	51	53	54
30	16	17	18	20	21	22	23	25	26	27	29	30	32	33	34	36	37	39	40	42	44	45	47	49	50	52
25	15	16	18	19	20	21	23	24	25	26	28	29	30	32	33	34	36	37	39	40	42	43	45	46	48	50
20	15	16	17	18	19	21	22	23	24	25	27	28	29	30	32	33	34	36	37	38	40	41	43	44	46	47

In another approach, Mui and Wong (2006) examined the acceptable noise level in an office environment by interviewing 422 occupants about their perceived aural environment in 61 air conditioned offices in Hong Kong. This study concluded that the probability of an occupant's acceptance of an office aural environment was correlated with a logistic regression curve, shown in Figure 5.16. They added that at the probable optimum noise level of 57.5 dBA, the probability of acceptance is about 0.86, as determined by the correlation (P<0.0001). Thus, maintaining a lower noise level would result in a higher acceptance; however, site investigation showed that a small population would not accept any aural environment, no matter what the noise level was.

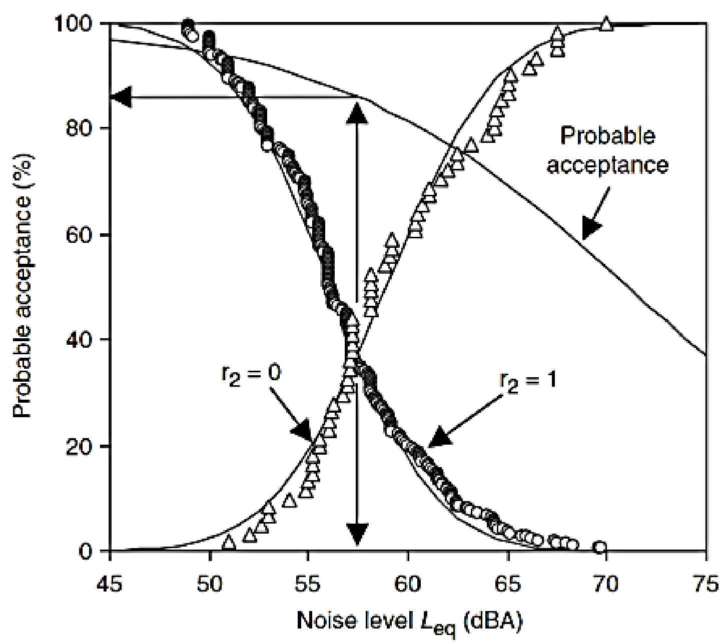


Figure 5.16 Occupants' acceptance vs. Noise level

The regression equality for the probability is expressed as follows:

$$Probability\ of\ acceptance = \frac{\exp(9.54 - 0.134\ Leq)}{1 + \exp(9.54 - 0.134\ Leq)}$$

Equation 5-5

where:

L_{eq} is the noise level in dBA.

This probability of acceptance will be used to describe the acoustics quality inside each space. The regression equation is used to draw the relation between the space acoustics quality and the noise level. Table 5-19 represents the calculation, using equation 5-5, of each noise level and the indoor acoustic utility values. A utility value equal to 1 represents the best case and zero represents the worst.

Table 5-19: Noise levels and the indoor acoustic utility values

dB(A)	Acoustic Quality	dB(A)	Acoustic Quality	dB(A)	Acoustic Quality
0	0.999	45	0.970	90	0.074
5	0.999	50	0.944	95	0.039
10	0.999	55	0.897	100	0.020
15	0.999	60	0.817	105	0.010
20	0.998	65	0.696	110	0.005
25	0.997	70	0.539	115	0.002
30	0.996	75	0.375	120	0.001
35	0.992	80	0.235		
40	0.984	85	0.135		

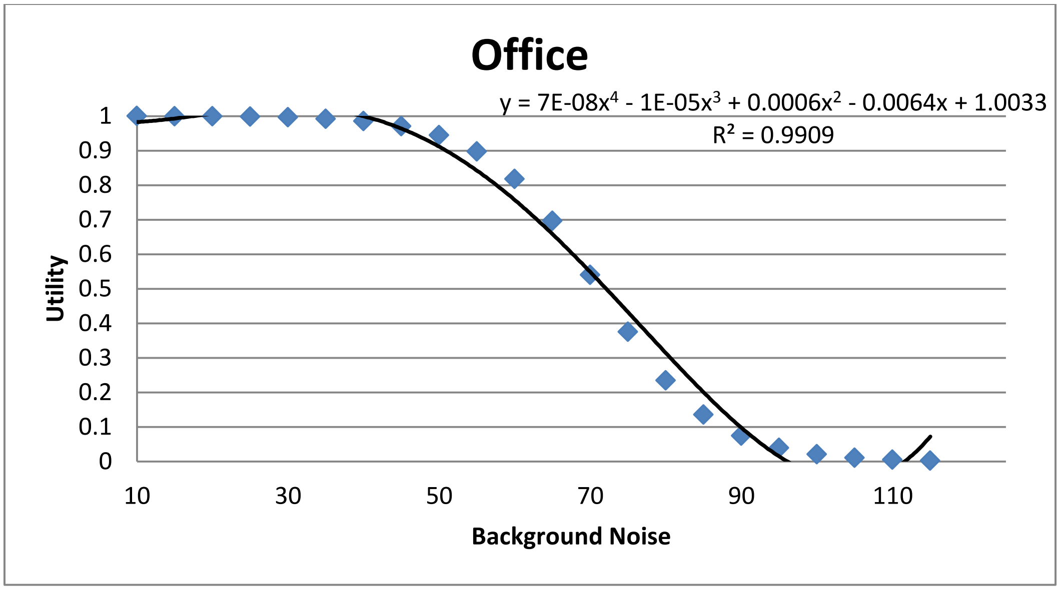


Figure 5.17 Office acoustic quality utility curves

Using the same regression equation, other space types' acoustic qualities can be calculated by adjusting the probability of acceptance (0.86) to the average of ASHRAE (2007) recommended dBA.

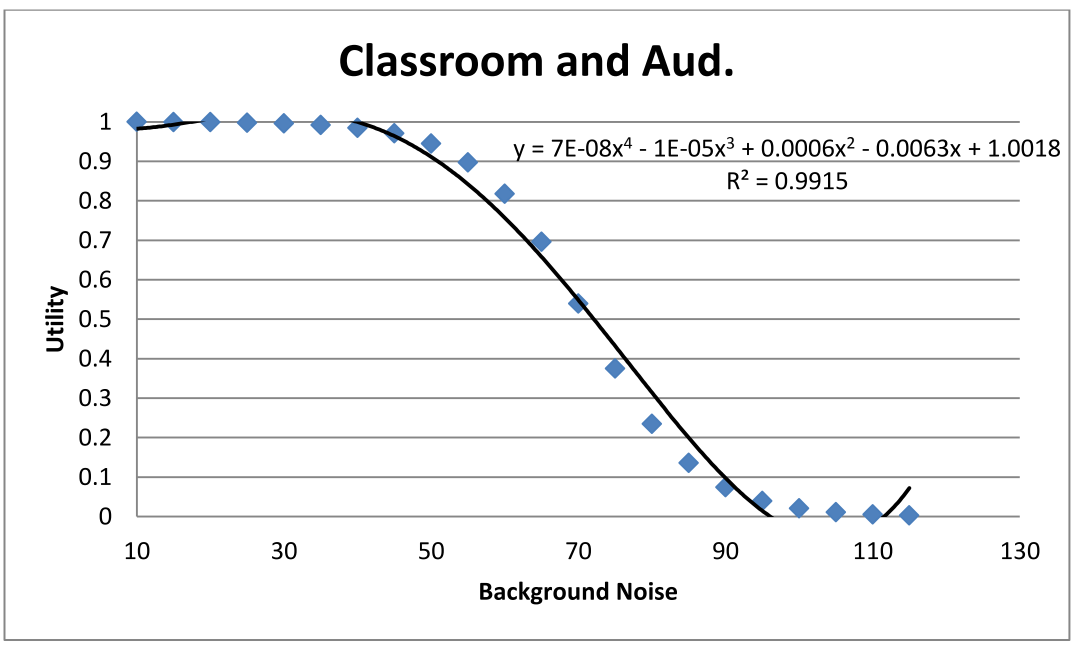


Figure 5.18 Classroom acoustics quality utility curves

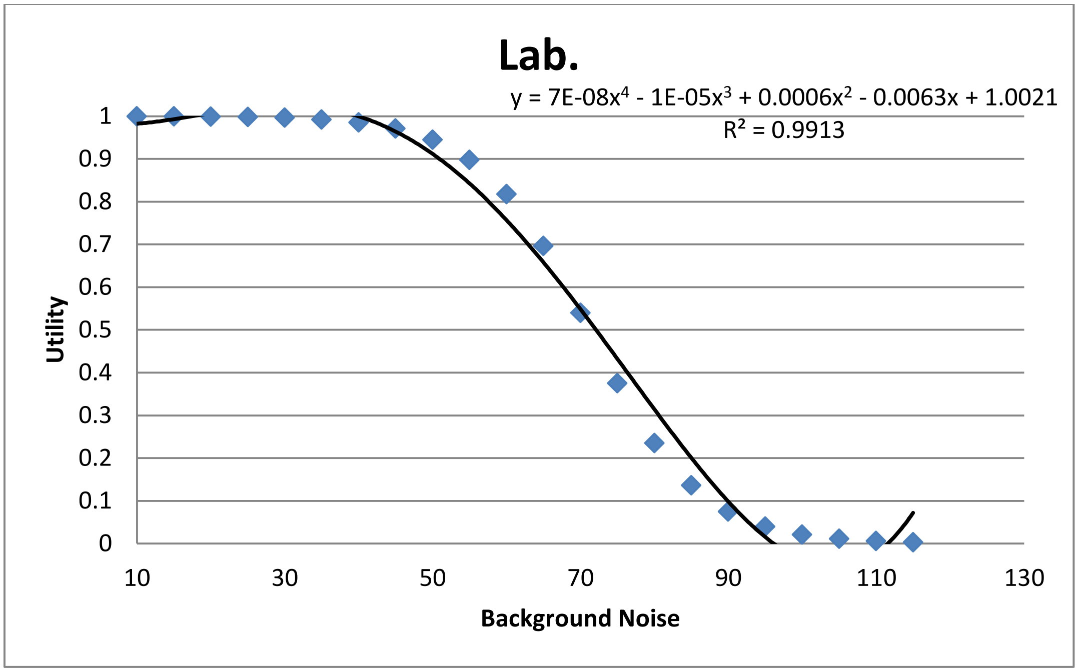


Figure 5.19 Laboratory acoustics quality utility curves

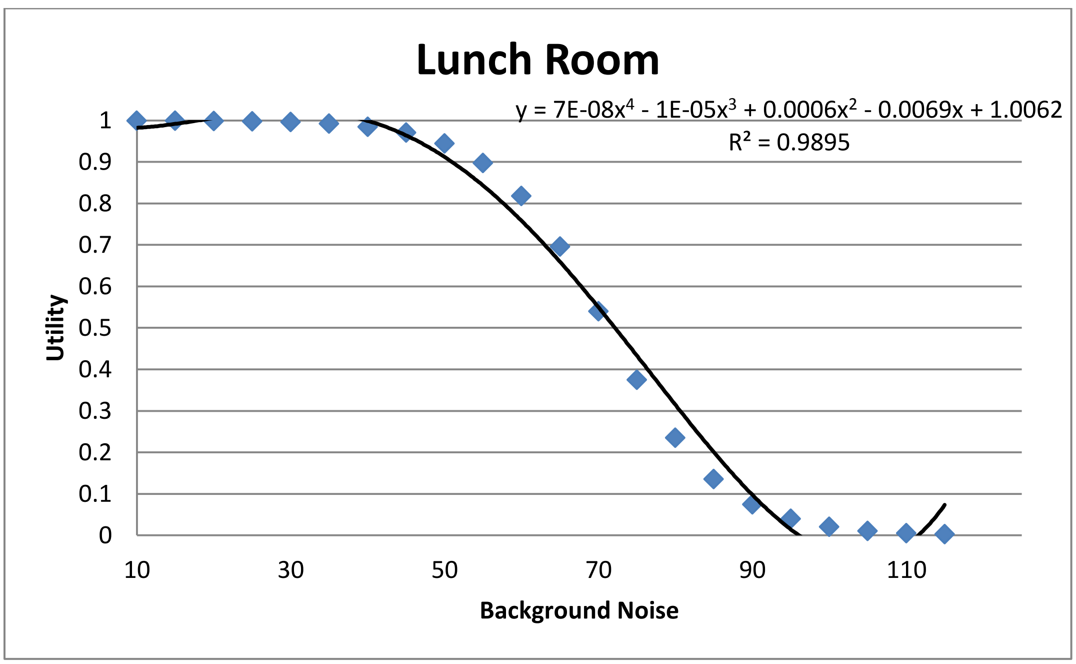


Figure 5.20 Lunchroom acoustics quality utility curves

iv. Lighting Quality

Lighting quality can improve worker productivity and the aesthetic appearance of spaces, facilitate education and enhance occupants and visitors' moods; incorrect lighting can have a negative effect on each of these issues. There have been several attempts to quantify and provide numerical guidance to lighting designers for the quality of adequate light. However, there is no one generally-accepted definition of what "high quality" lighting is, and there is also no commonly-accepted metric of lighting quality that can predict the effect of the luminance environment on occupants (Vitch and Newshame, 2006). Several factors may contribute to the enhancement of the quality of lighting, such as horizontal and vertical illuminance, color rendering, the uniformity factor, glare index, and so on. However, the most common factors that designers depend on in their light design are horizontal illuminance as well as the lighting fixtures distribution. IESNA lighting design has introduced recommendations for the standard values of illuminance for each space type according to the task conducted within. Table 5-20 contains recommended light levels for spaces inside a typical education building according to IESNA's lighting design guide (2000).

Table 5-20: Recommend light levels for each space type (IESNA, 2000).

Space type	Horizontal Illuminance (lux)
Class	500
Laboratory	500
Office	500
Lobby/corridor	50/100
Restroom	50
Lunch Room	100
Auditorium	100 or 500 according to the use

The above values are the recommended minimums for each task; thus, the amount of illuminance in each space type must not be less than the recommended values. However having illuminance value higher than the recommended with no reason for that affects the cost effectiveness of the electricity consumed by the Lighting fixtures. According to lighting designers, in case the level of illuminance is less than the standard the light quality and poor distribution of lighting fixtures, this will certainly affect the quality of lighting. In this research and from the perspective of the lighting illuminance and distribution, it was assumed that the lighting quality decreases with the quantity of light and poor distribution. The maximum allowable spacing between fixtures= fixture spacing criteria x mounting height, it was set that the spacing criteria equals 1.5 the mounting height (height from the mounting plane up to the lighting fixture) (IESNA, 2000).

Table 5-21 shows the suggested utility value equivalent to the values of both Lighting illuminance considering the 500 Lux as the recommended value as in the case of the class, laboratory, and office, it shows also the utility value equivalent to the spacing between lighting fixtures considering a spacing criteria value equals to 1.5. This utility values and thus the equations are flexible to be changed according to the recommended values. Figure 5.21 and Figure 5.22 show the utilities curves and the corresponding equations for both the lighting illuminance and the fixtures spacing

Table 5-21: Recommend light levels for each space type (IESNA, 2000).

Lighting Illuminance	Spacing criteria	Equivalent Quality Value
800	0.9	1
750	1.0	1
700	1.1	1
650	1.2	1
600	1.3	1
550	1.4	1
500	**1.5**	**1**
(90%) 450	1.6	0.9
(80%) 400	1.7	0.8
(70%) 350	1.8	0.7
(60%) 300	1.9	0.6
(50%) 250	2.0	0.5
(40%) 200	2.1	0.4
(30%) 150	2.2	0.3
(20%) 100	2.3	0.2
(10%) 50	2.4	0.1
(0%) 0	2.5	0

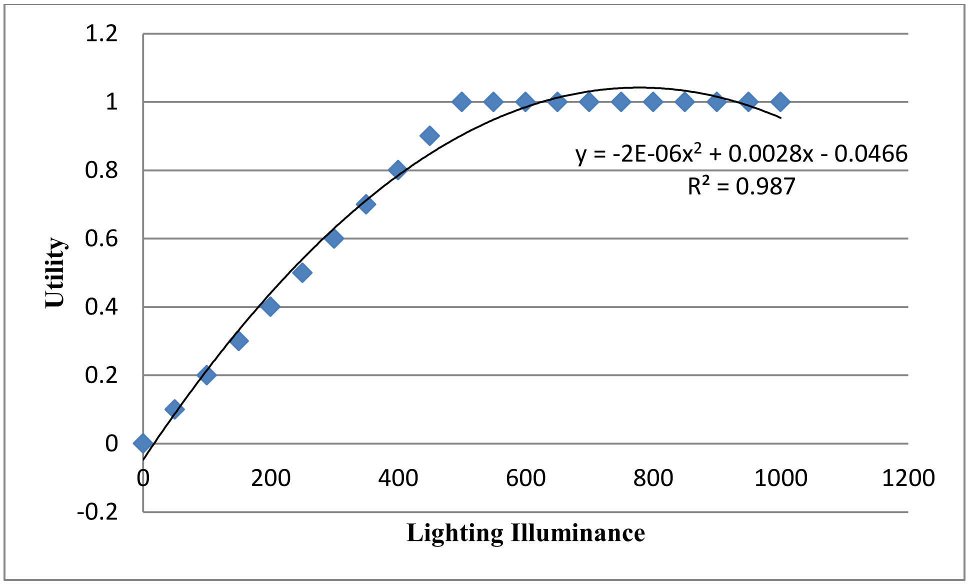


Figure 5.21 Lighting illuminance utility curve for an office

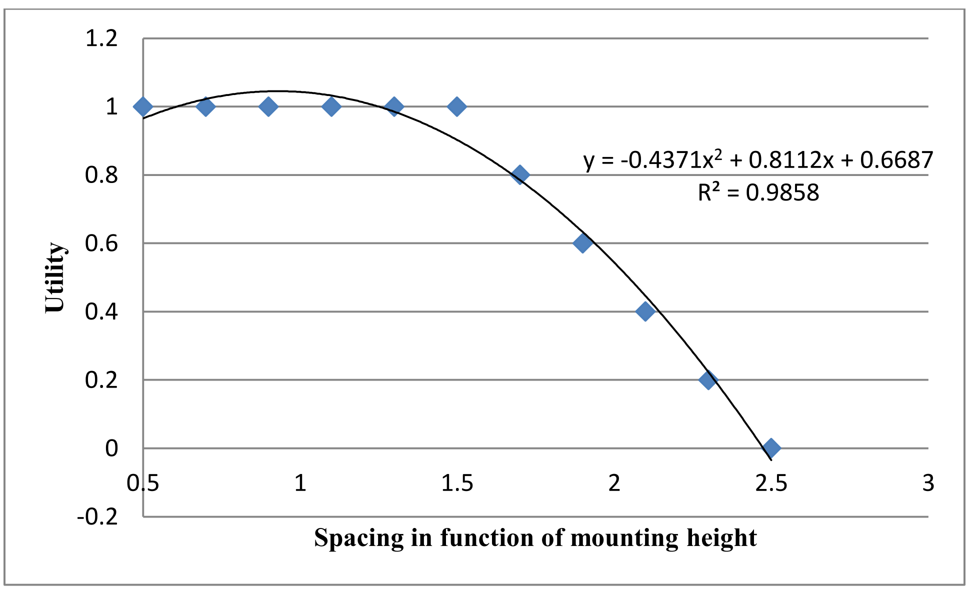


Figure 5.22 Lighting fixture spacing utility Curve

5.1.8 Building's IEQFs threshold values

It was adjusted to have a threshold for all IEQFs and their sub-criteria of 50% as it is in all cases adjusted to the recommended maximum value or evident discomfort. It means that any IEQF utility value falls below the "0.5" will give an alarm as it raises an occupant safety issue. At that moment it should interrupt the condition assessment process and may stop it, unless it is requested by the facility manager to proceed with the process

5.2 BIM Model Development

5.2.1 Overview

This section explains how the integrated condition assessment process will be implemented through a model which converts the assessment data input of inspectors into quantified values that make its calculation a (relatively) simple task. This is achieved by developing an assessment model that can be associated with some generic evaluation schemes. All of the framework steps and models discussed earlier will be implemented and applied through the Building Information Modeling (BIM) technology. In other words, the assessment process will be done using BIM. This research implements BIM as a single-repository virtual model into which all of the condition assessment data provided by an inspector during the inspection process will be input. BIM is capable of recognizing building components in its fixed asset hierarchy (Category-Family-Family type-Instant) while being a user-friendly tool for analyzing a building's internal spaces. It can link those components to the space that hosts them by relating a component's ID to a space's ID. How the BIM will be used throughout the model development process and how the new parameters of the physical and the environmental process are added and implemented will be explained first. The next step is to show how the data will be extracted from the BIM to the integrated data model, followed by a presentation of the resulting automation of the process of space and building condition assessment.

5.2.2 Condition to run the model

There are some conditions that should be met before implementing the integrated condition assessment model. The model considers both the physical and environmental conditions of a building; however, the physical condition is divided into two steps. The first step is to check the structure of the building; if there are no obvious structural symptoms the model can be implemented. In case any symptoms of structural problems are recorded, applying either destructive or non-destructive tests according to the need and recommended by the consultant is recommended. If the building passes these tests, another test should be applied; the integrated condition assessment structural threshold. If it does not pass the destructive or non-destructive tests, the problems and their location should be reported and then checked if they can be rehabilitated. If the building passes the structural threshold, the model can be implemented. If it does not pass, then the possibility of rehabilitation should be verified. After rehabilitation, the model can be implemented. If there is no possibility of rehabilitation, then a report of demolition is the recommendation. Figure 5.23 summarizes this condition statement that is required before implementing the model.

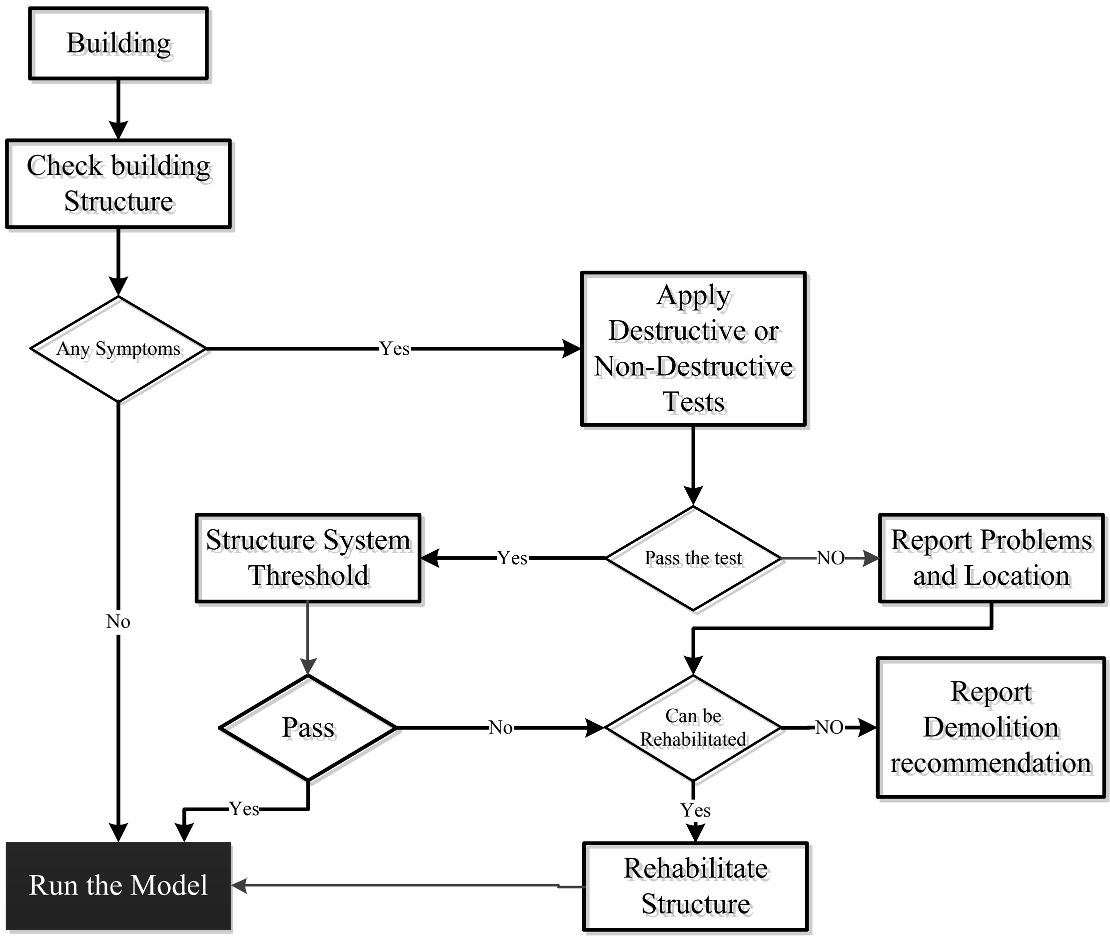


Figure 5.23 Condition statement required before implementing the model

5.2.3 Identify New Attributes and Parameters

Based on the previous discussion, new attributes and parameters will be identified and assigned to the required hierarchy levels. The following two points will explain how building elements' specifications are used and modified to provide physical and environmental condition assessment inputs to the integrated assessment model.

Assign Indoor Environmental Quality Factors (IEQFs): The second level in the asset hierarchy is the space level; where space is the principal evaluated element.

IEQFs are assigned as parameters to each space. Each IEQF will have attribute(s) with which to be assessed. The average value of the attributes will provide the condition value of each factor. The inspector will be required to make a field measurement for each attribute using the appropriate device and input them as illustrated in Figure 5.24. This measurement will then be converted to a utility value using the utility curve developed for each attribute in order to set a condition value, and thus each IEQF condition value will be calculated.

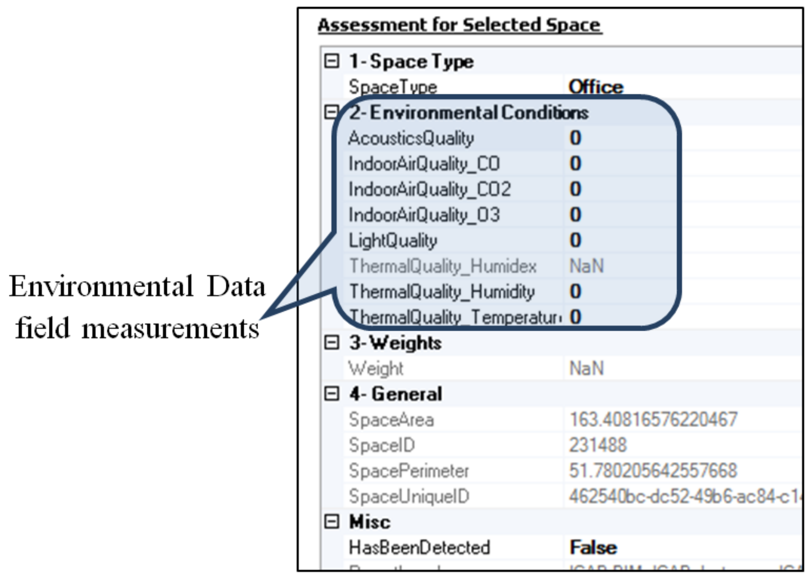


Figure 5.24 Environmental field measurements' data input

Assign Physical Evaluation Criteria: The physical assessment requires the assessment of each building category (architectural, mechanical, and electrical). Through the asset hierarchy, the evaluation criteria will be assigned to the family type level, and then the condition of each building category can be calculated by 'rolling up'. In cases where the inspector prefers to use the direct condition rating for any of the physical elements inside a building, the option of giving an overall grade to a particular element is also available. The inspector will be required to evaluate each instance, either by the direct condition rating or by the developed evaluation criteria at the instance level; and thus each category condition will be calculated.

Figure 5.25 shows the process of evaluating the condition of a door as a physical element inside a space. Data input is conducted by the inspector; the figure shows the two options available to the inspector: either to choose the direct condition or to use the evaluation criteria which will be converted later into one number that represents the overall condition of that element.

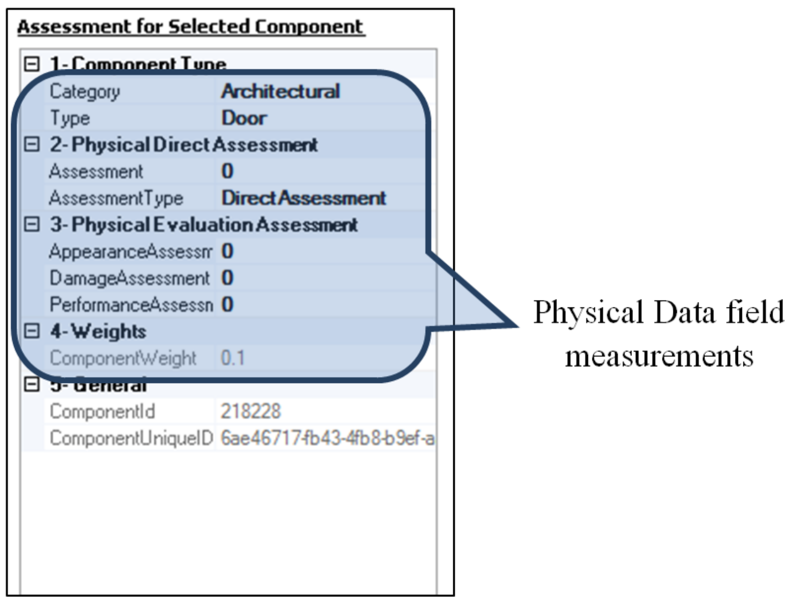
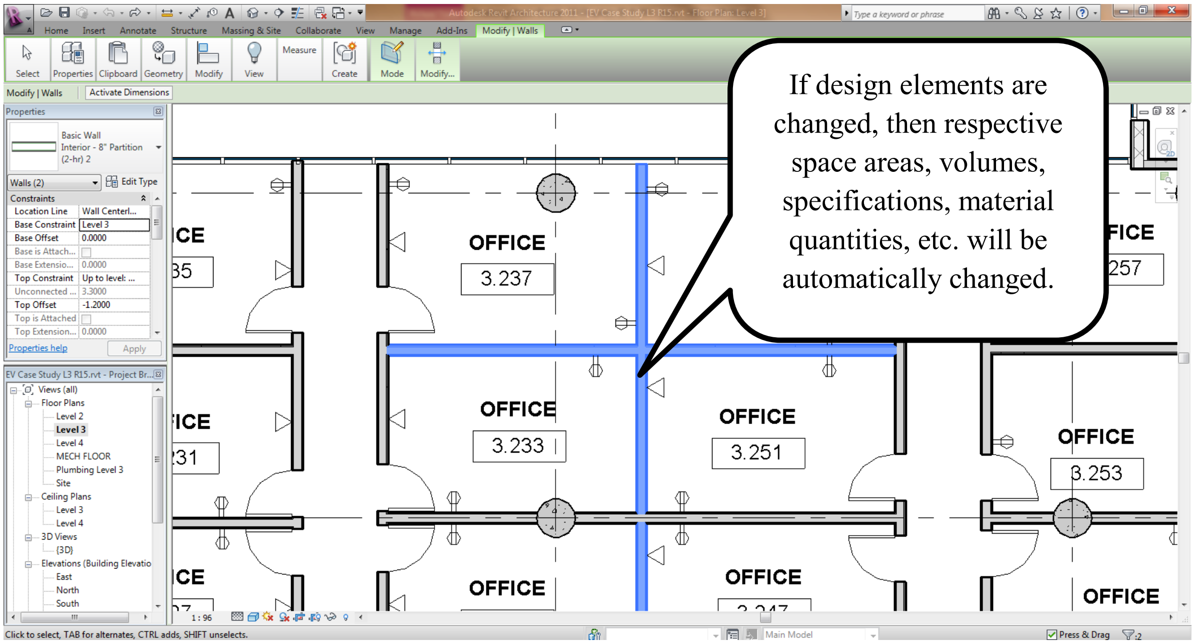


Figure 5.25 Physical assessment field measurements data input

5.2.4 Parametric Relationship

One of the most important features of Building Information Modeling is represented by the parametric relationships, which indicate that certain components inside the model have a logical interconnection. In other words, changing any property of any component inside a model such as location, material, or dimensions could have an impact throughout the model, and any component linked to that changed component will be modified automatically. This prevents the need for reworking and reduces errors, in addition to reducing the time required for modifications and increasing accuracy. The example of changing the location of a wall, as presented in Figure 5.26, will clarify this point from the facility management point of view and illustrate the potential of BIM models in this aspect. In a building, spaces are identified using different boundaries (walls, ceiling, floors), and changing the location of a wall, for example, does affect some other aspects such as the area and volume of the space. These changes are in addition to the changes that occur in the neighboring spaces as well. As explained above, the wall defines the space; every component located within the boundaries is considered as a component inside this particular space, thus its condition affects the condition of this particular space. One other aspect that will be affected is the area of the space itself and that (those) of the neighboring space(s); the area of each space is a factor, along with the space type, in calculating the relative weight of each space inside the entire building. Therefore, a single wall modification has an effect on the condition of the entire building. When any component is added or removed from a space, the model will automatically change the condition of the space and thus of the entire building. The concept of parametric relationships in BIM is a potential that solves these kinds of problems, so that when a change occurs anywhere in a building it is automatically reflected everywhere and the affected components are modified.



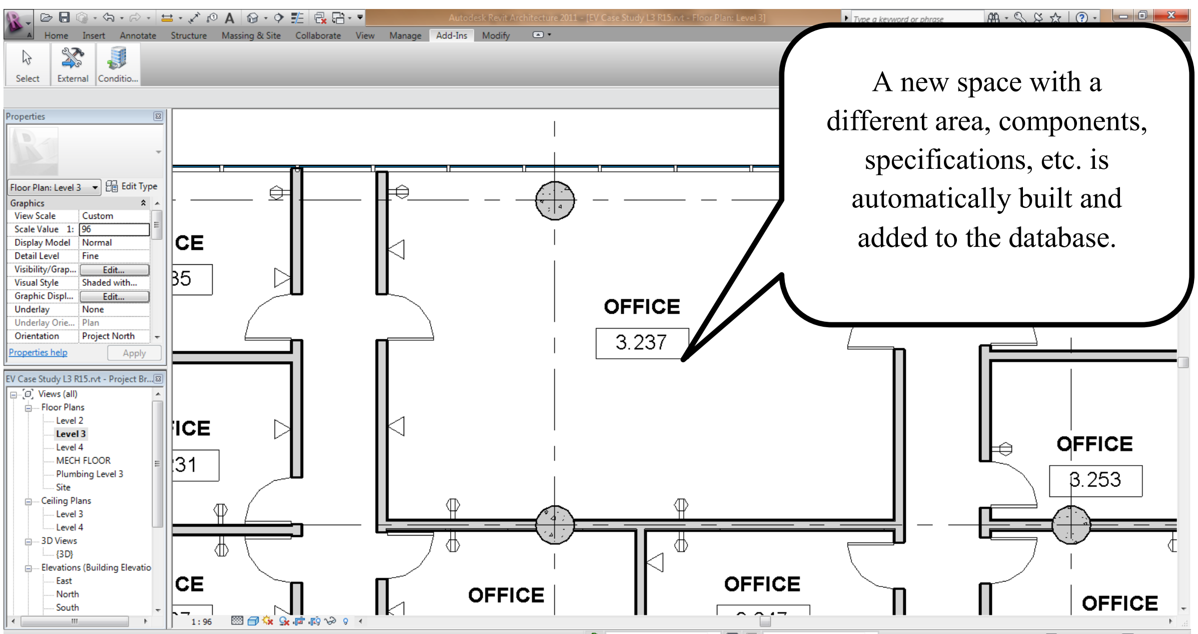


Figure 5.26 Properties of space are linked with building elements

5.2.5 Periodic Condition Assessment

In the asset management process, an asset manager is required to effectively maintain, upgrade and operate the physical asset. As stated before, proper asset management is based on a condition assessment that can reflect assets' current serviceability and failure risk, as well as quantify their current value (Urquhart et al,. 2005). Since the process of asset management is continuous as long as the asset exists, the asset manager will need to conduct periodic condition assessments of the building. These can be monthly, bimonthly, semiannually, annually, etc.; the facility manager is responsible for determining the optimal time span between each condition assessment process. The BIM provides the option of storing the records of each condition assessment process along with their date, as shown in Figure 5.27, as well as providing the option of comparing these condition assessments. It is certainly possible that some problems could be identified by tracking the changes in the conditions of spaces and their internal physical and environmental conditions by utilizing this comparison feature.

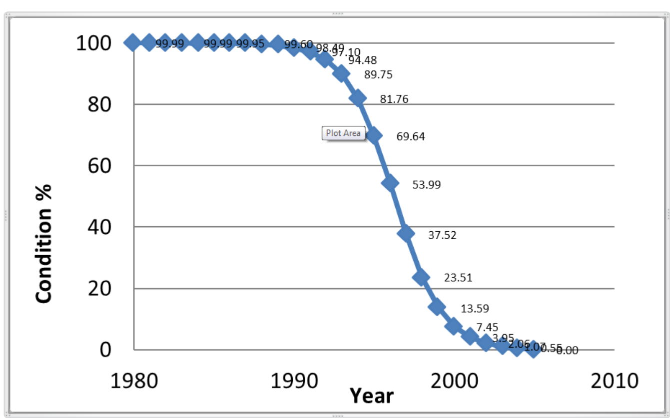


Figure 5.27 Deterioration of building component with time

This detection aspect is in addition to the benefits of the automatic recording of a building's condition assessment and its internal space details and the ability to use this data in the future.

Educational building materials have a certain life span, which is naturally affected by proper care or the lack of its proper recommended maintenance (RSMeans/Reed Construction Data, 2009). If the building components are properly maintained and protected from accidents, this will lead to a long life span. It is also important to note that the construction date of a facility does not control or influence the possibility of asset failure. An educational facility's functional age is determined by the duration since it had a major renovation (RSMeans/Reed Construction Data, 2009). The suggested average useful life spans of building components, calculated from an average of past historical data, are presented in Table 5-22 (RSMeans/Reed Construction Data, 2009).

The Public Sector Accounting Board (PSAB) comprises senior government executives and expert in government financial reporting. In June 2006, the PSAB approved PS 3150, which requires municipalities across Canada to report Tangible Capital Assets (TCA) on their Statement of Financial Position (i.e. balance sheet),effective from January 1st, 2009. PS 3150 also requires a new format for municipal financial statements and stipulates that tangible capital assets be amortized on the Statement of Operations. In accordance with some published reports and some interviews with municipal engineers, Table 5-23 shows the useful life for each building component inside a building facility. Using an assumption that the condition of any component inside a building is in the process of straight-line deterioration, the condition of any component can be calculated using the date it was first installed (or completely renovated) and the useful life of the component.

5.3 Integrated Data Model

In order to calculate the physical and environmental conditions of each space, the integrated condition assessment of each space, and the physical and environmental as well as the integrated condition of a whole building, all of the output extracted from a BIM model must be properly categorized and assessed. The following section will explain the whole process of exporting, organizing, and finally analyzing the data.

The BIM model saves all of the parameters and attributes for building spaces, along with component information. All of this information is associated with a unique ID, so that no conflicts can occur when dealing with data exchange and export. Based on this ID uniqueness feature, all of the components' characteristics can be exported from the BIM model and imported to the data model. Multi-paradigm programming language will be used to develop the data model, which will be needed by both the assessment model and the user-friendly tool. After importing all the output of the BIM model to the multi-paradigm programming language, the physical condition of the space will be calculated automatically based on the condition value exported from the BIM model and the weights stored in the software database. Figure 5.28 shows the model implementation methodology for a single space, indicating that it is composed of three main phases: (1) BIM development, (2) the integrated data model, and (3) the integrated condition of the space.

Table 5-22: Suggested average useful life spans of building components (RS Means/Reed Construction Data, 2009)

Item	Years
I. Major Construction	
A. Reinforced Concrete Frame	
1. Masonry Exterior	
a. Heavy	45
b. Light & Medium	40
B. Steel Frame	
1. Masonry Exterior	
a. Heavy	45
b. Medium	35
c. Light	30
2. Metal Exterior	
a. Heavy	45
b. Medium	35
c. Light	30
C. Wood Frame	
1. Masonry Exterior	
a. Heavy	35
b. Medium	25
2. Metal Exterior	
a. Heavy	30
b. Medium	25
c. Light	20
3. Wood Exterior	
a. Heavy	25
b. Light & Medium	20
II. Electrical & Mechanical Equipment	
A. Electrical Systems	
1. Lighting Systems	
a. Conduit & Wire	20
b. Fixtures	15
c. Flood Lighting	15
2. Power Feed Wiring	
a. Bus Duct	25
b. Capacitor	20
c. Power Feed Wiring Maine	25
d. Switch Boards	20
e. Switch Units	20
3. Transformers	
a. Wet Type	20
b. Dry Type	15
B. HVAC Systems	
1. Air Conditioning Systems	
a. Central including ducts & piping	15
b. Window Type	10
c. Cooloing Towers	15
2. Heating Systems	
a. Furnaces & Boilers	20
b. Radiators, Convectors, Piping	25
c. Unit Heaters, gas & steam piping	20
d. Unit Heaters — Electrical	15
3. Ventilating Systems including fans & exhausters	15
C. Plumbing Systems	
1. Drinking Water Systems	
2. Fixtures	
3. Piping	
a. Cast Iron Waste	35
b. Concrete	30
c. Copper	30
d. Plastic	20
e. Steel	30
f. Vitified Tile	
4. Sprinkler Systems	
a. Wet & Dry Systems	30
b. Fire Pumps	20
c. Hose Housings	
1) Wood	15
2) Steel	20
3) Masonry	30
5. Sump Pumps	
a. Small	10
b. Large	15
6. Water Heaters — gas & electric	10
7. Water Wells	25
D. Service Systems	
1. Elevators (all types)	20
2. Fire Alarm	20
3. Intercom	15
4. Telephone	15
III.Miscellaneous Items	
A. Bulkheads	
1. Concrete	30
2. Steel	25
3. Timber	20
B. Chimneys	
1. Brick or concrete	35
2. Steel-lined	25
3. Steel-unlined	20
C. Culverts	
1. Concrete	30
2. Galvanized Steel	20
D. Curbing	
1. Concrete	25
E. Fencing	
1. Brick or Stone	30
2. Chain Link	20
3. Concrete	30
4. Wire	10
5. Wood	10
F. Flag Poles	25
G. Incinerators	
1. Commercial Type, steel fire brick lined	20
2. Concrete block or brick	20
3. Steel	15
H. Paving and Walks	
1. Asphalt on gravel or stone	15
2. Brick	20
3. Concrete	20
4. Gravel, stone, cinders	10
5. Parking area guard rails	10
I. Platforms	
1. Reinforced Concrete	35
2. Wood frame on concrete piers	20
3. Wood frame on wood posts	15
J. Railroad sidings	25
K. Resevoirs, concrete	35
L. Retaining Walls	
1. Brick	30
2. Concrete	40
3. Steel	25
4. Stone	40
5. Wood	15
M. Sheds	
1. Brick, tile or concrete block with wood frame	25
2. Brick, tile or concrete block with steel frame	35
3. Metal clad, steel frame	27
4. Metla clad, steel frame	20
5. Wood siding and frame	20

Table 5-23: PSAB's suggested useful life spans.

Building Subsystem Useful Life	(years)
ACCESSIBILITY SYSTEM	**25**
DRAINAGE	**30**
ELECTRICAL	**25**
EQUIPMENT	**20**
INTERIOR FINISHES	**40**
FIRE SYSTEMS	**30**
FURNITURE	**10**
FIXTURES	**15**
HVAC	**20**
MECHANCIAL	**20**
EXTERIOR FINISHES	**40**
SECURITY	**15**
STRUCTURAL	**75**
WATER SYSTEM	**30**

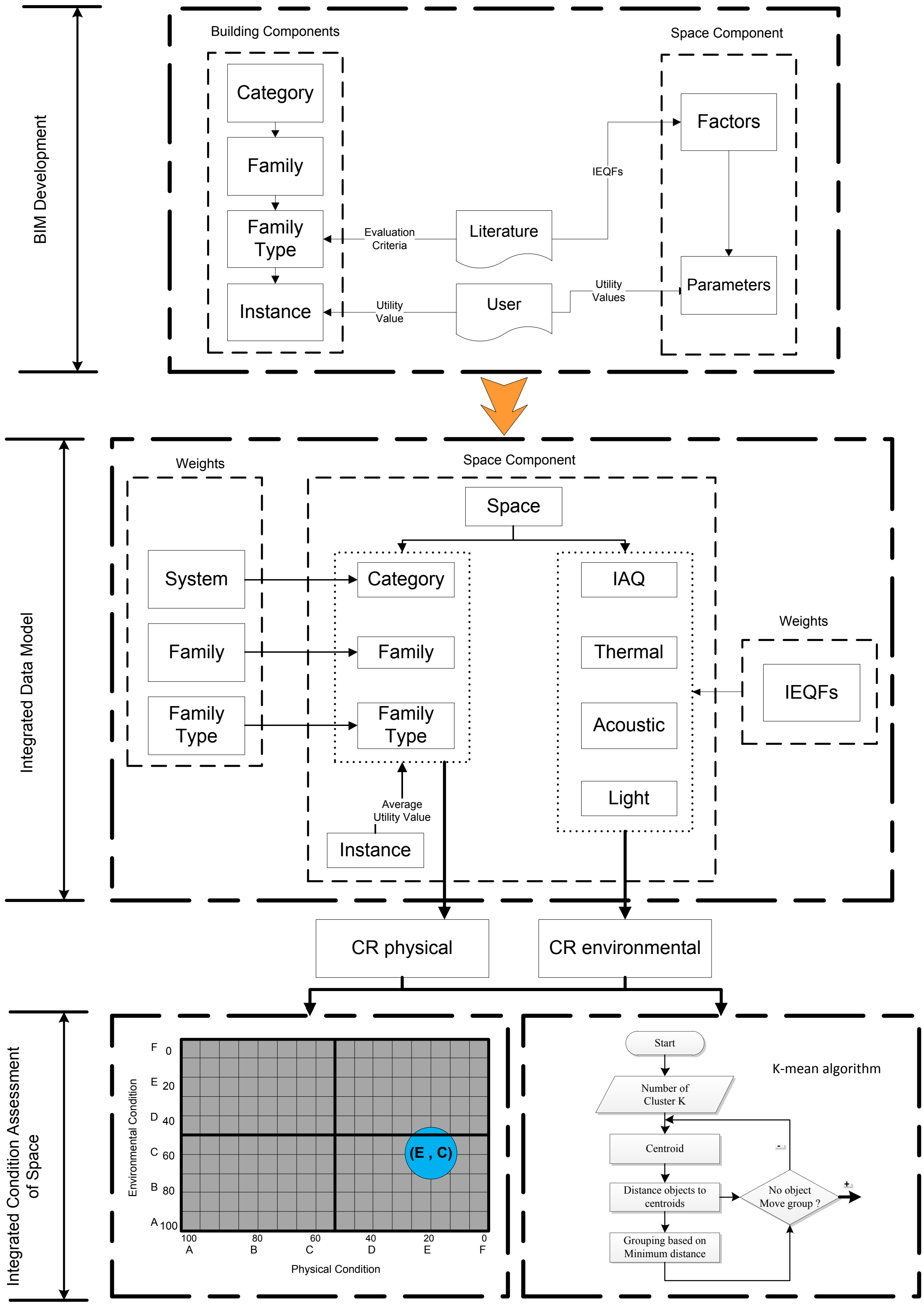


Figure 5.28 Model Implementation Methodology for a single space

5.4 Building Condition Assessment Model

5.4.1 Space Physical and Environmental Condition

Spaces are assessed according to their internal physical and environmental conditions. A space's physical condition is calculated using the weighted average of the conditions of the three main categories inside it. Each category is represented by some families which belong to it, similarly, each family is represented by the different family types which belong to that family, and finally each family type is represented by the instances that belong to that type. The rolling up method starts from the lowest level in the asset hierarchy and ends at the physical condition of a space. The condition of the family type, such as an "Interior - 8" Partition (2-hr) 2" is the average condition of all instances belonging to that family type. The condition of a family (e.g. walls) is the average conditions of all the family types that belong to it. The next step is calculating the condition of the categories (e.g. Architectural Category), which will be calculated using MAUT. Each family that belongs to that category will have a relative weight in that particular space; using the weight and the condition of each one, the category condition can be calculated. Figure 5.29 shows the rolling up process of calculating the physical condition of a space throughout the asset hierarchy.

Space environmental assessment is calculated using the weighted average of the condition of the four IEQFs. Each IEQF is represented by its sub-criteria. Using a utility curve developed specifically for each sub-criterion, the field measurements will be converted to a utility value.

Figure 5.30 shows the process of calculating the environmental condition of the space as a product of the principal evaluated elements.

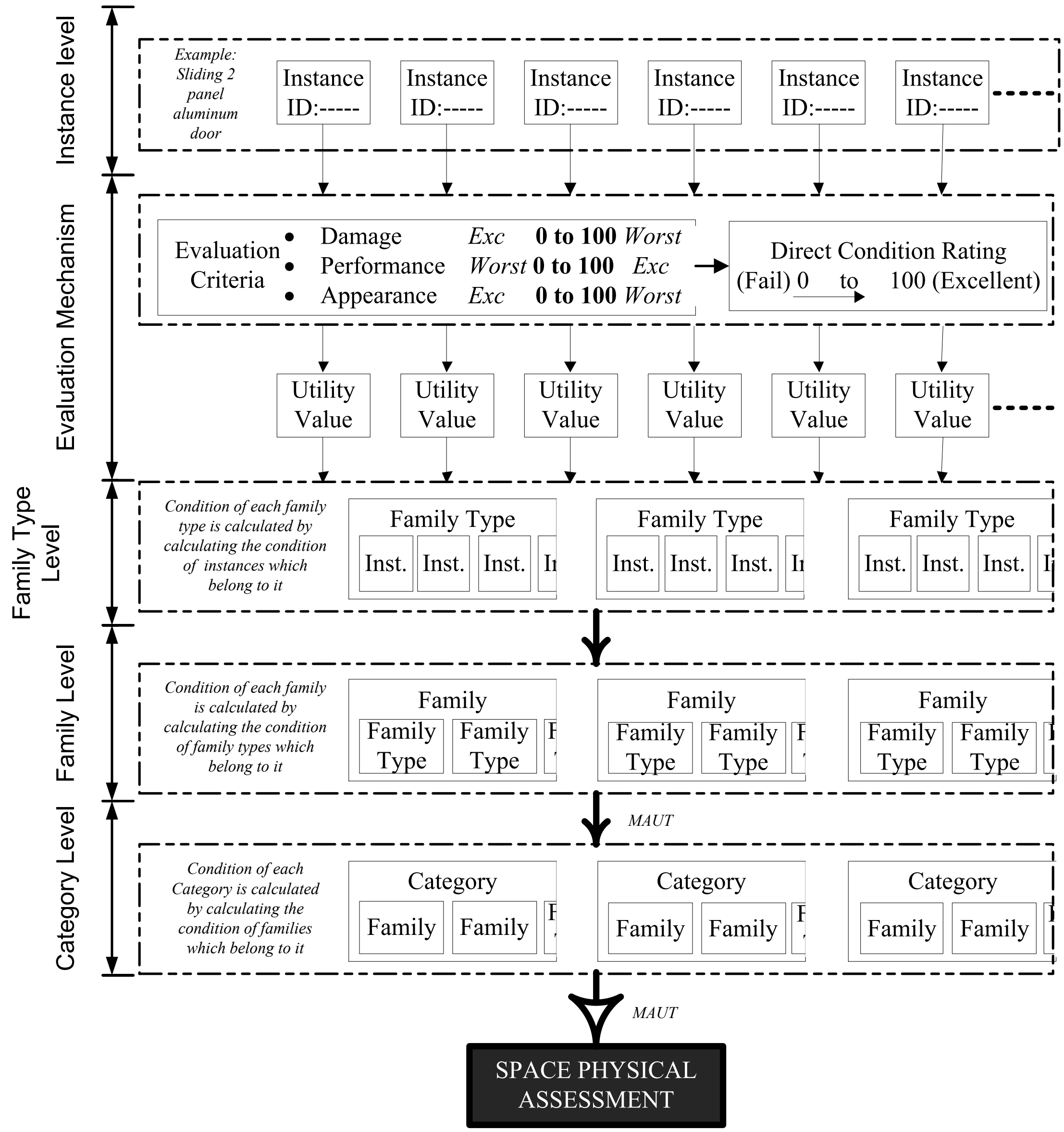


Figure 5.29 The physical condition of space throughout the asset hierarchy

The Physical and Environmental conditions of a space will be represented by radar charts to give a clearer vision of the exact problems on the level of the sub-criteria. This clear representation is in addition to the possibility of checking the exact problem in each sub-criterion at any time after applying the assessment. Figure 5.31 shows an example of a radar chart representing the physical condition of a space; it represents the physical conditions of the three categories inside each space. This chart is used when the facility manager wants to track the problems and related poor conditions inside a building and needs to dig further to determine the reasons for good or bad conditions. The radar chart is on the level of the building categories; however, facility manager may track problems in more detail by tracking the conditions of the sub-criteria (families), such as the conditions of doors inside the Architecture category.

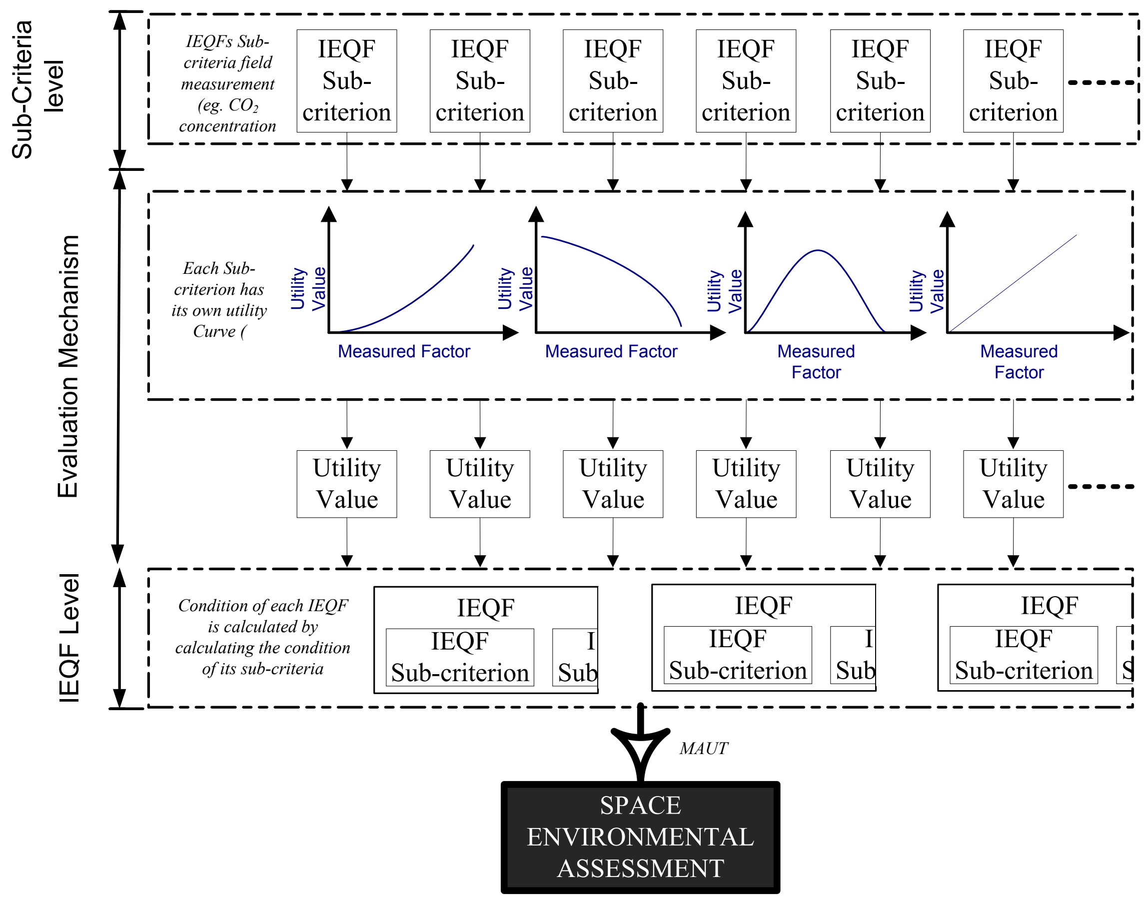


Figure 5.30 The process of calculating the environmental condition of a space

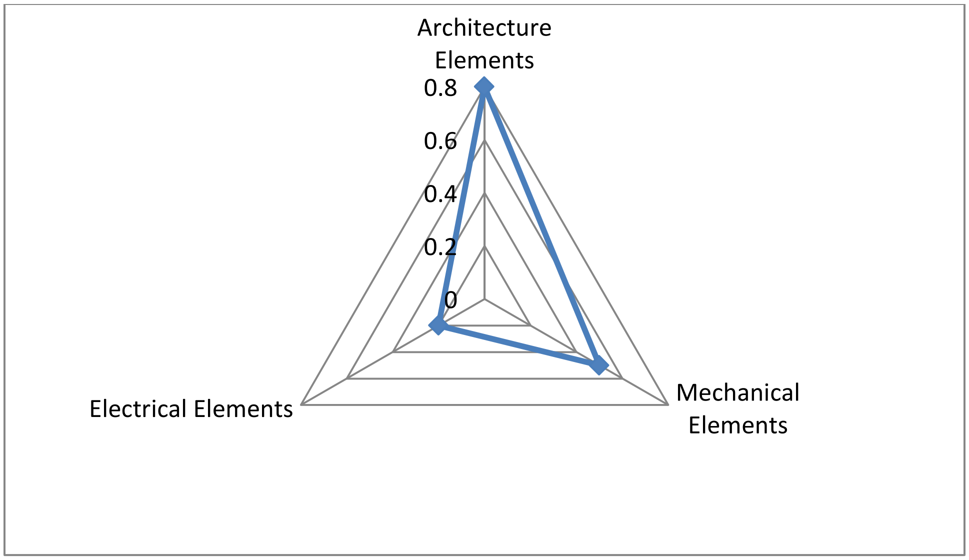


Figure 5.31 Physical condition radar chart for a space

Figure 5.32 shows another example of the environmental condition of the same space and the condition of each indoor environmental quality factor**.** This chart is used when the facility manager wants to track the environmental problem of spaces and to know the reason for the good or bad conditions of spaces. Facility managers can uncover more details by tracking the conditions of the IEQF's sub-criteria, such as the concentrations of carbon monoxide in the indoor air quality.

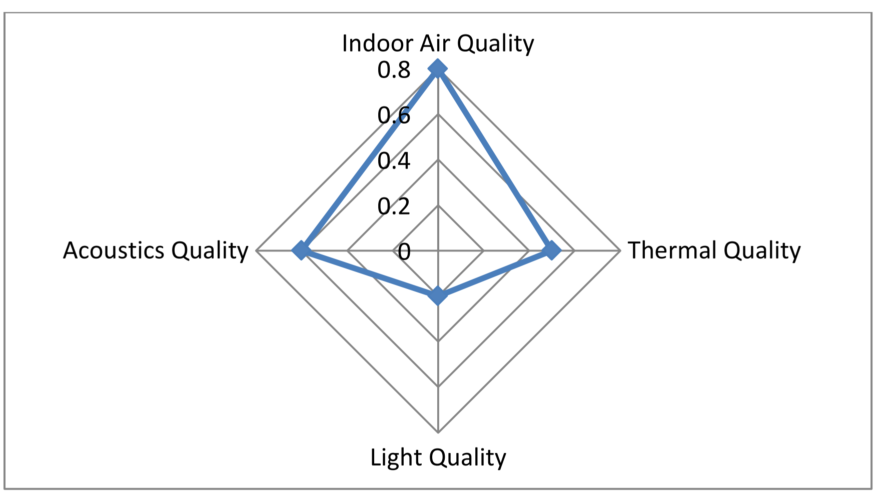


Figure 5.32 Environmental condition radar chart for a space

5.4.2 Space Integrated Condition Assessment

The process of calculating the condition of a space is simply the integration of the physical and the environmental conditions into one model. There are two possible scenarios:

- Combining them in one model by developing self-organizing maps for clustering the physical and environmental conditions via an unsupervised clustering technique. As stated before, both the physical and environmental conditions of a space are divided into 6 grades each (A to F). They form a matrix of 36 different options (6 X 6); these options represent the physical and environmental conditions of any space. Figure 5.33 shows a matrix of the 36 different options.

F	X_{AF}	X_{BF}	X_{CF}	X_{DF}	X_{EF}	X_{FF}
E	X_{AE}	X_{BE}	X_{CE}	X_{DE}	X_{EE}	X_{FE}
D	X_{AD}	X_{BD}	X_{CD}	X_{DD}	X_{ED}	X_{FD}
C	X_{AC}	X_{BC}	X_{CC}	X_{DC}	X_{EC}	X_{FC}
B	X_{AB}	X_{BB}	X_{CB}	X_{DB}	X_{EB}	X_{FB}
A	X_{AA}	X_{BA}	X_{CA}	X_{DA}	X_{EA}	X_{FA}
ENV./PHYS.	A	B	C	D	E	F

Figure 5.33 Space Integrated Condition Assessment Matrix

Clustering software using clustering techniques such as the K-mean will be used for this purpose; the obtained transformed deduct values will be grouped or clustered into six categories of condition classes. Figure 5.34 shows how a Self-organizing-map (SOM) will integrate those two numbers by clustering the data points into six groups.

F	C	D	E	E	F	F
E	C	D	D	E	F	F
D	B	D	D	D	E	F
C	B	B	B	D	E	E
B	A	A	B	B	C	E
A	A	A	B	B	C	C
ENV./PHYS.	A	B	C	D	E	F

Figure 5.34 Generated Clusters using the K mean clustering technique

- The second technique is to combine the two conditions in a bubble diagram as a graphical representation. The bubble diagram represents the physical and the environmental conditions as the X and the Y axes, respectively. The location of the bubble (building integrated condition) shows where the problem is and indicates its severity. For example, in Figure 5.35 a space is shown with a condition (E,C), which means "E" in the physical condition with a condition index of "20" and "C" in the environmental condition with a condition index of "60".

Figure 5.36 shows the model represented in a function modeling language, IDEF0, in which input, output, mechanism, and control are shown in order to be transformed in the next step in the programming language. The final output of this model is the integrated condition assessment of a space. The whole diagram is one function in the IDEF0 representation of the Integrated Condition Assessment model of the entire building illustrated in Figure 5.37.

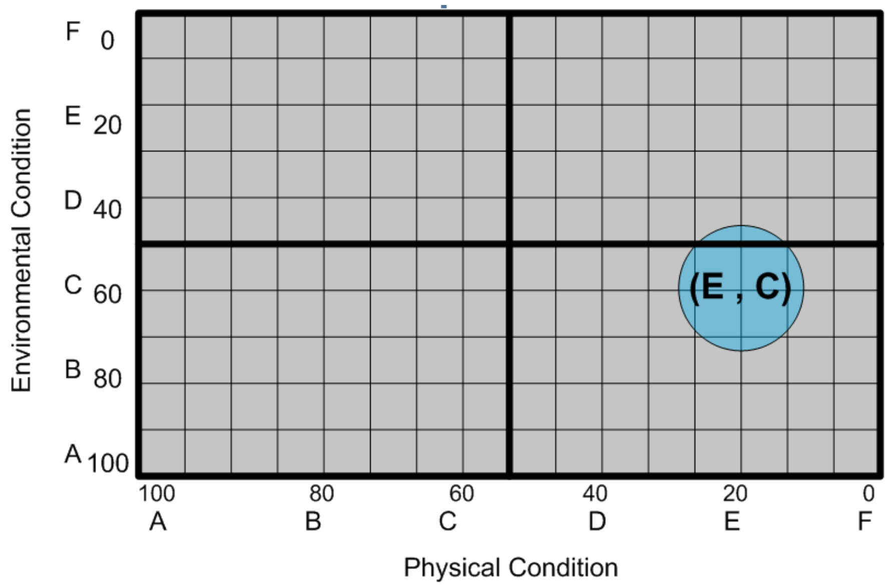


Figure 5.35 Space Integrated Condition Assessment represented in a bubble chart

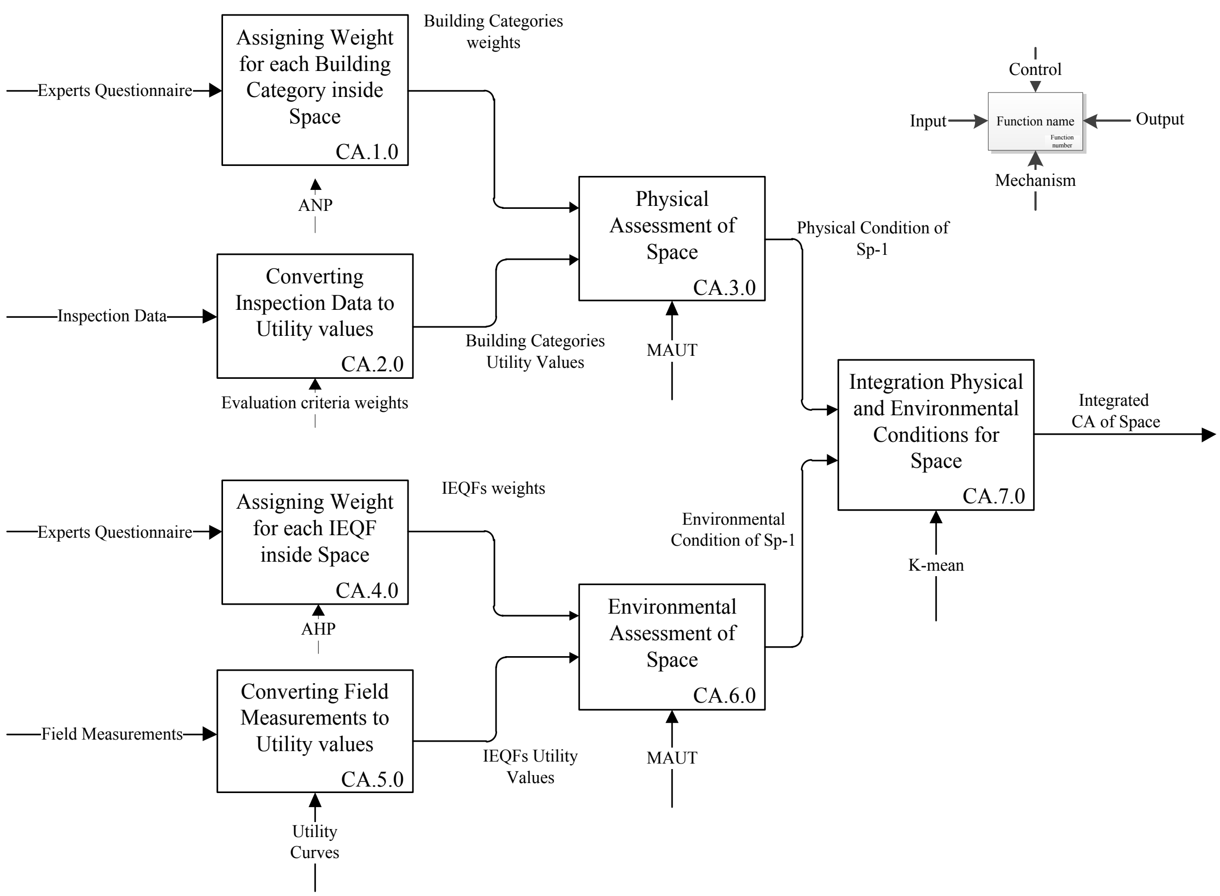


Figure 5.36 IDEF0 representation of the space integrated condition assessment process

5.4.3 Building Integrated Condition Assessment

The process of calculating the condition of a building can involve any of the following three scenarios:

i. <u>Graphical representation of the building spaces in one bubble diagram</u>

This indicates the physical and environmental conditions of the building spaces. Figure 5.38 shows the process of calculating the entire building condition assessment by combining all the spaces where each space is represented as a bubble in the bubble chart which is illustrated in finally Figure 5.39.

- The circles represent the different spaces inside the building;
- The color of the bubble represents the space type;
- The size of the bubble represents the relative weight of the space type compared to other space types in the same building; and
- The location of the circle represents its physical and environmental conditions.

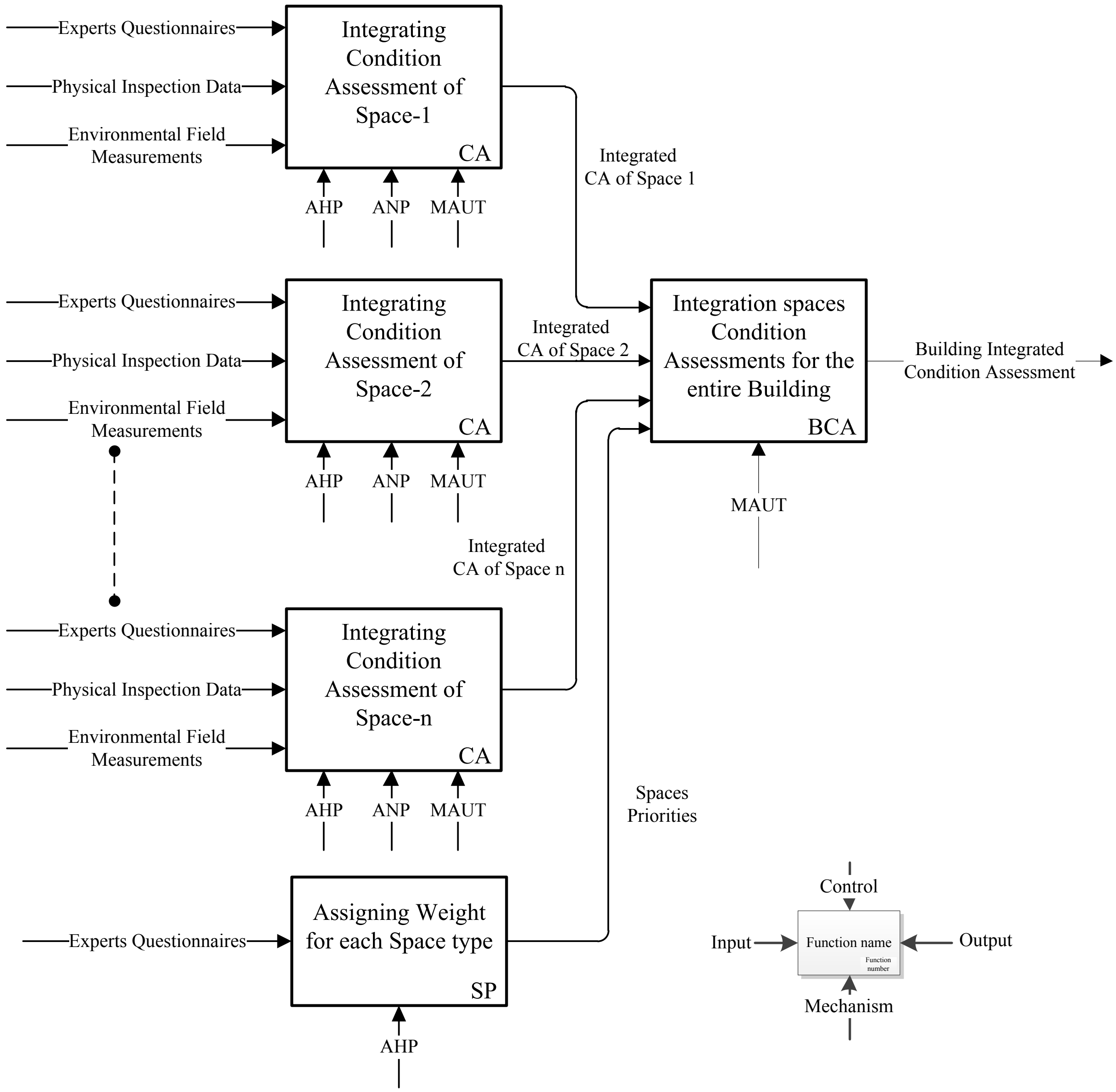


Figure 5.37 IDEF0 representation of the building integrated condition assessment process

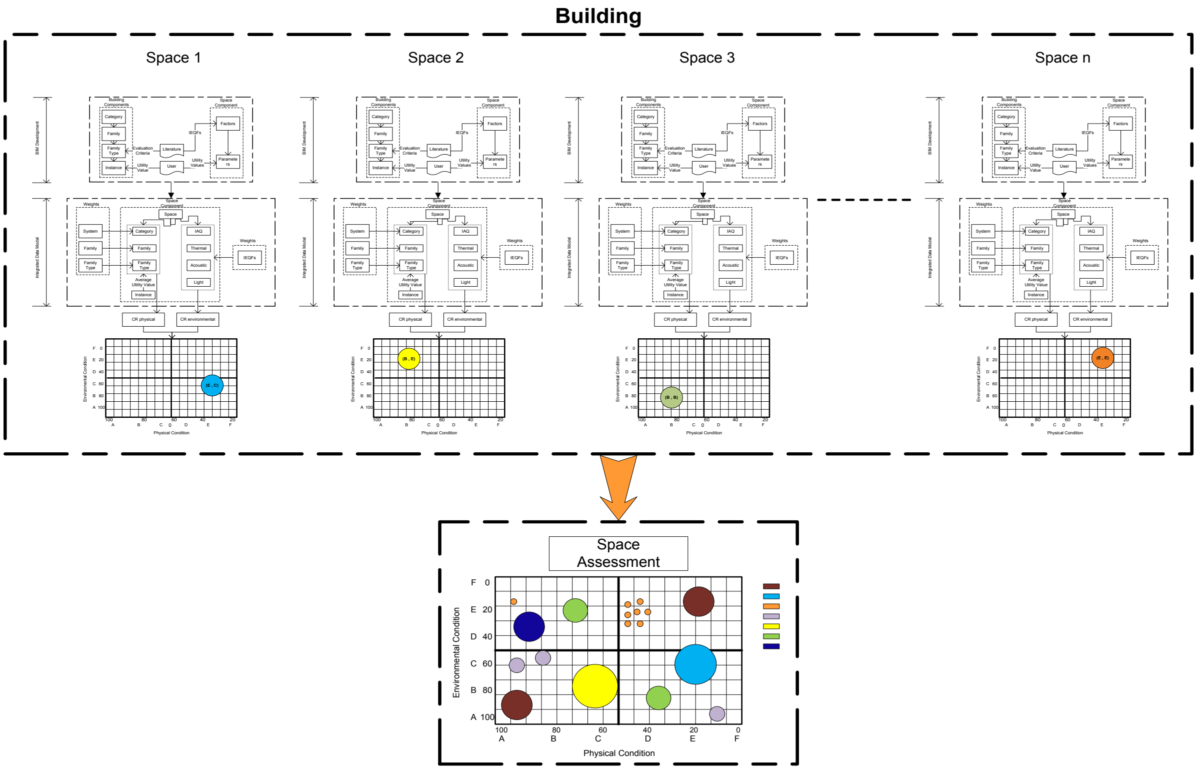


Figure 5.38 The process of assessing a whole building through its internal spaces

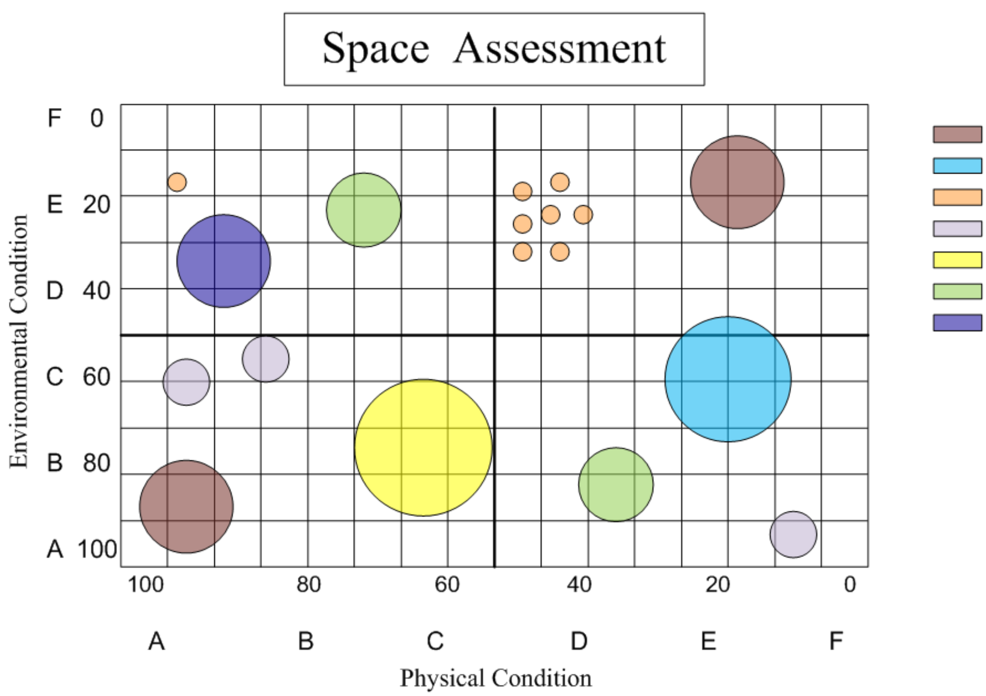


Figure 5.39 The bubble diagram shows all spaces inside the building

ii. Representing the entire building condition in one bubble diagram

- **Building Physical Condition Assessment:** A one-bubble diagram indicates how to calculate the overall physical condition of a building using the physical condition of each space and its relative weight. The following equation is used

$$\boldsymbol{PC\ (B) = \sum_{i=1}^{n} PC(SP_i) \times W.SP_i}$$

Equation 5-6

- **Building Environmental Condition Assessment:** The overall environmental condition of the building is calculated using the environmental condition of each space and its relative weight by means of Equation 5-:

$$\boldsymbol{EC\ (B) = \sum_{i=1}^{n} EC(SP_i) \times W.(SP_i)}$$

Equation 5-7

Figure 5.40 shows the process of calculating the overall physical and environmental condition of an entire building and how it is then represented on the bubble diagram.

iii. Integrating the condition for the entire building in one model

With the integrated condition assessment of each space, achieved by using unsupervised clustering, along with the relative weight of each space among others in the same building, MAUT can then be used to calculate the integrated condition assessment of the entire building using the following equation:

$$C\ (B) = \sum_{i=1}^{n} C(SP_i) \times W.(SP_i)$$

Equation 5-8

where:

$C(B)$ is the integrated condition of the whole building, and

$W.(SP_i)$ is the weight of each space inside the building.

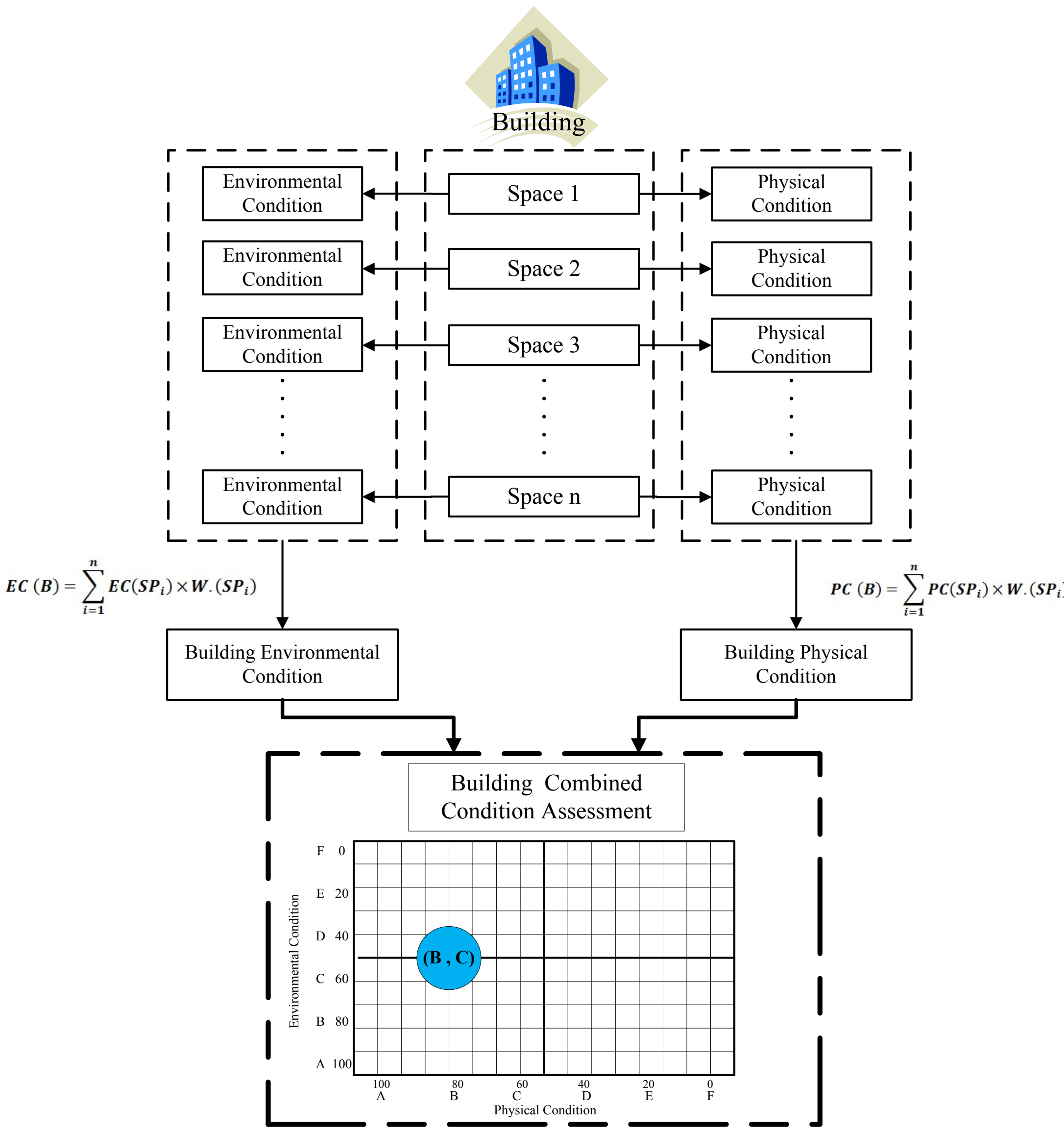


Figure 5.40 The process of assessing a building in an integrated approach

5.5 Summary

This chapter covered the BIM model development and its implementation. The first part before the model development was to check the reliability of the collected data in chapter 4. Several methods were applied for this purpose. Statistical analyses such as checking the mean, trimmed mean, median, and standard deviation in addition to Crombach's alpha were all checked and the data proved to be reliable and can be used. The next part was to calculate the relative weight of each single space inside the building using an equation that considers the relative weight of the space type which the space belongs to in addition to the space type share of area inside the building. It was found that the "classroom" space type has the highest relative weight inside the educational buildings. The next step was to calculate the physical elements relative weight through the ANP using the Super Decisions software. The next step was to calculate the IEQFs relative weights inside each space using the AHP. Finally evaluations criteria and assigning the building components condition threshold were both calculated at the end of this part. The next part was to develop the utility curves for all the IEQFs and their sub-criteria inside each space using the codes and standards. They are organizing, minimum, recommended, and maximum values and concentrations of those attributes. The next part was developing the BIM model and how the integrated condition assessment process will be implemented through a model which converts the assessment data input of inspectors into quantified values that make its calculation a (relatively) simple task. It showed also how the BIM is used throughout the model development process and how the parameters of the physical and the environmental process are added and implemented. The process of extracting data from BIM to be used in the integrated data model and the calculations processes was also illustrated in addition to the process of the data input during the inspection process. The conditions of running the model and the complete calculations and integrations process were presented.

Chapter 6: Automated tool (ICAB)

6.1 Introduction

The BIM concept has been applied by different software developers such as Revit, Bentley, ESSI, CATIA, etc. Each has its pros and cons; however, Revit's customization capabilities have been significantly extended over the past few years. Revit's .NET Application Programming Interface (API) allows users to program with any .NET compliant language including VB.NET, C#, and managed C++. Revit has thus been selected here to be customized so that the integrated condition assessment model can be applied in its API and added as a plug-In.

6.2 Tool Development (ICAB)

The integrated data model and the assessment process discussed earlier in chapter five will be implemented in this section in the context of tool development. The Integrated Condition Assessment Model for Buildings (ICAB) is the tool developed to automate the process; Figure 6.1 shows the system architecture for the development process. The application development process shown is composed of six modules that serve on all interfaces of the tool; each module contains some processes. As indicated in this figure, there are some mutual relations between the modules which illustrate how they are linked together.

6.2.1 <u>Graphical user interface:</u>

Users interact with the user interface module and input general information about the project; this information will be stored in the database as a resource for future projects and to organize historical data for the current project. This interface allows users to input the physical and environmental field measurements for each component or space inside a building, as shown in Figure 6.3. Users can insert photos of specific components and add comments or descriptions associated with each component or space inside a building. This information will be stored and attached to those components in the system database. It will be shown in the following sections how to insert comments and photos attached to each component inside a building.

6.2.2 BIM software:

The modified Revit software with the integrated condition assessment model in its API is used to develop the building model. It will feed the model with data, such as the number of spaces, the area of each space, the component families and family types, in order to identify components inside each space, recognize components shared between more than one space, etc. The BIM model should be accurate and reliable to avoid any problems and errors during the assessment process. The main model will be able to extract and store data inside the BIM software database.

6.2.3 Expert Judgment Data:

This module is responsible for preparing all of the subjective data required by the model for calculating relative weights or priorities. The facilities manager or the facilities management company will develop Pair-wise-comparisons (PWCs) for the physical components, environmental quality factors, and spaces types inside a building to determine the relative weights of each as a function of the building type. This module is also used to develop PWCs for the evaluation criteria used to assess the physical components and to use with the environmental quality factors' codes and guidelines to develop the utility curves that will be used in the MAUT to convert the field measurements to utility values.

6.2.4 Database:

Data input by the user(s) and data converted or calculated by the model will be stored in this database module. The stored data can be reused by the model during the reporting process, as well as being treated as historical data used in the process of calculating the deterioration curves of the different building components.

6.2.5 Model:

The model module is composed of three parts. The first is the automatic detection processes, through which the model will automatically detect the building's floors, spaces and the physical components inside each space as well as their IDs from the BIM software. This detection process then assigns the environmental evaluation's attributes for each space inside the building. The second part contains the preparation processes, which subjective assessment will be converted to weights using the AHP technique. Field measurements will be converted into utility values using utility curves (equations). The relative weights of each space inside the entire building will be calculated by using the space's areas and the PWCs to determine spaces' priorities. The third part is the calculation processes, in which the spaces' physical and environmental conditions are calculated with the MAUT technique. Using the unsupervised K mean, an integrated condition assessment of each space is calculated. Finally, the integrated condition assessment of the entire building is calculated.

6.2.6 Reporting:

This module is responsible for reporting the results of the model in the form of graphical or numerical representations. Graphical representations are curves and bubble diagrams; while numerical representations are in the form of numbers and tables.

The program was developed using an object-oriented programing language, c#, and Figure 6.2 shows ICAB object model diagram and the relations between the different classes.

Figure 6.3 shows a snapshot of the application interface. The spaces detected inside the building are shown on the left side of the snapshot. The components inside each space are also shown in this snapshot. On the right side of the snapshot the measured physical and environmental assessment data can be assigned to each component and space during data input.

Environmental field measurements are input during the inspection process according to the assigned units for each environmental quality factor. Physical component inspection data are input by either the direct condition rating or by means of the components' evaluation criteria. Figure 6.4 shows how the inspector will be inputting data into his tablet PC on the ICAB application in a very simple, accurate, and rapid manner.

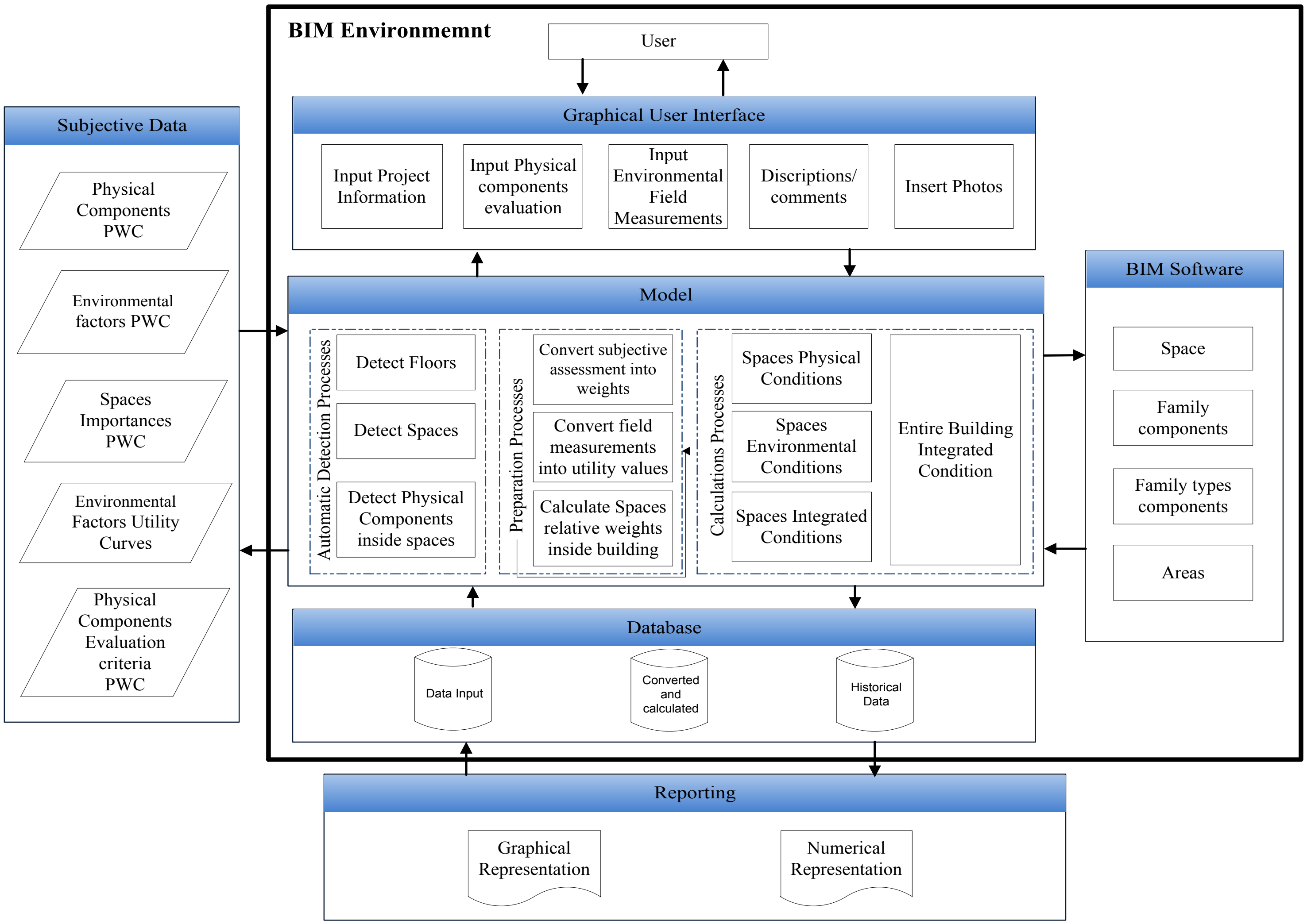


Figure 6.1 System Architecture

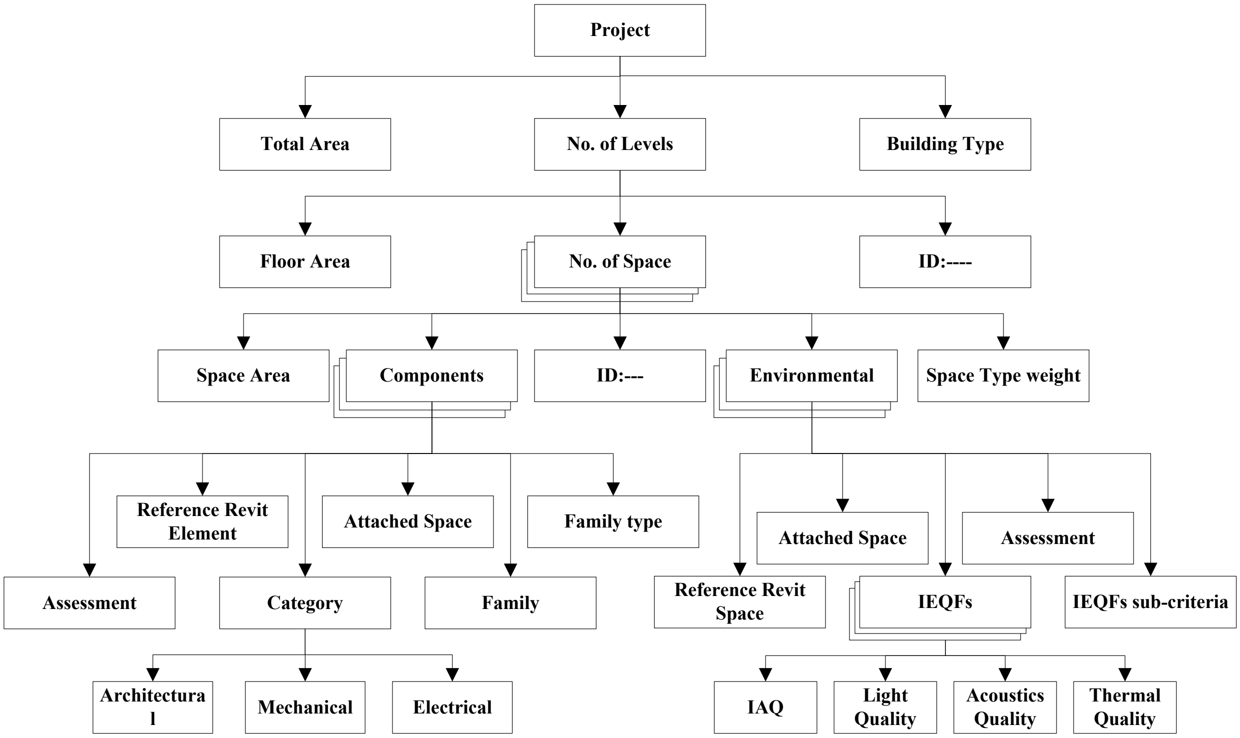


Figure 6.2 ICAB object model diagram

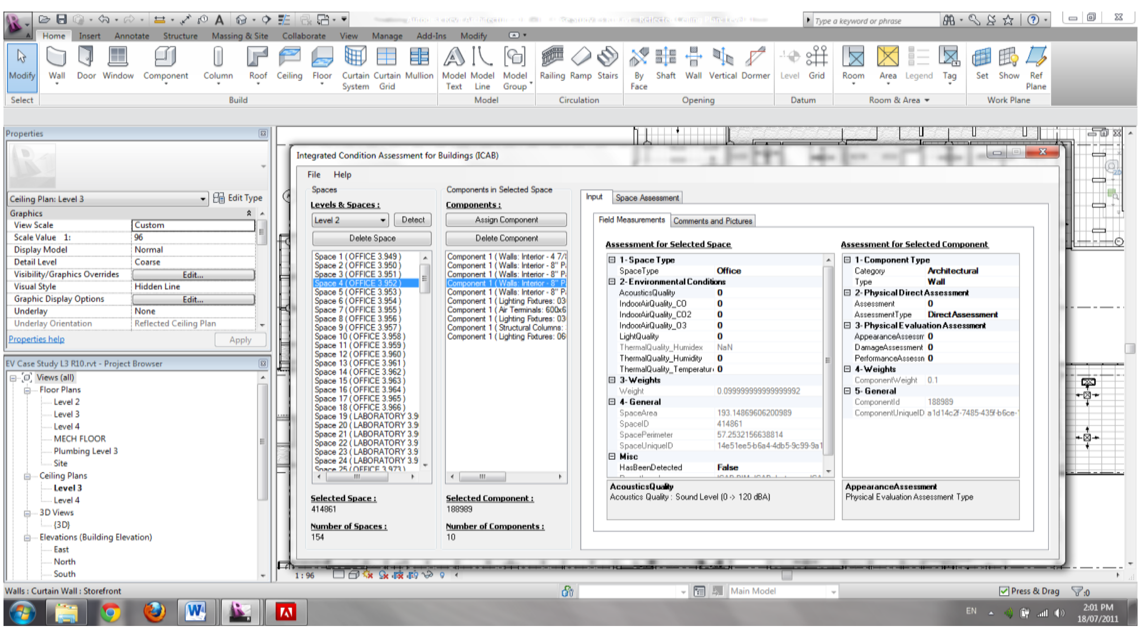


Figure 6.3 User interface

Figure 6.4 Inspector holding tablets PC with the ICAB application

The overall condition rating of any component will be automatically calculated if the evaluation criteria method is selected, using the relative weight of each evaluation criterion assigned from the expert judgment data. A user will be able to take or browse any photo from the computer and assign it to any component; moreover, users can write and assign any comment or description to any component, as shown in Figure 6.5.

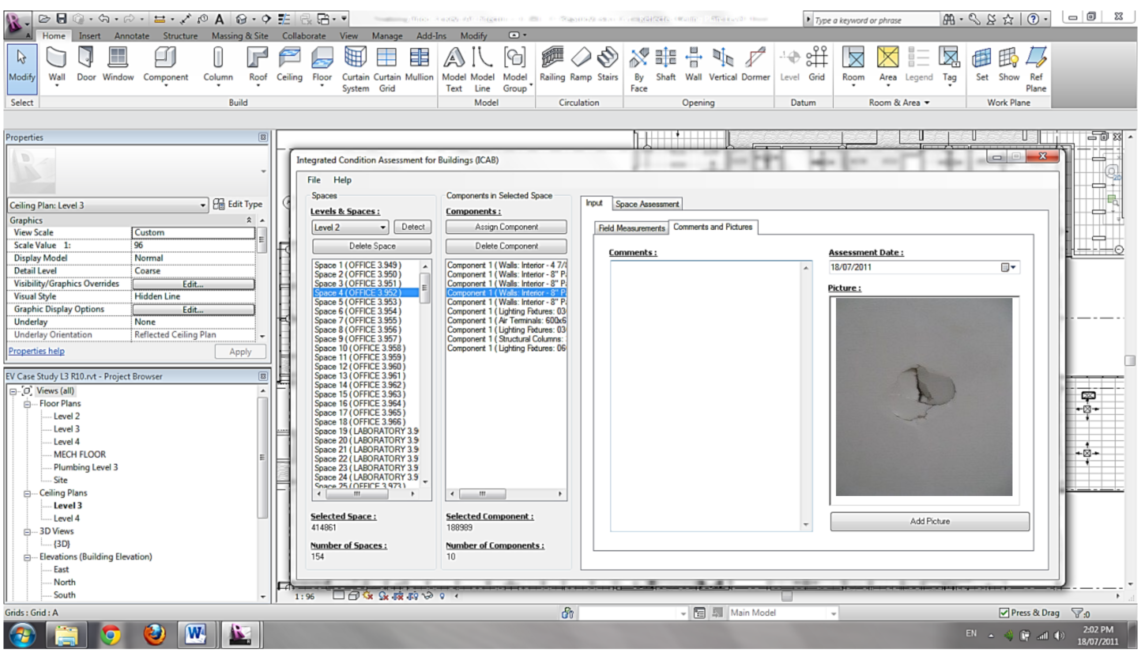


Figure 6.5 The capability of adding photos and comments and of attaching them to any component

6.3 ICAB Implementation to case study

6.3.1 Building the case study model

A BIM model was developed as a part of the model testing procedures followed by the methodology validation at the end of this chapter. The BIM model is based on the available plans (architectural, mechanical, electrical and plumbing). All the required data were available in .pdf files (2D format). Revit© software was used to develop the BIM and all of the missing data were assumed. All of the construction data, such as the components' materials as well as their specifications were either available in the documents, or assigned during site visits to the building. Data was assumed if they were hard to be found. Since the design components have parametric relationship with each other, the sections, elevations, and perspectives were generated automatically, as shown in Figure 6.6. Spaces were assigned and tagged in accordance with the building site visits and observations.

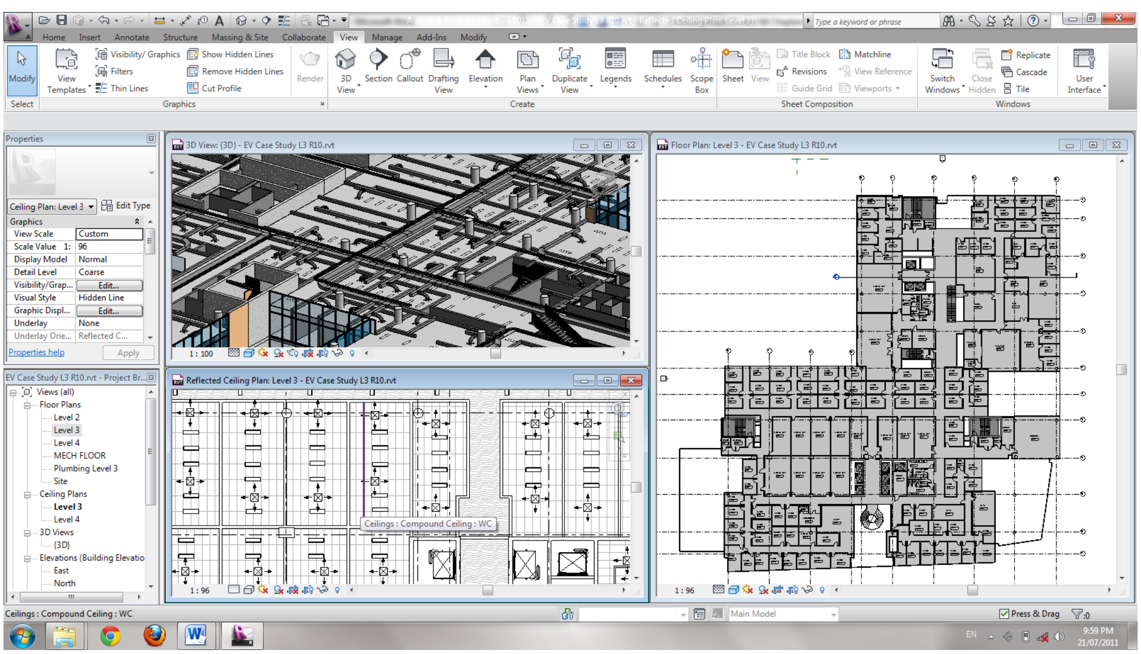


Figure 6.6 Building the case study model

6.3.2 Creating a new project

After creating the BIM model, the second step is to start the building condition assessment process. The ICAB is added to the Revit system in the Add Ins menu; to start the integrated building condition assessment, the user needs to start the ICAB while the required Building file is opened in Revit, as shown in Figure 6.7.

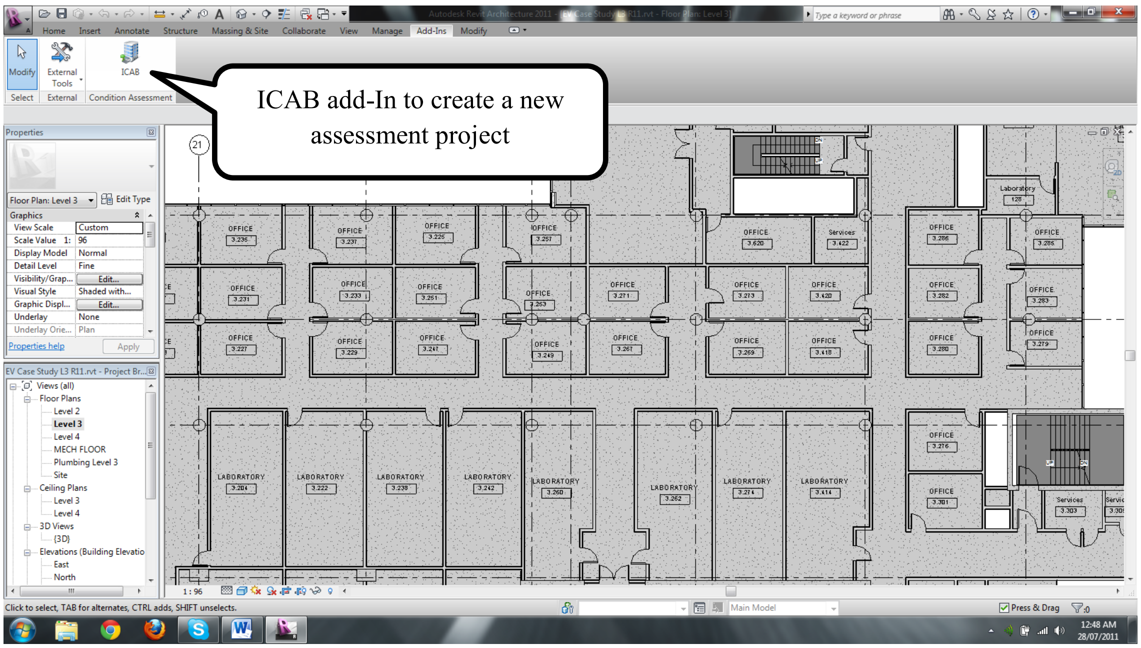


Figure 6.7 ICAB add-in for creating a new building assessment project

6.3.3 Selecting the assessment date and the project detection process

After starting the ICAB, the user is required to press on the “detect” command for the model to start detecting the different floors and spaces inside the building, as shown in Figure 6.8. The ICAB will begin, and assign the date of the inspection process. The user may also change the date and assign a different date. All of the inspection process and the data input for this purpose will be attributed with the assigned date. This date is very important in calculating the deterioration of the components inside a building, as indicated in the following steps.

6.3.4 Assigned components inside each space

After completing the detection process, all the physical components inside the space will be automatically assigned and attributed to the space they belong to. Architectural, electrical, mechanical, and structural components inside the space will be added, and the user can also assign any component he/she views as related to any particular space. The components added into each space are those components that will be assessed; the space's physical condition will be determined according to their condition. Figure 6.8 shows the window of the menu for the components assigned to each space.

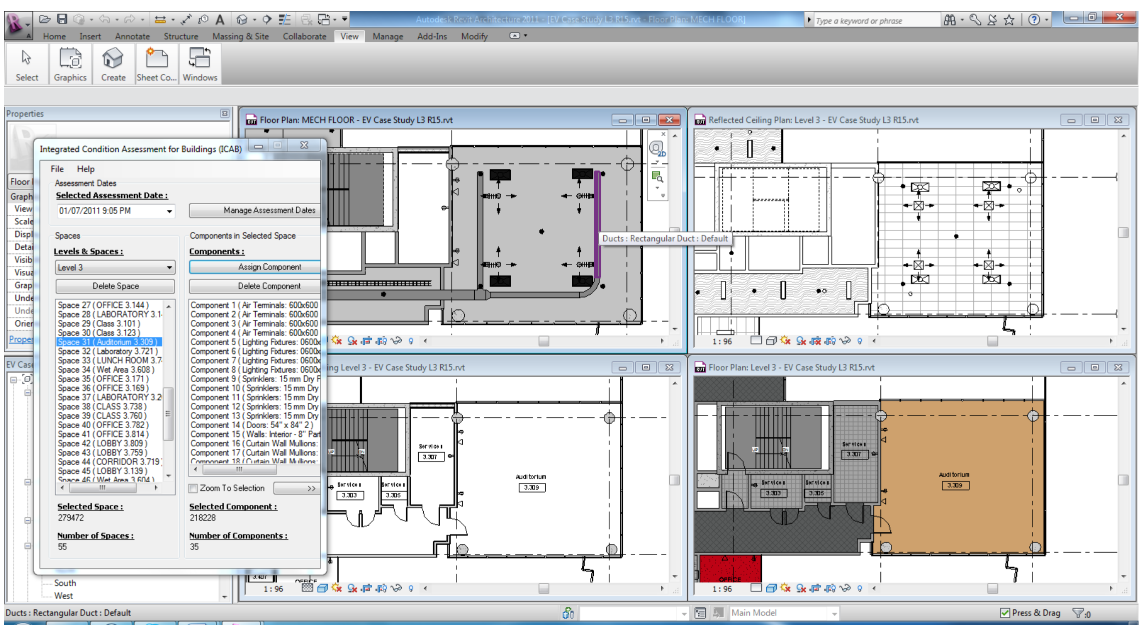


Figure 6.8 The menu window of the components assigned to each space

6.3.5 Physical and Environmental field measurements input

The process of inputting the physical and environmental field measurements is shown in Figure 6.9. Each of the indoor environmental quality factors has its own attributes; the inspector is required to make his/her field measurements using the required device and input the data in the data input window according to the inscribed units. The environmental quality factors and their sub-criteria are all automatically attributed to each space once it is detected by the model from the BIM software.

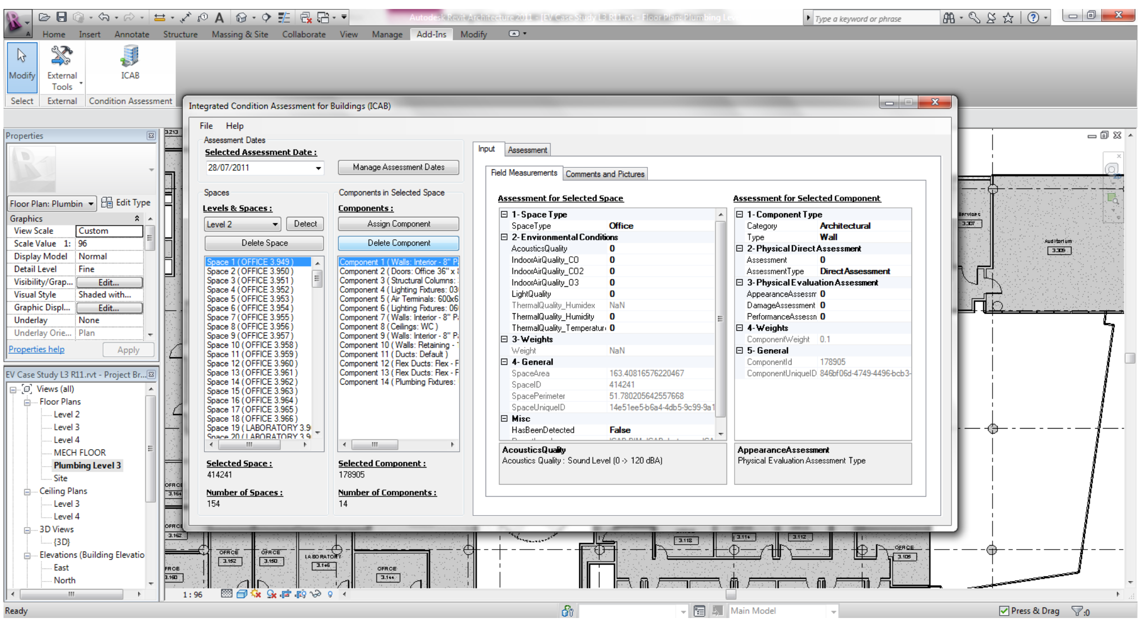


Figure 6.9 Physical and environmental field measurements data input

The model provides a range for each attribute value and recognizes incorrect values that are out of the possible ranges. For example, if an inspector tries to input an amount of sound level greater than 120 dbA or a negative sound value that value will not be accepted. On the other hand, the inspector is required to apply his/her judgment to all the physical components inside the space using any of the predefined methods. These will become the direct condition ratings, for which he/she will be required to give an overall evaluation to each component inside the space or to judge the three evaluation criteria: performance, damage and appearance.

6.3.6 Building & spaces condition assessment calculations, Results, & discussions

<u>Spaces' condition calculations:</u> After inputting all the required physical and environmental field inspection measurements, the next step is to calculate the condition of each space and the condition of the entire building, physically and environmentally. Pressing on the "Start Condition Assessment" button launches the automatic processing of these calculations. As seen in Figure 6.10, the bubble diagram is developed automatically and all the spaces are plotted in the form of bubbles; the x-axis represents the physical condition and the y-axis represents the environmental condition. Each space type has its own bubble color and the size of the bubble represents the relative importance of the space in this particular building.

All floors can be represented in one bubble chart; however, the user can plot each floor in a separate bubble chart to facilitate the visual process. The user will also be able to track the exact problem for the physical and the environmental conditions of the space through the second level, which is the sub-criteria level in the tabular form of the assessment as shown in Figure 6.11.

The physical categories (architectural, mechanical, and electrical) are indicated, in addition to a visual tracking the condition of the third assessment level, the families (for example, doors and walls in the architectural category).

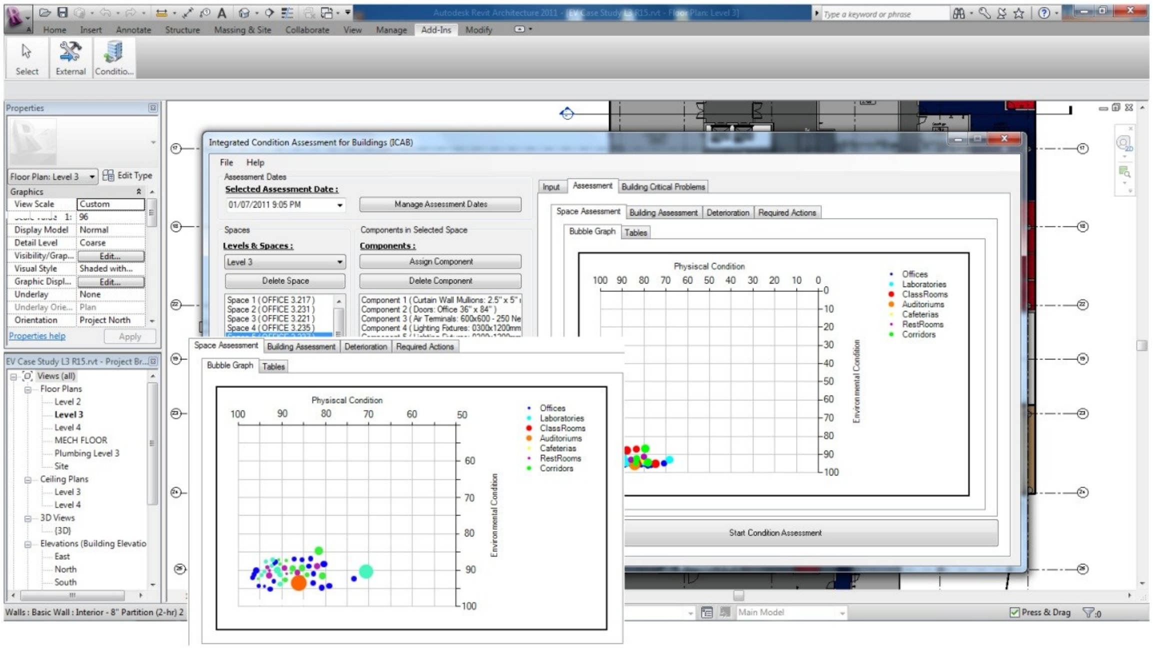


Figure 6.10 Developed bubble chart representing condition of spaces inside the building

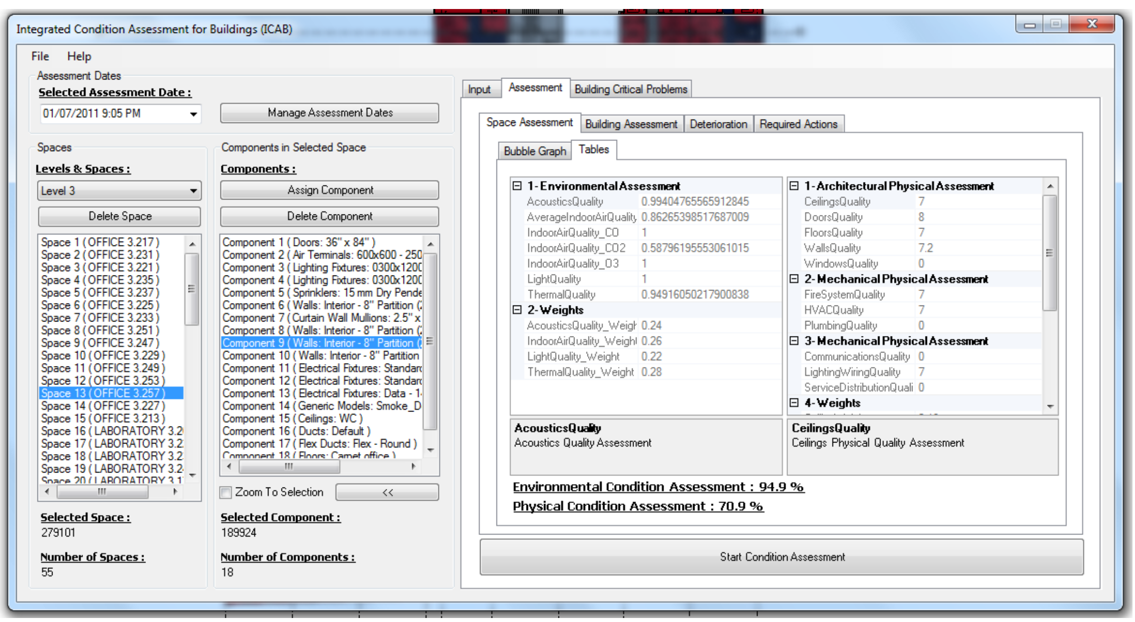


Figure 6.11 The condition of spaces inside the building represented in tabular form

By pressing on the tabular tab, the assessment results will be presented in the form of tables so that the user can check the condition assessment of all of the components. The user also can return back to the input tab to see the inspector's assessment for each component and where the exact problem with a given component lies, to help deduce the cause. It is even possible to know the exact problem of a component if it is part of its performance, appearance, or if it has any kind of damage.

Building condition calculations: The next tab is for "Building Assessment". The physical and environmental conditions of the entire building are represented in this "tab" in numerical and graphical format. The integrated condition assessment calculated using the K-mean clustering technique is also represented in this tab. Figure 6.12 shows the entire building's physical, environmental, and integrated conditions. As indicated in the figure, the physical condition is 84.33% while the environmental condition is 93.60%. The integrated condition of the entire building is 89.43%, calculated using the K-mean clustering technique explained previously.

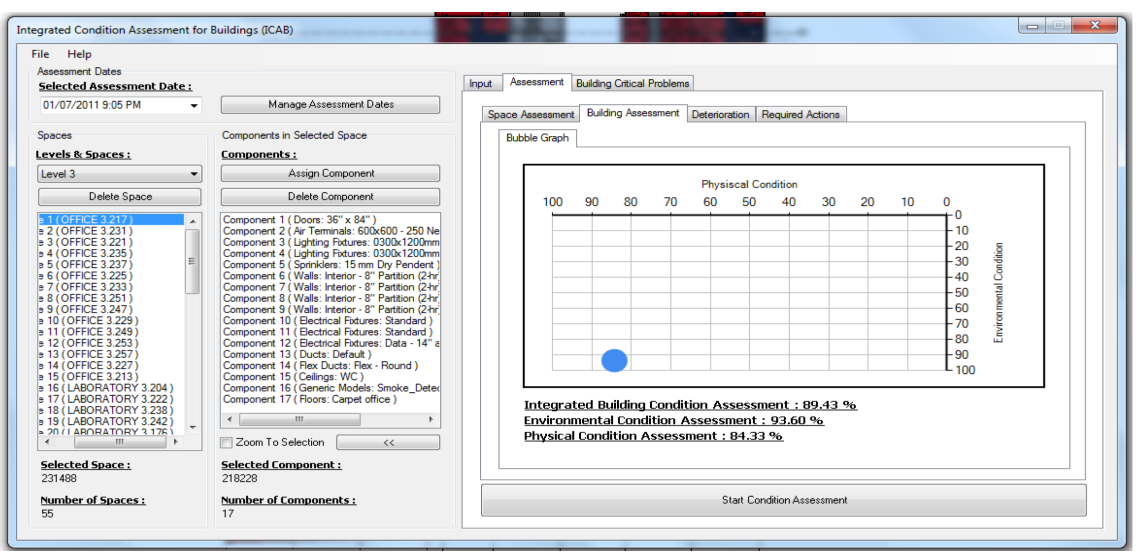


Figure 6.12 Entire building's physical, environmental, and integrated conditions

6.3.7 Deterioration Calculations

This portion explains the process of calculating the deterioration of each component inside a building as well as the deterioration of the space as a whole. By recording the inspection process and the physical and environmental measurements and assigning a date, the model can be used as a database for historical data that can be used in the process of predicting the deterioration and performance of a building and its components. Based on the life span of each component, it was assumed that the condition of a component will be poor (20%) at the end of its useful life. Straight line deterioration was assumed in order to assume that the condition of a building's component to predict the condition of the building in the years 2016 and 2030 using Table 5-22 and Table 5-23. In the 2011 records, real data from field measurements were applied. Figure 6.13 shows the process of plotting the condition a space physically and environmentally and indicates that the physical and the environmental conditions of the space deteriorate over time if only regular maintenance is applied. Figure 6.14 shows the process of plotting the deterioration of a component in the building. Historical data will be then used to correct the intermediate condition of every single component and system inside the building by updating the deterioration curve with the current condition. Figure 6.15 shows the integrated, physical and environmental conditions, for all building spaces and for the entire building, calculated by using the individual useful life of each component.

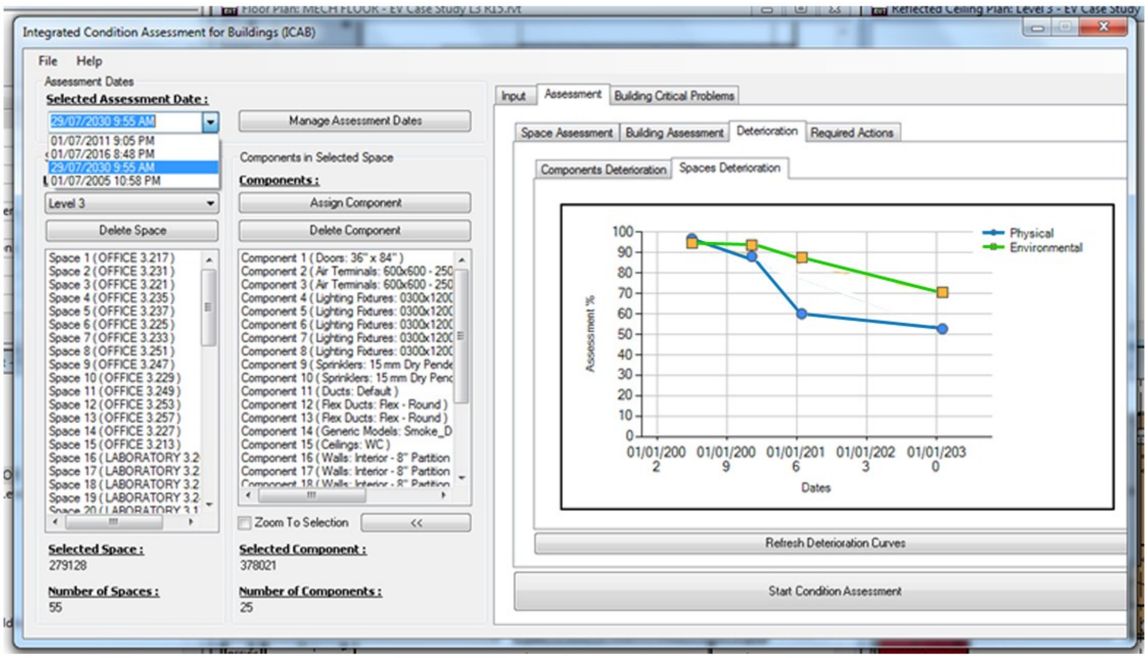


Figure 6.13 The physical and environmental condition deterioration of spaces

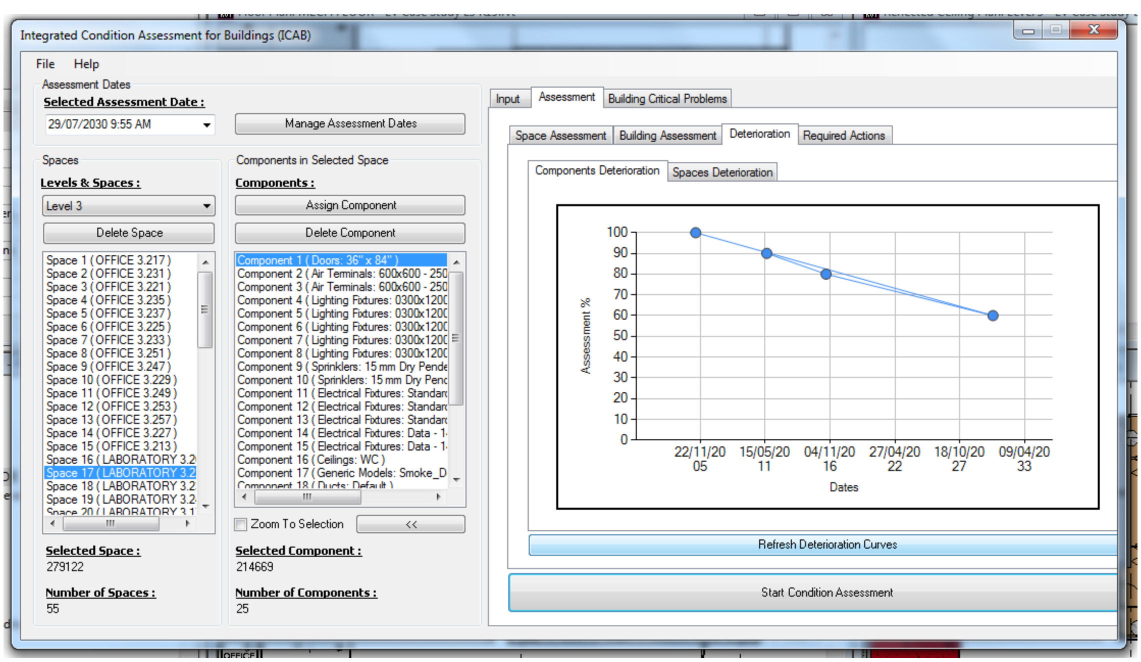


Figure 6.14 Deterioration of the component's physical condition

6.3.8 Building Critical Problems and Required Actions

The third higher tab in the software is the “Building Critical Problems”. In this tab, critical problems inside spaces are reported. Components having conditions below the threshold assigned by the experts are reported as components that have unsafe physical condition. The components are reported with their IDs inside the BIM model, the dimensions, and the date of their inspections in order to facilitate the next process if corrective maintenance is required. Additive models used in the MAUT calculate the condition of the categories, spaces, and thus the building using the weighted average; which might not show problems of components that by having critical problems or spaces having dangerous indoor air quality which will affect the safety of the building occupants. In this part unsafe conditions of critical components are reported as red light for the facility manager to take a quick or instant action.

Figure 6.16 shows the critical physical or environmental conditions for spaces and components and Figure 6.17 shows the window of the required action assigned for each component developed from the building component physical condition index.

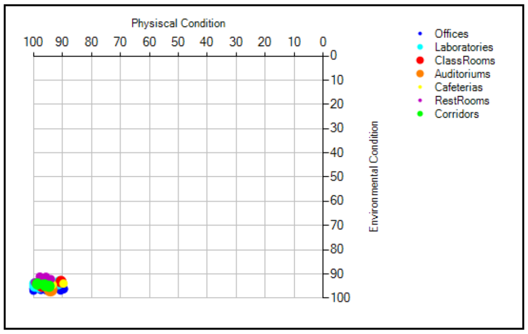
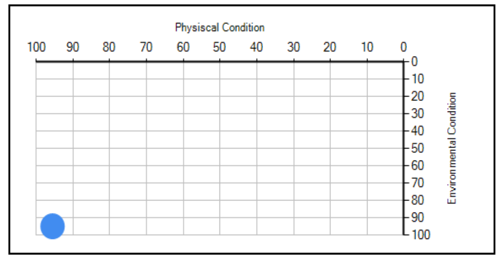
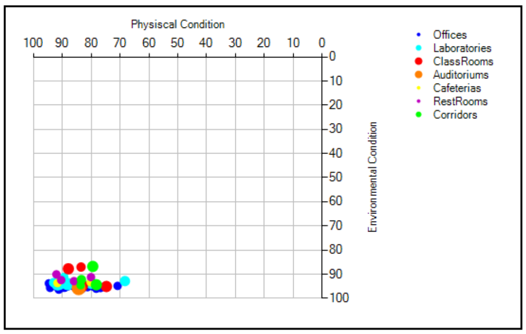
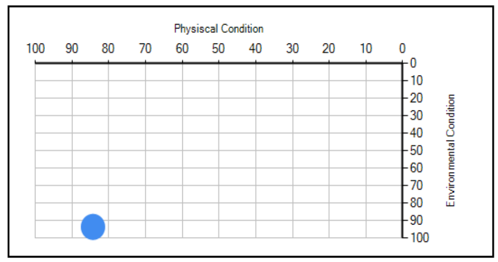
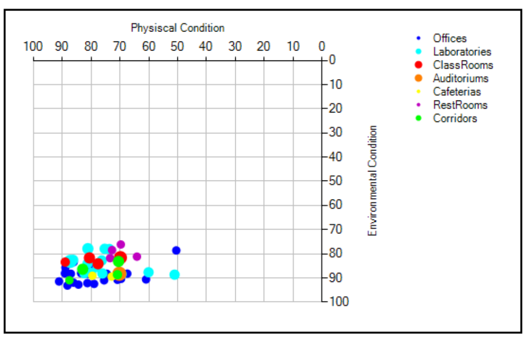
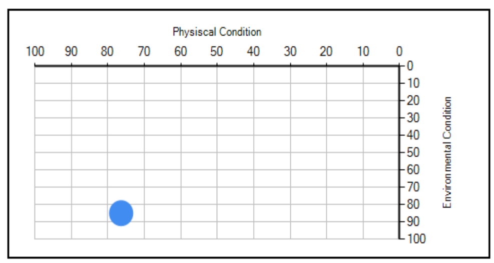
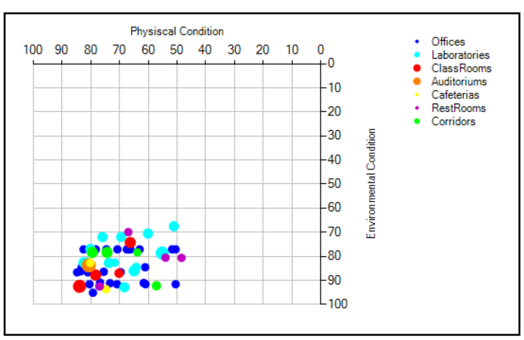
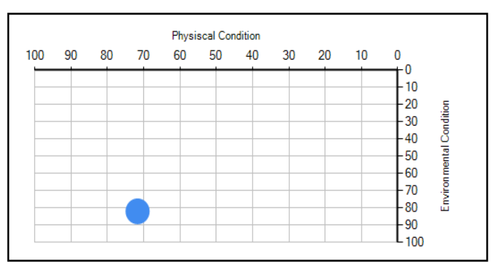
Year	Spaces Condition	Building Condition
2005		 Integrated Building Condition Assessment : 95.20 % Environmental Condition Assessment : 94.89 % Physical Condition Assessment : 95.58 %
2011		 Integrated Building Condition Assessment : 89.43 % Environmental Condition Assessment : 93.60 % Physical Condition Assessment : 84.33 %
2016		 Integrated Building Condition Assessment : 81.10 % Environmental Condition Assessment : 84.96 % Physical Condition Assessment : 76.37 %
2030		 Integrated Building Condition Assessment : 77.39 % Environmental Condition Assessment : 82.04 % Physical Condition Assessment : 71.70 %

Figure 6.15 Spaces and Building Conditions deterioration over time

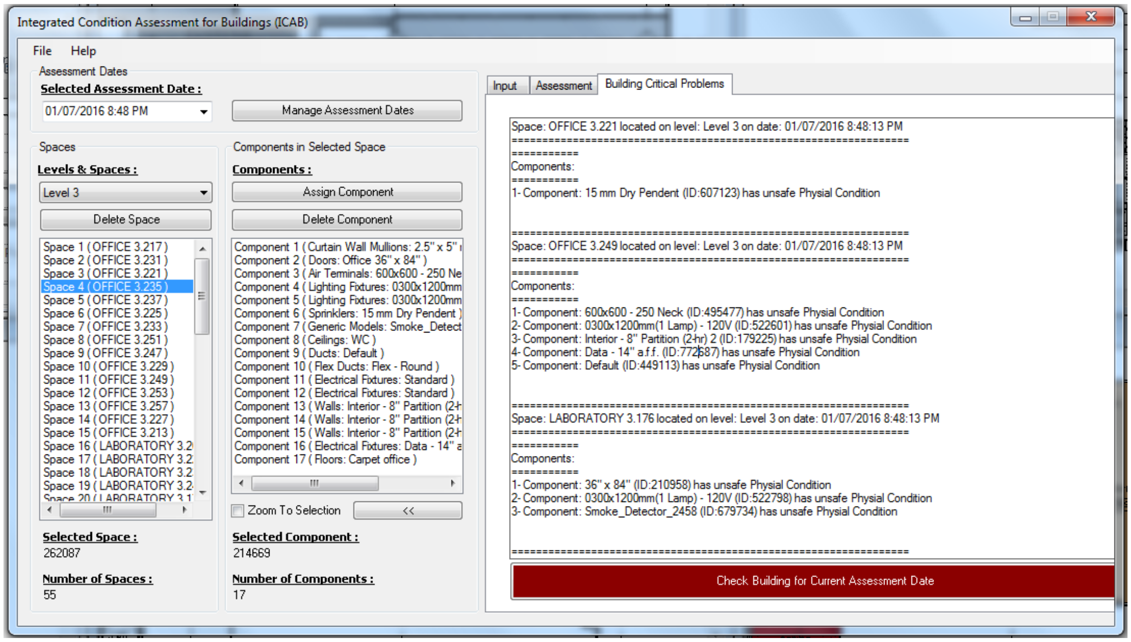


Figure 6.16 Critical physical or environmental conditions for spaces and components

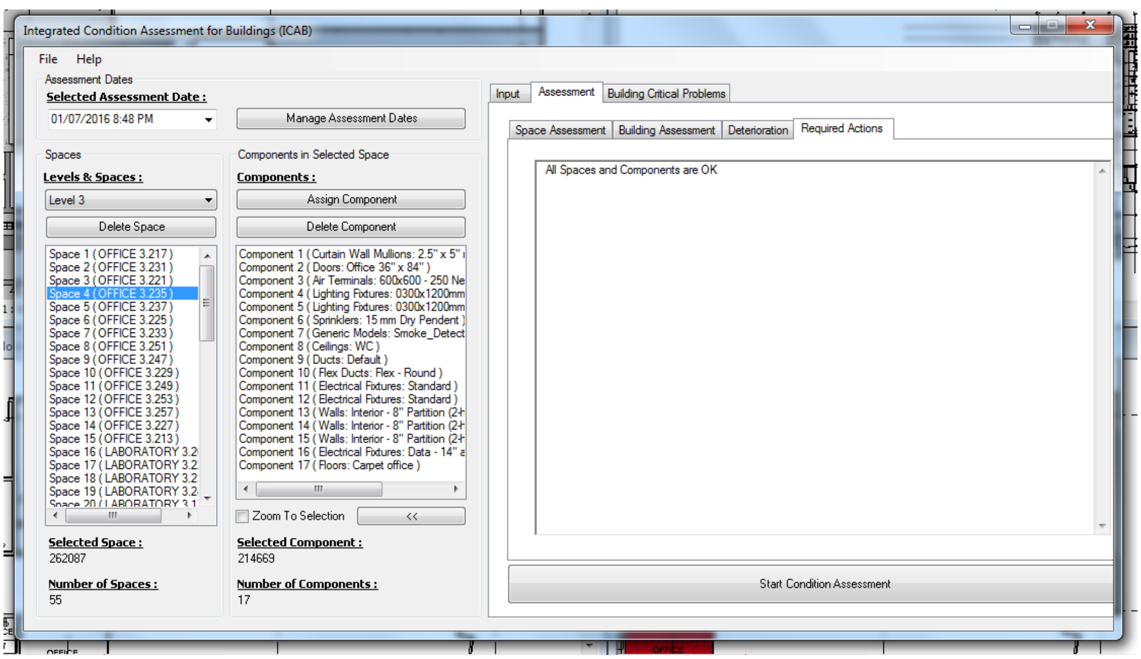


Figure 6.17 Required action window as a quick guide line for the facility manager

6.4 Model Validation

The case study results were validated by comparing the results of the building condition assessment calculated using the proposed model with the results of the building condition assessment conducted by a team of building facilities managers. A report was prepared for the current condition assessment of the floor by the facilities management team showing the problems in the physical condition of some components such as damaged gypsum walls, damaged doors, some walls that required painting, cracks in the floor, missing ceiling tiles, burnt lights, etc. The team was directed to provide an entire floor condition assessment grade from "0" to "100", with "0" representing failure and "100" an excellent case. They calculated the overall floor condition to be "85%".Interestingly, step by step calculation following the research proposed model during the model testing stage on the case study arrived at an assessment of "84%" for the current physical condition of the floor It is clear that the two results are almost identical; however the current environmental condition of the floor calculated using the proposed model for the floor indoor environmental quality was "93%". The integrated floor condition, which is the integration of both the physical and the environmental conditions using the K-mean clustering technique, is "89%". This change is attributed to the contribution of the environmental condition to the integrated one. As represented here, the environmental condition of the floor was a reason to raise the overall integrated condition; if the environmental condition was less than the physical one it would have caused the integrated condition to drop and becomes lower than the physical condition.

6.5 Validation of the proposed Methodology

Validating an information system, new methodology, or design technique is a problematic issue; as there is typically no theory, no hypothesis, no experimental design, and no data analysis to which traditional evaluation criteria can be applied (WEBER, 1997). Rescher (1997) stated that human knowledge consists of two types: (1) Theses or "knowledge that" which defines statements or assertions about the world; and (2) Methods or "knowledge how" which defines ways of doing things. Scientific research has been primarily focusing on propositional knowledge, which is "knowledge that", as it is generally about establishing the truth of particular propositions (hypotheses). He added that methods have no truth value but only a practical value. This means that a method does not describe any external reality, since it cannot be true or false, but it can only be effective or ineffective. In other words, any method can only be established by its applicative success in practice; so validating a method should not be to demonstrate that the method is "correct" but that it would be a rational practice to adopt the method based on its practical success. Moody et al. (2003) defined Pragmatic or practical success as "the efficiency and effectiveness with which a method achieves its objectives". They developed an evaluation framework that was specifically conceived for IS design methods, the Method Evaluation Model (MEM). The core of the MEM is called the Method Adoption Model (MAM). The MAM is based on the constructs and relationships of Davis' Technology Acceptance Model (TAM) (Davis, 1989), which is an evaluation framework for information technology in general. Figure 6.18 shows the constructs of the MEM and the causal relationships between them. Although the MEM considers adoption in practice as the ultimate criterion of a method's success, other variables can be measured and evaluated to predict the likely acceptance of a method. One of these variables is efficacy, which combines efficiency (the extent to which a method reduces the effort to perform a task) and effectiveness (the extent to which a method improves the quality of the result) (Moody et al., 2003). Thus task performance can be improved in two ways:

- Efficiency improvement: by reducing the effort required to complete a task; and
- Effectiveness: improving the quality of the result.

According to the literature, Moody et al. (2003)'s theoretical model has been adopted in order to validate the methodology and the information system design based on the following attributes:

- **Actual Efficiency:** the effort required to apply a method'
- **Actual Effectiveness:** the degree to which a method achieves its objectives;
- **Perceived Ease of Use:** the degree to which a person believes that using a particular method would be free of effort;
- **Perceived Usefulness:** the degree to which someone a person believes that a particular method will be effective in achieving its intended objectives;
- **Intention to Use:** the extent to which a person intends to use a particular method; and
- **Actual Usage:** the extent to which a method is used in practice.

This approach is used due to the absence of a formal integrated condition assessment model that considers both physical and environmental aspects that the proposed model can be compared to, as well as the absence of previous models that assess buildings according to internal spaces.

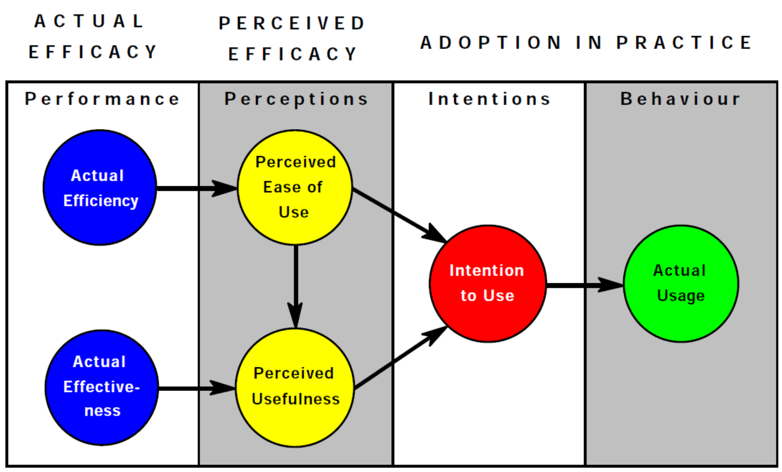


Figure 6.18 Method Evaluation Model (Moody, 2003)

The method evaluation model is implemented through a structured interview with facility managers employed at the University of Montreal. Recently, the university has been working on implementing BIM technology for managing all of its buildings on its two campuses. A complete presentation showing the objectives, methodology, model results, model flexibility, and benefits was conducted first for the entire model and then for the automated tool, followed by a session of questions where they showed interest in the idea, methodology, and its importance. Finally, they completed a questionnaire (Figure 6.19) that asked these experts to provide an assessment of the model according to the previous attributes. Each expert was required to enter responses in the individual cells indicating his assessment of each attribute on a scale from “does not meet my expectations” to “Exceptional”.

Attribute	Please check (√) in the right scale					Explanation
	Does not meet expectations 0%	Below expectations 25%	Meets expectations 50%	Above Expectations 75%	Exceptional 100%	
Actual Efficiency						The effort required to apply a method.
Actual Effectiveness						The degree to which a method achieves its objectives.
Perceived Ease of Use						the degree to which a person believes that using a particular method would be free of effort
Perceived Usefulness						The degree to which a person believes that a particular method will be effective in achieving its intended objectives.
Intention to Use						Intention to Use: the extent to which a person intends to use a particular method.
Actual Usage						The extent to which a method is used in practice.

Figure 6.19 Questionnaire Form for the Methodology Validation

The collected responses were analyzed to give a general overview on how the industry will react towards the new condition assessment methodology as well as to the automated tool. Figure 6.20 illustrates the responses' mean values for the six attributes used to validate the methodology.

The results illustrated Figure 6.20 show that all the attributes' scores passed the intended research target, which was to meet expert's expectations. Four attributes went beyond that to an "above expectations" score, one had a score of "87.5", which is higher than the "above expectations" score, and one had a lower score. Therefore, the methodology, model, and the automated tool have all proven to have a potential to be used as a condition assessment model in the facilities management phase.

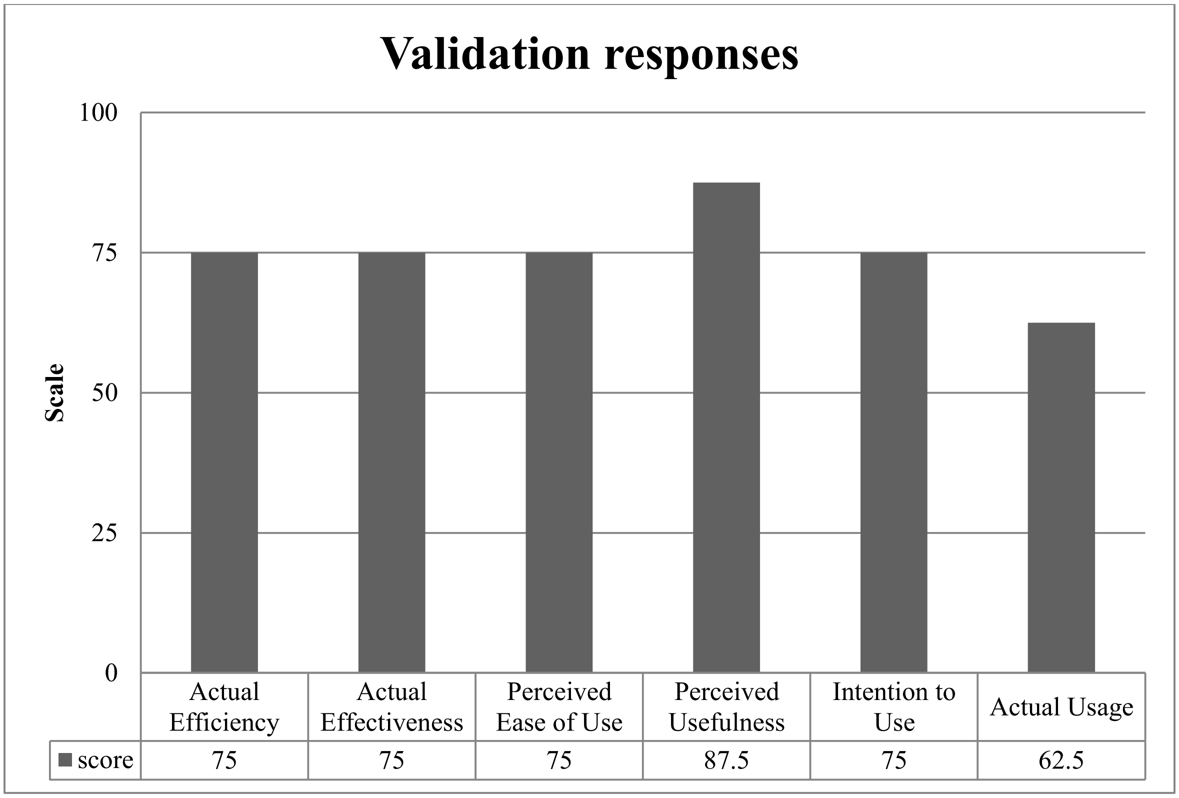


Figure 6.20 Experts' responses validating the model

6.6 Summary

This chapter presented the automated tool “Integrated Condition Assessment Model for Buildings” (ICAB) which was developed using the C# in Revit’s .NET Application Programming Interface (API). It was selected to be customized so that the integrated condition assessment model can be applied in its API and added as a plug-In. The built system architecture is composed of six modules that serve on all interfaces of the tool; each module contains some processes and there are some mutual relations between the modules which illustrate how they are linked together. A BIM model was then developed based on the available plans (architectural, mechanical, electrical and plumbing). All the required data were available in .pdf files (2D format). Revit© software was used to develop the BIM and ICAB was implemented to the selected case study as a proof of concept and for the purpose of testing the model. Most of the features of the ICAB were presented, showing how to input the field measurements, the calculations processes, final results different formats, tracking components and spaces deteriorations, required actions, etc.

Chapter 7: Conclusions, Limitations & Future Research

7.1 Research Conclusions

This research proposes an Integrated Condition Assessment Model for Educational Building that considers buildings' physical and environmental aspects. The research methodology is based on managing a building according to its spaces; so that space is the major research element, evaluated according to its internal physical elements as well as the quality of its indoor environment.

Several types of surveys, including unstructured, semi-structured, and structured interviews with questionnaires, were conducted in order to assign the most important factors affecting buildings and their occupants. Data collected from the questionnaires were verified for reliability and then used in the model development process; the value of Cronbach's Alpha varied between "0.41" (minimal reliability) to "0.988" (high reliability), with an average reliability of "0.70" (acceptable reliability). The data analysis showed that the relative weights of spaces vary in accordance with building type. For example, the "classroom" space type, which is the main element that hosts most of the education processes, had the highest relative weight, and followed by the "laboratories", while the "office" space type's relative weight was the Lowest among all the space types. In addition to the building categories, the sub-categories and IEQFs are different from one space type to another, which proves the hypothesis that a space's function and the tasks conducted within it affects its importance. For example, the relative weight of the mechanical system in a space such as a "laboratory" is higher than in a "class". In auditoriums the acoustics quality was proven to be the most important factor due to the criticality and complexity of acoustics design in an auditorium. For "Restrooms", “Laboratories”, and “Lunchrooms”, IAQ was the most important aspect and so had the highest relative weight.

The Analytical Hierarchy Process (AHP) and the Analytical Network Process (ANP) were used to calculate the relative weights of all the assessment attributes. ANP provided an improved, effective, and realistic approach to assess building components’ relative weights inside spaces, and then to roll these up for the entire building. It was used when it was necessary to address the interdependencies between building components, which means that the deterioration of one component may affect the condition of another component, and this deterioration varied in different space types. The results of this research draw the attention on the importance of building components in different spaces. This should guide further design and construction processes, as well as helps in prioritizing different processes in the facility management phase. Using codes, standards, and guidelines values of each IEQF sub-criteria were calculated along with the utilities value calculated using previous researches that linked the relation between users’ acceptances and the measured values of each attribute.

The Multi Attributes Utility Theory (MAUT) was selected to calculate the physical and environmental conditions of each space as it seeks to measure these values, one dimension at a time, followed by an aggregation of these values across the dimensions through a weighting procedure. One of the downsides of the MAUT is that it may mask sometimes the condition of any component in the facility examined; this problem was addresses in this research using a critical threshold for each component. These critical thresholds will raise a flag if any component’s condition has dropped below the threshold as it is an occupant safety issue; these thresholds were applied on both physical and environmental assessments process. “K-mean” clustering, which is one of the most popular unsupervised learning algorithms that solve the clustering problems , was conducted to calculate the integrated condition of each space. Since it is not obvious what a good number of clusters is in each case; several attempts as trial and error as well as some engineering sense were conducted in order to find the most suitable number of clusters that best represents the integration. Finally, the MAUT was used again to calculate the condition of the entire building. Calculating the physical or the environmental condition of the entire building is also available using the MAUT.

The proposed methodology enhances the capability of an object-oriented Building Information Model (BIM) to be used as an advanced tool for storing, exchanging and transferring assessment data inputs, as well as in the assessment process itself. BIM is used as a single-repository virtual model to input all of the condition assessment data provided by an inspector during the inspection process thanks to its capability to recognize building components in its fixed asset hierarchy (Category-Family-Family type-Instant) and then to locate them in their space where IEQFs can be measured and inspected. BIM also exploits the potential of parametric relationships, which means that if a user changes a particular building component it will be changed wherever that component is used, and any component linked to it will be updated automatically. The integrated data model and the assessment process are implemented in the context of tool development. The Integrated Condition Assessment Model for Buildings (ICAB) is the tool developed to automate the process; it integrates with Autodesk Revit© 2011 (a BIM solution software).

Finally, an evaluation scheme was developed to rate buildings and their internal spaces to assist facilities managers in diagnosing problems and thus aid and improve decision making. The model was implemented and tested using data collected from experts and from field measurements taken in educational building in Montreal. The methodology and the automated tool were validated using interviews and questionnaires. The results from validating the methodology with experts in the field were mostly "above expectations" for all the validation attributes. Facilities managers found that the methodology has good potential when used as a condition assessment model in the facilities management phase. The case study results were validated by comparing the results of the building condition assessment calculated using the proposed model with the results of the building condition assessment conducted by the building facilities managers. Their overall condition of the building achieved an "85%" rating. As calculated step by step following the proposed model during the model testing stage of the current case study, the current physical condition of the floor evaluated was "84.33%". However, the current environmental condition of the same floor, calculated using the proposed model for indoor environmental quality, was rated at "93.60%". The floor integrated condition, determined by the integration of both the physical and the environmental conditions using the K-means clustering technique, is "89.43%". This change is attributed to the contribution of the environmental condition to the integrated one.

The space oriented inspection process is found to be facilitating the job of inspectors as they can use their tablet PCs and easily orient themselves in the rooms that contain all the physical and environmental attributes to be inspected and measured. This process also helps to identify, locate, and diagnose building problems and assist in the building maintenance decision making process. The process may be found to have high cost at the beginning due to the overhead cost of the BIM model, the inspector and the software, however on the long run the cost of the facilities management process as a whole will be reduced as a result of the automation process itself and the benefits of BIM. The proposed framework is flexible and can be easily adapted to suit various building types. It can serve as the backbone for a larger decision support system for sustainable building maintenance management. The developed condition rating outputs can be used as the basis for deciding what, where, and when to maintain, repair, rehabilitate, or replace. The model can also be used to automatically develop deterioration curves for each specific component in each space by using recorded data in each condition assessment process along with their dates. This feature would be valuable in the process of planning and implementing maintenance programs, for budget allocation, and for decision making. Finally, the proposed condition assessment model proved to be useful during the facilities management phase as well as useful for the condition assessment consultants when identifying asset values for buyers and investors at the time of building purchase.

7.2 Research Contributions

The research contributes to the development of an Integrated Condition Assessment Model that considers both buildings' physical and environmental aspects. This model would assist owners and facilities managers in the condition assessment phase during the asset management process by applying several tools and techniques to provide an integrated rating evaluation in the final outputs. The contributions of this research would be beneficial to facilities management consultants, facilities management departments in local municipalities, school boards, and BIM vendors. Based upon the proposed model, the main contributions are summarized as follows:

1. Development of a new **"space-based"** assessment evaluation platform for buildings that makes it possible to consider the environmental aspects of a building and which deals with spaces and volumes. Another advantage is of this platform is that it can consider the nature of the task conducted within any given space; this task-specific aspect has been shown to affect the criticality and importance of building systems as well as being a factor for calculating the indoor environmental quality. The space-based assessment platform also allows the model to be easily integrated with other facilities management modules, such as space management, move management, sustainability and environmental aspects, energy consumptions, etc., and this capability is obviously a plus at the design stage of a building.
2. Development of a framework and of models that make it possible to integrate the evaluation criteria of both physical and environmental assessments on the level of spaces and for an entire building. The new framework and methodology considers the physical aspects alongside occupants' comfort and well-being, thus making a better environment for building occupants possible and contributes to better recognition of human aspects, which leads to more productivity and occupant satisfaction, in addition to preserving the buildings and keeping them in good condition.
3. Factors that affect the physical and environmental condition of a building and its spaces are identified and attributed inside space types. Then, an evaluation schemes

were designed for all these factors based on codes, standards, current practices, and experts' opinions.

4. Implementing the developed framework using Building Information Modeling (BIM) as a single-repository virtual model in order to store, exchange, and transfer assessment data inputs for various elements of a building. Thus, it broadens the use of object-oriented modeling as part of BIM evolution in the construction industry, and contributes to the extension of BIM implementation in the facilities management phase. As a result, it proposes a framework that is less subjective, faster and less-costly due to the efficient and interactive inspection and data transfer processes.

5. The research methodology is flexible and can be adapted to suite any type of facility. In addition, facilities managers can change some variables in the model in order to follow any specific codes, standards, and benchmarks as required, as well as to represent the identified concepts, goals to be fulfilled, other building features, and attributes to be considered in other building types.

7.3 Research Limitations

The developed models have some limitations and they are listed below:

- The physical evaluation criteria relative weights, as well as the physical condition threshold were generalized and calculated using the AHP on the "family" level, such as "windows". It may be more accurate and representative if it could be calculated on the "family type" level; for example different types of windows and their materials may vary in their evaluation criteria's relative weights and physical condition thresholds.

- Indoor Air Quality sub-criteria were calculated using the average without considering the difference in the effect of the different air contaminants on human health. This aspect could be improved.

7.4 Recommendations for Future Research

Since the current research focuses on developing an integrated condition assessment model for educational buildings, further research may enhance the model and extend its use. Recommendations and future research are summarized in the following points:

Model Enhancement

- Incorporating more environmental factors in the model development process, such as considering sound echo as part of acoustics quality, considering air velocity in the thermal quality, vertical light intensity in the light quality, and VOC concentration in the indoor air quality, etc. Those factors will add to the strength of the model.
- More reliable and more accurate data for the relative weights of spaces, physical elements, and environmental factors can be calculated by undertaking more questionnaires/surveys. Modeling the uncertainty of data through simulation should also provide more accurate estimates and better represent real life.
- In this research the AHP and the ANP were both used, but the ANP is a technique which gives improved, more effective and more realistic results. However the technique is very data hungry. Applying the survey questionnaires on a larger level will provide better results.

Further research and extensions

- Modeling the diagnosing phase by using BIM and exploiting the potential of attributing problems to locations.
- Modeling the level-of-service for the different building categories and components as well as the indoor environmental quality.
- Every building type has its own properties, nature, and its internal space types; and applying and testing the research methodology to other building types such as office buildings, healthcare, commercial, etc. may reveal other attributes and concerns.
- Extending the methodology to predict building component deterioration and optimizing fund allocation as well as considering risk strategies.
- Radio-frequency identification (RFID) can be utilized to help automatically locate an inspector in the space to be assessed.
- Modeling the Benefit-Cost ration (BCR) of the condition assessment process.

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APPENDICES

Appendix A

Sample of the Survey/Questionnaire

Pair-Wise Comparison

In this study the following sets of s matrixes are needed to be completed based on your experience, the relative importance of each category and sub category are based on a 1-9 scale with the following interpretations (Saaty 1982).

which **9** = Absolute importance of one over compared one

7 = Very strongly

5 = Strongly

3 = Moderately

1 = Equally important

Measured on an integer-valued I - 9 scale as mentioned above.

If for example parameter" A" is moderately more important than parameter "B" then the value will be 3 in the "A" direction. Let us determine a pair wise comparison matrix of a four parameter model the parameters are A, B, C and D. Say,

A is **moderately** more important than B

A has **absolute** importance than C

D is **very strongly** important than A

Then the comparison matrix can be written as follows:

	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
A				√						**B**
	√									**C**
								√		**D**

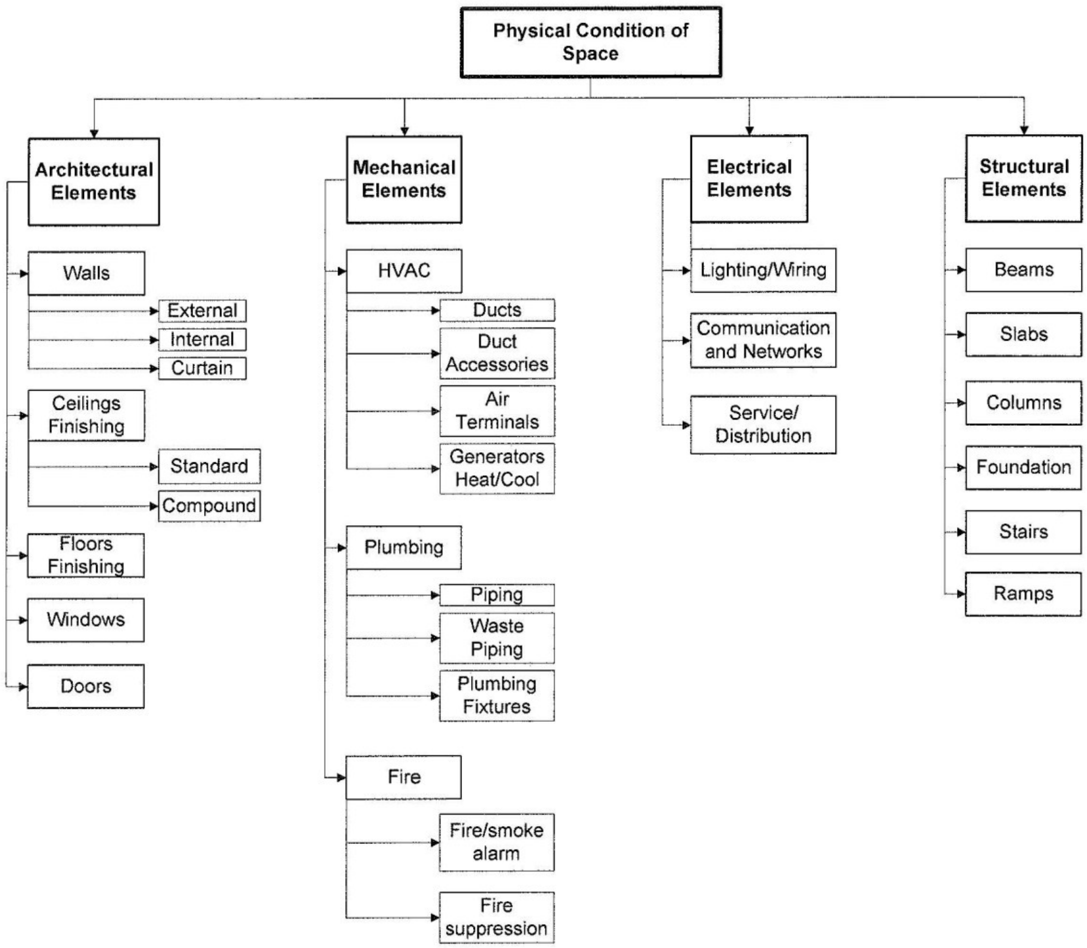
Spaces' Priorities

In this part, you are kindly requested to do pair wise comparison for the importance of Spaces inside an educational building. Comparing each two spaces in a pair wise comparison, you are kindly asked identify the weight of each space with respect to another inside this particular building type (Educational Building).

Table 1 (pair wise comparison for spaces)

Spaces Priorities in an Educational Building											
	Degree of Importance or Preference										
Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)	Remarks
Classrooms				X						Laboratory	
			X							Office	
		X								Lobby/corridors	
			X							Restroom	
		X								Lunch Room	
			X							Auditoriums	

Building Categories and Sub-Categories relative weights



Importance of each building category inside each space type

Space Type	Criterion (X)	Degree of Importance or Preference									Criterion (Y)
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Classrooms	Architectural					X					Mechanical
						X					Electrical
Offices	Architectural					X					Mechanical
						X					Electrical
Laboratories	Architectural							X			Mechanical
								X			Electrical
Restrooms	Architectural									X	Mechanical
				X							Electrical
Cafeteria	Architectural								X		Mechanical
					X						Electrical
Lobby/ Corridors	Architectural			X							Mechanical
									X		Electrical
Auditoriums	Architectural		X								Mechanical
							X				Electrical

CLASSROOM

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?											
		Degree of Importance or Preference									
Category	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Elements	Walls					X					Ceilings
						X					Floors
					X						Windows
					X						Doors
Mechanical Elements	HVAC					X					Plumbing
						X					Fire System
Electrical Elements	Lighting/Wiring				X						Communication
						X					Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?											
		Degree of Importance or Preference									
With respect to:	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Category	Mechanical Category						X				Electrical Category
Mechanical Category	Architectural Category							X			Electrical Category
Electrical Category	Architecture Category				X						Mechanical Category

OFFICES

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?											
Category	Criterion (X)	Degree of Importance or Preference									Criterion (Y)
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Architecture Elements	Walls					X					Ceilings
						X					Floors
				X							Windows
				X							Doors
Mechanical Elements	HVAC					X					Plumbing
						X					Fire System
Electrical Elements	Lighting/Wiring						X				Communication
						X					Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?											
With respect to:	Criterion (X)	Degree of Importance or Preference									Criterion (Y)
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Architecture Category	Mechanical Category						X				Electrical Category
Mechanical Category	Architectural Category							X			Electrical Category
Electrical Category	Architecture Category				X						Mechanical Category

LABORATORIES

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?

Category	Criterion (X)	Degree of Importance or Preference: (9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Elements	Walls					X					Ceilings
							X				Floors
			X								Windows
						X					Doors
Mechanical Elements	HVAC					X					Plumbing
					X						Fire System
Electrical Elements	Lighting/Wiring				X						Communication
						X					Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?

With respect to:	Criterion (X)	Degree of Importance or Preference: (9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Category	Mechanical Category					X					Electrical Category
Mechanical Category	Architectural Category							X			Electrical Category
Electrical Category	Architecture Category							X			Mechanical Category

RESTROOMS

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?											
		Degree of Importance or Preference									
Category	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Elements	Walls					X					Ceilings
						X					Floors
			X								Windows
						X					Doors
Mechanical Elements	HVAC					X					Plumbing
				X							Fire System
Electrical Elements	Lighting/Wiring			X							Communication
						X					Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?											
		Degree of Importance or Preference									
With respect to:	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Category	Mechanical Category			X							Electrical Category
Mechanical Category	Architectural Category			X							Electrical Category
Electrical Category	Architecture Category						X				Mechanical Category

CAFETERIAS

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?											
		Degree of Importance or Preference									
Category	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Elements	Walls					X					Ceilings
						X					Floors
				X							Windows
				X							Doors
Mechanical Elements	HVAC					X					Plumbing
						X					Fire System
Electrical Elements	Lighting/Wiring			X							Communication
						X					Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?											
		Degree of Importance or Preference									
With respect to:	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Category	Mechanical Category				X						Electrical Category
Mechanical Category	Architectural Category				X						Electrical Category
Electrical Category	Architecture Category						X				Mechanical Category

LOBBY/CORRIDORS

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?											
		Degree of Importance or Preference									
Category	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Elements	Walls					X					Ceilings
						X					Floors
			X								Windows
			X								Doors
Mechanical Elements	HVAC		X								Plumbing
				X							Fire System
Electrical Elements	Lighting/Wiring		X								Communication
					X						Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?											
		Degree of Importance or Preference									
With respect to:	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Category	Mechanical Category							X			Electrical Category
Mechanical Category	Architectural Category		X								Electrical Category
Electrical Category	Architecture Category		X								Mechanical Category

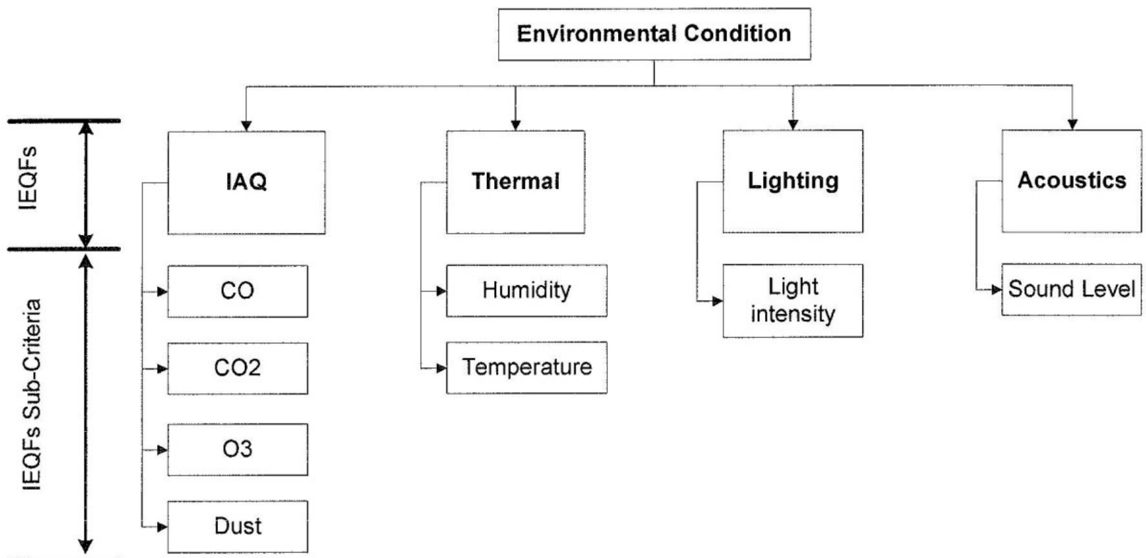
AUDOTORIUMS

With respect to each category, how much is contribution for each criterion when compared to the other on physical condition?											
		Degree of Importance or Preference									
Category	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Elements	Walls					X					Ceilings
						X					Floors
			X								Windows
				X							Doors
Mechanical Elements	HVAC		X								Plumbing
					X						Fire System
Electrical Elements	Lighting/Wiring			X							Communication
				X							Services / Distribution

With respect to each category, how much is contribution for each category when compared to the other on its condition?											
		Degree of Importance or Preference									
With respect to:	Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)
Architecture Category	Mechanical Category							X			Electrical Category
Mechanical Category	Architectural Category			X							Electrical Category
Electrical Category	Architecture Category		X								Mechanical Category

Indoor Environmental Quality relative importance

In this part, you are kindly requested to do pair wise comparison for the indoor environmental quality factors (IEQFs) inside each particular space type; in other words, all the spaces with the same type will have the same IEQFs relative weights. So you are kindly asked to identify the weight of each IEQF with respect to another inside of a particular space type.



Importance of each Indoor Environmental quality factor inside each space type											
Space Type	Criterion (X)	Degree of Importance or Preference									Criterion (Y)
		(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	
Classrooms	Indoor Air Quality			X							Acoustics Quality
				X							Light Quality
					X						Thermal Quality
Offices	Indoor Air Quality			X							Acoustics Quality
				X							Light Quality
					X						Thermal Quality
Laboratories	Indoor Air Quality		X								Acoustics Quality
				X							Light Quality
						X					Thermal Quality
Restrooms	Indoor Air Quality		X								Acoustics Quality
			X								Light Quality
			X								Thermal Quality
Cafeteria	Indoor Air Quality			X							Acoustics Quality
					X						Light Quality
					X						Thermal Quality
Lobby/ Corridors	Indoor Air Quality			X							Acoustics Quality
					X						Light Quality
				X							Thermal Quality
Auditoriums	Indoor Air Quality			X							Acoustics Quality
				X							Light Quality
				X							Thermal Quality

Appendix B

K-mean Clustering iterations

1. Sample of the SPSS K-mean Clustering outputs

Spaces #	Physical	Phys. U.	P Grade	Environmental	Env. U.	E Grade	6 Clusters	7 Clusters	8 Clusters	9 Clusters	10 Clusters
1	97.00	0.97	1	94.00	0.94	1	1	1	1	1	1
2	29.00	0.29	5	32.00	0.32	5	6	7	6	7	6
3	53.00	0.53	4	29.00	0.29	5	5	2	3	6	10
4	31.00	0.31	5	23.00	0.23	5	6	7	6	7	6
5	55.00	0.55	4	29.00	0.29	5	5	2	3	6	10
6	3.00	0.03	6	20.00	0.2	6	6	7	6	7	6
7	25.00	0.25	5	37.00	0.37	5	6	7	6	7	6
8	63.00	0.63	3	87.00	0.87	2	4	4	8	8	8
9	37.00	0.37	5	46.00	0.46	4	6	5	5	9	7
10	27.00	0.27	5	20.00	0.2	6	6	7	3	6	10
11	40.00	0.4	5	4.00	0.04	6	6	7	3	6	10
12	77.00	0.77	2	73.00	0.73	3	3	3	7	5	2
13	2.00	0.02	6	31.00	0.31	5	6	7	6	7	6
14	23.00	0.23	5	17.00	0.17	6	6	7	3	6	10
15	44.00	0.44	4	50.00	0.5	4	5	5	5	3	7
16	12.00	0.12	6	33.00	0.33	5	6	7	6	7	6
17	47.00	0.47	4	45.00	0.45	4	5	5	5	3	7
18	10.00	0.1	6	14.00	0.14	6	6	7	6	7	6
19	95.00	0.95	1	64.00	0.64	3	3	3	7	5	2
20	53.00	0.53	4	82.00	0.82	2	4	4	8	8	8
21	41.00	0.41	4	76.00	0.76	2	4	4	8	8	8
22	67.00	0.67	3	34.00	0.34	5	5	2	3	3	4
23	7.00	0.07	6	3.00	0.03	6	6	7	6	7	6
24	10.00	0.1	6	98.00	0.98	1	2	6	4	2	5
25	49.00	0.49	4	55.00	0.55	4	5	5	5	3	7
26	79.00	0.79	2	62.00	0.62	3	3	3	7	5	2
27	29.00	0.29	5	63.00	0.63	3	2	5	5	9	9
28	0.00	0	0	50.00	0.5	4	3	3	7	5	2
29	38.00	0.38	5	64.00	0.64	3	2	5	5	9	9
30	68.00	0.68	3	66.00	0.66	3	4	4	8	3	8
31	42.00	0.42	4	4.00	0.04	6	5	2	3	6	10
32	12.00	0.12	6	38.00	0.38	5	6	7	6	7	6
33	81.00	0.81	2	79.00	0.79	2	1	1	1	1	1
34	70.00	0.7	3	57.00	0.57	4	5	2	7	3	4
35	64.00	0.64	3	86.00	0.86	2	4	4	8	8	8
36	62.00	0.62	3	16.00	0.16	6	5	2	3	6	10
37	47.00	0.47	4	71.00	0.71	3	4	5	5	9	7
38	89.00	0.89	2	10.00	0.1	6	5	2	2	4	3
39	97.00	0.97	1	5.00	0.05	6	3	2	2	4	3
40	92.00	0.92	1	61.00	0.61	3	3	3	7	5	2
41	46.00	0.46	4	96.00	0.96	1	4	4	8	8	5
42	27.00	0.27	5	3.00	0.03	6	6	7	3	6	10
43	34.00	0.34	5	86.00	0.86	2	2	6	4	2	5
44	61.00	0.61	3	81.00	0.81	2	4	4	8	8	8
45	70.00	0.7	3	79.00	0.79	2	4	4	8	8	8
46	79.00	0.79	2	9.00	0.09	6	5	2	2	4	3
47	32.00	0.32	5	57.00	0.57	4	6	5	5	9	7
48	9.00	0.09	6	65.00	0.65	3	2	5	5	9	9
49	21.00	0.21	5	30.00	0.3	5	6	7	6	7	6
50	25.00	0.25	5	25.00	0.25	5	6	7	6	7	6
51	87.00	0.87	2	53.00	0.53	4	3	3	7	3	4
52	72.00	0.72	3	84.00	0.84	2	4	4	8	8	8
53	70.00	0.7	3	53.00	0.53	4	5	2	7	3	4
54	40.00	0.4	5	76.00	0.76	2	2	6	4	2	5
55	88.00	0.88	2	68.00	0.68	3	3	3	7	5	2
56	42.00	0.42	4	62.00	0.62	3	4	5	5	9	7
57	22.00	0.22	5	19.00	0.19	6	6	7	3	6	10
58	71.00	0.71	3	63.00	0.63	3	4	4	8	3	8
59	75.00	0.75	3	66.00	0.66	3	4	4	8	3	8
60	23.00	0.23	5	58.00	0.58	4	6	5	5	9	7
61	91.00	0.91	1	20.00	0.2	6	3	2	2	4	3
62	97.00	0.97	1	80.00	0.8	2	1	1	1	1	1
63	12.00	0.12	6	19.00	0.19	6	6	7	6	7	6
64	82.00	0.82	2	80.00	0.8	2	1	1	1	1	1
65	12.00	0.12	6	24.00	0.24	5	6	7	6	7	6
66	77.00	0.77	2	14.00	0.14	6	5	2	2	4	3
67	66.00	0.66	3	98.00	0.98	1	4	4	8	8	8
68	22.00	0.22	5	99.00	0.99	1	2	6	4	2	5
69	53.00	0.53	4	87.00	0.87	2	4	4	8	8	8
70	28.00	0.28	5	24.00	0.24	5	6	7	6	7	6
71	6.00	0.06	6	97.00	0.97	1	2	6	4	2	5
72	30.00	0.3	5	33.00	0.33	5	6	7	6	7	6
73	85.00	0.85	2	41.00	0.41	4	3	3	7	3	4
74	78.00	0.78	2	40.00	0.4	5	3	2	2	4	4
75	60.00	0.6	4	69.00	0.69	3	4	5	5	9	7

2. Trials of clustering the data using the SPSS and k-mean technique

SPSS output | **Modified output**

6 Clusters

SPSS output

6	3	5	5	5	6	6
5	3	3	5	5	6	6
4	3	3	5	5	6	6
3	3	3	4	4	2	2
2	1	1	4	4	2	2
1	1	1	4	4	2	2
E/P	1	2	3	4	5	6

Modified output

6	3	5	5	5	6	6
5	3	3	5	5	6	6
4	3	3	5	5	6	6
3	3	3	4	4	2	2
2	1	1	4	4	2	2
1	1	1	4	4	2	2
E/P	1	2	3	4	5	6

7 Clusters

SPSS output

6	2	2	2	2	7	7
5	3	2	2	2	7	7
4	3	3	2	5	5	5
3	3	3	4	5	5	5
2	1	1	4	4	6	6
1	1	1	4	4	6	6
E/P	1	2	3	4	5	6

Modified output

6	3	3	3	3	5	5
5	2	3	3	3	5	5
4	2	2	3	4	4	4
3	2	2	2	4	4	4
2	1	1	2	2	3	3
1	1	1	2	2	3	3
E/P	1	2	3	4	5	6

8 Clusters

SPSS output

6	2	2	3	3	3	6
5	2	2	3	3	6	6
4	7	7	7	5	5	6
3	7	7	8	5	5	5
2	1	1	8	8	4	4
1	1	1	8	8	4	4
E/P	1	2	3	4	5	6

Modified output

6	3	3	4	4	4	5
5	3	3	4	4	5	5
4	2	2	2	4	4	5
3	2	2	2	4	4	4
2	1	1	2	2	3	3
1	1	1	2	2	3	3
E/P	1	2	3	4	5	6

9 Clusters

6	4	4	6	6	6	7
5	4	4	3	6	7	7
4	5	3	3	3	9	7
3	5	5	3	9	9	9
2	1	1	8	8	9	9
1	1	1	8	8	2	2
E/P	1	2	3	4	5	6

6	3	3	5	5	5	6
5	3	3	4	5	6	6
4	2	4	4	4	4	6
3	2	2	4	4	4	4
2	1	1	2	2	4	4
1	1	1	2	2	3	3
E/P	1	2	3	4	5	6

10 Clusters

6	3	3	10	10	10	6
5	3	4	4	10	6	6
4	2	4	4	7	7	6
3	2	2	8	7	9	9
2	1	1	8	8	5	9
1	1	1	8	5	5	5
E/P	1	2	3	4	5	6

6	3	3	5	5	5	6
5	3	4	4	5	6	6
4	2	4	4	4	4	6
3	2	2	2	4	5	5
2	1	1	2	2	3	5
1	1	1	2	3	3	3
E/P	1	2	3	4	5	6

Appendix C

Cronbach's Alpha Reliability Calculations Sample

Sample of the Cronbach's Alpha Reliability tests for the indoor air quality factors data in a laboratory

Case Processing Summary

		N	%
Cases	Valid	4	100.0
	Excluded[a]	0	.0
	Total	4	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.947	.949	23

Item Statistics

	Mean	Std. Deviation	N
Q1	.247500	.1252664	4
Q2	.250000	.1250000	4
Q3	.250000	.1443376	4
Q4	.250000	.2044275	4
Q5	.250000	.2607681	4
Q6	.250000	.2660057	4
Q7	.250000	.1804006	4
Q8	.250000	.2209447	4
Q9	.250000	.1250000	4
Q10	.250000	.2044275	4
Q11	.250000	.2357023	4
Q12	.250000	.2115385	4
Q13	.250000	.1685033	4

Q14	.250000	.1367753	4
Q15	.250000	.2209447	4
Q16	.250000	.2209447	4
Q17	.250000	.2929428	4
Q18	.250000	.2558140	4
Q19	.250000	.1666667	4
Q20	.250000	.1874139	4
Q21	.250000	.2115385	4
Q22	.250000	.2209447	4
Q23	.250000	.1443376	4

Inter-Item Correlation Matrix

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23
Q1	1.000	.998	.622	.660	.502	.446	.709	.452	.998	.660	.176	.679	.717	-.577	.452	.452	.448	.591	.386	.455	.679	.452	.622
Q2	.998	1.000	.577	.616	.460	.394	.711	.406	1.000	.616	.157	.636	.677	-.522	.406	.406	.395	.636	.333	.404	.636	.406	.577
Q3	.622	.577	1.000	.999	.487	.603	.123	.503	.577	.999	.680	.997	.992	-.905	.503	.503	.641	.052	.577	.980	.997	.503	1.000
Q4	.660	.616	.999	1.000	.497	.605	.161	.509	.616	1.000	.666	1.000	.997	-.903	.509	.509	.642	.089	.577	.969	1.000	.509	.999
Q5	.502	.460	.487	.497	1.000	.979	.747	.997	.460	.497	-.301	.502	.511	-.801	.997	.997	.967	-.377	.971	.434	.502	.997	.487
Q6	.446	.394	.603	.605	.979	1.000	.604	.990	.394	.605	-.142	.605	.605	-.885	.990	.990	.998	-.458	.998	.580	.605	.990	.603
Q7	.709	.711	.123	.161	.747	.604	1.000	.693	.711	.161	-.553	.181	.222	-.371	.693	.693	.570	.181	.569	-.034	.181	.693	.123
Q8	.452	.406	.503	.509	.997	.990	.693	1.000	.406	.509	-.274	.512	.517	-.818	1.000	1.000	.980	-.438	.986	.464	.512	1.000	.503
Q9	.998	1.000	.577	.616	.460	.394	.711	.406	1.000	.616	.157	.636	.677	-.522	.406	.406	.395	.636	.333	.404	.636	.406	.577
Q10	.660	.616	.999	1.000	.497	.605	.161	.509	.616	1.000	.666	1.000	.997	-.903	.509	.509	.642	.089	.577	.969	1.000	.509	.999
Q11	.176	.157	.680	.666	-.301	-.142	-.553	-.274	.157	.666	1.000	.657	.638	-.328	-.274	-.274	-.089	.271	-.157	.724	.657	-.274	.680
Q12	.679	.636	.997	1.000	.502	.605	.181	.512	.636	1.000	.657	1.000	.999	-.902	.512	.512	.642	.107	.576	.963	1.000	.512	.997
Q13	.717	.677	.992	.997	.511	.605	.222	.517	.677	.997	.638	.999	1.000	-.897	.517	.517	.640	.147	.573	.947	.999	.517	.992
Q14	-.577	-.522	-.905	-.903	-.801	-.885	-.371	-.818	-.522	-.903	-.328	-.902	-.897	1.000	-.818	-.818	-.907	.237	-.870	-.887	-.902	-.818	-.905
Q15	.452	.406	.503	.509	.997	.990	.693	1.000	.406	.509	-.274	.512	.517	-.818	1.000	1.000	.980	-.438	.986	.464	.512	1.000	.503
Q16	.452	.406	.503	.509	.997	.990	.693	1.000	.406	.509	-.274	.512	.517	-.818	1.000	1.000	.980	-.438	.986	.464	.512	1.000	.503
Q17	.448	.395	.641	.642	.967	.998	.570	.980	.395	.642	-.089	.642	.640	-.907	.980	.980	1.000	-.456	.996	.622	.642	.980	.641
Q18	.591	.636	.052	.089	-.377	-.458	.181	-.438	.636	.089	.271	.107	.147	.237	-.438	-.438	-.456	1.000	-.515	-.096	.107	-.438	.052
Q19	.386	.333	.577	.577	.971	.998	.569	.986	.333	.577	-.157	.576	.573	-.870	.986	.986	.996	-.515	1.000	.566	.576	.986	.577
Q20	.455	.404	.980	.969	.434	.580	-.034	.464	.404	.969	.724	.963	.947	-.887	.464	.464	.622	-.096	.566	1.000	.963	.464	.980
Q21	.679	.636	.997	1.000	.502	.605	.181	.512	.636	1.000	.657	1.000	.999	-.902	.512	.512	.642	.107	.576	.963	1.000	.512	.997
Q22	.452	.406	.503	.509	.997	.990	.693	1.000	.406	.509	-.274	.512	.517	-.818	1.000	1.000	.980	-.438	.986	.464	.512	1.000	.503
Q23	.622	.577	1.000	.999	.487	.603	.123	.503	.577	.999	.680	.997	.992	-.905	.503	.503	.641	.052	.577	.980	.997	.503	1.000

Summary Item Statistics

	Mean	Minimum	Maximum	Range	Maximum / Minimum	Variance	N of Items
Item Means	.250	.248	.250	.003	1.010	.000	23
Item Variances	.041	.016	.086	.070	5.492	.000	23
Inter-Item Covariances	.018	-.036	.078	.114	-2.141	.000	23
Inter-Item Correlations	.446	-.907	1.000	1.907	-1.103	.259	23

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Q1	5.500000	9.413	.742	.	.944
Q2	5.497500	9.449	.696	.	.945

Q3	5.497500	9.218	.868	.	.943
Q4	5.497500	8.890	.876	.	.941
Q5	5.497500	8.708	.795	.	.942
Q6	5.497500	8.616	.841	.	.941
Q7	5.497500	9.401	.512	.	.946
Q8	5.497500	8.901	.796	.	.942
Q9	5.497500	9.449	.696	.	.945
Q10	5.497500	8.890	.876	.	.941
Q11	5.497500	9.678	.182	.	.951
Q12	5.497500	8.846	.881	.	.941
Q13	5.497500	9.064	.894	.	.942
Q14	5.497500	10.855	-.969	.	.958
Q15	5.497500	8.901	.796	.	.942
Q16	5.497500	8.901	.796	.	.942
Q17	5.497500	8.455	.856	.	.941
Q18	5.497500	10.119	-.113	.	.957
Q19	5.497500	9.146	.819	.	.943
Q20	5.497500	9.074	.789	.	.943
Q21	5.497500	8.846	.881	.	.941
Q22	5.497500	8.901	.796	.	.942
Q23	5.497500	9.218	.868	.	.943

Appendix D

Indoor Environmental Quality measurement tools

CASELLA CEL

CEL-600 Series

Digital Sound Level Meters

www.casellacel.com

IDEAL

Think Environment Think Casella

Introduction

The CEL-600 series sound level meters use the latest digital technology to give standards of performance never seen in such a compact design.

Using a high resolution colour TFT display, the CEL-600 series is specifically designed to ensure taking noise measurements is quick and easy.

Different models are available depending on your requirements for use in general workplace noise measurements, up to full industrial hygiene requirements where octave band analysis is required for the effective selection of hearing protection.

Octave band measurement screen

Key Features

- Compact, rugged design
- Simple operation
- Single large measurement range
- Large memory
- High resolution colour display
- Real-time octave band analysis
- Simultaneous measurement of all workplace noise parameters
- Instrument menu in 7 languages
- Pre-defined and user configurations available
- Automatic calibration function
- Long battery life

Applications

- Workplace noise assessments
- Selection of hearing protection
- Calculation of noise exposure
- Ensuring compliance with workplace noise legislation
- Machinery noise tests

High Resolution Colour Display

- Unique colour coding of measurements
- Bright backlight
- View in all light conditions

The CEL-600 series uses colours of the high-resolution display to aid the user in making measurements. Measurement screens are colour coded depending on the mode of operation. For example, during a measurement run, the header and footer of the display is green (shown right), whereas when a run is stopped they are red, similar to traffic lights for 'stop' and 'go'.

Measured parameters are displayed in different colours, and the bar graphs are illustrated with the same colours to give an easy understanding of the noise climate.

Broadband measurement

CASELLA CEL

Simple Operation

- Intuitive menu structure
- Multilingual user interface
- Predefined and user selectable setups

The CEL-600 series was designed with ease of use in mind. The menu structure is designed to pick up and use without the use of a manual. A simple icon structure is used with word prompts for each selection, available in seven languages.

The instrument has six selectable setups. Four pre-defined setups can be used to satisfy local workplace noise legislation. Two user setups can be defined to display parameters and weightings as required. Regardless of the setup used, the CEL-600 series measures and stores all parameters and weightings even if not selected. These can be viewed if necessary on the software.

Up to 100 measurements can be stored without the need to download. All runs are date and time stamped. When connected to a PC via the USB connection, the CEL-600 series acts like a memory card, so data files can be moved to a PC and easily reviewed without the need for proprietary software.

Multi-lingual user interface

Set-up selection

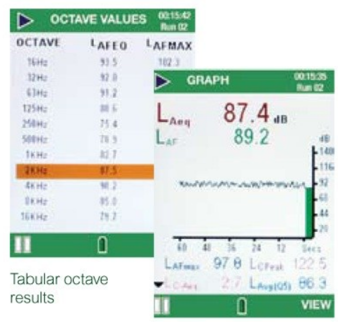
Digital Technology

- Large measurement range
- Simultaneous measurement
- Automatic calibration
- Real-time octave band analysis

By using Digital Signal Processing (DSP) technology, the CEL-600 series measures all the workplace noise parameters simultaneously with necessary time and frequency weightings, preventing incorrect setup of the instrument. The instrument has a single large measurement range of 20-140dB, eliminating the need to change measurement range and preventing errors.

On the CEL-620B model, octave analysis is performed in real-time, saving time compared to performing measurements sequentially.

Octave band results are shown in both bar-graph and tabular form with the dominant frequency highlighted. Time history of the broadband noise level is displayed in real-time, so a user can see how the noise level varies with time.



Tabular octave results

Time history display

Instrument Range

- Range of instruments available
- Future proof upgrade ability
- Complete measurement kits
- All models available in Class 1 or Class 2

The CEL-600 series comprise of the CEL-610, CEL-620A and CEL-620B. The CEL-610 measures instantaneous and maximum sound pressure levels. CEL-620 models are also integrating so measure average noise levels as well as peak levels for workplace noise legislation. CEL-620A model also simultaneously measures the L_C and L_A used within the HML method for the selection of hearing protection. In addition, the CEL-620B model performs real-time octave band analysis from 16Hz to 16kHz, values which are used in the octave band method for selection of hearing protection.

If future requirements change, any instrument can be upgraded to a higher model without returning to Casella.

Complete measurement kits are provided with an acoustic calibrator in a robust kit case complete with instruction manuals and calibration certificates.

Automatic calibration

SPECIFICATION

Applicable Standards:

IEC 60651 - 1979
IEC 60804 - 2000
IEC 61672 - 2002
ANSI S1.4 -1983 (R2006)
ANSI S1.43 - 1997 (R2007)

Octave filters (CEL-620B model only):
IEC 61260 Class 0
ANSI S1.11-2004

Technical:

Total measurement range:	20 to 140dB RMS (single range), 143.0 dB Peak
Frequency weightings RMS:	Simultaneous A, C & Linear (Z)
Frequency weightings Peak:	Simultaneous A, C & Linear (Z)
Time weightings:	Simultaneous Slow, Fast & Impulse
Amplitude weightings:	Q3, Q4 and Q5 (Q4 & Q5 applicable to L_{avg} only)
Thresholds:	70 to 90 (dB) in 1 dB steps (applicable to L_{avg} only)
Noise floor:	<33dB(A) Class 2, <25dB(A) Class 1
Runs stored:	100
Display:	320x240 pixel transmissive colour TFT
Frequency bands:	11 octave bands 16Hz to 16kHz (CEL-620B model only)
Calibration information:	Stores pre and post run calibration date, time and level
Output (P.C.):	USB 2.0 'A' to 'Mini B'
Batteries:	3 x AA Alkaline (supplied) or rechargeable
External power:	9-14V DC at 250mA via 2.1mm connector
Battery life:	11 hours with backlight on, 20 hours backlight off
Tripod mount:	1/4" Whitworth socket
Size mm (in):	72 x 229 x 31mm (2.8 x 9.0 x 1.2")
Weight gm (oz):	295g (10.4oz)

Measured Parameters:

CEL-610
L_{XY}, L_{XYmax}

CEL-620A
L_{XY}, L_{XYmax}, L_{XYmin}, L_{Xeq}, L_{Xpeak}, L_{avg}, L_C-L_A, L_{XIeq}, L_{TM3}, L_{TM5}, L_{AE}

CEL-620B
L_{XY}, L_{XYmax}, L_{XYmin}, L_{Xeq}, L_{Xpeak}, L_{avg}, L_C-L_A, L_{XIeq}, L_{TM3}, L_{TM5}, L_{AE}

Octaves: L_{XY}, L_{Xeq}, L_{XYmax}

Where X is the frequency weighting A, C or Z and Y represents time weighting Fast (F), Slow (S) or Impulse (I).

All weightings simultaneously measured where appropriate.

Environmental:

In operation:	Relative humidity of 5% to 90% (non-condensing)
	Temperature 0 to 40ºC (class 2), -10 to 50ºC (class 1)
	Atmospheric pressure of 65 to 108kPa
In storage:	Relative humidity of 5% to 90% (non-condensing)
	Temperature -20 to 60ºC
	Atmospheric pressure of 65 to 108kPa

ORDERING INFORMATION

CEL-610/2:	Digital Sound Level Meter (Class 2)
CEL-620A/2:	Integrating Digital Sound Level Meter (Class 2)
CEL-620B/2:	Integrating Octave Band Sound Level Meter (Class 2)
CEL-610/1:	Precision Digital Sound Level Meter (Class 1)
CEL-620A/1:	Precision Integrating Digital Sound Level Meter (Class 1)
CEL-620B/1:	Precision Integrating Octave Band Sound Level Meter (Class 1)

All instruments and calibrators are provided with calibration certificates.
Casella CEL also has a UKAS calibration facility if required.

INSTRUMENT KITS

Complete kits are available with acoustic calibrator (CEL-110), kit case, windshield, instruction manuals and USB cable. For a complete instrument kit add /K1 to the part number e.g. CEL-610/2/K1. A typical instrument kit is pictured on the right.

OTHER ACCESSORIES

CEL-6840	Standard kit case
CEL-6843	Executive kit case
CEL-6841	Windshield
CEL-110/1	Acoustic Calibrator Class 1
CEL-110/2	Acoustic Calibrator Class 2C
CEL-6718	Lightweight tripod
CEL-251	Microphone Class 1
CEL-252	Microphone Class 2
PC18	Universal power supply
CMC51	USB download cable

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Distributed By:

SM08006 v1.1 May 08

Digital Light Meters

CASELLA CEL

APPLICATIONS:

warehouses, factories, office buildings, restaurants, schools, library, hospitals, photographic, video, parking garages, museums, art galleries, stadiums, building security.

Display:

- 3½ digit LCD with a maximum reading of 2000
- Overload indication
- Low battery indication

Functions:

- According to JISC1609:1993 and CNS 5119 general A class specifications
- Spectral response close to CIE luminous spectral efficiency
- Measures intensities of illumination in units of Lux or Foot-candle
- Measures lights source across all the visible range
- Length of wire for light sensor: approximately 1.5m
- Cosine angular corrected

Model Selection	M129004	M129005
Data hold	●	●
DC analog output		●
Max/ Min /AVG hold		●
Max hold	●	
Zero adjustment	●	●

Sensor	Silicon photodiode and filter	
Measuring range	20 (M129005), 200, 2000, 20000, 200000 Lux 20, 200, 2000, 20000 Foot-candle	
Accuracy	+/- 3% (Calibrated to standard incandescent lamp 2856° K) +/- 8% (other visible light source M129004) +/- 6% (other visible light source M129005)	
Angle deviation from cosine characteristics	30°	+/- 2%
	60°	+/- 6%
	80°	+/- 25%

Dimensions	
Meter size (LxWxH)	130x55x38mm
Sensor size (LxWxH)	80x55x25mm
Weight (including battery)	250g

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YES 206 Falcon

Description:

The YES 206 Falcon LH offers convenience and ease-of-use for measurement of indoor carbon dioxide, temperature and humidity. The built-in data-logger can be configured via PC to record up to 24 months of data. The stored information can be downloaded to a computer for analysis and printing.

Specifications:

Operating range:

- CO_2: 0-9999ppm
- temp: 0-50°C
- RH: 5%-95%

Power source: Lead acid rechargeable/AC adapter
Operating time: 10 hours
Dimensions: 213 x 144 x 53 mm
Construction: ABS plastic

Applications:

Site surveying, environmental assessments, etc.

Digital Psychrometer
SAM990 by General Tools

Temperature, Humidity, Wet Bulb, Dew Point
Features of instruments at 5 times the price !

Features

- Digitally displays temperature, humidity, wet bulb, dew point.
- Wet bulb & dry bulb temperature.
- Microprocessor based, extremely accurate.
- Memory (MIN / MAX).
- Super fast. Wet bulb calculated in 5 seconds.
- No water necessary.
- No twirling, no reading charts.
- Electronic capacitance type polymer film sensor.
- F/C switch, data hold.
- Measurement range: -20°C to 50°C (-4°F to 122°F).
- Humidity accuracy: ±5% @ 25°C from 10% to 90% RH.
- Temperature accuracy: ±1°C or ±1°F (ranges).
- Batteries: 2 AAA alkaline (included).
- Low battery Indicator.
- Handy pocket clip.

Cross Reference

- **Replaces Bacharach:** 12-7011, 12-7012, 12-7013
- **Replaces Taylor:** 1330, 1330C, 1330P