A Framework for Efficient Condition Assessment of the Building Infrastructure

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Currently, in North America, a large percentage of infrastructure assets, including education and healthcare buildings, are deteriorating rapidly due to age and over capacity. The budget constraints under which municipalities and public agencies operate also make the sustainability of these buildings a serious challenge. This is particularly so when capital renewal programs are downsized to save money, thus hindering the proper inspection of buildings and the allocation of renewal funds. In addition, building inspections and condition assessments are generally resource intensive, subjective, time-consuming, and costly. To support capital renewal decisions that pertain to buildings, this research introduces a comprehensive condition assessment framework that overcomes the drawbacks of the existing processes. A prototype of the framework utilizing hand-held devices has been developed and tested on the capital renewal program of the Toronto District School Board (TDSB).

The framework is innovative on three main fronts: (1) it utilizes available reactive-maintenance records to predict the condition of components and to prioritize inspection tasks among limited available resources; (2) it employs a unique visual guidance system that is based on extensive surveys and field data collection to support uniform condition assessment of building components; and (3) it introduces a location-based inspection process with a standardized building hierarchy. The research contributes to restructuring the inspection and condition assessment processes, providing a better understanding of the interactions among building components, integrating capital renewal and maintenance data, and developing a practical condition assessment framework that is economical, less-subjective, and suitable for use by individuals with less experience. The framework also incorporates permanent documentation of the condition of the asset along its life cycle, and aids in scheduling inspections so as to maintain low-cost condition tracking. Ultimately, the proposed system will provide timely and sufficient information to facilitate accurate repair decisions for maintaining the building infrastructure.

The framework is of benefit to both researchers and practitioners. Its formulation is innovative and helps building owners automate most inspection tasks, quantify the impact of alternative funding scenarios, and reduce the cost of asset management. In addition, because asset management is a less-developed multi-billion dollar business, the research is expected to

establish leading technology and know-how that will help Canadian companies gain a competitive global advantage. At the municipality level, the proposed prototype is expected to assist managers in arriving at decisions that will ensure the cost-effective operation of buildings and uninterrupted service to the public.

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To My Parents, My Husband, and My Son

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Chapter 1
Introduction

1.1 General

Infrastructure includes a broad category of assets that are usually owned by the government or by large firms and that provide the basic facilities, services, and installations needed for the functioning of a community or society. Therefore, infrastructure touches almost all aspects of life, including transportation, communication systems, water services, schools, and hospitals. Managing infrastructure, however, is highly challenging due to the generally large size of the facilities, complex nature, and high costs.

While civil infrastructure can be seen as the foundation of economic growth, a large percentage of its assets are rapidly deteriorating due to the effects of age and aggressive environment. In addition, their capacity is insufficient to meet the increased demand resulting from population growth (Bordogna 1995). In 2005, the American Society of Civil Engineers released a report card on the infrastructure in the United States (U.S.A) (Figure 1.1) that gave failing grades to many infrastructure systems and estimated that $1.6 trillion (U.S.) would be required to bring the U.S. assets to an acceptable condition (ASCE 2005). Statistics also show huge shortfalls in spending compared to needs (U.S. Census Bureau 1999). Because they constitute the largest infrastructure sector, the highest infrastructure expenditures in the U.S. and Canada are directed at non-residential buildings (63% and 37%, respectively) (U.S. Census Bureau 1999; Statistics Canada 1995) (Figure 1.2). They also show a large shortfall in expenditures for rehabilitation and repair.

Schools and educational facilities form the largest portion of non-residential building infrastructure, firstly because of the extensive network of such facilities, and second, because they have billions of dollars in backlogged maintenance. In the ASCE report card of 2005, the school sector was given a grade of D with no considerable improvement shown since 2001 (ASCE 2001; ASCE 2003). The report card also shows that 59,400 schools (approximately three-quarters of the schools in the U.S.) require repairs, renovations, or modernization in order to be considered in acceptable condition (U.S Department of Education 1999). The National Education Association announced that the funds required would be more than $268 billion (U.S.) (NEA 2000). In Canada, the largest school board, the Toronto District School Board

(TDSB), with more than 600 schools, suffers from a similar serious backlog of renewal needs (RECAPP 2006).

2001 and 2003

	2001 Grade	2003 Trends		2001 Grade	2003 Trends
Roads	D+	↓	Wastewater	D	↓
Bridges	C	↔	Dams	D	↓
Transit	C-	↓	Solid Waste	C+	↔
Aviation	D	↔	Hazardous Waste	D+	↔
Schools	D-	↔	Navigable Waterways	D+	↓
Drinking Water	D	↓	Energy	D+	↓

Bottom Line - All Categories	2001 GPA
Total Investment Needs:$1.6 Trillion	D+

Grade Definitions: **A** = Exceptional; **B** = Good; **C** = Mediocre; **D** = Poor; **F** = Failing; **I** = Incomplete.
Each category was evaluated on the basis of condition and performance, capacity vs. need, and funding vs. need.

2005

2005 Report Card for America's Infrastructure

Aviation	D+
Bridges	C
Dams	D
Drinking Water	D-
Energy	D
Hazardous Waste	D
Navigable Waterways	D-
Public Parks & Recreation	C-
Rail	C-
Roads	D
Schools	D
Security	I
Solid Waste	C+
Transit	D+
Wastewater	D-

America's Infrastructure G.P.A. = D

Total Investment Needs = $1.6 Trillion (estimated 5 year need)

Figure 1.1: ASCE Report Card on the U.S. Infrastructure

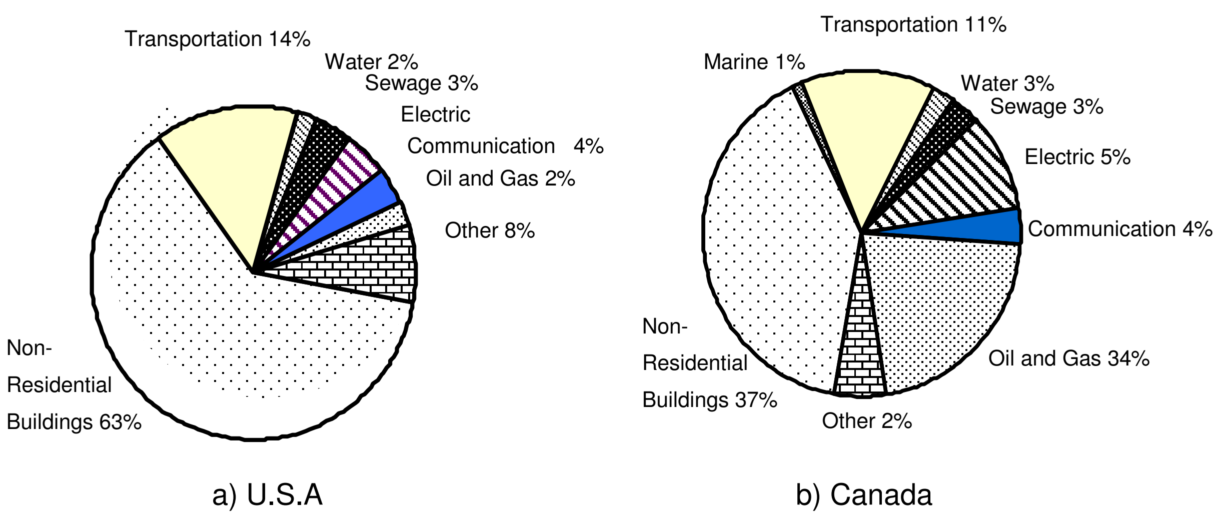


Figure 1.2: Average Yearly Expenditures by Type of Infrastructure

It is thus apparent that the severe deteriorating condition of schools and educational buildings, coupled with the huge backlog of expenditures, has made the maintenance management of educational buildings a complex and challenging task. There is therefore a need to develop new tools and techniques to support decisions related to building maintenance and repair within the limited budgets of educational organizations.

In response to these infrastructure challenges, several asset management systems have evolved. Their main functions include an assessment of current condition; a prediction of future deterioration; the selection of maintenance and repair strategies; the improvement of condition after the repair; and the prioritization of which building components should be repaired, given the budget constraints.

An asset management system, therefore, involves strategic decisions about the repair, replacement or up-grading of specific components or systems within the building asset. These decisions depend largely on the current physical condition of such components/systems. Thus, it is the original condition assessment of the building that governs all subsequent asset maintenance decisions.

1.2 Research Motivation

As discussed earlier, non-residential buildings in North America are aging and need attention. Most of the schools and educational buildings that were built in the 1950s and 1960s, for example, are now more than 45 years old (Figure 1.3) and need extra care. Therefore, improving the asset management process for educational buildings is expected to provide substantial benefits for one of the largest infrastructure sectors.

The goal of this research is to develop a comprehensive framework for an efficient condition assessment process of infrastructure buildings such as schools. The main focus is on the integration of maintenance data to facilitate efficient inspection planning and to improve the condition assessment process (for capital replacement purposes) for the inter-related building components. The research has been motivated by the following specific challenges inherent in the current process: the lack of integration between maintenance/repair and capital renewal functions, the need for efficient inspection planning, and the need for less-subjective condition assessment.

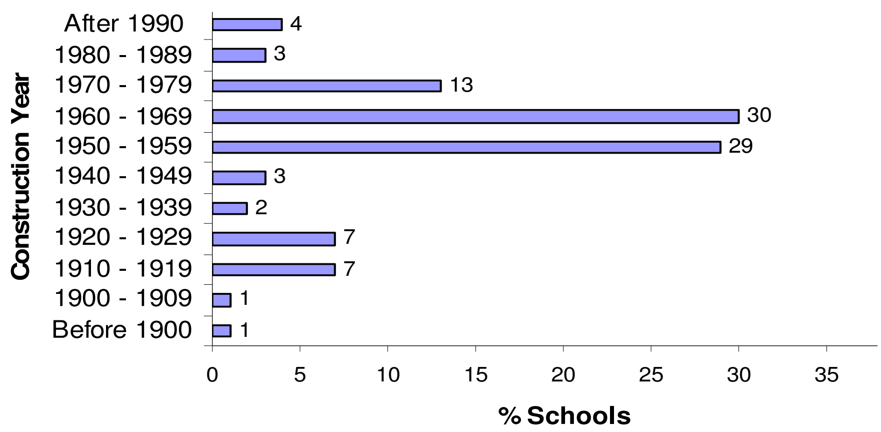


Figure 1.3: Age Distribution for Toronto Schools

1.2.1 Lack of Integration between Maintenance/Repair and Capital Renewal Functions

The current process of inspecting building assets, particularly for large owner organizations, is highly resource intensive. The sustainability of such assets becomes a greater challenge when capital renewal programs are downsized to save money, which affects the ability to properly inspect buildings and allocate renewal funds. Typically, building owners manage their inventory through two complementary functions: a reactive maintenance/repair program for continuously maintaining the operability of the building inventory and a capital renewal program for indicating when to replace existing assets. Each involves a different level of detail and produces different output. Although the literature describes the asset management tools and techniques that have been introduced to help asset managers make cost-effective decisions regarding how and when to repair/replace their existing assets, few studies have been directed toward the integration of the maintenance/repair and the capital renewal functions, either within organizations or among the support tools available. As a result, performance data about the assets have become scattered between these two functions.

1.2.2 The Need for Efficient Inspection Planning

The literature shows that some effort has been made to speed up the current process of field inspection of buildings (DfES 2003; Lewis and Payant 2000). However, the process is still resource-demanding task that must be repeated frequently. Further, as described in the literature and as noted during field visits, the typical inspection process can be described as time-consuming and unstructured. In addition, one or more of the following is usually lacking:

a. a well-defined method of digitally locating building components,

b. standardization of building components,

c. organized pictures of building components, and

d. a mechanism to keep a historic record of condition.

Developing proper means for condition prediction and prioritization of inspection tasks among the limited resources available can help in extending the life of inspection data, thus efficiently planning the inspection effort to save time and money.

1.2.3 The Need for a Less-Subjective Condition Assessment

One of the greatest obstacles to the development of an efficient condition assessment process is the subjectivity and ensuing lack of accuracy. Traditionally, a condition assessment for a building is performed through visual inspection by experts in specific building systems, e.g., architectural, structural, electrical, and mechanical. While many asset management systems incorporate some measures to ensure uniformity such as staff training and the use of a numeric-based rating system, the current condition assessment process is nevertheless highly subjective and its accuracy is highly dependent on the experience and training of the field inspectors and assessors.

There is thus a need for a new comprehensive system of condition assessment that is more structured, faster and more affordable, that provides less-subjective results, and that ensures a useful link between the asset management data and the maintenance data.

1.3 Research Objectives and Scope

The primary objective of this research is to develop a new framework to support efficient field inspection and condition assessment of the building infrastructure. The proposed framework will support building asset management decisions by addressing the problems associated with the traditional process of assessing the condition of buildings. The proposed framework consists of three main components: condition prediction and inspection planning based on the available reactive-maintenance records, a visual guidance system to support the visual condition assessment of the building components, and a location-based inspection process with a standardized building hierarchy.

The detailed objectives of the present research are the following:

a. Understand and examine the challenges posed by the current condition assessment process from the perspective of a large a owner organization.

b. Explore a mechanism that will make the building inspection process more aligned with the organizational objectives and more efficient with respect to the use of the available resources.

c. Restructure the condition inspection process into a location-based visual process for easy inspection of standardized building components.

d. Develop an approach that uses the available maintenance data and resources to predict the condition of components and prioritize them for inspection purposes.

e. Identify and investigate the defects, symptoms, and interrelationships among top building components.

f. Develop a simple approach to reduce the subjectivity in the condition assessment of the identified building components.

g. Develop a computer prototype using hand-held devices for an efficient inspection and condition assessment that suits less experienced individuals.

h. Use sample school buildings to experiment with the proposed framework.

In essence, the research aims at developing a computerized decision support system that would require less time and money for field inspection and provide a more uniform condition assessment. The decision support system would aid condition assessment professionals and organizations, such as municipalities and government agencies, to make appropriate funding and maintenance decisions in order to ensure the most cost-effective sustainable operation of the building infrastructure.

The proposed research focuses on field inspection and condition assessment for educational buildings. However, the proposed developments can also be applied to other infrastructure buildings such as offices, hospitals, shopping malls, etc. It should also be noted that this research deals with building condition assessments for the purpose of facilitating maintenance and replacement decisions only. Assessments for other purposes, such as purchasing, insurance, and privatization, are beyond the scope of this study.

1.4 Research Methodology

The approach for achieving these objectives consists of the following steps:

a. *Review of the literature*: An extensive survey of the literature was carried out in order to examine existing condition assessment and asset management systems. Based on the review, the limitations of the available systems were identified. The most appropriate features of replacement-based maintenance strategy and condition rating were selected to be included in the proposed condition assessment framework. In addition, the top building components with respect to maintenance expenditure were identified for further analysis.

b. *Selecting a case study*: The Toronto District School Board (TDSB) was selected as the case study for this research. The case study helped identify organization's differing objectives for building inspection, as well as the challenges they face with respect to the inspection process. This examination provided a thorough analysis of the improvements needed in the inspection process. In addition, the Facilities Services Department of TDSB provided reactive-maintenance data and other relevant information related to the condition assessment process they use for their educational buildings.

c. *Development of a system for condition prediction and inspection planning*: To improve the inspection process, a simplified, standardized, and largely automated condition indication system has been developed. The proposed system is based on examining and establishing a correlation between the TDSB's reactive-maintenance data and the condition of the components. This correlation facilitates the efficient scheduling of available TDSB resources. The proposed system was developed by

    - standardizing the building hierarchy, including all possible sub-components;

- designing a simple user interface using colour coding to link building components with digital building plans;
- programming a built-in camera to effortlessly take and store pictures of the inspected items in their associated database location; and
- implementing the prototype on hand-held ultra-mobile personal computers (UMPC) to facilitate mobility and fast inspection.

d. *Development of a visual guidance system*: To reduce subjectivity, a built-in pictorial database of components at different conditions has been developed to serve as visual and performance-related guidance for the assessment of the condition of building components. The first step in developing the database was the identification of the top building components that require the most expenditure for maintenance. This step was accomplished through an examination of the literature and discussions with experts in the industry. Extensive surveys were then carried out among experienced personnel at the TDSB to provide an understanding of the defects, symptoms, and interrelationship among these top building components. In addition, samples of pictures of the identified building components were collected at various life-cycle stages and conditions. The results of the surveys were integrated to form the visual guidance system that will support less-subjective condition analysis and assessment.

e. *Testing and validation*: The proposed prototype was successfully tested on a set of five Toronto District School Board schools. The use of the prototype on an UMPC proved to be beneficial and greatly enhanced both mobility and ease of inspection.

1.5 Thesis Organization

The remainder of the thesis is organized as follows:

Chapter 2 presents a literature review of the traditional and the most recent efforts related to condition assessment, particularly condition evaluation mechanisms, inspection and data collection processes, and the analysis of the inspection data.

Chapter 3 discusses the field study of the Toronto District School Board (TDSB). The chapter focuses on the current maintenance-related systems at the TDSB and the details of and findings from the field visit. The chapter also lists the improvements needed which form the basis of the development of the prototype system for the efficient condition assessment of building components.

Chapter 4 introduces the first component of the proposed condition assessment framework: a mechanism for condition prediction and inspection planning. Aspects related to this component, such as data collection and data analysis, are dealt with in depth.

Chapter 5 introduces an advanced visual guidance system to support the condition assessment of building components. The building components with the highest maintenance expenditure are identified, and background information about these identified components is presented. The details of extensive surveys of experienced TDSB personnel are also provided.

Chapter 6 discusses the third and the final component of the proposed framework: a location-based inspection process with a standardized building hierarchy. The chapter explains how all three components were integrated through a prototype computer system. The features of the prototype are presented, along with the TDSB case study that was used to validate the prototype and demonstrate its usefulness.

Chapter 7 summarizes the research work, highlights its contributions, and offers recommendations for future research.

Chapter 2
Literature Review

2.1 Introduction

Condition assessment is defined 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 are assigned to serve (Rugless 1993)." Condition assessment is the most important function in the asset management process as it forms the basis of or the starting point for other functions such as the decisions to repair or replace.

This chapter presents a comprehensive review of the state-of-the-art efforts described in several areas related to the condition assessment process, including asset hierarchy, evaluation mechanisms, field inspection, and condition analysis.

2.2 Infrastructure Assets: The Ongoing Crisis

Infrastructure includes basic facilities, services, and installations needed for the functioning of a community or society, such as transportation and communication systems, water and power lines, and public institutions, including schools and post offices. Since the late 1970s, signs of an ailing infrastructure have caught the attention of the media and the public. *America in Ruins: The Decaying Infrastructure* by Choate and Walter (1981) became famous and brought attention to the consequences of infrastructure with respect to loss of lives and property. Users, investors, and public officials became more concerned after hearing about critical incidents involving the sudden collapse and failure of infrastructure components. Public awareness of these incidents and identification of potential failure areas have led to a perception of an infrastructure crisis (Hudson et al. 1997).

In April 1971, standards for developing a bridge-inspection program were issued in the United States (Infrastructure 1992). Since then, bridge management systems and inspection programs have continually improved. This response was unfortunately the result of a real crisis, when 39 year old Silver Bridge collapsed in West Virginia in 1967, resulting in 46 lost lives and a great deal of property damage (Hudson et al. 1997). Although the history of collapses is gloomy, it has provided strong motivation for research and for governments to invest money, time, and effort. Table 2.1 provides examples of failures, none of them due to natural disasters such as earthquakes or tornadoes, but rather to other causes, most probably lack of maintenance and repair, inadequate inspection and condition evaluation, insufficient funding, or more generally, inadequate management.

Table 2.1: Examples of Infrastructure Problems/Failures

Year	Infrastructure Crisis	Repayments	Reference
1982	An 80-year-old aqueduct failed in New Jersey, U.S.A.	Three days with no drinking water for 300,000 residents.	Kwiatkowski 1986
1983	A bridge collapsed in Connecticut, U.S.A.	3 killed and 3 seriously injured.	Wagner 1984
2000	A high school gym roof collapsed in Cleveland, U.S.A.	3 students and 2 adults injured.	I Civil Engineer 2005 a
2001	A bridge collapsed in northern Portugal.	Up to 70 people were feared dead.	I Civil Engineer 2005 b
2002	A school staircase collapsed in north China.	21 teenage students died and 47 more were injured.	People's Daily 2005
2002	A nine-story apartment building collapsed in St. Petersburg, Russia.	3 killed, and about 430 people left homeless.	I Civil Engineer 2005 c

In literature, failure has been defined as the incapacity of a constructed facility or its components to perform as specified in the design and construction requirements. Failure refers to two conditions: collapse and distress (Wardhana and Hadipriono 2003). A building collapse occurs when the entire structure or substantial part of it comes down: the structure loses its ability to perform its function. Distress refers to the un-serviceability of a structure or of one or more of its component that may or may not result in a collapse (Wardhana and Hadipriono 2003). Table 2.2 shows the number of building failures that occurred from 1989 to 2000 in the U.S.A, during the construction and service phases of projects. It is clear from this table that the majority of building failures during service (126 of 177) involved partial collapse, possibly an indication of inadequate inspection and maintenance during the service life of these buildings.

Table 2.2: Number of Failures With Respect to Stage of Failure Occurrences

Types of Failure	Construction Phase	Service Phase
Distresses	1	16
Partial Collapses	35	126
Total Collapses	11	35
TOTAL	**47**	**177**

2.3 Building Maintenance: A Challenge

Maintenance covers a broad range of activities, e.g., inspection, preventive maintenance, repair, and rehabilitation, in order to preserve an asset in its original condition (Vanier 2001). Maintenance for buildings is a complex task largely due to the complexity of buildings in terms of their large number of components that have different maintenance requirements. To demonstrate the complexity of managing building assets, a typical school building can be considered. The building can have about 170 components (Interior Door, Roof, Boiler, Transformer, etc). Furthermore, different instances of each of these components can be part of the same building. A roof component, for example, can have several sections, depending on the size of the school. Schools also have multiple instances of windows, boilers, and doors. Assuming that each component has only three instances, the resultant total is about 500 unique components or instances. Therefore, in order to evaluate the condition of a school building, 500 discrete components (grouped into 170 categories) need to be inspected, rated, and further analyzed in order to determine the overall condition (Elhakeem and Hegazy 2005). Since these 500 components apply to only one school, the degree of complexity is multiplied many times in the case of a school board that manages hundreds of schools. One example is the Toronto District School Board (TDSB), which is responsible for 642 schools, for which the inspections, analysis, and ratings involve more than 300,000 components.

However, despite huge investments, the maintenance of buildings has been neglected for a long time due to the scarcity of funds (Telcholz 1995; McCall 1997). According to De Sitter's Law of Fives, if maintenance is not performed, then repairs equaling five times the maintenance costs are required. In addition, if the repairs are not implemented in time, then renewal expenses can reach five times the repair costs (De Sitter 1984). As well, postponing maintenance activities compounds the amount of deferred maintenance (work that has been postponed or phased for future action), leading to a huge backlog. As a result of this deferred maintenance backlog, there has been a growing awareness worldwide of the importance of building maintenance (Vanier 2001; Bourke and Davies 1997; Cane et al. 1998; Underwood and Alshawi 1999).

2.4 Educational Buildings: A Greater Challenge

Educational buildings cover a wide range, from kindergarten schools to large universities. Within this range, elementary and high schools are the most difficult to manage and maintain due to their large number and scattered locations. Schools should provide a physical setting that is appropriate and adequate for learning (NCES 2003 a). Therefore, the condition of a school has a direct impact on students' achievement (McCall 1997). The literature cites numerous instances indicating that students learn better in an environment that is pleasant, safe, and free of health hazards (Earthman et al. 1995; NCES 2003 a). In an international seminar in Austria (1998) on "Improving the Quality of Educational Buildings," ample research was presented indicating that the quality of facilities has an impact not only on educational outcomes but on the well-being of students and teachers (Hinum 1999). Hinum (1999) further emphasizes that poor maintenance increases running costs, such as for energy and cleaning. Energy expenditure, for example, can amount to more than one-third of premises-related expenditures; reducing energy consumption can help not only to save money but also to reduce carbon dioxide emissions and other forms of pollution. Other consequences of poor maintenance include the deterioration of parts of the building, an unsafe and unhealthy environment, a lower quality of teaching and learning, and a lower quality of living.

Thus, it can be concluded that the condition of schools is an important concern. This study, therefore focuses on the condition assessment of school buildings in particular, in order to facilitate better maintenance and repair decisions.

Currently, the condition of school buildings in North America, including Canada, is constantly changing, i.e., deteriorating, for the following reasons:

a. *Age*: The average age of schools in North America is more than 40 years (NCES 2003 b). Table 2.3 shows the average age of schools by region in the U.S.A, based on State Education Department data. In Canada, school facilities exhibit the same trend. For example, most schools in Toronto were built before 1970 and are currently more than 45 years old (McCall 1997). This data suggest that thousands of obsolete or run-down schools are in need of replacement or modernization (McCall 1997).

Table 2.3: Average Age of School Buildings in New York State

No.	School Area	Average Age
1	New York	57
2	Rural counties	48
3	Small Cities	44
4	Suburbs	43

b. *External and internal conditions*: A harsh environment is one of the main reasons for the deterioration of most building components. A component's location (e.g., direct or indirect exposure to sunlight) and usage (e.g., actual use as opposed to recommended use), also affects the level of deterioration of building components (NCES 2003 a).

c. *Enrolment capacity*: Currently, schools in North America are experiencing an additional pressure due to enrolment overflow from new immigrants (McCall 1997). As a result, since 1990, school enrolment numbers have exceeded capacity and are projected to continue to increase in coming years, which creates extra pressure on school maintenance and repair programs.

d. *Advances in information technology*: Advancements in information technology with their accompanying fast rate of obsolescence have brought many changes in the field of educational and learning systems. These technological changes demand upgrades to the current building systems in terms of teaching and learning technologies (McCall 1997).

e. *Inadequate maintenance*: Studied have shown that in New York State, 90% of schools report a need to upgrade or repair buildings to good overall condition (GAO 1996). Given the tremendously insufficient funds for maintenance and repair, this figure represents a major obstacle to achieve the goal of adequate maintenance.

2.5 Asset Management Systems

To respond to the challenges in managing and maintaining assets, several asset management systems have been developed. As defined by Hudson et al., in 1997, an asset management system is an operation package consisting of the methods, procedures, data, software, policies, decisions, etc. that enable the carrying out of all the activities involved in asset management. According to the literature, the main functions of an asset management system (Figure 2.1) include:

a. assessment of the current condition,

b. prediction of future deterioration,

c. selection of maintenance and repair strategies,

d. after-repair condition improvement, and

e. prioritization of building components for repair given the budget constraints.

Of these functions, condition assessment is the most important because its results represent the starting point for other functions such as deterioration prediction or repair selection. The remaining part of this chapter will therefore focus on the research related to condition assessment.

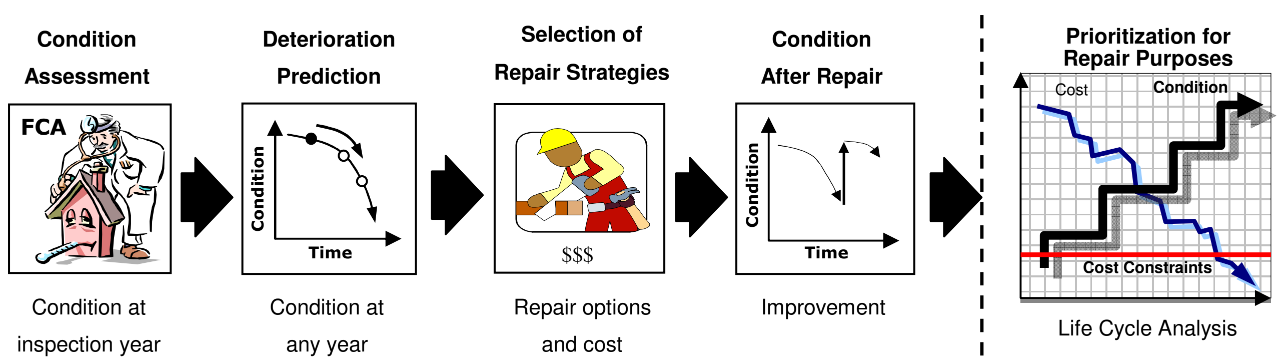


Figure 2.1: Main Functions of an Asset Management System

2.6 Condition Assessment

Condition assessment is the basis for determining the level of preventive maintenance needed for a building's systems and components (NCES 2003 b). In the literature, condition assessment has been defined in different ways, some of which are tabulated in Table 2.4.

Table 2.4: Definitions of Condition Assessment

No.	References	Definitions
1	Straub 2003	A tool for assessing the technical performance of the properties to underpin long-term maintenance expectations
2	Chouinard et al. 1996	The evaluation of the condition of the functional system that meets the desired objectives
3	Telcholz 1995	A service provided by design professionals which included the performance of building audits, primarily for reports of building deficiencies, to raise the building's performance to its original "new " potential
4	Sadek et al. 2003	A system inventory and inspection to evaluate the current condition of the system based on established measures of the condition
5	Strong 2004	A vehicle for producing a complete inventory of deficiencies in a facility by thoroughly assessing the existing physical conditions and functional performance of buildings, equipment, utilities, and grounds
6	Rugless 1993	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
7	DfES 2003	A tool to provide a systematic, uniform and objective basis for getting information on the state of the premises
8	Fagan and Kirkwood 1997	An information system customized for the input, storage, manipulation, and reporting of facility-related information
9	Kaiser 1993	A process for inspecting and reporting the physical condition and functional performance of building and infrastructure systems and components
10	NCES 2003 a	A data collection process with the goal of conducting a comprehensive inventory that meets the needs of the entire district management effort in a coordinated manner and thereby avoids the need for redundant collection efforts
11	JCEF 2004	A state of repair of building infrastructure that takes into consideration all the building systems from roofs and windows to electrical and mechanical systems
13	Lewis and Payant 2000.	A process whereby the organization's facility systems, components and sub components are evaluated as to their condition.

The literature suggests that, ideally, a condition assessment must be performed annually (Lewis and Payant 2000; NCES 2003 b; DfES 2003) because the longer the period between inspections, the more extensive the inspection becomes. If a condition assessment is performed on a regular basis, then the assessment is much easier (NCES 2003 b). However, a limiting factor when considering the frequency of condition assessments is the cost involved in the inspection. Information with an appropriate level of detail must be collected during the field inspection. Collecting information that is too detailed and not subsequently used is wasteful. On the other hand, information with insufficient detail also wastes resources.

A condition assessment can be performed by an outside consultant (or contractor) or by in-house staff. In the determination of who performs the assessment process, cost is a major constraint. Small districts may not be able to afford a specialist whereas larger organizations might employ several. It is important, however, that the condition assessment team possess a thorough understanding of facility maintenance and operations and have enough time to perform the task properly. The literature (Lewis and Payant 2000; NCES 2003 b; DfES 2003) states that all inspection team members be well trained in the inspection procedures and be qualified to conduct the inspection. In addition, NCES (2003 b) states that regardless of the size of the school district and the organizational affiliation of the inspectors (also called surveyors), the inspection should be carried out by teams of two or more rather than by an individual (Shahin et al. 1987). The inspector should be accompanied by someone who is intimately familiar with the facility being assessed, e.g., a custodian or maintenance staff member who works in the facility on a regular basis.

Since the 1980s, condition assessment systems have been developed exclusively for individual types of infrastructure assets. For example, PAVER was developed for pavement management (Shahin 1992), RAILER for railroad tracks (Shahin 1986), BRIDGER for bridges (NRC 1998), ROOFER for roofs (Bailey et al. 1989), GRIPPER for underground gas pipes (NRC 1998), and BUILDER for buildings (Uzarski and Burley 1997). RECAPP and TOBUS are additional recently developed condition assessment tools for buildings. Other commercial condition assessment software systems include ARCHIBUS and FacMan. Since the focus of this research is on buildings, some of the condition assessment software systems for buildings (BUILDER, RECAPP, and TOBUS) are discussed in detail in the subsequent subsections. A brief description of these systems follows:

a. *BUILDER* was developed by the U.S. Army Corps of Engineers at the Engineering Research and Development Centre - Construction Engineering Research

Laboratory (ERDC-CERL) in Champaign, Illinois. BUILDER provides engineers and facility managers with a tool that supports decisions regarding when, where, and how best to maintain buildings and their key components. BUILDER is Windows®-based software with functions that include an inventory of major building components; checklist-style, pen-based inspections; condition indexes; functionality ratings; and condition prediction capabilities (BUILDER 2002).

b. *RECAPP®* (Re-Engineering the Capital Asset Priority Plan) was initially developed to support data gathering and reporting for audit clients. It includes an inventory of building major components, checklist-style inspections, and condition indexes. It has been used widely for school boards, municipal infrastructure management, and airport authorities (PPTI 2006).

c. *TOBUS* is the most recent framework developed by the European Commission (D.G. XII) in the JOULE II program. Its condition assessment covers the degree and extent of physical degradation and the work necessary to renovate office buildings (Brandt and Rasmussen 2002).

A condition assessment system is performed primarily to facilitate the ranking of all the components of all assets according to the amount of needed repair. Four main steps (Figure 2.2) in a detailed condition assessment are discussed in the following subsections.

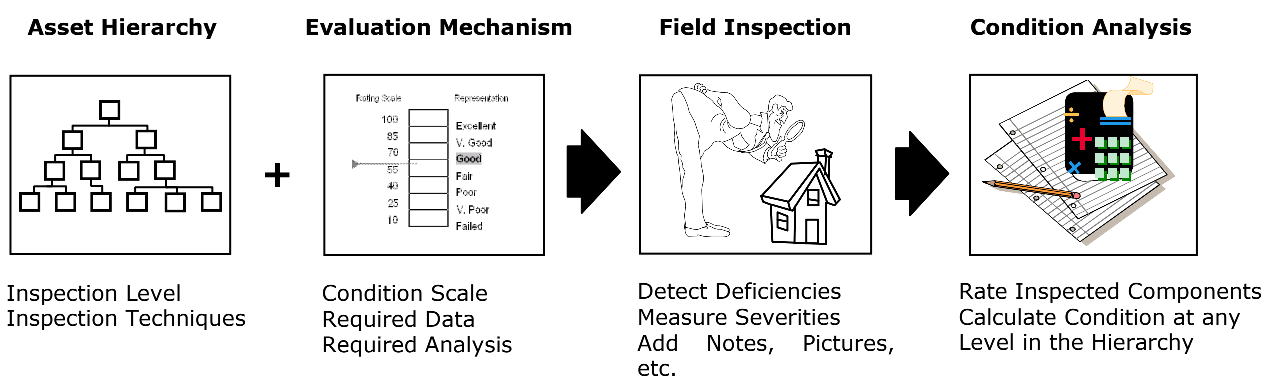


Figure 2.2: Main Steps in the Condition Assessment Process

2.6.1 Asset Hierarchy

As an essential step in condition assessment, a building must be hierarchically decomposed into its main components. The hierarchy is intended as a means to classify and cluster these components in different categories. For example, a building can be divided into different disciplines or systems (electrical, mechanical, etc.), that can be further divided into more detailed component level (interior doors, exterior doors, windows, ceiling, etc.). The grouping of components into a branch in the hierarchy may be done to reflect similar characteristics (e.g., materials), similar inspection needs (Uzarski and Burley 1997).

Literature shows that there are five main elemental classification systems used for data exchange around the globe: 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).

A standardized and consistent format for defining a building hierarchy can help in the sharing of data across departments within an organization. A study by Elhakeem (2005) combined the benefits of 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 (e.g. school boards). The main benefits of the proposed hierarchy are to facilitate the process of revising assessed components, to evaluate the performance of each department in keeping its components in a safe and satisfactory condition, and to permit the organization of possibly organize the allocation of funds among various systems according to organizational preferences.

Other efforts to establish a hierarchy of building objects have been discussed within the domain of building information modeling and in the proprietary efforts by government agencies to establish asset management systems. One example of information models is the work by Hegazy et al. (2001) that involved the creation of a building project hierarchy (BPH) from a central library of building components. The hierarchy was useful in representing multidisciplinary design data within each building space. In terms of proprietary efforts by government agencies, Table 2.5 is a summary of representations and systems that have been developed.

Table 2.5: Proprietary Representations of Building Information

	Reference	Agency/State	Hierarchy
1	NCES 2003 b	All America	11 systems and 106 components/subsystems
2	WSDOT 2000	Washington, U.S.A	9 major systems with 44 components
3	JCEF 2004	State of Arkansas, U.S.A	11 systems and 67 subsystems
4	ADOE 1997	Alaska, U.S.A	19 systems for each condition evaluation form
5	DfES 2003	U.K	12 building elements

In addition to standardization and proprietary efforts, various commercial software systems have either developed their own building component hierarchies (e.g., BUILDER, RECAPP, and TOBUS) or have adapted one of the standardized building element formats. Table 2.6 presents a summary of three commonly used commercial software systems for asset management that have building hierarchy feature for condition assessment.

Table 2.6: Commonly Used Condition Assessment Software Systems

	Name	Hierarchy
1	TOBUS	70 objects, 256 types
2	RECAPP 2002	7 disciplines, 32 system level, 133 assembly level, 169 component level
3	BUILDER 2002	12 systems with 150 components

The asset hierarchy used in BUILDER (Table 2.7) illustrates how a building is divided into 12 systems, and then subdivided into a total of about 150 components. From Table 2.7, it can be seen that the hierarchy ends at the subcomponent level (level 4, e.g., “frame,” “surface,” and “hardware” subcomponents of the “interior wooden door” component). Each subcomponent is assigned an importance factor (called a value factor) from 0 to 1 in order to facilitate the calculation of the condition at the higher component level. One of the advantages of this particular hierarchy is the use of a separate level (level 3, section) to classify components based on material, age, etc. As an added feature, BUILDER has a list of 20 generic distress types to be used for evaluating the condition of any subcomponent.

Another example of a building hierarchy is that of the RECAPP system, as shown in **Error! Reference source not found.**. In this hierarchy, four main levels are specified for decomposing a 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 any instance of a component. The hierarchy, however, does not have a standardized list of components for all assets (buildings). Furthermore, the number of instances per component is not fixed (e.g., a component can have three instances in one building and five in another). The system requires the manual addition of new instances for the parts of a component that show a specific condition (e.g., a group of doors or windows, or one of the boilers, etc.), which makes managing these instances time-consuming.

Table 2.7: Asset Hierarchy for BUILDER 2.1 (2002)

Level 1: System	**Level 2: Component**	**Level 3: Section**		**Level 4: Subcomponent**		**Generic criteria for condition assessment**
Site	Floor Surface	**- Material**		Frame	(0.52)	- Broken
Structural	**Interior Doors**		Glass	Hardware	(0.47)	- Clogged
Roofing	… etc.		Metal	Surface	(0.71)	- Corrosion
Exterior			**Wood**		↑	- Cracked
Circulation		- Age				- Damage
Exterior Closures		- Area				- Deterioration
Interior Construction		- Floor				- Displaced
Plumbing		- …etc.			Value factor	- Efflorescence
HVAC						- Excessive Noise/Vibration
Electrical						- Holes
Fire Suppression						- Loose
Conveying						- Missing
Total = 12	**Total = 150**					**Total = 20**

The most recently developed condition assessment system, TOBUS, has a checklist of databases with 70 objects, such as roofing, façade and fire protection. The objects are subdivided into 12 types (maximum) to account for differences in the material or design of the object.

Thus, it can be concluded that asset hierarchy is an essential part of all condition assessment systems. Irrespective of the type, an ideal building hierarchy should have logical and consistent asset hierarchy decomposition so that a component or backlog can be quickly and easily tracked. In addition, it should have an appropriate mechanism for calculating condition indices for the building components.

Table 2.8: Asset Hierarchy for RECAPP 1.0 (2002)

Level 1: Discipline	Level 2: System	Level 3: Assembly	Level 4: Component	Level 5: Instance	Component-specific Deficiency list	
- Property **- Arch./ Structural** - Conveying System - Mechanical - Electrical - Environmental - Functional	- Foundations - Superstructures - Exterior Closures - Roofing **- Interior Construction**	- Partitions - Moveable Partitions - Internal Doors - Internal Door - Hardware **- Interior Wall Finishes** - Floor Finishes - Ceiling Finishes	- Paint Wall Covering - Vinyl Wall Covering **- Stucco Wall Finish** - Ceramic Wall Tile - Glazed Wall Cover.	**i.e.,** Wall 1 Wall 2 … Wall n	- Excessive Cracking or spalling - Uneven surface - Wall Penetrations not Properly Sealed - Water damage	(50%) (15%) (10%) (25%) ↑
					Deficiency weights, reflecting effect on the component	
Total = 7	Total = 32	Total = 133	Total = 169 Components		Total = 885 Deficiencies	

2.6.2 Condition Evaluation Mechanism

The condition of a single instance of a component can be evaluated either or both of two approaches: a distress survey and a direct-condition rating survey (Uzarski 2002). Uzarski reported that the distress survey procedure is an accurate and reproducible approach. It provides a record of what needs to be fixed in the inspected instance. The direct-condition rating approach is less accurate but much faster. It involves a visual inspection of each component and an evaluation of that item against a set of criteria. In a recent study by Uzarski (2007), the distress survey approach was divided into two groups: distress surveys with or without sampling. Uzarski also suggested that each type of condition survey is better suited for a particular stage in the component's life cycle, as shown in Figure 2.3.

A decision about the use of a direct rating approach or a distress survey approach requires knowledge of the purpose of the assessment. If the purpose is merely to identify the condition of the component, then the direct-condition rating approach is sufficient. However, if the purpose is to identify current problems, then the distress survey approach should be used (Uzarski 2002).

Much research has been directed towards identifying proper evaluation criteria in order to assess the performance of building components (Ashworth 1996; Chew and De Silva 2003). However, regardless of the criteria used and their level of detail, the results of the assessment process very much depend on the accuracy of the subjective field inspection process. Existing systems require an experienced inspector to judge (with respect to any criteria) the condition of an asset during the inspection process itself. Such inspectors are therefore very costly and will require long time to inspect.

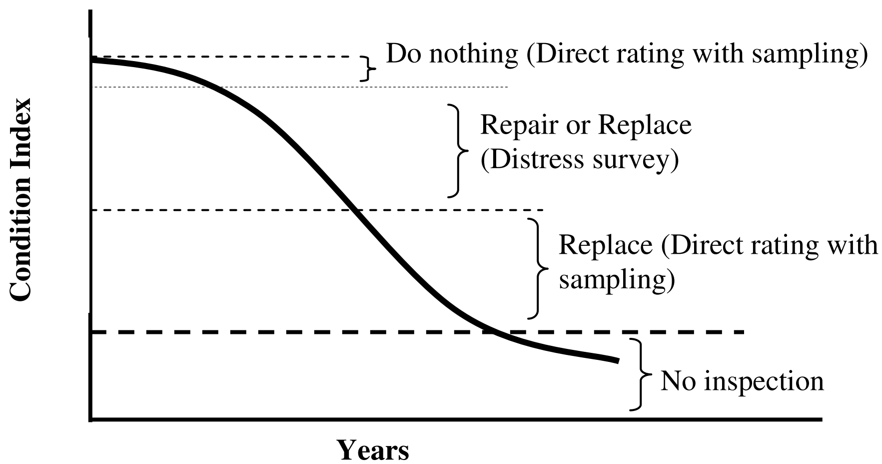


Figure 2.3: Component life cycle with repair versus replacement needs (based on Uzarski 2007)

The evaluation criteria, as discussed with respect to BUILDER and RECAPP, represent possible deficiencies that suit the distress-condition rating method. In the RECAPP system, each component has a separate list of specific deficiencies, with weights that reflect their relative impact on the condition. In the field, inspectors judge the severity of each possible deficiency and RECAPP then calculates a condition index, as will be discussed later. BUILDER, on the other hand, uses its 20 generic distress types in the evaluation process. In the field, the inspector evaluates each subcomponent relative to these 20 distress types, providing his judgment for two measurements (density and extent) for each distress type. This process, however, is complicated and time-consuming. For example, to evaluate a component with only three subcomponents, the inspector is required to provide 20*2*3=120 subjective measurements, based on which a condition index is calculated.

TOBUS uses the direct-condition rating approach to evaluate the condition of building components. TOBUS evaluates the current condition by using four degradation codes to diagnose the physical degradation level of the object (Table 2.99). However, the disadvantage here is that the components are not decomposed as in BUILDER and RECAPP. For example, an external window is the lowest level in the TOBUS building hierarchy. It is not broken down further with respect to types of deficiencies or materials. In addition, the evaluation of the components is highly subjective because unlike BUILDER and RECAPP, TOBUS has no numeric scale.

Table 2.9: Representation Codes for Diagnosis of the TOBUS Objects

Code	Type Exists
A	Good Condition
B	Some Deterioration
C	Mean Deterioration
D	Service Life is over and immediate repair required

In any system, the values of the condition indexes provide the means of comparing the condition of various components. The condition index scale for building components is usually from 0 to 100, where 0 represents a critical (failure) condition and 100 represents a new condition. No matter which numeric scale is used, a linguistic representation can be derived from the numeric values, as in the example from BUILDER, shown in Figure 2.4 (Uzarski and Burley 1997). Other examples of condition scales and corresponding linguistic representations are listed in Table 2.1010.

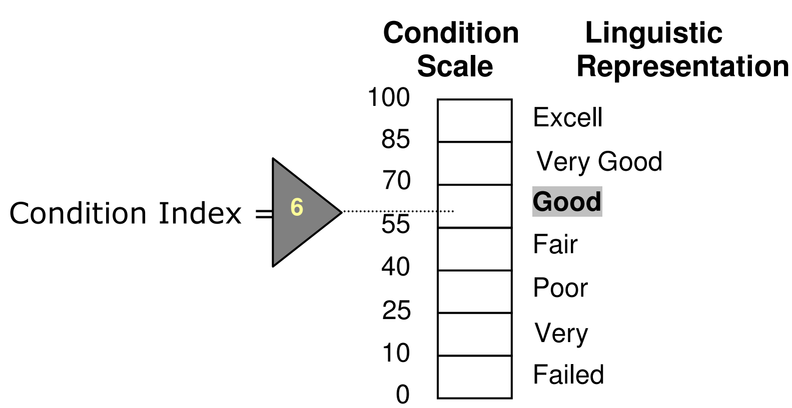


Figure 2.4: Condition Scale and Linguistic Representation

Table 2.10: Rating Scales and Representations

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)

2.6.3 Inspection and Data Collection

Evaluating the condition of building components using a distress survey requires full knowledge of the deficiencies possible in each component. To accurately detect these distresses and measure their severity, a systematic approach to field inspection is crucial. The goal of the inspection process is to obtain the data required in order to measure and/or calculate performance or to evaluate the condition (calculating a numeric value that reflects a specific condition).

Inspection should be performed consistently, accurately, and as objectively as possible. To ensure uniformity in assessment, training for inspectors is recommended (Setzer et al. 1995). To standardize the process, many researchers have developed checklists and deficiency lists for inspection (e.g., RECAPP 2002; BUILDER 2002). These lists can be in either paper or electronic format. Some researchers, on the other hand, try to automate the inspection process using robots, images, satellite technology, automated devices, and/or smart sensors (e.g., Maser et al. 1997). Many programs and techniques developed in the literature can be categorized into four main groups:

a. Visual inspection
b. Photographic and optical methods
c. Non-destructive evaluation methods and
d. Smart sensors.

Table 2.11 provides a summary of these efforts. Among the various techniques and technologies that can be used for the condition assessment of facilities, only visual inspection suits the nature of building assets, which have multiple diverse components with different requirements. Visual inspections are defined as organized and planned visual examinations conducted by technically proficient personnel (Lewis and Payant 2000). The result of these inspections is a report that depicts the deficiencies or problems for the building components and systems of the facility. The report is then used for budgeting and planning.

Visual inspection, however, is not easy. It is expensive and time-consuming (Hammad 2003). Field inspectors must record the condition of every component in the facility using one of the following methods (DfES 2003):

a. *Manual input*: This method uses pen and paper for subsequent input into the management program, which is almost invariably some form of computer software. This option, however, is time-consuming and has drawbacks.

b. *Tape dictation*: Information is recorded in audio format for subsequent program input. This option is fast, but requires practice; otherwise, problems can be encountered because the inspector cannot see, and hence readily check, the data recorded. Tape dictation can also cause difficulties with the occupiers of the buildings. Extraneous noise, either from the occupiers or from other factors such as weather or traffic, can corrupt the recording.

Hand-held computers: This method allows direct input to the management program. This option has the advantage of one-step data entry as opposed to two-step process required for the above methods. The literature also shows that facility managers benefit most from computerized maintenance management systems (CMMS) if they organize the instructions for and scheduling of their inspections in the same system used to organize other types of facility work. The

Table 2.11: Inspection Techniques Used in the Literature

	Reference	Application Areas	Technique	Equipments	Measurements	Comments
Visual Inspection	Greimann et al. 1997; Uzarski 2002; Straub 2003; Strong 2004; Shohet et al. 2002.	Buildings, Highway, and other structures	Data is recorded on paper or handheld devices	Simple tools, cameras, and subjective observation	Anchorage movements, elevation changes, deflections, misalignments, cracks, dents, and corrosion	Most useful in buildings, however, time-consuming, costly, subjective, labour intensive, prone to errors
Photographic and Optical	Abraham et al. 1997; Fukuhara et al. 1990; Fundakowski 1991.	Mostly for bridges, Highways, and Underground Utilities	Evaluate the condition by analyzing the images	Video/digital/ scan cameras, closed-circuit TV , and/or mechanical gyroscope	Roughness, cracks, and damaged area	Minimum disturbance to public, safe for inspectors, fast, and accurate; needs standardization in the area of image resolution
Non-Destructive Evaluation	Maser and Zarghamee 1997; Heiler et al 1993; Lee and Chou 1993, Lo and Choi 2004; Maser 1995; Warhus et al. 1995.	Aqueducts; transportation infrastructure; bridges; some building components; etc.	Collect images from various sources to be analyzed	Infrared thermograph, laser, ultrasonic sensors, and ground penetration radar equipments	Hot or wet areas; bridge deck de-lamination, rebar corrosion, and pavement roughness	Minimum disturbance to public, safe for inspectors, fast, and accurate
Smart Sensors	Kumapley and Beckemeyer 1997.	Bridges	Measure the deformation and transmit the results continually using sensors	Small self-contained battery-powered transducers	Displacements, strains, rotations, and accelerations of key bridge elements	Real-time data collection and processing

advantage of computers for field inspection is their ability to store and retrieve large amounts of information such as past records and pictures. Accuracy is also increased because data can be fed automatically into a central database. One possible disadvantage, however, is the cost of inspectors relative to that of data-input clerks.

c. *Wearable computers*: On-site inspection requires inspectors to be hands-free most of the time because they need to move continuously while taking measurements and notes. Interesting research has been conducted with respect to the use of wearable computers for inspecting bridges (Hammad 2005).

Irrespective of the method used for recording the condition of the facility, a number of problems are associated with field inspection. One of the major problems identified in the literature is the subjectivity of the inspector's judgment about the condition of a building component or a system (Kempton et al 2001). This subjectivity can be due to the inspector's specific individual experience, attitude towards risk, use of "rules of thumb," and biases (Scott and Anumba 1996; Hogarth 1987). Table 2.12 lists other problems associated with visual inspection (DfES 2003).

Table 2.12: Potential Field Inspection Problems

Factor	Likely Effect	Action to Minimize
Inexperienced survey team	Poor quality and consistency of surveys.	Upgrade team to an adequate level. Increase training element and/or level of supervision.
Inadequate supervision or management	Increased risk of substandard surveys either being done in the first instance or not detected.	Provide adequate supervision and management. Alternately, upgrade team so that less supervision and management are required.
Undue occupier influence	Skewed or incomplete survey data; greater time taken.	Avoid contact with occupier if not required for the purpose of the survey. If avoidance is not possible, seek to minimize contact in survey.
Adverse environmental conditions	Greater time taken; risk to quality of work.	Manage time as far as practical; for instance, work inside when it is dark or raining. Consider adjusting hours worked to avoid disruption.
Inadequate time allowed	Program disruption or overrun. Inefficient working or incomplete surveys.	Increase resources or re-cast program.
Software system glitches	Unpredictable; can include lost or corrupted data.	Use pilot surveys to test systems. Apply rigorous quality assurance procedures.
Data lost on site or in transit	Understatement of repair and renewal requirement.	Provide diligent and frequent delivery to data inputting stations.

Figure 2.5 and Figure 2.6 show two screen shots of the inspection survey systems used by BUILDER and RECAPP, respectively. Both systems allow the user to add pictures, notes, general information, and detailed descriptions of the deficiencies.

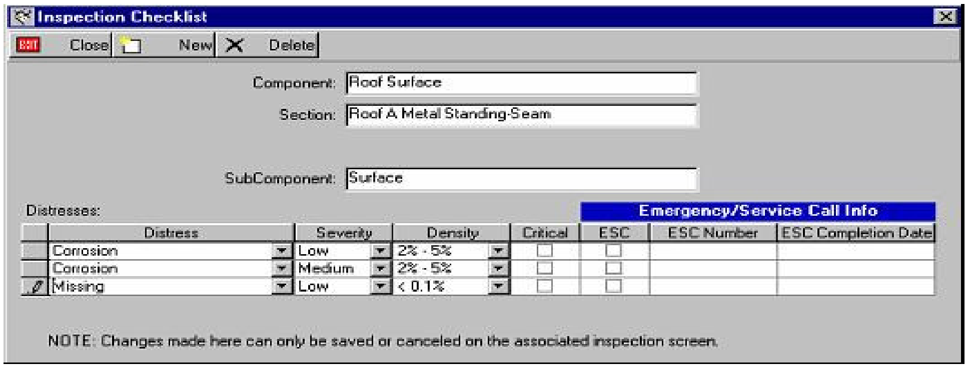


Figure 2.5: BUILDER Inspection Checklist

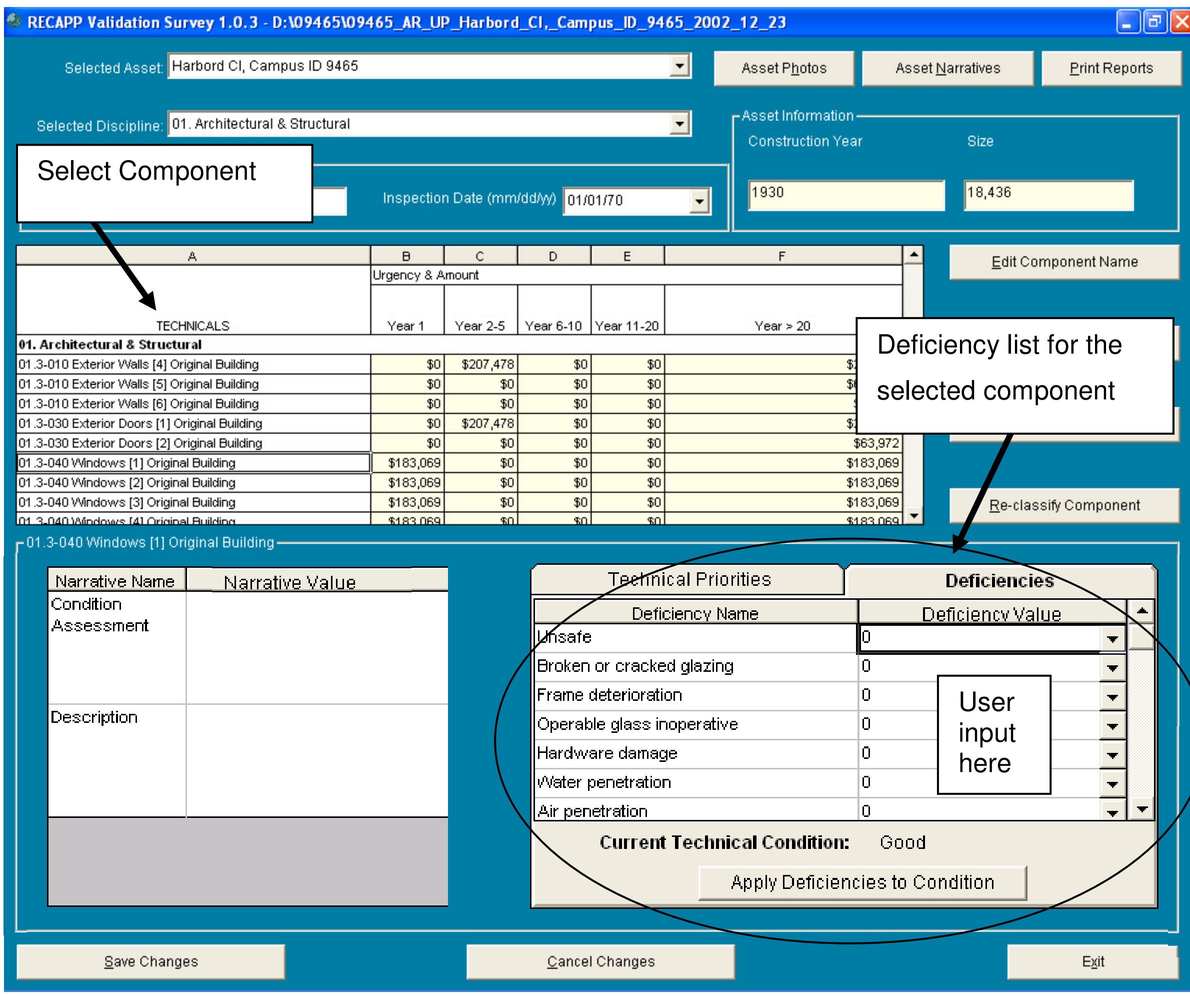


Figure 2.6: RECAPP Validation Survey Form, Version 1.0.3

TOBUS, on the other hand, uses pictures as visual guidance for assessing the condition of the building components during field inspection. For each degradation code, one or more sample photos illustrate the type of degradation so that the inspector on location can compare the actual case with the database examples. The development of this system claims that the photos lead to a more homogeneous diagnosis of an object, which is independent of the inspector or his professional background (Brandt and Rasmussen 2002). In another research related to pavement defects (PMIM 2005), pictures have been used to demonstrate and explain the severity of pavement cracks (Figure 2.7). The use of pictures in such research work supports the developments of the proposed research framework described in Chapter 5.

Slight: Less that 8" in width and less than 1.5" depth.

Moderate: From 8" to 15" in width and 1.5" to 2.5" in depth.

Severe: More than 15" in width and greater than 2.5" in depth.

Figure 2.7: Severity Level of Pavement Cracks

2.6.4 Analysis of Inspection Data

Because the data provided by the inspection process is in the form of measurements of the severity of the deficiencies of a component, some analysis is required in order to translate these measurements into a condition value. Once the condition of a component is calculated, that value can be used to calculate the condition at any level in the asset hierarchy (condition aggregation).

The inspection data is analyzed based on the type of evaluation method (direct-condition rating or distress rating). If the evaluation used the direct-rating method at the system level, an index is calculated for the whole facility: the Facility Condition Index (FCI). The FCI is considered as standard tool, which is used by architects, engineers, and facility planners to compare the condition of school facilities and determine whether it is more economical to fully modernize an existing school or to replace it (NCES 2003 b). The FCI is calculated as follows (NCES 2003 a):

$$\text{Facility Condition Index (FCI)} = \frac{\text{Cost to Correct Deficiencies}}{\text{Current Facility Replacement Value}} \qquad (2.1)$$

The cost to correct deficiencies equals the estimated total costs to repair all life-cycle, maintenance, and design deficiencies. Replacement value is the cost to replace an existing structure with a new structure of the same size at the same location, which can be calculated as follows:

Replacement Value = Gross square footage of the existing building * Estimated cost (per square foot) to design and build a new school (2.2)

If the condition assessment, on the other hand, is performed at a more detailed level (using the distress rating method) for all the instances of the components, the analysis results in a condition index (CI) for each component. This more accurate approach identifies the specific defects and their severity for all building components and then combines them (by rolling them up) at the upper levels to produce an accurate assessment of the building at every level. Since this research focuses on determining a replacement strategy based on the assessment of building components, the first approach, i.e. direct-condition rating, is more suitable.

Using a deficiency list such as the ones in BUILDER and RECAPP, field measurements can be easily used to calculate the facility condition index. In the BUILDER hierarchy shown in Table 2.7, the section level identifies components by age, material, etc. For each section, samples are selected for inspection; sampling guidelines are included in the documentation for BUILDER. The calculations then consider all the subcomponents of the selected sample. The subcomponent condition index (CIS) is calculated using the weighted-deduct density model developed by Uzarski and Burley (1997). The model relates the observed degree and severity of deterioration for all 20 generic types of distress as shown in Table 2.7. Equation (2.3) is then used to calculate the condition for the uth subcomponent.

$$\mathrm{CIS}_u = 100 - \sum_{i=1}^{p} \sum_{j=1}^{m_i} a(T_{j1} S_{j1} D_{ij}) F(t,d) \tag{2.3}$$

where CIS_u = the condition index for the uth 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

m_i = the number of severity levels for the ith distress type

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

Once the CIS values for all subcomponents in the sample are calculated, BUILDER then calculates the full component's condition index using the relative value factors of the subcomponents as weights (Figure 2.8). The condition at any level in the hierarchy, including the system level and the overall building level, is also calculated using the weight. As illustrated in Figure 2.8, the rolling-up process progresses from bottom to the top of the hierarchy, where the Parent Condition Index (PCI) is computed from the weighted average of its Children Condition Index, weighted by size/quantity or replacement cost.

The process of extracting the condition is much easier in RECAPP than in BUILDER because the hierarchy in RECAPP uses a specific list of deficiencies for each component. Hence, only the severity of each of these deficiencies has to be checked, evaluated, and then weighted according to the pre-specified weight for each defect. The weights are normalized so that the summation of weights = 100%. Equation (2.4) is used in RECAPP to calculate the condition.

$$CI_j = 100 - \frac{\sum_{i=1}^{d} W_i \cdot S_i}{100} \tag{2.4}$$

where CI_j = the condition Index for the j^{th} (component or section)

W_i = the weight for deficiency i

S_i = the severity extent for deficiency i

i = the counter for possible deficiencies in component j

The condition index is a value that ranges from 0 to 100:

a. From 0 to 10 represents a Critical condition
b. From 11 to 24 represents a Poor condition
c. From 25 to 49 represents a Fair condition
d. From 50 to 100 represents a Good condition

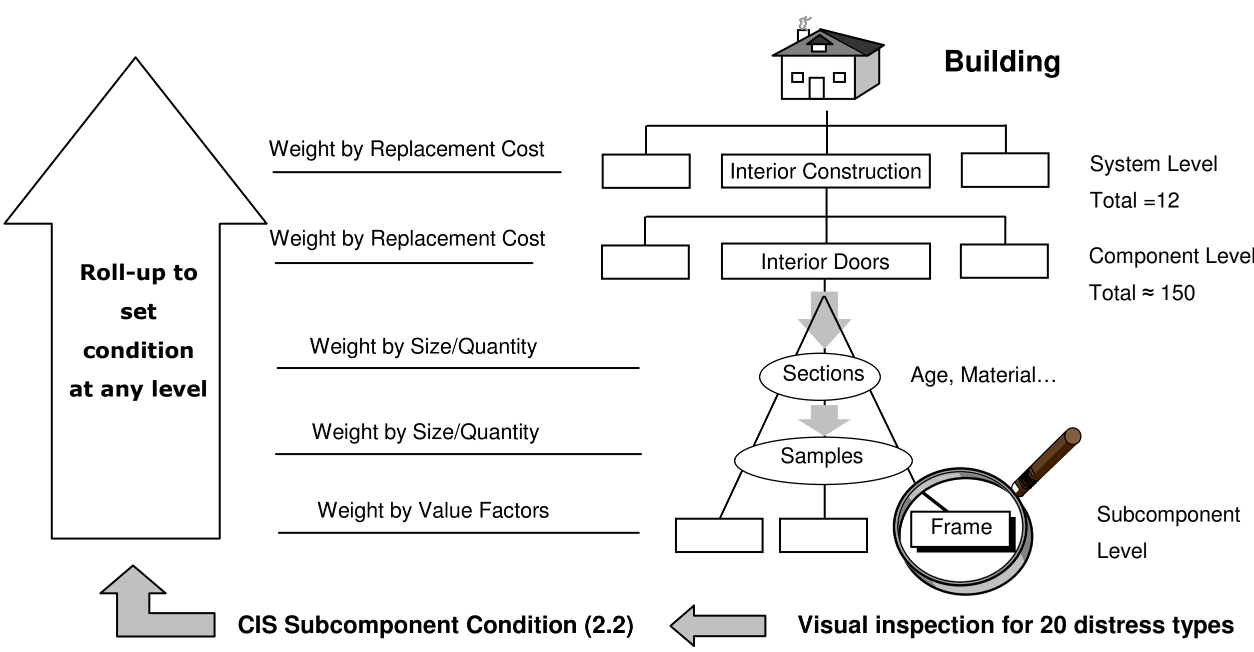


Figure 2.8: BUILDER Condition Assessment Processes

For example, if a component has four deficiencies D_1, D_2, D_3, and D_4 with weights of 10, 30, 45, and 15, respectively, and if the inspector determined corresponding severities of 25, 30, 10, and 15, then the CI = 100 – (10*25+30*30+45*10+15*15)/100 = 81.75, which implies that the component is in good condition. Although this approach depends on deficiencies, RECAPP also gives the user the option of bypassing the deficiency list and giving an overall evaluation for the component (i.e., good, fair, poor, or critical), based on experience. RECAPP's default, however, is to give a direct assessment.

As explained, both BUILDER and RECAPP use weights to calculate the condition of the component and to roll up the condition to higher levels in the hierarchy. These weight values however, are explained in these systems without reference to the way they are deduced. The literature also shows limited efforts to determine these weights for building components. Shohet and Perelstein (2004), for example, used the life-cycle costs of various building systems to determine their weights. Langevine et al. (2005) used the analytical hierarchy process (AHP) to determine the weights through a process of comparing for the relative importance of the elements within each individual level in the hierarchy.

In TOBUS, the nature of the work required for retrofitting a building object is characterized by four work codes as shown in Table 2.13. For each object type, the nature of the work is defined by a work code, which in general, corresponds to the degradation code. The inspector, however, selects the work codes independently from the degradation codes for two reasons. First, one may wish to select more (or less) extensive work or not to repair at all. Second, conditions other than physical degradation may have an influence on the selection of the nature of work (Brandt and Rasmussen 2002).

Table 2.13: Representative Work Codes Associated with the TOBUS Diagnosis

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

Table 2.14 presents a comparison of the existing condition assessment software systems in terms of their features, advantages, and disadvantages.

Table 2.14: Comparison of the Existing Condition Assessment Software Systems

<table>
<tr><th>Software</th><th>Features</th><th>General Comments</th></tr>
<tr><td>BUILDER</td><td>• Detailed building hierarchy
• Standard deficiency check list for all subcomponents
• Add pictures, notes, general information.
• Industry standard (AutoCAD)
• Numeric scale</td><td rowspan="3">• Time-consuming
• Complicated (severity, density)
• Subjective
• Needs experts
• Managing instances is difficult
• Managing pictures is difficult
• Components are not linked to their location within the building</td></tr>
<tr><td>RECAPP</td><td>• Detailed building hierarchy
• Detailed deficiency descriptions for each component (Component-dependent deficiency factors with weights).
• Add pictures, notes, general information.
• Less complicated as only severities need to be checked</td></tr>
<tr><td>TOBUS</td><td>• Detailed database for building macro and micro objects
• Evaluates physical degradation of the condition
• Works for retrofit up-gradation for improvement
• Fast (on-line)</td></tr>
</table>

2.7 Conclusions

Although there are a variety of techniques and technologies that can be applied to perform condition assessment, only visual inspection suits the nature of building assets because of the diversity of the components involved. In summary, the literature review reveals that the current condition assessment systems suffer from the following drawbacks:

a. *Unstructured, time-consuming, and expensive processes*: Currently, field inspection of buildings is carried out by experienced and knowledgeable inspectors who perform both the inspection and the analysis on-site, in order to identify the component's current condition. The time required for inspecting a particular building depends on the level of detail, the size and number of components, the accessibility and complexity of the facility, resources allocated, and the time available. The inspection process entails a large portion of the expert's time being spent on tasks that do not require their expertise, such as moving from one location to another, taking pictures, and writing notes. The process can also be extremely expensive, when the number of facilities is large. A typical school board, for example, may administer several hundred schools that require detailed assessments. Inspectors must assess each component at every school, which involves a large amount of time and money. The current approach of manually adding/deleting/managing instances of components (e.g., a group of windows, or a single boiler with specific problems) is extremely time-consuming. There is a need to reduce the time required for the inspection process by standardizing the list of components and avoiding the addition or deletion of instances. Further, adding pictures of the inspected components is a manual process that again takes a great deal of time and is difficult to manage. Therefore, new, fast, affordable, and reliable condition assessment system is needed.

b. *Lack of a mechanism for prioritizing inspections*: No mechanism exists for prioritizing inspection tasks and identifying critical items that need immediate inspection. In addition, no mechanism exists for efficiently deploying available inspectors, and minimizing the frequency of inspections.

c. *Subjectivity of the assessments*: The existing condition assessment process is highly subjective in nature because it involves the varied perceptions of the field inspectors. Recent improvements in this area have introduced electronic checklists or deficiency lists. Often, however, to save time, deficiency lists (which need detailed analysis of their relative weights) are bypassed in favour of use quick subjective assessments. In addition, no support mechanism exists to help the inspector differentiate between assessment categories (good, fair, poor, or critical). Existing systems, therefore, can be described as good databases that provide enough spaces for the addition of pictures and notes during the condition assessment process but do not provide adequate guidance for the performance of correct assessments.

d. *Lack of time-related condition records*: Almost all existing condition assessment systems lack permanent documentation of the evolution of each component's condition over time. Therefore, the field inspector cannot quickly make visual comparisons with the previous condition of the building component.

e. *Detailed inspection that is unsuitable for replacement-based strategies*: Conducting the condition inspection at the detailed deficiency level is excessively time-consuming and is too detailed to be useful for making decisions about replacement. A direct ranking of Good, Fair, Poor, or Critical is more useful, but requires that subjectivity be reduced.

Chapter 3
Field Study: Building Inspection Challenges and Needs

3.1 Introduction

This chapter presents an examination of the differing objectives that organizations can have for building inspection, and of the challenges inherent in the inspection process. Based on the examination the inspection process is thoroughly analyzed with respect to improving the process and aligning it with the objectives of the building asset management policy of large owner organizations. The introduction includes a discussion of the distinction between repair and replacement-based objectives in building asset management. A field study to identify inspection problems and needs in several buildings belonging to a large owner organization is then described.

3.2 Objectives of Building Asset Management

Sustaining the serviceability and safety of infrastructure networks is highly challenging, particularly with stringent budgets. A variety of asset management tools and techniques have therefore been introduced to help asset managers with the difficult decisions regarding when to repair or replace their existing building stock and how to do so cost-effectively.

The literature has generally recommended a clear separation of the functions that support day-to-day operations (referred to as maintenance and repair) from other capital renewal functions that are intended to upgrade the asset inventory (Vanier 2001b; BRB 1994; Melvin 1992; NRC 1996), as shown in Figure 3.1. Maintenance and repair are interventions required in order to ensure that an asset is adequately operable and involve both preventive maintenance and reactive-maintenance (response to urgent problems). On the other hand, capital renewal is a planned action for upgrading (a form of repair) or completely or partially replacing an existing asset, sometimes with an asset that has different functionality or is in a different location. This distinction between operational maintenance and capital renewal functions is reasonable since owner organizations often handle these functions through two separate departments with different budgets. The Toronto District School Board (TDSB) is an example of such an organization.

However, lack of efficiency in one function affects the other. Vanier (2001b), for example, reported that when insufficient money is spent on maintenance and repair, owners accumulate a large maintenance deficit, which leads to premature failures that require replacement. The two functions have been discussed in detail by Vanier (2001), who estimated the size of the expenditure for each, as shown Table 3.1.

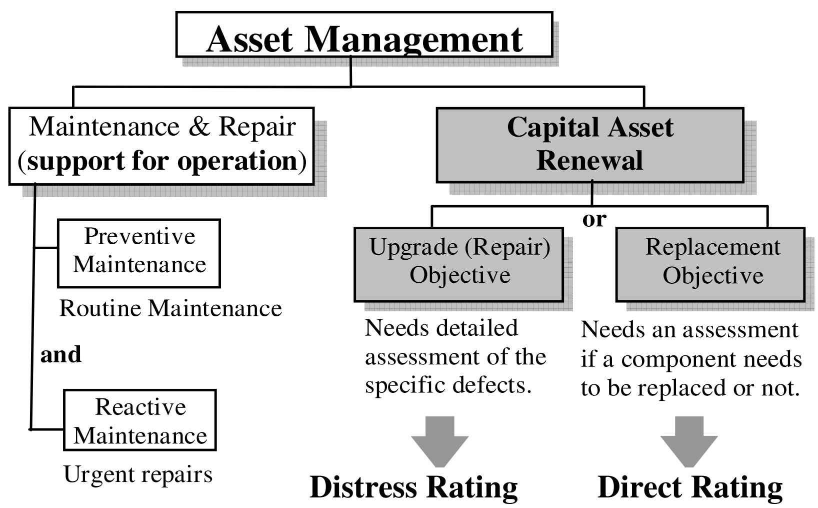


Figure 3.1: Repair versus Replacement Objectives of Capital Renewal

Table 3.1: Maintenance, Repair, and Capital Renewal in Canada and US ($ Billions)

Parameter	Canada	U.S.A[a]	Total
Maintenance and Repair	$58.8	$588.00	$646.8
Capital Renewal	$45.6	$456.00	$501.6
Total	**$104.4**	**$1,044**	**$1,148.4**

[a] Based on a 10X multiplier of the Canadian figures to represent ratios of national populations

As shown in Figure 3.1, capital asset renewal programs may adopt either an upgrade (i.e., repair-based) or a replacement-based strategy, depending on available resources and the level of detail desired. A repair-based strategy is more general and more challenging than a replacement-based strategy because asset replacement can be considered a special case of repair.

Despite the distinction between repair and replacement-based objectives, Uzarski et al. (2007) presented the two options as suitable at different stages in the life cycle of a component (Figure 3.1), with different inspection needs at each stage.

Organizations may downsize, outsource, and/or expand any of their asset management functions, which may affect their ability to adopt either strategy for asset renewal. A repair-based strategy, for example, becomes the only choice when the organization uses a single department to handle all its maintenance, repair, and renewal needs. Downsizing the capital renewal function, on the other hand, may render the repair-based analysis too detailed and too demanding of resources. Within the constraints of the organization, therefore, the decision about which strategy to use affects the overall efficiency of the organization's asset management.

Many studies acknowledge the difficult choice between replacement and repair strategies (Seifert 1987; Lembo 2002). For example, the study on windows by Munch-Petersen (1984) presumes that repair will often be an economical solution. The study justifies the wood in old windows to be of high quality and hence is easy to repair and maintain. The study focuses on providing alternatives for economical wooden window repairs. Elhakeem (2005 a) proposed a visual condition assessment program (V-CAP) as part of asset management framework. The study introduced the concept of visual guidance for windows. A list of possible deficiencies and their symptoms was derived for a variety of operation types of windows. However, this research best suited a repair-based strategy for asset management. The current research is based on the idea of visual guidance but is aimed at a replacement strategy.

The literature contains arguments in favour of the replacement option. For example, older windows may have reached a stage beyond repair or beyond reasonable maintenance costs. Sometimes, it works out to be economical to replace a set of windows rather than to perform a large number of individual repair operations. Furthermore, repairs may not be financed through loans, whereas replacement is considered an investment. There are times when the assessor is unaware of alternatives for repair and therefore prefers replacement as a rehabilitation strategy (Munch-Petersen 1984). Among other studies favouring replacement-based strategies are the ones by Gunnilla et al. (1984).

The choice of an appropriate strategy (repair or replacement-based) has a significant impact on the choice of inspection method to be used in the assessment of building components. As illustrated in Figure 3.1, if the objective of the asset management system is to repair deteriorated components to increase service life, then those components must be inspected in great detail in order to define the specific repair needs. In this case, the most suitable inspection and condition assessment is a distress survey. As the name implies, for each building component, the distresses need to be identified and their severity levels, quantified in order to ascertain the overall condition of the asset. On the other hand, if the objective of the asset management is component replacement, then employing a detailed level of inspection and assessment would waste resources and effort. In such a case, assessment is performed at the macro level in order to define whether a component is in good, fair, poor, or critical condition.

It is important to note that detailed inspection is generally a difficult and inefficient process for the following reasons (Uzarski et al. 2007):

a. During the inspection visit, the inspector has to inspect all systems and components irrespective of their condition, condition history, or importance.
b. The budget for inspection indicates the frequency of site visits thus leading to under inspection or missed opportunities for optimal maintenance decisions.
c. The cost estimate for maintenance derived during the inspection process, often times becomes obsolete due to delays on funding.

Ideally, an efficient asset management system would incorporate features appropriate to the organization's adopted strategy. Unfortunately, existing asset management systems, while incorporating many useful features, do not specify how their features are appropriate for the structure and objectives of the user organization. In addition, they do not provide any guidance regarding which inspection process most suits the asset management objective of the organization.

3.3 Case Study Organization: The Toronto District School Board (TDSB)

To facilitate the structuring of a replacement-based asset management system, the challenges faced by the Toronto District School Board (TDSB), which is the largest school board in Canada and the fifth largest in North America (Director's Annual Report 2004-05), are highlighted. The TDSB owns more than 600 schools and administrative buildings, scattered throughout the

Metropolitan Toronto area. The TDSB divides the Toronto area into four smaller areas: North East (NE), North West (NW), South East (SE), and South West (SW), as shown in Figure 3.2. Each area consists of six "school families" and each school family contains approximately 24 schools. Each school is defined by its unique ID number, family, type (elementary/secondary), construction year, size (m^2), original construction cost, and address. Figure 3.3 shows hierarchy of the TDSB schools.

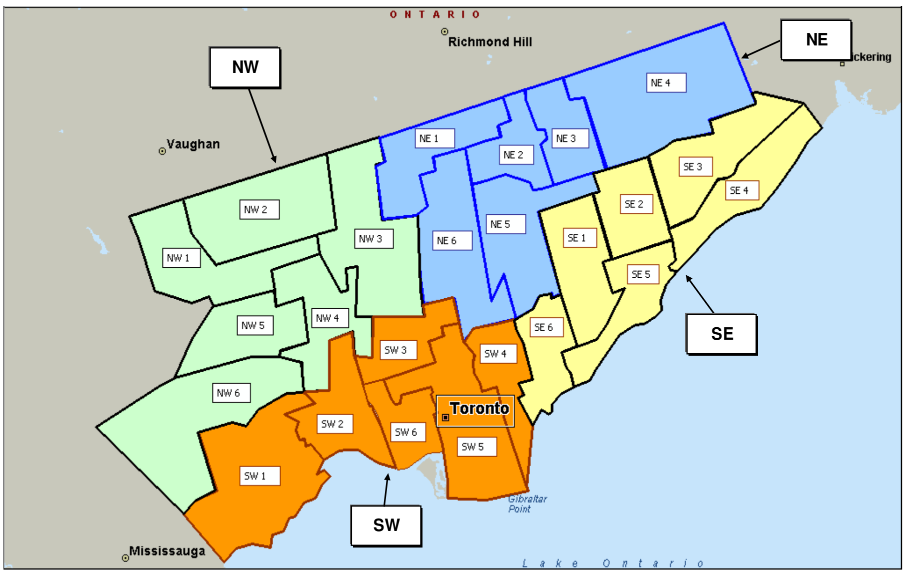


Figure 3.2: Arrangements of the 600 Schools at the TDSB

In 2005, the median age observed for TDSB buildings was 56 years and the average age was 44 years (Elhakeem 2005b). Currently, 95% of schools are at least 50 years old (Issa et al. 2008) and the majority of these buildings (59%) have a poor facility condition index, as shown in Figure 3.4 (Facility Services Review 2007). Because many TDSB buildings are aging, sustaining their healthy operation has become essential, particularly with limited budgets for capital replacement projects. It is a huge challenge, therefore, not only to inspect the large inventory of buildings but also to devise suitable mechanisms for identifying the most critical items and their funding needs.

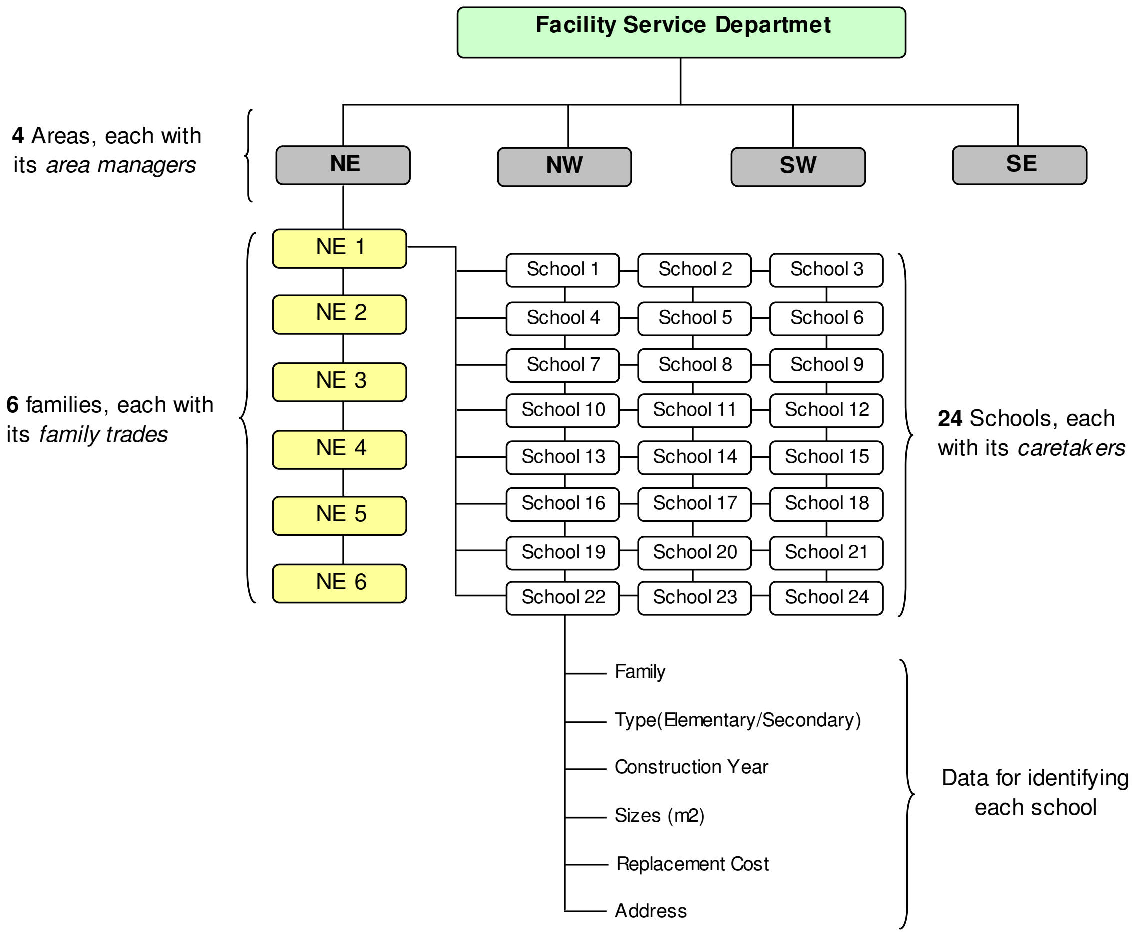


Figure 3.3: Hierarchy of the TDSB Schools

For the effective management of maintenance programs, responsibilities are distributed at different levels within the facilities services department at TDSB. Each area or region level is assigned one area manager. The area managers (Facility Team Leaders) are the direct management connection to the site. They manage all caretaking staff and maintenance repairs by skilled trades and act as liaison with school management and the community.

At each family level are assigned one assistant area manager and a group of experienced trades personnel (approximately ten) in various categories (roofing, carpentry, mechanics, etc.), who carry out the regular preventive maintenance.

At the lowest level, each school is assigned one to three caretakers, depending on the size of the school, who are in charge of daily checking and minor maintenance work that requires no specific expertise. Caretakers address the day-to-day operation of the facility and can contact the family trades personnel for urgent maintenance needs such as a leaking roof or mechanical failure. In such a situation, the family trades personnel can either fix the problem or, if the task is large and requires a specific work order, design work, or an external contract, refer it to the central office. The family trades personnel report to the family manager, who in turn reports to his area manager. All area managers report to the head of the Facility Service Department.

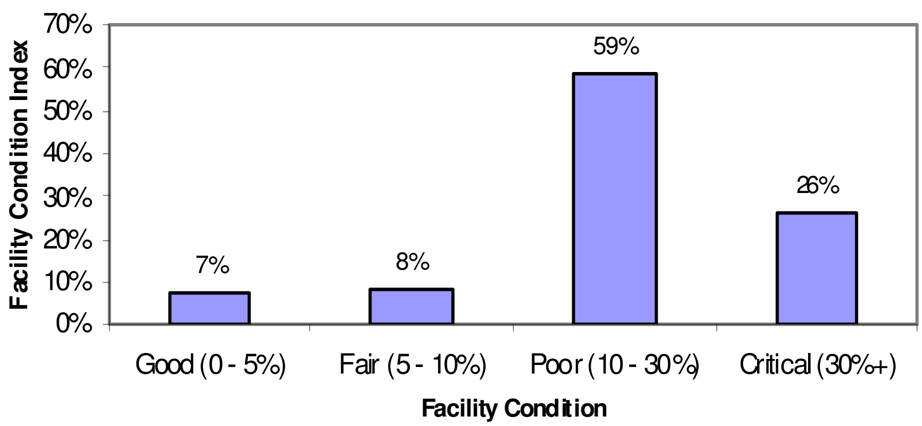


Figure 3.4: Facility Condition Index for TDSB Schools

At the organization level, after school support, which includes teaching, facility services form the next major department (by number) of the TDSB organizational structure. The Facilities Services Department is committed to the planning and provision of safe, clean, and healthy learning and working environments for students, staff, and community in all TDSB facilities. This department manages diverse construction programs that cover new construction, minor rehabilitation, and major reconstruction jobs.

3.4 Maintenance-Related Systems at the TDSB

Maintaining the large number of assets at the TDSB has become a challenging task. The TDSB has a large Operations Department (OD) with preventive and reactive-maintenance expertise in different fields. The OD uses an Enterprise Resource Planning software system (SAP) that is applied in the whole TDSB intranet to integrate payroll, invoicing, contracts, and all details about maintenance work orders. In addition to the OD, the TDSB has a Capital Renewal Section under its Facilities Management Department (FMD), which administers a $50 million annual program for capital renewal projects, delivered through the Construction Services Section using in-house crews and outside contractors (Attalla et al. 2004). To determine which building components to include in the yearly renewal program, the FMD utilizes computerized asset management software, RECAPP (PPTI 2006). The TDSB uses the software to implement a repair-based capital renewal strategy, whereby detailed deficiency-level inspections are conducted for all components. Based on the inspection data, the software prioritizes components and allocates funds accordingly.

Because of the high cost of asset management, in recent years to save money, the TDSB has downsized its Capital Renewal Section. Downsizing has greatly affected the ability of the in-house personnel to frequently inspect conditions at the schools, to identify critical items, and to properly allocate the replacement budget. The TDSB therefore issues costly contracts every few years to outsource the inspection process; visiting all buildings once takes about three years. In addition to the high cost involved, the inspection data is still subjective and assigns the same priority level to many components (e.g., many schools with poor roof sections), thus incorporating less diversification and making the allocation of funds among the schools difficult and inaccurate.

To improve its asset management practice, the TDSB is currently interested in investigating improvements to their capital renewal programs in terms of improving the accuracy of allocating funds and of reducing the costs of asset management. The first aspect of the study focused on improving the existing repair-based strategy to facilitate more accurate decisions, which resulted in the improvements suggested in another study by Elhakeem (2005). These suggested improvements, while reducing subjectivity, still require the TDSB to invest in costly inspection contracts. As an alternative, TDSB has initiated a study to investigate the use of a replacement-based strategy to suit its downsized resources and save the cost of external contracts. To clearly define the scope of the study, initial site visits were made to six schools, and all the steps in the existing asset management process were analyzed. From this initial analysis, several areas of potential improvement were identified and are discussed in section 3.6.

3.5 Field Study

An understanding of the practical aspects of the condition assessment process at the TDSB and similar organizations was obtained through field visits conducted in two parts: preliminary visits and secondary visits. The preliminary field visits involved only observation of the current condition assessment process as performed by expert inspectors for three TDSB schools. After a detailed understanding and in-depth knowledge of the current process for the condition assessment of the schools was acquired, the secondary visit was designed. Its goal was hands-on data collection for a different set of three schools in order to identify the challenges associated with the condition assessment process. The details of both visits are discussed below.

3.5.1 Preliminary Field Visits

To analyze and understand the practical problems associated with the current condition assessment process, three Toronto District School Board (TDSB) schools were visited in the company of an experienced TDSB inspector. During the visits, notes were taken about the condition inspection process, data collection, and data entry. In addition, informal discussions were held with the inspector and the school's caretaker to gain their input and insight about the current system. Based on the visits, the following observations were made:

a. *On-site data collection*: The process included talking with the caretaker, followed by taking digital pictures and recording site survey notes. The inspector carries a laptop with an Excel spreadsheet that includes the generic checklist as shown in Figure 3.5. Possible building components are listed, and the inspector marks the caretaker's opinion about the presence or absence of components along with their condition and location, described in text form. An average of 150-200 pictures per school were taken of all the marked components on the checklist using a regular digital camera. The pictures were taken randomly in the order of the inspector's path through the school. Site inspection is thus a manual process for collecting data, which is later assessed in the office.

b. *In-office data entry and assessment*: In the office, the inspector enters data for the items that could not be completed on site, and pictures are loaded onto the computer. Based on the inspector's memory and his path through the school, all the components in the checklist are re-assessed, and the data is updated and entered into the RECAPP software system (

c. Figure **3.6**). Entering the data for one school takes about a week. For accurate entry, the inspector may need to refer to the SAP work order data to confirm that old equipment observed during the visit has been replaced. Loading pictures at the connect points is also a time-consuming task.

6	Assembly		Condition	Caretaker Comments	Instance Number	Number of Units	Location	(V
7	**Site Work**							
8	00.1-010 Underground Utilities	☑	fair	gas, hydro, water and sewers. Transformer was replaced around 2004				ga
9	00.1-011 Aboveground Utilities	☐						
10	00.1-012 Signage	☑	Fair	electric lawn sign is new in 2005, remainder is in fair condition				
11	00.1-013 Undeveloped Lands	☐						
12	00.1-014 Site Related Stairs, Plazas & Decks	☑	Good	west side near Royal York				
13	00.1-015 Retaining Walls	☐						
14	00.1-016 Soft Landscaping	☑	Good	courtyard is the responsibility of the art dept				
15	00.1-017 Site Improvements	☑	Fair	south fence and wrought iron near front of the building				
16	00.1-018 Stormwater Management Systems	☑	Good	no reported problems				
17	00.1-019 Septic Systems	☐						
18	00.1-020 Water Well Systems	☐						
19	00.2-010 Paved Parking Lots	☑	Poor	cracking and uneven surfaces. North lot belongs to hydro				
20	00.2-011 Paved Roadway	☑	Poor	cracking and uneven surfaces. North lot belongs to hydro				
21	00.2-012 Paved Playgrounds	☐						
22	00.2-013 Paved Sports & Recreational Spaces	☐						
23	00.2-014 Paved Walkways	☑	Poor	same condition as parking lots				
24	00.2-015 Traffic Control Devices	☑	Good	nort driveway and football field		2		
25	00.2-010 Unpaved Parking Lots	☐						
26	00.2-011 Unpaved Roadway	☐						
27	00.3-012 Unpaved Playgrounds	☐						
28	00.3-012 Unpaved Playgrounds - Playscapes	☐						
29	00.3-013 Unpaved Sports & Recreational Spaces	☑		track, soccer field				
30	00.3-014 Unpaved Walkways	☐						
31		☐						

Figure 3.5: Sample of the Checklist Used for Inspection at the TDSB

d. *In-office data entry and assessment*: In the office, the inspector enters data for the items that could not be completed on site, and pictures are loaded onto the computer. Based on the inspector's memory and his path through the school, all the components in the checklist are re-assessed, and the data is updated and entered into the RECAPP software system (

e. Figure **3.6**). Entering the data for one school takes about a week. For accurate entry, the inspector may need to refer to the SAP work order data to confirm that old equipment observed during the visit has been replaced. Loading pictures at the connect points is also a time-consuming task.

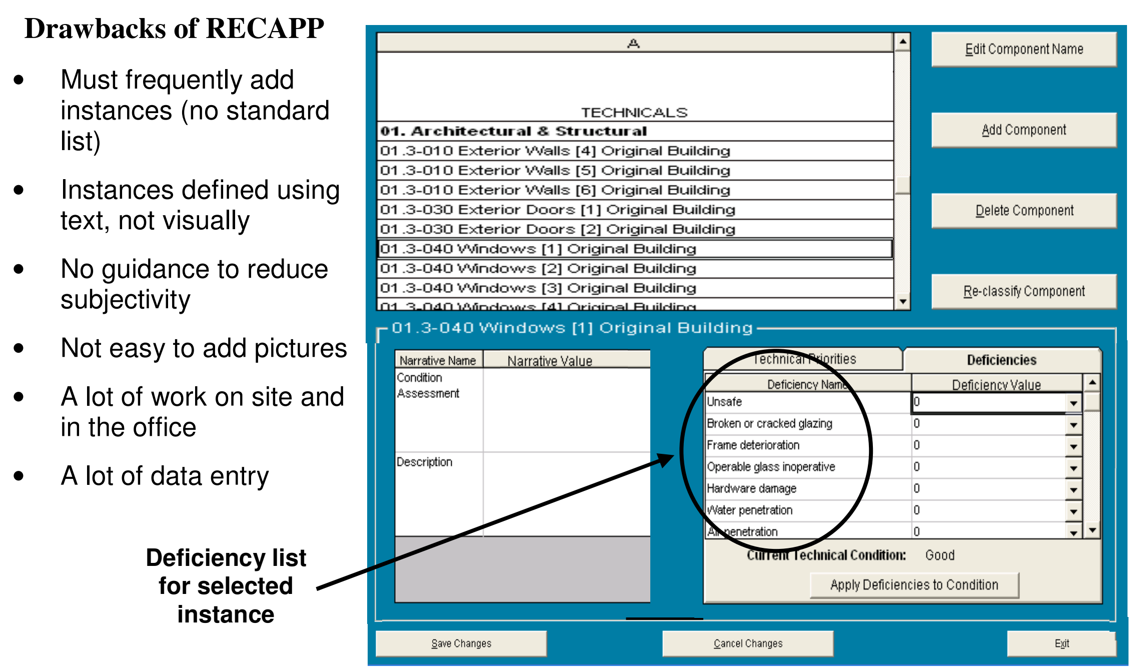


Figure 3.6: Sample of Data Entry in RECAPP after School Inspection

3.5.2 Secondary Site Visits

Secondary site visits were made in order to gain hands-on experience with the condition assessment process. The visits were focused on a different set of three TDSB schools that were identified for inspection by the TDSB staff. The site visits included a detailed survey of the schools and lengthy discussions with the caretakers. To save time and money, in addition to digital pictures, high-resolution detailed video recordings were made of the components in order to capture the deficiencies associated with each component. The recordings were designed to provide permanent documentation of the condition of the components. The caretakers were found to be very cooperative and were knowledgeable about every component in the schools.

3.6 Field Study Findings

The findings and observations from the preliminary and secondary site visits to TDSB schools were recorded. The field visits provided an understanding of the drawbacks of the current condition assessment process, and revealed specific areas for improvements (Table 3.2). In addition, factors affecting the condition of the building components and the cause-effect relationships among building components were apparent.

Table 3.2: Identified Problems and Associated Improvement Needs with respect to the Condition Assessment Process of TDSB Schools

Concern	Observed Problem	Improvement Needs
Inefficient inspection	Inspection at the deficiency level is excessively time-consuming and is not beneficial for supporting replacement decisions.	A direct ranking (Good, Fair, Poor, or Critical) is more useful but requires an accurate quantification method.
List of building instances not fixed	The current approach requires manually adding new instances for the parts of a component that show a specific condition. This is extremely time-consuming, and can be problematic if data is not updated frequently.	There is a need to avoid adding/deleting instances to speed the process. There is also a need to standardize the list of components and instances.
Historic condition data lost	Existing system overwrites condition data, hence offering no way to track the condition of components over time.	Historical records of the building condition need to be saved for future reference.
Locations of instances not defined	The locations of instances are defined only manually on printed plans. Pictures are also not linked to their components.	A simple approach is needed to let the user mark the condition (& link pictures) on digital floor plans. This will make the process faster & easier to track.
Inefficient scheduling of inspection tasks	No mechanism exists either for prioritizing inspection tasks and defining the critical items that need immediate inspection, or to efficiently utilize available inspectors.	There is a need for a mechanism to minimize inspection frequency through automated condition indicators, among existing TDSB resources.
Inspection subjectivity	No guidance exists for inspectors to help them perform uniform assessment.	A pictorial database can be developed to offer realistic visual guidance during assessment.
Lack of information sharing among departments	Since the operations department does not share information with capital renewal, the maintenance history of components is not known during inspection.	The information needs to be linked between various departments for better coordination.
Lack of automation	Inspection is done manually on-site and the data is entered into the software in the office.	There is a need for a better way for the inspection to be completed on site.
No clear understandin g of cause-effect relationship	No information is available about the most common areas of component interaction.	Different cause-effect relationships among various components need to be surveyed.
Inefficient data collection on-site	Inspite of the RECAPP Validation Survey (RVS) (the hand-held tool for on-site inspection), TDSB is still using Excel checklists to collect data as RVS is slow, text-based, and confusing.	There is a need for a faster and more reliable tool to be used for on-site inspection.

The literature (section 2.3 in Chapter 2) and discussions with the inspector during the field visits also identified factors that affect the condition of the school components. The facility condition index (FCI) is the first and the most direct indicator of a building's condition. The higher the FCI, the lower the condition of the building components. The FCI also indicates the need for building components to be renewed. Another factor is related to the size of the school: current capacity versus permissible capacity in terms of the number of pupils. If the current enrolment capacity exceeds the permissible capacity of the school, the building would deteriorate faster because of overuse. Similarly, the type of school, i.e., elementary versus secondary, also affects the school's overall condition. It has been reported that secondary schools tend to have a higher rate of vandalism and accidental damage compared to elementary schools (U.S. Department of Education 1999). Many studies further identify the factors leading to vandalism (Black 2002).

The demographics of the students, such as their age, gender, and financial background also affect the deterioration of the building. Among other factors affecting the condition of school are the level of maintenance and the type of neighbourhood (residential, commercial, or industrial). The neighbourhood's crime rate, employment rate, and the income level also affect the condition of the school. A summary of the factors affecting the condition of the school are provided in Table 3.3.

Table 3.3: Factors Affecting the School Condition

	Factors Affecting School Condition
1	Facility Condition Index (FCI)
2	Type of school (elementary, secondary, etc)
3	Demographic factors of students (age, gender, background)
4	Age or major year of renovation of school
5	External and internal conditions
6	Size (enrolment capacity)
7	Advances in information technology
8	Maintenance frequency

For efficient and effective decision making about the building condition, a graphical means of examining the above factors is preferred. One such way to enable effective visualization of all of the factors is through a geographic information system (GIS). Geographic Information Systems were one of the fastest-growing computer-based technologies of the 1990s (Jeljeli et al., 1993).

A GIS is a very powerful tool for evaluating and planning utility network improvements and for supporting maintenance management systems. According to McKibben and Davis (2002), the integration of a GIS with a Computerized Maintenance Management System (CMMS) has shown significant benefits for both public and private water utilities. Therefore, all school-related data could be linked to a GIS system to provide a visual representation of the results and thus aid in decision making. This area, however, is a topic for future research.

Buildings are complex due to their several interlinked components. From the field study and from the discussion in chapter 2, it is clear that a defect in one component can affect another and that a mutual relationship between cause and effect exists within a building. Causes can be studied and effects can be predicted, and from the effect, the cause can be determined. For example, effects in the interior such as stains, wet ceilings, rust, cracks, yield clues to their causes. Room usage, humidity (such as in the roof over the swimming pool), temperature, and air movement are also important in the consideration of effect and the determination of cause (William 1979). During the field visits, the inspector provided examples of the cause-effect relationships among building components, as summarized in Table 3.4.

Table 3.4: Interrelationship among Various Building Components

Observation	Cause	Check	Result	Strategy
Low room heating/cooling	Window/door not closing properly (functional problem).	Check for hardware problems.	More load on mechanical system.	Repair window/door problem.
Horizontal and vertical cracks on load-bearing wall	Water Infiltration in cavity wall.	Check for roof flashing (cracks on above level), or foundation problems.	If cracks on upper level, infer repair flashing; else repair foundation.	Repair foundation or roof flashing.
Damaged ceiling in washroom	Plumbing fixtures leakage at upper level.	Check washrooms on upper floor.	Mould formation (health and safety concern)	Repair plumbing leakage on top floor.
Damaged/old breaching or boiler	Breaching or boiler repair/ replacement	Check boiler condition (replacement/repair) and review breaching condition accordingly.	Inoperable boiler or highly deteriorated breaching.	Boiler and breaching go together.
Sudden outburst of water from water fountain on main floor	Clogging/blockage in pipes.	Check for hydrostatic pressure in the sewage pipe.	Ceiling damaged	Clear and de-pressurize pressure in sewage pipe.

3.7 Conclusions

Based on the discussion in this chapter, the following conclusions can be made:

a. The Toronto District School Board (TDSB) and many other similar organizations have alternative objectives for capital asset management: repair or replacement. Each type of objective has advantages and disadvantages and requires specific system development.

b. The current condition assessment process is resource-intensive, which is a problem for organizations that have downsized preventive maintenance and capital replacement personnel. In this case, capital asset management needs to focus on a replacement, rather than repair strategy, which is the case in the current research.

c. The current condition assessment process is highly subjective, time-consuming, costly, and lacks automation.

d. The field study discussed in this chapter helped to
   - provide hands-on experience with condition assessment problems,
   - identify improvement needed, and
   - reveal information that supported the developments described in Chapters 4, 5, and 6.

Chapter 4
Condition Prediction and Inspection Planning

4.1 Introduction

To support replacement-based capital asset management given limited resources, a new framework is proposed that will address the problems associated with the traditional condition assessment process for buildings. The proposed framework consists of three main components: (1) condition prediction and inspection planning (based on the reactive-maintenance history), (2) a visual guidance system that will support a standardized, fast, and less-subjective inspection of building components, and (3) location-based inspection using a standardized building hierarchy. The framework is focused on process automation that is particularly appropriate for large organizations that have limited resources with respect to condition assessment and capital asset management. The condition prediction and inspection planning system is described in detail in this chapter. Details of the visual guidance system are explained in Chapter 5, and the location-based inspection process is presented in Chapter 6.

4.2 Components of the Proposed Framework

As indicated in the Chapter 3, the following are the three main drawbacks of the current condition inspection and assessment process at the TDSB:

a. The current condition inspection process is resource-intensive, time-consuming, and costly. Resource downsizing has led to a need for changes in this process in order to use fewer resources and by visiting only sites where inspecting the components is absolutely necessary.

b. Currently, the inspected data is entered in narrative text format on-site, and then the assessment is completed in the office. A simple approach is needed so that the user can mark the condition (Good, Fair, Poor, or Critical) directly on digital floor plans that show the component(s) being inspected and thus complete the assessment process on-site. The process will then be faster and easier to track.

c. The current condition analysis and assessment process for building components is highly subjective. Even if the number of site visits is reduced, an expert must go still to the site for a visual inspection and assessment. This process involves immense subjectivity as the expert generally has varied perceptions of the condition of the component. If time and money are saved by having the caretaker perform this task, there might be problems associated with unions and personal bias. A visual guidance system that would guide the assessors and reduce subjectivity is needed.

To overcome these three main drawbacks, the proposed framework is structured with three components, as shown in Figure 4.1.

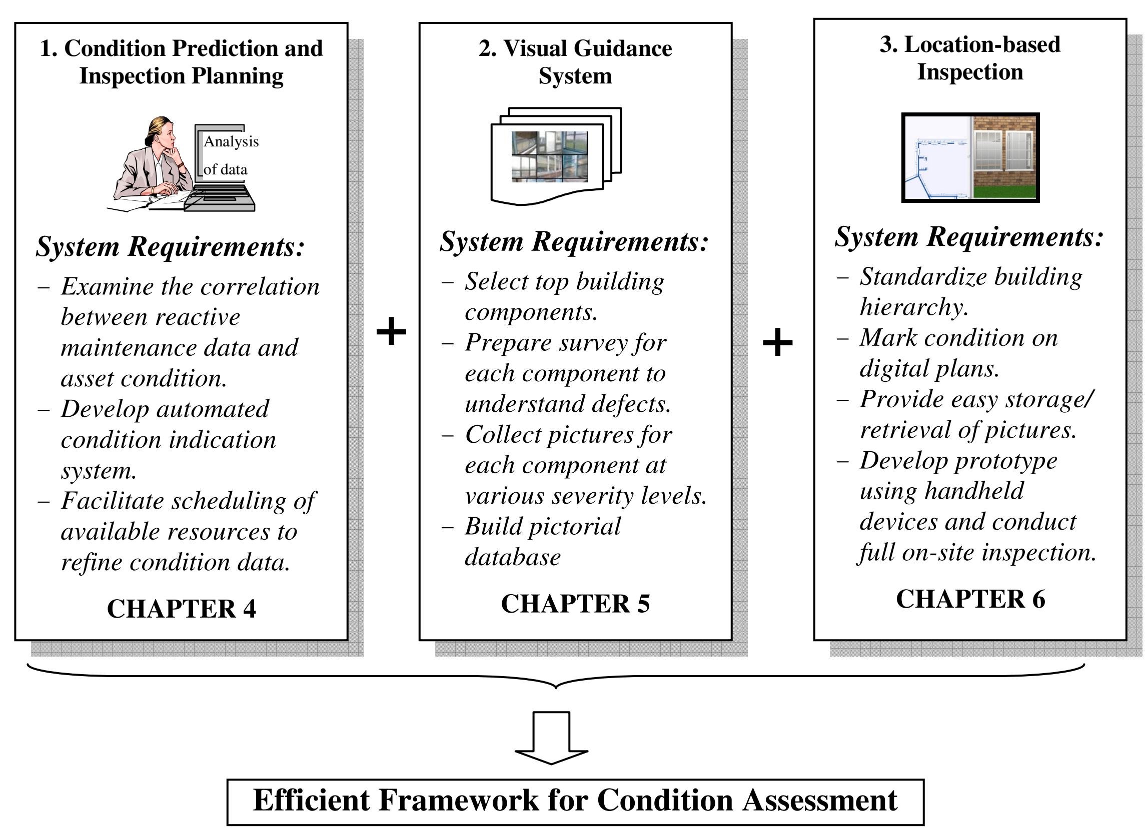


Figure 4.1: Components of the Proposed Framework

4.3 Proposed Condition Prediction and Inspection Planning

It is clear from existing literature and the discussion in Chapter 3 (section 3.2) that there is a lack of integration between the maintenance/repair and the capital renewal functions, not only within organizations, but also among the support tools available. Therefore, performance data about the assets can become scattered between these two functions. On the maintenance and repair side, Vanier (2000) reviewed more than 300 Computerized Maintenance Management Systems (CMMSs) and found them mature and useful for managing work orders, trouble calls, equipment cribs, invoicing, time recording, and storing inventories and preventive maintenance schedules. This important data, however, is seldom transferred and utilized to support life-cycle costing and service life prediction, which are vital for asset management (Vanier 2000). On the other hand, several asset management support tools are currently available to support capital renewal decisions for individual assets or for a group of similar components (e.g., BUILDER (Uzarski and Burley 1997), RECAPP (2006), and TOBUS (Brandt and Rasmussen 2002)). Such systems, however, lack integration with CMMS and enterprise resource planning systems (Halfawy et al. 2005). In addition, they may not incorporate all the functions necessary for asset management, and do not distinguish between repair-based and replacement-based objectives, as noted earlier.

This research focuses on supporting a replacement-based building asset management strategy appropriate for organizations such as the Toronto District School Board (TDSB) that run suitable maintenance and repair programs and small (or downsized) capital renewal programs. In a climate of downsizing, however, capital renewal decisions are neither simple nor straightforward. This research, therefore, investigates the challenges imposed by a constrained capital renewal program, integrates data from capital renewal and reactive maintenance systems, suggests ways to structure the inspection process to make it faster and less costly, and develops an automated condition indication system that improves capital renewal decisions in large owner organizations.

To facilitate the structuring of a replacement-based asset management system, the challenges and problems faced by the Toronto District School Board (TDSB) are addressed. As discussed in Chapter 3, the current process of condition inspection and assessment is a resource-demanding task that must be repeated frequently. The proposed system therefore has the goal of extending the life of existing data to reduce inspection frequency, in addition to efficiently prioritizing and scheduling of inspection tasks among the limited available resources. Since it is common knowledge that efficient maintenance of assets keeps them in good working condition without the need for replacement, the proposed system investigates the implied relationship between the condition of the component (needed for capital renewal) and the number of repair work orders (i.e., the reactive-maintenance data) completed for this component per year (the TDSB's SAP system has full information about all maintenance work orders). This relationship helps to establish an automated indicator of the condition of the building components so that unnecessary inspection visits can be avoided and inspection can be limited to the items that show conflicting information.

4.3.1 Data Collection

To carry out such an analysis, repair and reactive-maintenance records for a sample of 88 schools were obtained from SAP system at the TDSB (Table 4.1). Two types of data were collected from the schools: (1) general data from RECAPP (Figure 4.2) which included information about the school type (elementary or secondary), construction year, size (in square metres), and replacement value (in dollars); and (2) specific data from SAP (Figure 4.3) which contained the maintenance or repair work order data, including work description, code, priority, actual cost, and repair duration, for 2005 and 2006. Data was collected for two years to ensure consistency in the conclusions to be drawn from one year to the next. Acquiring the specific data was a highly extensive task due to the size and the confidential nature of the data. A total of 41,642 work orders were extracted from the SAP system.

Table 4.1: Brief Summary of All Data Provided

Year	Area	Family	Type	Number of Schools	Total number of Work Orders	Total Cost of Work Orders
2005 and 2006	NE	NE 1	Secondary Elementary	4 24	3,212 7,547	$1,220644 $2,356848
		NE 2	Secondary Elementary	3 21	3,546 7,794	$1,197581 $2,538071
		NE 3	Secondary Elementary	3 16	2,309 6,889	$830,203 $2,197,496
		NE 4	Secondary Elementary	2 15	2,857 7,488	$1,177,801 $2,452,824
TOTAL			**88 SCHOOLS**		**41,642**	**$13,971,468**

	A	B	C	D	E	F	G
1	School No.	Family	Type	Construction Year	Size (m2)	Replacement Cost ($)	Address
2	1	NE1	S	1968	15,219	$22,198,592	50 Francine Dr.
3	2	NE4	E	1981	3,730	$5,034,157	112 Goldhawk Trail
4	3	NE4	S	1976	22,964	$32,870,991	1550 Sandhurst Cir
5	4	NE4	E	1984	5,661	$7,845,254	70 Fawcett Trail
6	5	SW2	E	1910	9,844	$10,333,648	265 Annette Street
7	6	SE5	E	1958	1,941	$2,933,006	30 MacDuff Crescent
8	7	NE1	E	1975	3,492	$4,345,726	55 Freshmeadow Dr.
9	8	NE1	E	1949	3,334	$6,304,845	171 Avondale Ave.
10	9	NE4	E	1989	3,813	$4,811,851	380 Goldhawk Trail
11	10	NE4	E	1973	5,655	$5,887,526	120 Berner Trail
12	11	NE2	E	1971	4,875	$7,142,480	85 Beverly Glen Boulevard
13	12	NE2	E	1956	3,256	$4,847,707	95 Brian Dr.
14	13	NE2	E	1963	3,007	$6,308,521	60 Bridlewood Blvd
15	14	NE4	E	1974	3,241	$4,840,536	151 Brimwood Boulevard
16	15	NE3	E	1974	3,241	$4,840,536	25 Brookmill Boulevard
17	16	NE4	E	1975	2,920	$4,331,383	151 Burrows Hall Boulevard
18	17	NE4	E	1953	4,305	$6,439,706	1965 Brimley Rd.
19	18	NE1	E	1949	3,293	$3,919,500	211 Cameron Ave
20	19	SW6	S	1912	55,081	$58,972,632	725 Bathurst Street
21	20	NE3	E	1967	4,119	$7,326,826	109 Chartland Boulevard
22	21	NE2	E	1975	2,488	$3,800,717	390 Cherokee Boulevard

Figure 4.2: Sample of General Data about TDSB Schools

	H	I	J	K	L	M	N	O	P	Q
1	School No.	Year	System	Total Cost Act ($)	Order no.	Short Description	Basic start	Basic finish	P	Code3
5115	10	2005	PLUMBING	$95.50	50741244	repair & or remove asbestos	2005.04.28	2005.04.29	1	GC16
5135	10	2005	PLUMBING	$495.18	50790432	Fire Supr Sys Ann Insp A Berner Trail	2005.10.11	2005.10.31	6	GJ02
5164	10	2005	PLUMBING	$211.56	50753748	slop sink plugged	2005.05.26	2005.05.31	2	GO01
5165	10	2005	PLUMBING	$928.94	50701218	floor drain backing up	2005.02.01	2005.02.02	1	GO01
5166	10	2005	PLUMBING	$137.55	50808250	tap handels broken in girls wash room	2005.09.27	2005.10.04	2	GO02
5167	10	2005	PLUMBING	$132.23	50737849	kindergarten sink leaking behind wall.	2005.04.25	2005.04.28	2	GO02
5168	10	2005	PLUMBING	$132.23	50742776	plumber for sink taps slop sink	2005.05.02	2005.06.14	3	GO02
5169	10	2005	PLUMBING	$105.78	50786670	service rm hot water taps leaking	2005.08.22	2005.08.25	3	GO02
5170	10	2005	PLUMBING	$158.67	50732372	sink plugged staff room	2005.04.14	2005.04.19	3	GO02
5171	10	2005	PLUMBING	$165.06	50805114	service room sink is pluged	2005.09.22	2005.09.29	2	GO02
5172	10	2005	PLUMBING	$137.55	50808249	sink in service room pluged	2005.09.27	2005.10.04	3	GO02
5173	10	2005	PLUMBING	$235.12	50805115	taps not working in the kindergarten w/r	2005.09.22	2005.09.29	3	GO02
5174	10	2005	PLUMBING	$137.55	50808248	bradly not working in boys w/r	2005.09.27	2005.10.04	2	GO02
5175	10	2005	PLUMBING	$583.44	50692409	no water-bradley-girls wr-1st fl	2005.01.14	2005.01.17	1	GO02
5176	10	2005	PLUMBING	$1,206.47	50732368	toilet not woking	2005.04.14	2005.04.19	3	GO08
5177	10	2005	PLUMBING	$132.23	50753389	girls washroom 2nd stall no flush	2005.05.24	2005.05.27	2	GO08
5178	10	2005	PLUMBING	$446.18	50855252	toilet base broken	2005.12.16	2006.01.30	3	GO08
5179	10	2005	PLUMBING	$105.78	50786676	toilet leaking from base boys by office	2005.08.22	2005.08.25	3	GO08
5180	10	2005	PLUMBING	$82.53	50821088	flushometer leaking boys 1st fl w/r	2005.10.19	2005.10.26	3	GO08
5181	10	2005	PLUMBING	$132.23	50786673	toile in the boys secound floor w/r	2005.08.22	2005.08.25	2	GO08
5182	10	2005	PLUMBING	$158.67	50753747	JSHOMETRE NEEDS TO BE REPLAC	2005.05.26	2005.05.31	2	GO08
5183	10	2005	PLUMBING	$185.12	50753388	boys washroom urinals not working	2005.05.24	2005.05.27	2	GO09

Figure 4.3: Sample of Specific Data about TDSB Schools

4.3.2 Data Analysis

Once the data were collected, the database functions of Excel, such as sorting, grouping, automating, and linking were used to prepare the data for statistical analysis. Since the component hierarchies for RECAPP and SAP are not identical, special effort was required to synchronize the component hierarchies using Visual Basic tools. Details of the proposed hierarchy are discussed in Chapter 6.

The results from both RECAPP and SAP were combined in order to obtain a spreadsheet that contained all relevant information about the 88 sample schools. The general data and specific maintenance data for all schools were merged to create a large spreadsheet in order to facilitate the analysis, as shown in Figure 4.4. The left side of the merged spreadsheet shows the general information that relates to the school to which a work order applies. The right side shows the details related to each work order, such as the year, system, total cost, order number, and start and finish dates. In this way, the full information about location, cost, duration, and resources was then ready for analysis.

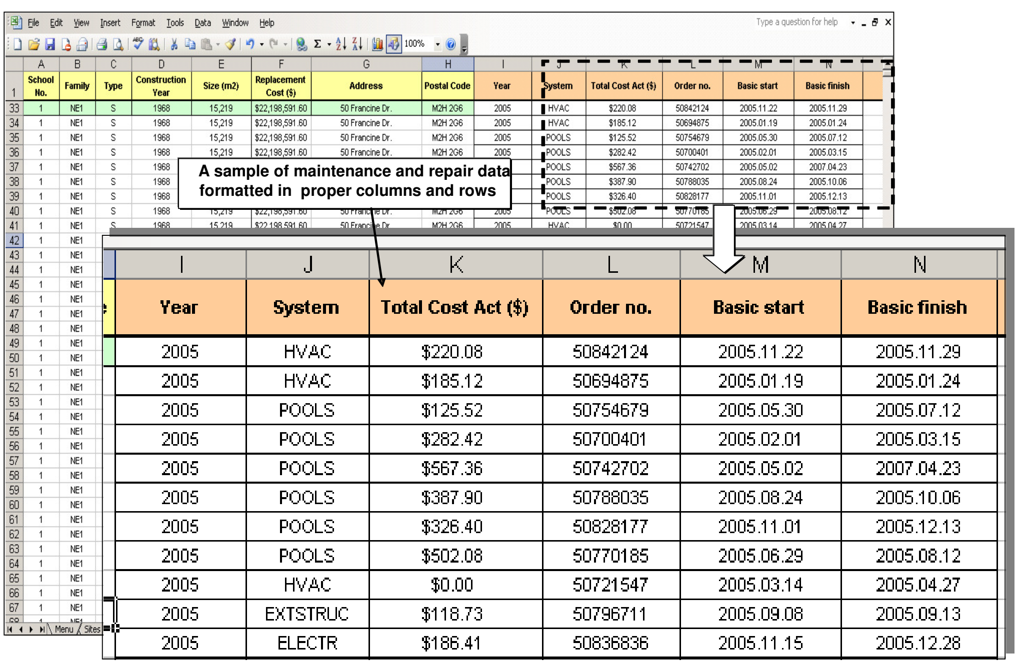


Figure 4.4: Sample of the Merged Spreadsheet

Preliminary analysis of the data identified 23 building systems (Table 4.2); the ones that required the most maintenance (or repair work orders) are highlighted in Figure 4.5. As part of the analysis, the maintenance data for each building system was analyzed separately to test whether a relationship exists between the condition of the system and the yearly maintenance data documented in the TDSB. Such a relationship will be beneficial for predicting the condition of a system from available maintenance data, without inspection. For verification, the analysis was carried out on the 2005 and 2006 data for the HVAC systems and the boilers. The results in Figure 4.6 show logical trends: the older the system, the worse its condition, and consequently, the more maintenance work orders it experiences. This proves that the number of work orders is a good indicator of condition. A similar analysis proved that the cost of work orders is another good indicator of condition for both the components.

Table 4.2: Preliminary Analysis of Various Building Systems

Year	System	Brief Description	Total Number of Work Orders	Total Cost
2005 and 2006	AHU	Air Handling Unit	1,111	$374,548
	BAS	Building Automation Systems	495	$123,283
	Boiler	Boiler Systems	932	$434,372
	COMPARE	Compressed Air	523	$83,292
	ELECTR	**Electrical Systems**	**4,967**	**$1,885,271**
	ELECTRON	**Electronics Systems**	**3,097**	**$1,053,297**
	ELEVATOR	Elevator	12	$2,339
	EXSTRUC	External Structure Works	2072	$783,426
	FLEET	Fleet	9	$1,385
	GLAZING	Glazing Works	516	$140,228
	HVAC	**Heating, Ventilation, and AC**	**6,539**	**$2,597,590**
	INTSTRUC	**Interior Structure Works**	**7,729**	**$2,811,060**
	LIFTS	Lifts	141	$127,049
	OPSEQMT	Operations Equipment	2,574	$606,372
	PLAYGRND	Playground	812	$53,339
	PLUMBING	**Plumbing Systems**	**6,021**	**$1,954,584**
	POOLS	Pools	349	$197,371
	PORTABLE	Portables	1,441	$141,056
	PUMPS	Pumps	193	$121,786
	REFIG	Refrigerator	367	$121,679
	SCHEQMT	School Equipment	1,534	$384,616
	SIGNAGE	Signage Systems	67	$12,342
	SITEWORK	**Site Works**	**3,011**	**$1,128,459**
TOTAL	**23 SYSTEMS**		**44,512**	**$15,138,744**

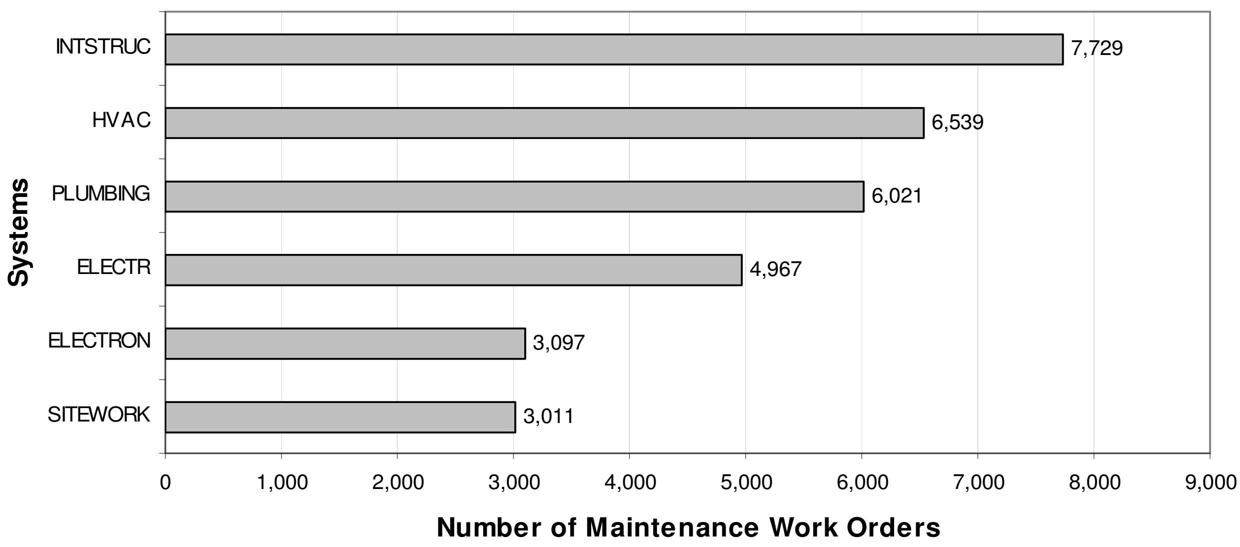


Figure 4.5: Most Frequent Types of Maintenance Work Orders

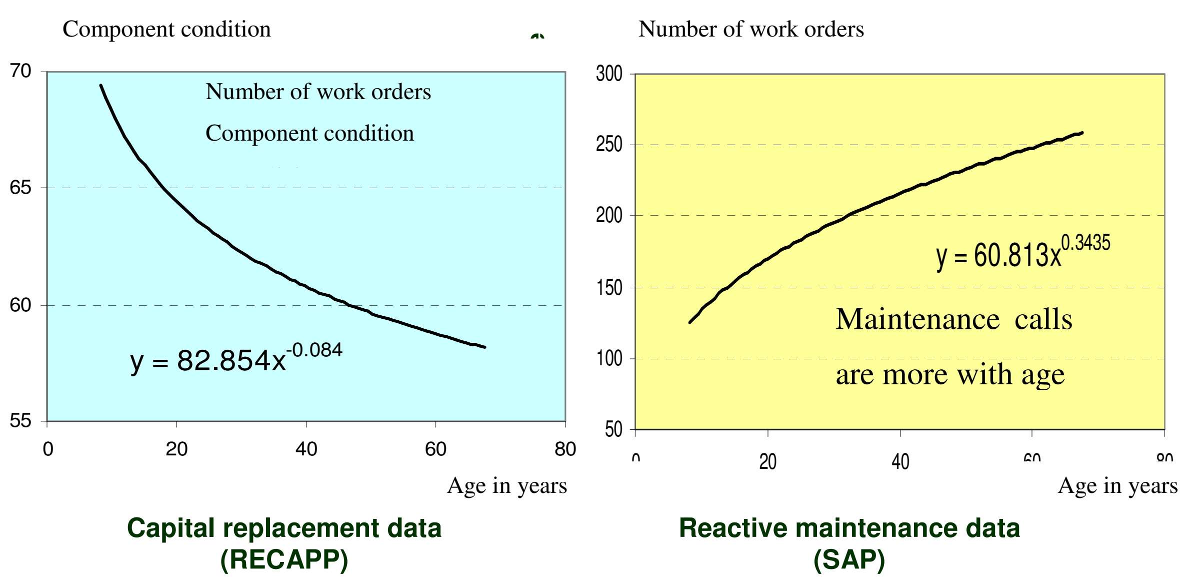


Figure 4.6: Relationship Between Condition and Maintenance Records (2006) for HVAC Systems

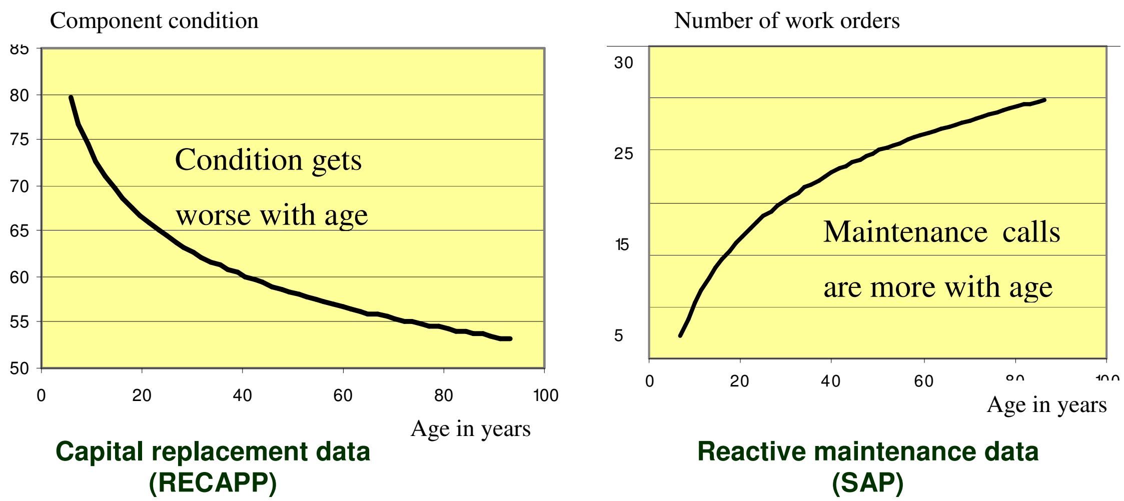


Figure 4.7: Relationship Between Condition and Maintenance Records (2006) for Boilers

Based on the proven relationship, a detailed analysis was carried out in order to establish a condition indication mechanism. Because the schools in one family have a consistent environment and similar demographical influences, for demonstration purposes, the sample used was the HVAC data for only elementary schools in the NE1 family. Using this data, two indicators of asset condition, “cost of work orders,” and “number of work orders,” were identified and two charts were developed based on the available data, as shown in Figure 4.8.

Figure 4.8a indicates the total costs of the HVAC work orders (normalized based on school area) for each of the 20 schools in the NE1 family, sorted in ascending order. The chart was used to define four equal zones related to the Good, Fair, Poor, and Critical condition categories. The maintenance cost ranges that define the four condition categories were thus determined, as shown in Figure 4.8a. Similarly, another chart (Figure 4.8b) was generated to define the HVAC condition based on the total number of maintenance work orders. The two charts were then used to compare the predictions of condition based on cost versus those based on the number of maintenance orders, as shown in Table 4.3. Similar predictions represent high consistency and confidence in the predicted condition. Contradicting conditions, on the other hand, indicate some inconsistency and can thus be used to prioritize which inspection tasks are needed in order to verify the true condition. In the last column of Figure 4.8, for example, only six schools of the 20 are selected for inspection: top priority is assigned to the schools that show a Critical condition in either of the two predictions.

It is noted that the schools that show Fair and Good conditions are not given priority for inspection. Once the inspection tasks are defined and prioritized for all the building systems, it is possible to schedule them depending on the available inspection resources within the organization.

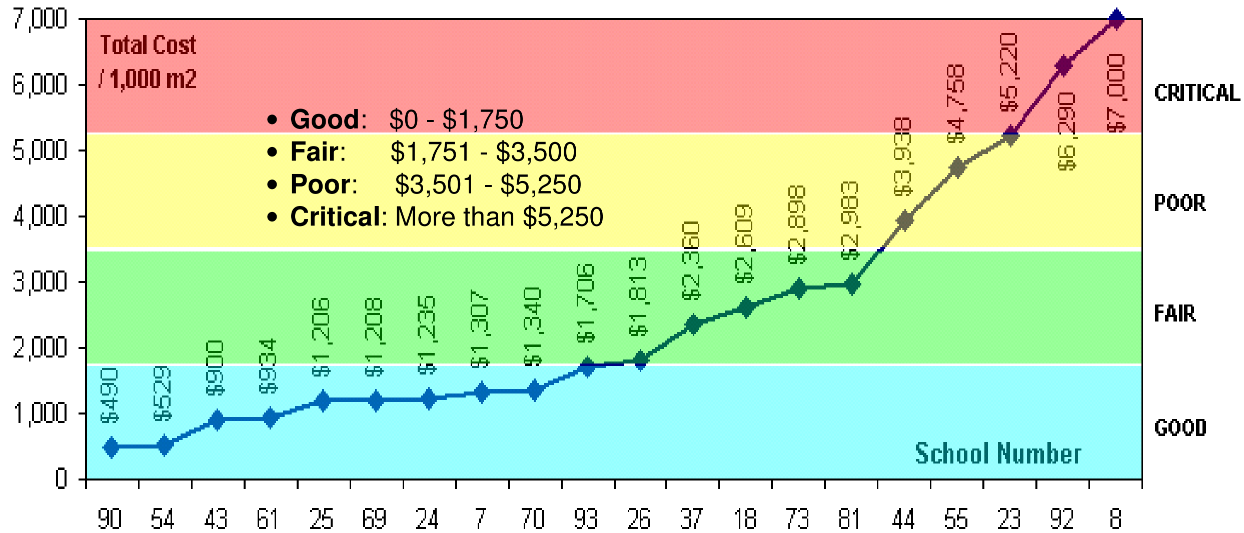
For validation purposes, data from 52 schools of NE1 and NE2 families was used to generate a set of condition ranges as shown in Figure 4.9. Similarly, data from 36 schools of NE3 and NE4 families was used to come up with another set of condition ranges as shown in Figure 4.10. These two sets of condition ranges were then mutually compared. The result of this analysis shows that the condition ranges are reasonable and hence can be applied to the whole inventory of the TDSB schools. It also proves that the number of work orders and their associated costs are good indicators of the HVAC system in schools.

Table 4.3: Inspection Priority Based on Condition Estimates

School Number	Condition Estimate 1 *Based on work order cost*	Condition Estimate 2 *Based on number of work orders*	Inspection Priority
7	Good	Fair	
8	Critical	Critical	
18	**Fair**	**Poor**	**2****[**]**
23	Poor	Poor	
24	Good	Good	
25	Good	Fair	
26	Fair	Fair	
37	**Fair**	**Poor**	**2**
43	Good	Fair	
44	**Poor**	**Fair**	**2**
54	Good	Fair	
55	**Poor**	**Critical**	**1**[*]
61	Good	Fair	
69	Good	Fair	
70	Good	Fair	
73	**Fair**	**Poor**	**2**
81	Fair	Fair	
90	Good	Good	
92	**Critical**	**Fair**	**1**
93	Good	Fair	

* Priority level 1 is for components that show “critical” in any column.
* Priority level 2 is for components that show “poor” in any column.

(a) Estimating HVAC condition as a function of reactive-maintenance costs



(b) Estimating HVAC condition as a function of the number of maintenance work orders

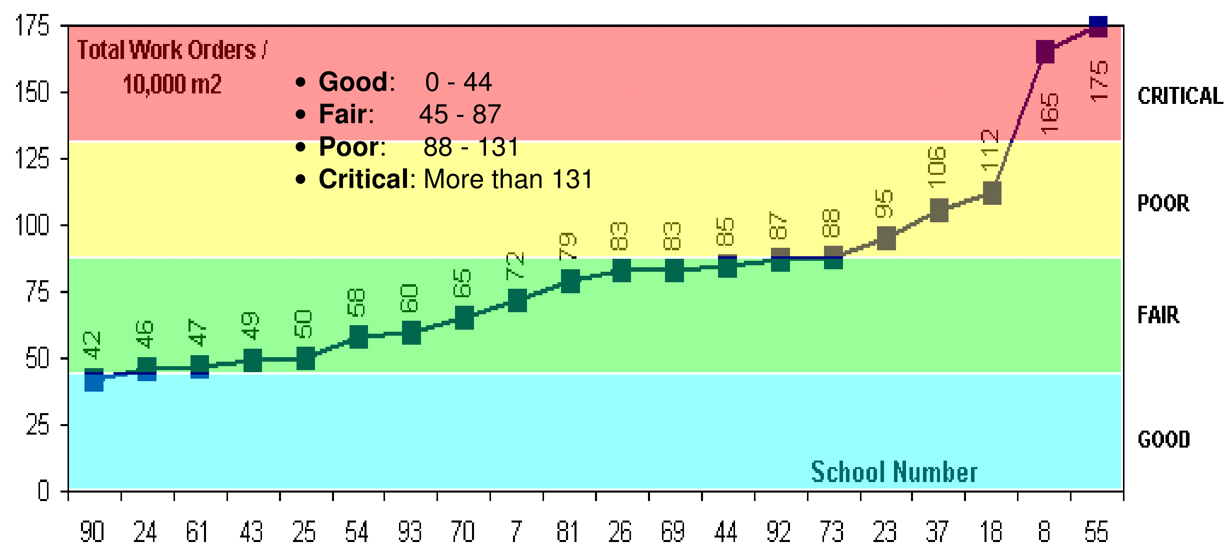
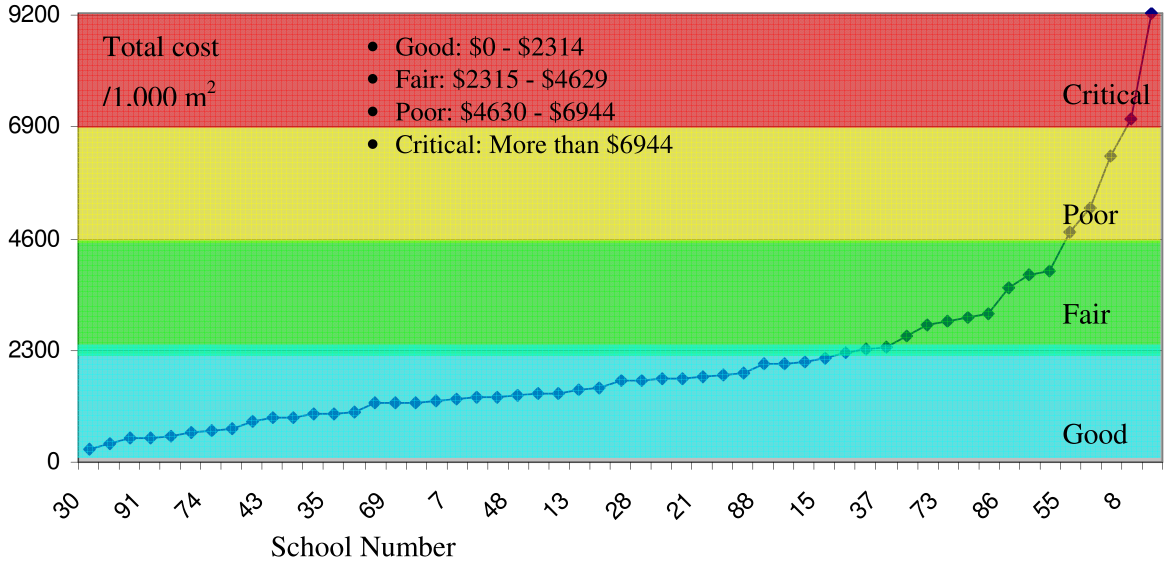


Figure 4.8: Two Condition Indicators Based on Maintenance Data for 20 Elementary Schools of NE1 family

(a) Estimating HVAC condition as a function of reactive-maintenance costs (2006) for 52 schools of NE1 and NE2 families



(b) Estimating HVAC condition as a function of the number of maintenance work orders (2006) for 52 schools of NE1 and NE2 families

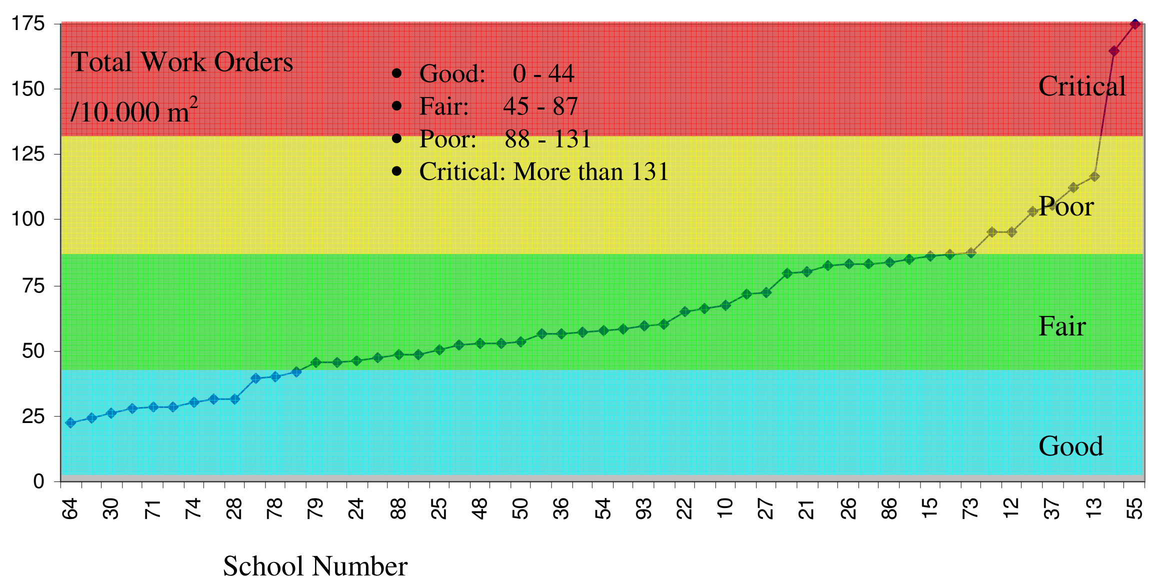
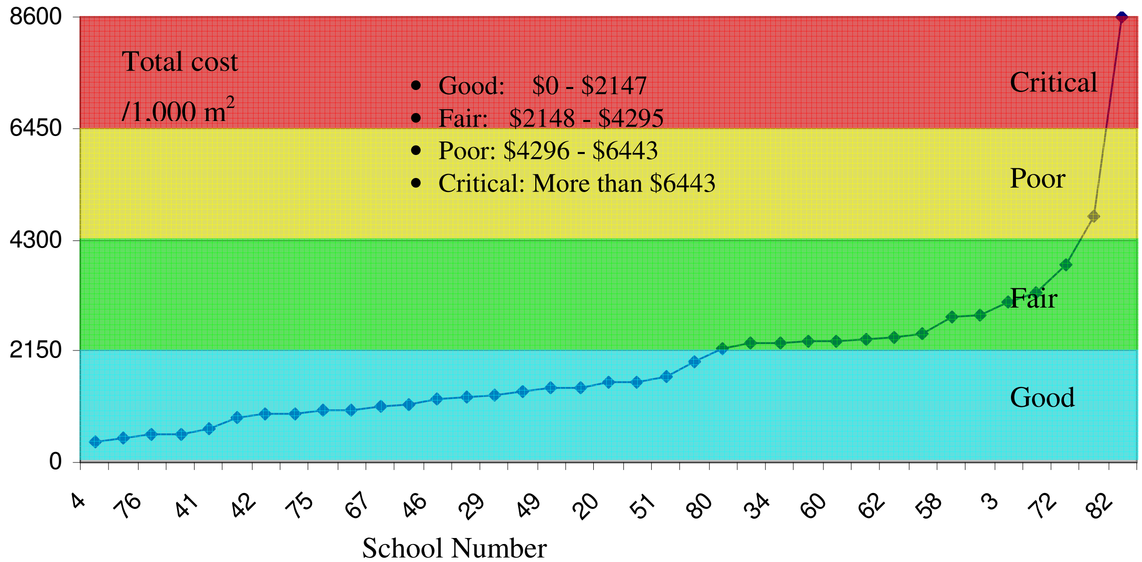


Figure 4.9: Two Condition Indicators Based on Maintenance Data for 52 Schools of NE1 and NE2 families

(a) Estimating HVAC condition as a function of reactive-maintenance costs (2006) for 36 schools of NE3 and NE4 families



(b) Estimating HVAC condition as a function of the number of maintenance work orders (2006) for 36 schools of NE3 and NE4 families

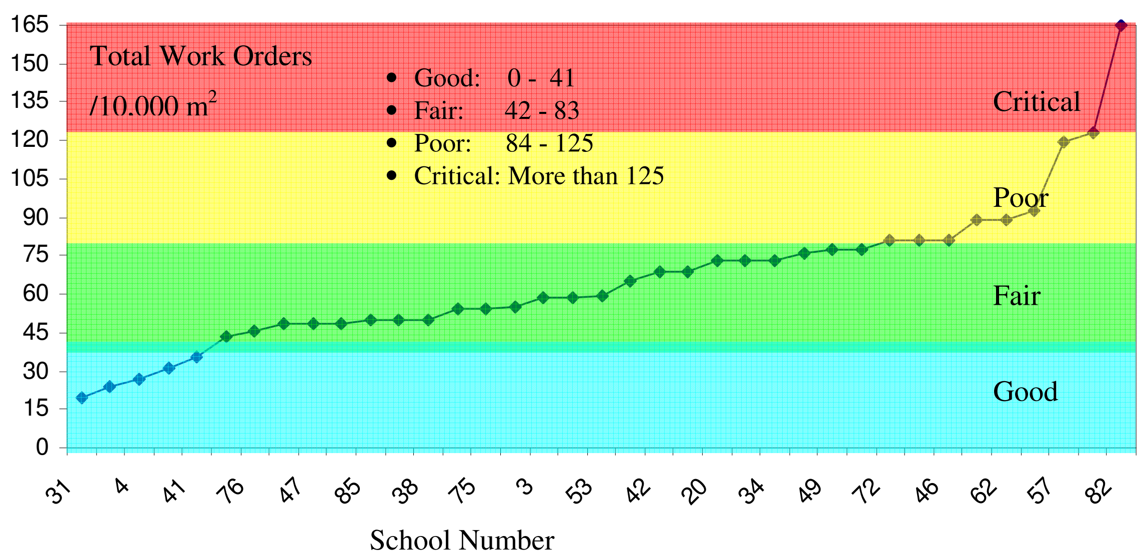


Figure 4.10: Two Condition Indicators Based on Maintenance Data for 36 Schools of NE3 and NE4 Families

4.4 Conclusions

Chapter 4 has introduced one essential component of the proposed framework: the condition indication and inspection planning. Analyzing the huge amount of interlinked reactive-maintenance data, collected from the TDSB identified two indicators of asset condition: (1) number of reactive-maintenance work orders and (2) cost of these work orders. A simple comparison of the two indicators highlights the components that have conflicting data, and are therefore given high priority for early inspection.

The development made with respect to condition prediction and inspection planning will help in the prioritizing of inspection tasks and the efficient scheduling of the limited available resources to conduct them, thus saving time and money. The proposed concept has been implemented in the form of a computer prototype system that is discussed in Chapter 6.

Chapter 5
Understanding the Deterioration of the Top Building Components: The Visual Guidance System

5.1 Introduction

This chapter identifies the important building components and their deterioration with respect to defects and symptoms, and their impact on other building components. First, the top five building components were identified through the literature and through discussions with experts in the industry. Second, information related to the deterioration of building components was collected from a large owner organization, the Toronto District School Board (TDSB). Extensive surveys were then carried out among experienced personnel at the TDSB in order to understand the various defects, deterioration, and interrelationship of these top building components. In addition, pictures were collected of the components at various conditions and stages in their life cycle.

In addition to shedding light on the deterioration process of costly building components, this chapter paves the way to the development of an advanced pictorial guidance system to support visual inspection and critical asset management decisions. The pictorial guidance system will help make the inspection process less time-consuming, more economical, and less-subjective. The development of the proposed system is discussed in the following sections and is illustrated in Figure 5.1.

5.2 Selection of Components

The first step in acquiring an understanding of the deterioration of building components over time was the selection of the components (Figure 5.1). The literature review in Chapter 2 indicated that the bulk of maintenance needs for buildings relate either to the external envelope or to the mechanical and electrical service installations (DfES 2003). The TDSB budget distribution (Table 5.1) for building components and further discussions with TDSB maintenance professionals confirmed the selection of these building systems because they consumed the largest proportion of the repair and maintenance budget (Attalla et al. 2000). In addition, the

TDSB personnel reported that for safety reasons, the fire alarm system, which is part of the electrical services, has the highest priority in the case of schools. Another study related to TDSB by Elhakeem (2005) that investigated the relative impact of a component's failure on safety, on building operation, and on other components, confirmed the importance of the fire alarm system, which received the highest score, in the case of TDSB schools. Based on these considerations, five components were selected for this study: roofing, windows, boilers, fire alarm system, and secondary switchgear (Table 5.2).

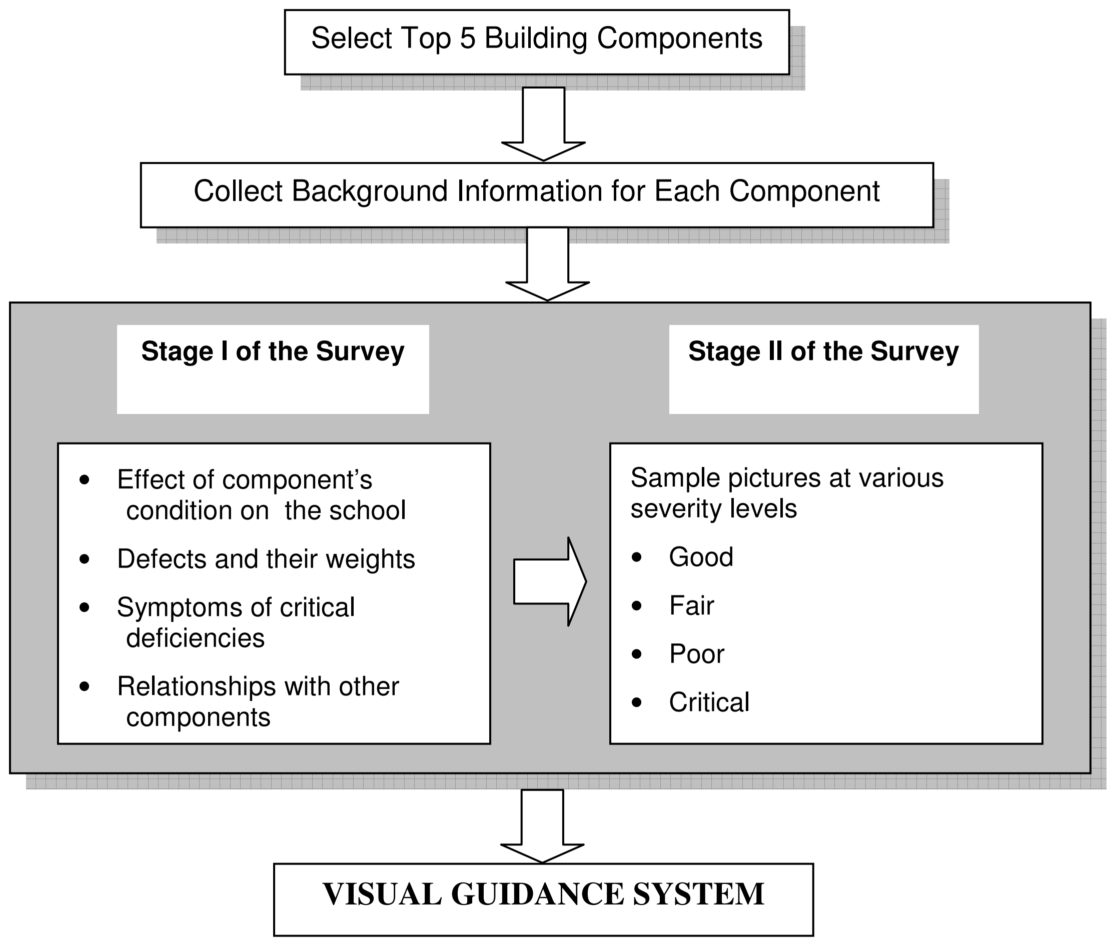


Figure 5.1: Survey Methodology

Table 5.1: TDSB Budget Allocation for Building Components

Building System	Component	Percentage of Yearly Budget
Electrical	Distribution (primary and secondary switchgear), light/power, communication, fire alarm system, emergency power, and transformers.	30%
Primary Structure (exterior)	Foundations, substructure, superstructure, windows, and roofing.	24%
Mechanical	Boilers, conveying, plumbing, heating, ventilation, cooling, pools, fire alarm system, and extinguishing system.	23%
Site	Parking, paved play area, play fields, drainage, playscape, fencing, and regulatory requirement.	13%
Secondary Structure (interior)	Substructure, partitions and doors, wall finishes, and floor.	7%
Program Contingency	-	3%
TOTAL		100%

Table 5.2: Top Five Selected Building Components

Building Components	
1	Roofing
2	Windows
3	Boilers
4	Secondary Switchgear
5	Fire Alarm System

5.3 Background Information about the Selected Building Components

To facilitate detailed deterioration analysis, published information about deterioration and the various defects associated with the five selected building components was obtained through an extensive literature review. This literature review formed the background information for the select components and was used to design the surveys, as explained in section 5.4. A brief description of the published information regarding each of the five components is presented in the following subsections.

5.3.1 Component 1: Roofing

Roofing is one of the main components of any building and is considered a relatively large investment (Suarez 1999). Many studies (e.g., ADOE 1997; NCES 2003 b) have identified roofing as one of the most frequently deteriorated building components. Therefore, being proactive with the health of a roofing system will ultimately reduce the building owner's financial liability (Suarez 1999).

The average life of a roof varies according to the type and material (Lewis and Payant 2000). However, the life expectancy, as with any other building component, is greatly influenced by the presence or absence of a maintenance program (Suarez 1999). According to the National Roofing Contractors Association, roofs not properly maintained will last approximately half of their anticipated service life (Suarez 1999).

Roof systems are generally divided into two classifications: low slope and steep slope, as shown in Figure 5.2 (NRCA 2007). Many studies (Bailey and Bradford 2005, Cullen and Graham 1996) have revealed that a built-up roof (BUR) system is the most common roof type in Canada. BUR systems are generally composed of alternating layers of bitumen and reinforcing fabrics that create a finished membrane (also called a roofing felt or ply sheet). The number of plies in a cross-section is the number of plies on a roof. Roofing felts are reinforced with either glass-fiber mats or organic mats. The bitumen typically used in BUR roof systems is asphalt, coal tar, or cold-applied adhesive. Surfacing for built-up roof systems includes aggregate such as gravel, slag, or mineral granules; glass-fiber or mineral-surfaced cap sheets; hot asphalt mopped over the entire surface; aluminum coatings or elastomeric coatings.

Previous studies (Cullen and Graham 1996; Cullen 1993) have surveyed the extent of problems encountered from 1993 to 1995 with several roof types, including the BUR. These studies reported the nature, frequency, and seriousness of problems experienced with BUR systems. The studies also identified problems and defects for each roof type and their severity levels. For example, Figure 5.3 shows the frequency of built-up roof problems.

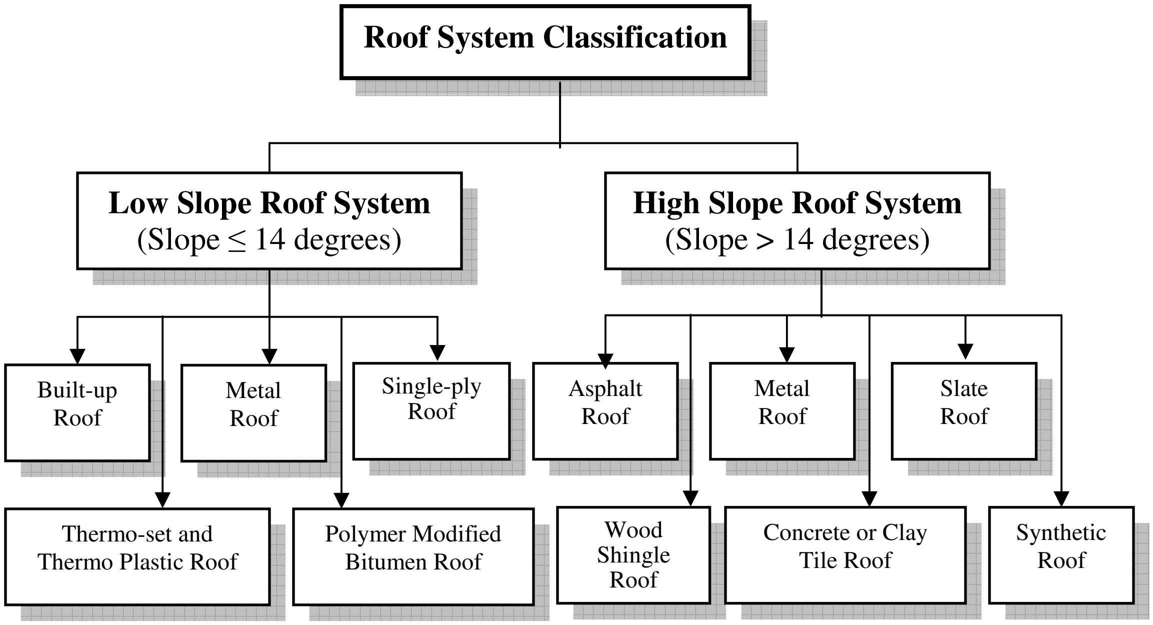


Figure 5.2: Roof Classification System

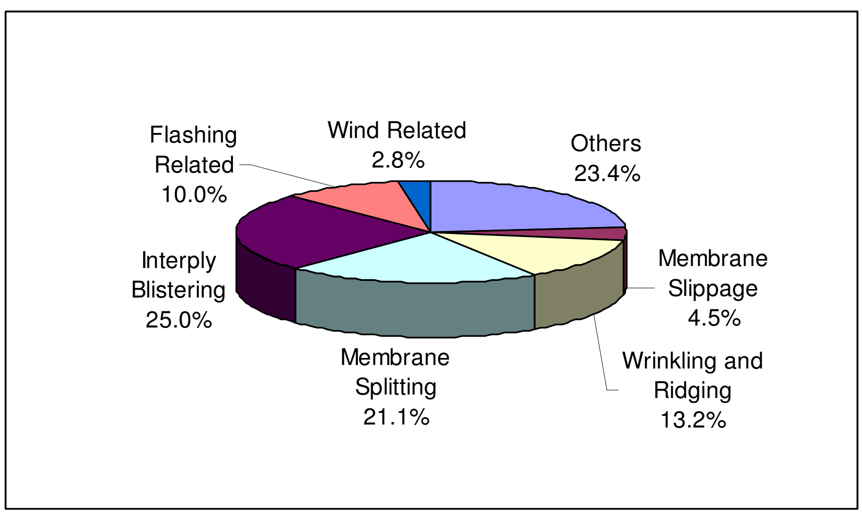


Figure 5.3: Frequency of Built-up Roof Problems

Asset management systems have been proposed as a way to help large building owners with decisions related to repair and replacement fund allocation, With respect to roofs, the ROOFER Engineering Management System (Bailey and Bradford 2005), developed by the Construction Engineering research laboratory (CERL), for example, has been used since 1989 by the U.S. army. ROOFER includes procedures for collecting inventory and inspection information, evaluating the condition of the roof, identifying repair or replacement strategies, prioritizing projects, and developing work plans. MicroROOFER, a microcomputer application that runs in a Windows 95/98/NT environment, provides data storage and analysis and generates management reports.

ROOFER condition assessment procedures are based on standardized visual inspection processes that include identifying and recording distresses, and measuring quantities. Each distress is categorized by severity level and specific defect. For example, for BUR systems, ROOFER defines 16 distresses and 93 defects. The inspection data provide the information needed to generate condition indexes for the major roof components as well as an overall roof condition index (RCI).

Many other researchers have successfully used ROOFER for their studies. One such example in Canada is a project called Building Envelope Life Cycle Asset Management (BELCAM) by the Institute for Research in the construction of the National Research Council of Canada building (Kyle and Vanier 2001 a and b). The study investigated methodologies and tools for calculating the remaining service life of building envelope components, with an initial focus on low-slope roofs. The researchers used MicroROOFER (version 1.3) for data collection from roughly 600 buildings in approximately 15 cities or towns across Canada. In their study, the distresses identified for built-up roofs, modified bituminous roofs, and a limited number of single-ply roofing systems were examined relative to climatic conditions and type of material. A list of visual roofing distresses, their severity levels, and their units of measurement were recorded for different types of roofing and were also linked to the age of the roof. The study revealed that distresses change over time. The majority of the reported distresses occurred on BUR roofs, with roughly one-third related to flashing. For modified bitumen installations, the flashing distresses accounted for 20% of those observed. The severity of the defects is typically expected to worsen with time irrespective of the type of roof.

Many researchers have examined individual roof defects in detail. For example, Martin (1979) studied membrane splitting and its causes. Murray (1979) explored membrane blisters in built-up roofs. In a technical report by the US army (1987), membrane and flashing defects of built-up roofs were discussed. As a roof does not age uniformly (Williams 1979), the report suggests dividing the roof into sections and rating each section separately as an effective method of inspection. The report recommends sampling as the most effective way of identifying distress and severity levels. In addition, extensive studies have been conducted with respect to the effects of moisture ingress (Desjarlais and Byars 1997; Busching 1979) and air leakages (Fishburn 1976).

5.3.2 Component 2: Windows

Windows are an important source of daylight, visual contact, ventilation, and fire escape (Granum 1984). In addition, they have a major effect on the energy consumption of any building. Therefore, any defect in the windows can cause air and noise infiltration, leading to energy loss due to heat transfer and consequent increase in the cost of operating the cooling/heating system (Daoud 1992). In cold countries such as Canada, a huge amount of power is used to operate the heating systems, especially during peak periods. Hence, the condition of the windows is crucial for conserving energy. However, historically, little consideration was given to the energy effectiveness of windows in the design and construction of buildings until the early 1970s (Carruthers 1987; Weidt et al. 1979).

Windows can be classified according to material (wood, metal, etc.), operation type (casement, sliding, hung, etc.), and energy effectiveness (based on U-value). However, regardless of the type of windows, their maintenance is extremely important for the overall health of the building.

Researchers have confirmed visual inspection methodology to be an accurate means of evaluation and identification of defects for the purpose of window maintenance (Daoud 1992). However, the choice between replacement and repair option for window maintenance has always been challenging for researchers. Both options are supported by studies. The option selected determines which evaluation techniques can be used (as discussed earlier in section 3.2 of Chapter 3). Distress evaluation of defects is ideal for a repair scenario whereas direct evaluation is more suited for replacement strategies. For example, the study by Daoud (1992) supported a defect identification and remedy mechanism (distress-rating evaluation) as a successful strategy in the case of repairs. The research identified anomalies in aluminum windows (sample size of 154 windows with eight operational types) installed in residential and commercial buildings (25 buildings) in Kuwait. The impact of the visible defects on performance was quantified, and the most common and influential causes of air leakage were identified. The study proved that windows with fabrication and installation defects produced higher air leakage rates than those with design and maintenance defects.

Another detailed study of defects leading to air leakage was conducted at the University of Berkeley, California (Weidt et al. 1979). The study measured and evaluated air leakage characteristics of 192 new windows installed in a residential area. The results showed a large percentage (40%) of the windows tested had air leakage in excess of the standards (ASHRAE). The study indicated that the performance of a window is affected by its operation type (e.g. casement windows by far outperform sliding and hung windows). The material of the window (wood or aluminum) does not have a significant impact on measured window performance. With the use of infrared thermography, the study also identified the areas of excessive air leakage to be corners, sills, and meeting rails. The research concluded that the areas of excessive air leakage could frequently be related to irregularities in the weather stripping, sash fit, and hardware.

A study of wooden windows by Gunnilla (1984) focused on identifying the types of damage, analyzing the causal relationships, and providing guidance for repairing and replacing damaged windows. This study established moisture ingress as the main cause of timber decay and concluded that the location of window is an important factor in window performance.

Carruthers (1987) identified attributes that are most relevant to the performance of windows: resistance to wind loading, resistance to air penetration, resistance to water penetration, ability to withstand operational and abusive forces, and accidental loading, thermal insulation, and durability.

Seifert (1987) reported that the service value of a window depends on the person who operates it after installation. The study differentiates between reconditioning, renovation (or reconstruction), and servicing and establishes an interrelationship among them. The author defines the following decisive criteria for comparing reconditioning the existing window and replacing it:

a. Cost of the work to be performed, including additional work, e.g. plaster, paint, blinds;
b. Life expectancy;
c. Assessment of the improvements that would result with respect to resistance to air and water penetration, thermal and sound insulation, and cleaning and ventilation;
d. Energy saved;
e. Expected maintenance costs; and
f. Increased living comfort and room atmosphere.

5.3.3 Component 3: Boilers

A Boiler is one of the most important components in a building: it is considered to be its heart (Lembo 2002). The replacement of the boiler is ranked as the number one priority for schools (Lembo 2002). The heart, however, cannot operate properly, even if replaced, if the organs are malfunctioning, and the veins and arteries, that is, the boiler system's piping are clogged. In an efficiently functioning heating system, the component's work together in harmony; thus, all components should be checked.

Boilers can be classified in many ways (Spring et al. 1981). The most common type of classification is according to installation methods (Figure 5.4). Boilers are also classified by the nature of the services they provide (stationary boiler, portable boiler, locomotive boiler, and marine boiler) and the type of construction (cast iron or steel).

Selection of the boiler type should be based on the life-cycle cost of the complete system and not just on the initial cost of the boiler (Holdaway 2006). In a study by Holdaway (2006), the type of HVAC system in use and resulting temperature of the hot water return were considered to be the most important factors in determining the type of boiler. The study also lists other factors affecting the choice of boilers, such as capacity, venting options, efficiency, footprints, capability of the maintenance staff, controls, and the overall construction budget (Holdaway 2006). In addition to cost constraints, Lembo (2002) suggests two further parameters for choosing a boiler in the case of school buildings: ease of replacement and the amount of demolition required to accommodate a new installation, and flexibility in sizing the plant down or up because schools often have additions, and generally to reduce costs, the existing boiler is used to heat the new addition.

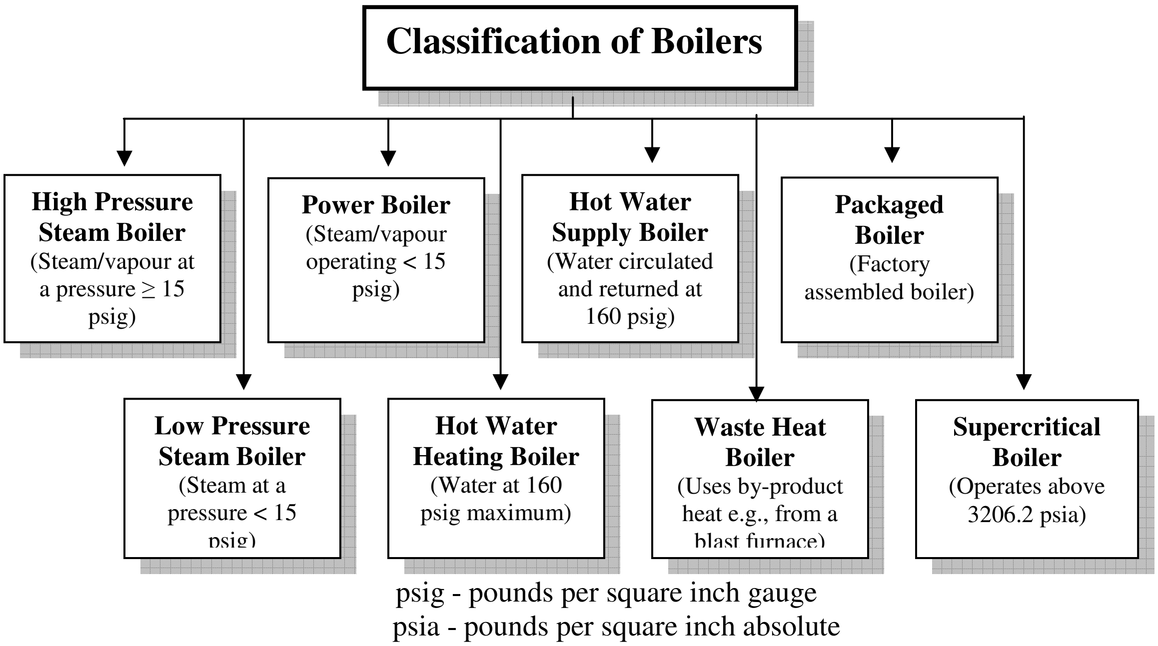


Figure 5.4: Classification of Boilers

Once the size of the boiler is determined, an efficient maintenance plan can limit the frequency of unexpected expenses. Adequate inspection and maintenance can help prevent the failure of the pressure parts (Shields 1961). The legislation sets up standards (ASME or NB rules) for design, installation, and inspection, both external and internal. An external inspection involves an examination by the authorized inspector while the boiler is in service. This inspection involves checking the boiler and its connections and is performed primarily to observe operation and maintenance practices. No particular preparation is needed other than to give the inspector convenient access to the unit and its connections. Internal inspection, on the other hand, involves a complete and thorough examination of all parts of the boiler, with the inspector entering the furnace and the drums, if they are large enough. The external casing is removed, as necessary, to permit a complete inspection (Shields 1961). The purpose of the internal inspection by an authorized inspector is to check on the structural soundness of the pressure-containing parts and to note any conditions that can affect the strength required to confine the pressure. (Spring et al. 1981). Water-side surfaces, stress points, riveted joints, lap joints, tubes (Dooley and McNaughton 1995; James 1998; Noori and Price 2005), baffles, boiler settings, connections, valves, and controls are some of the important areas that must be checked during an internal inspection (Shields 1961).

Therefore, extensive research has been conducted with respect to the internal inspection of boilers. Schuch (1991) strongly recommends four checks to be carried out during the internal inspection of boilers: evidence of corrosion or overheating, build-up of chemicals and impurities on the inside of the vessel, signs of thinning or cracking of the metal surfaces, and bulging or blistering of the metal surfaces.

Non-destructive testing equipment is being used in boiler inspection to locate potential areas of failure. Five major non-destructive tests are used: ultrasonic, radiography, magnetic particle, dye penetrant, and eddy current (Spring et al. 1981).

Brennan (1995) suggests the need for the school administration to actively participate in and support boiler maintenance and safety programs. The study suggests that every small accident be reported as they are the warning signals for larger accidents. Lembo (2002) further suggests that proactively addressing the condition of the boiler can considerably reduce downtime and properly prepare the school budget committee for the inevitability of a boiler replacement. The study recommends regular assessment and open communication with the maintenance staff as a good way of determining the need for replacement and of making replacement possible on a scheduled basis, during off-hours or during periods when school is not in session. Further, it is also suggested in the literature (ACHRN 1999) that good preventive maintenance is much less expensive than corrective maintenance, in which case the entire piece of equipment may need to be replaced.

5.3.4 Component 4: Fire Alarm Systems

A fire alarm system is a combination of devices designed to warn the occupants of the building of an emergency condition (Treasury Board of Canada 1992). It is considered to be one of the most important systems for any building as it provides early warnings that can save lives and minimize the damage to valuable property (Fire 1995). Fire alarm systems are required by law through building codes, fire codes, and special acts or bylaws. The choice of the particular type of equipment to be used in a fire alarm system depends on the nature of the occupancy, the size of the building, the number of occupants, and the level of protection desired (McEwen 1984).

A typical fire alarm system consists of a control unit, manually activated signaling boxes (pull-boxes), fire detectors, and audible alarm devices. There may also be visual signal devices to warn the hearing-impaired, annunciators to indicate the origin of the alarm signal, and emergency telephones and other equipment for communication between the central control panel and other parts of the building (Figure 5.5) (McEwen 1984).

The control unit transmits signals from signal boxes and fire detectors (smoke detectors and heat detectors) to the alarm signal devices (audible signals like bells, speakers, and sirens or visual signal like a strobe light), installed at strategic locations in the building. Depending on their size and complexity, buildings are generally divided into zones. Zoning can be by the use of either an annunciator panel or a coded audible signal system (McEwen 1984).

Two types of fire alarm systems are used in buildings: single-stage systems and two-stage systems. In a single-stage system, an alarm signal is immediately transmitted throughout the building to warn the occupants about the fire. In a two-stage alarm system, a distinct, generally coded, alert signal first advises the staff of the fire emergency. The staff immediately investigates the source of the alarm and, if a fire exists, activates the alarm signal. If the alert is a false alarm, staff can stop the coded alert signal and reset the system. The alarm signal is automatically set off after a predetermined period (usually five minutes) if the staff have not already activated or reset the alarm.

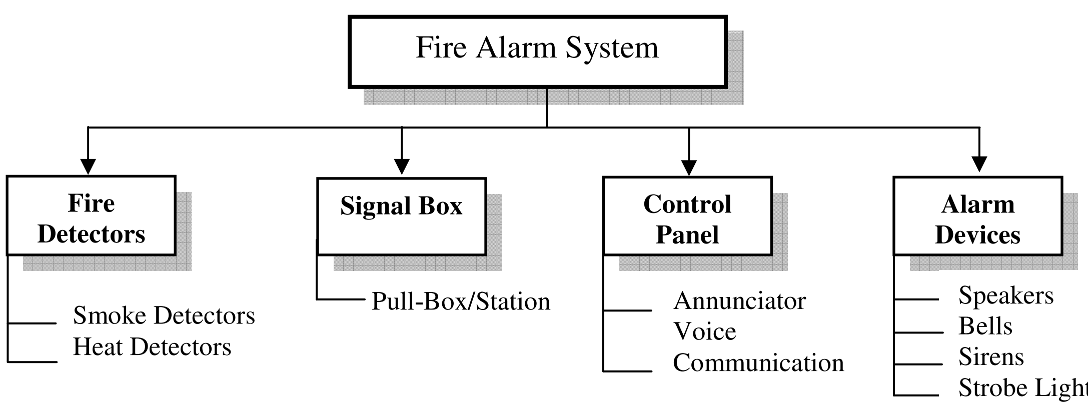


Figure 5.5: A Basic Fire Alarm System

Researchers have proven that serious operational problems result from false alarms caused by incorrect fire signals (Wilton 1994; Chow 1999). For example, New York's Greater Rochester International Airport experienced an unacceptably high frequency of false fire alarms. Dirty smoke detector heads were identified as the major cause of such alarms (Troy 1998 b). Further, Chow (1999) investigated the causes of false alarm in 17 sites in Hong Kong during a two-year period. The causes included detector faults (24.66%), fire services faults (4.61%), human errors such as broken glass (14.9%), construction work (23.85%), cable faults (2.71%), monitor module failures (3.25%), others (2.71%), and unknown (23.31%). Thus renovation work is one of the major causes of false fire alarms. Gases generated from welding can activate smoke detectors. Renovation may cause damage to fire alarm cables and removal of detectors and sprinkler heads. Therefore, special care must be taken during renovation to avoid activating detectors (Chow 1999).

Bryant (1992) examines the requirements for the cables and cable systems used in fire alarm systems. Holt (2006) discusses basic knowledge required for installing wiring and equipment for such systems. The study discusses the fire alarm cable installed beneath a raised floor, fire alarm circuits and their terminal and junction locations, and the power source for a fire alarm circuit.

Researchers have now become aware about of the importance of inspecting the fire safety system, especially in the case of schools. In 1958, a Chicago school fire resulted in the deaths of 92 children and 3 adults (NFPA 1996). The investigations identified a combination of the following causes:

a. The 13 minutes that elapsed between the start of the fire and the alarm being issued;
b. The building's lack of sprinklers, detectors, and stairway smoke vents;
c. The existence of a combustible interior finish;
d. The below-standard condition of the school's fire alarm system; and
e. Poor maintenance.

Following this event, 16,500 schools across the U.S. were thoroughly inspected for fire safety and required major safety improvements that were made within a year of the fire.

The 114 schools in the Austin (Texas) Independent School District (AISD) had experienced numerous problems with their fire alarm systems over the years. A review of the school buildings revealed that in addition to some buildings lacking fire alarm systems, many of the installed systems were not working or did not meet current fire codes (Troy 1998 a). An effort was made to change the way the school district purchased, tested, and maintained their fire alarm systems. The study lists the requirements for an efficient fire alarm system (Figure 5.6).

The Illinois Association of School Boards (1976) suggests that fire alarm systems should be tested every month. Their study describes techniques and procedures for inspecting and testing the heat and smoke detectors, fire panels, and alarm bells.

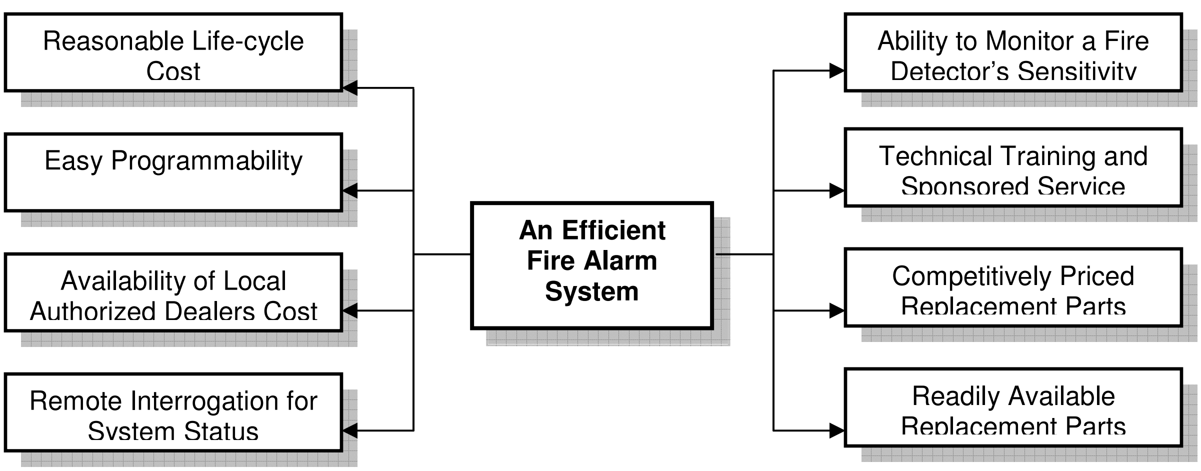


Figure 5.6: Requirements for an Efficient Fire Alarm System

5.3.5 Component 5: Secondary Switchgear

Switchgear controls and protects electrical networks so that the electricity supply can be safely utilized (Blower 1986). The main purpose of secondary switchgear is to accept electrical power from a primary switchboard. The secondary switchgear then distributes the power to points in the network where the voltage is either transformed to a lower value or where it is consumed without transformation, as when supplying to high-voltage machines (Stewart 2004). It consists of circuit breakers, switches, disconnectors (isolators), fuses, and earth switches.

Whensley et al. (1986) have estimated average switchgear operations through a survey of variety of operations over 40 years. The results show that 70% of the operations are carried out for maintenance purposes. The study also reports that the average life of a switchgear is 40 years but that most parts become obsolete at 20 years.

For a switchgear to perform its protective function satisfactorily, the following maintenance activities are defined: (Blower 1986):

a. Inspection includes any maintenance activity involving the scrutiny of an item without dismantling it and detecting items that may cause failure in the future. It may include an operational check.
b. Servicing includes work carried out without dismantling to ensure that the equipment is kept in an acceptable condition. It also includes cleaning, lubrication, and adjustment.
c. Examination involves an inspection with partial dismantling if required, supplemented by means such as measurement and non-destructive tests.
d. Overhaul is the work done with the objective of repairing or replacing parts which are found to be below standard by examination.

One function builds on another. Inspection may lead to the conclusion that servicing is desirable, or if the engineer suspects that all is not well, then an examination may be called for. The result of that examination may then be that an overhaul is required.

Safe operation and the quality of the supply are the most important requirements for switchgear, which can be achieved if all the touchable parts of the switchgear are grounded properly. For safety, Bokshorn et al. (1986) suggest the use of a three-position switch with visible grounding position. Lian (1986) presented a relaying algorithm for high-resistance ground fault protection. In addition, it is suggested that no switchgear operations take place without a system for checking possible consequences. All operations must take place in the presence of a responsible person (Blower 1986), and written rules for safe operation must be followed. Inspection of secondary switchgear is a specialized job that requires an expert. Lewis and Payant (2000) list aspects to be checked during the inspection of switchgear, such as exterior housing and enclosure grounding; interiors of compartments, cubicles, and drawers; and air and oil circuit breakers.

5.4 Deterioration Analysis: The Two-stage Survey

To achieve the objective of understanding the deterioration process of the top building components with respect to defects, symptoms, and their impact on other building components, a two-stage survey to be completed by TDSB personnel was designed. Stage I of the survey aimed at obtaining information about four important concerns related to building components: the effect of a component's condition on the safety and functioning of the school, defects of the components and their weights, the symptoms of critical deficiencies, and the relationships of the components with other components. Stage II of the survey involved collecting, sorting, and rearranging pictures of the components in different condition states. The results of both stages of the survey were then combined to form the basis for developing a visual guidance system for effective condition assessment.

In 2003, the TDSB hired experienced assessors to conduct a large condition assessment survey of about 600 Toronto schools. Individual reports that described the conditions and expected needs of the schools were derived from the survey in the form of condition assessment reports. These TDSB reports formed the basis of this study and hence were analyzed in detail. Since these reports include similar components at various ages (conditions) in different schools, they cover problems that occur throughout the life-cycle of a component. For this study, all reported text descriptions regarding the condition of each component were collected. Two types of information were then extracted from these reports: types of defects and their symptoms, and pictures related to those defects and symptoms. Information related to the types and symptoms of defects helped in the designing of Stage I of the survey, and the pictures were used to prepare Stage II of the survey. The details of both stages of the survey are discussed in the following subsections.

5.4.1 Stage I of the Survey

Based on the data available in the literature and the existing inspection data from the TDSB's large database, the defects for each of the building component were categorized according to their respective subgroups. For example, roof defects were categorized under four major sub-groups: membrane-related problems, drainage-related problems, flashing-related problems, and hardware-related problems. Stage I was a questionnaire that covered aspects of ach component, e.g., the effect of the component's condition on the safety and functioning of the school, component defects and their weights, the symptoms of critical deficiencies, and the relationships of the component with other components. The aim of this stage was to confirm and refine the definition of the defects and symptoms identified in the TDSB reports and the literature review. Stage I of the survey targeted TDSB experts in the field of the five selected components. Samples of Stage I of the survey are provided in Appendix A (1, 2, 3, 4, and 5, for the five components respectively). Each version of survey included four sections, as follows:

a. *The effect of the condition of the component on the school*: This section was aimed at providing an understanding of the level of safety concern, the level of school interruption, and the level of damage to other components when the component is in various conditions (Very Good, Good, Fair, Poor, and Critical). This section also included questions related to the remaining service life of the component in various conditions. The latter questions were intended to provide an indication of the replacement time required at various conditions.

b. *The seriousness of the defects in the component*: This section focused on understanding the relative importance of a component-specific defect. In the case of the first survey related to roofing, the respondents were asked to enter values from 1 to 10 (1 = same importance and 10 = much more important) to provide a measure of relative seriousness of the defect compared to the other roof defects identified. This section of the survey was later changed and refined for the other four components in order to facilitate easy user input. For the remaining four components, the respondents were asked to enter a relative weight (in terms of percentage) for each of the identified defects for the respective components. The user was also given the option of entering an additional unlisted defect for each component based on their experience and knowledge.

c. *Symptoms of defects in the component*: In this section the respondents, indicated the condition of the component based on various symptoms. This information was later used Stage II of the survey, which involved ranking of distress pictures.

d. *The effect of the deterioration of the component on other building components*: In this section, the respondents provided examples of how component failure or damage affects other school components. This information was intended to illustrate the interrelationship of the building components.

5.4.2 Stage II of the Survey

This stage of the survey was aimed at creating a database of pictures of the building components ranked according to the degrees and condition of the defects. To achieve this objective, a preliminary database was first created by extracting pictures from the extensive database of assessment reports and other historical data of the TDSB schools. Under each category of defect from Stage I, symptoms were identified and pictures were found for each symptom. The pictures were then sorted according to four levels of severity; Good, Fair, Poor and Critical. The survey for each of the identified five components was implemented in a simple Excel spreadsheet and sent to group of experts (called focus groups) in the respective fields to confirm the preliminary assigned condition of the picture. Drop-down menus and zoom functions were added to make it easier for the experts to enter their assessments. Provisions also were made for the user to be able to add more or modify the existing text for each picture. Example of Stage II of the roofing survey is shown in Figure 5.7.

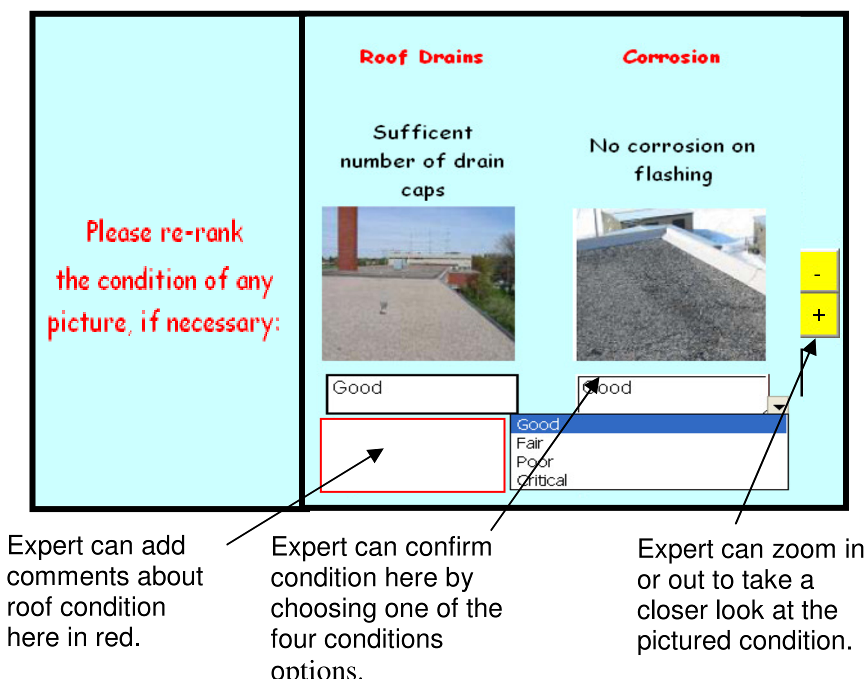


Figure 5.7: Example of Roofing Picture Database for Stage II of the Survey

5.5 Results of the Two-Stage Survey

The results of Stage I of the survey were collected and analyzed in order to obtain a better understanding of the deterioration process of the components. The results were used to produce a preliminary arrangement of the available pictures of the five components at the various levels of severity for use in Stage II of the survey. The results and analysis of Stage I and Stage II of the survey are discussed in the following subsections related to the five components.

5.5.1 Results of the Roofing Survey

Results of Stage I of the Survey: Of 20 Stage I survey related to roofing sent to the TDSB experts, 14 responses were received, the details of which are as follows:

a. *The effect of the condition of the component on the school*:

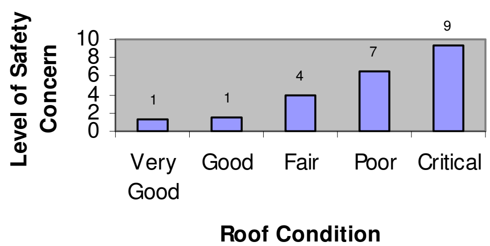
- As shown in Figure 5.8 a, the average score for the impact of a roof in critical condition on safety was 9 (i.e., very high), and the score for poor condition was 7.
- As shown in Figure 5.8 b, the average score for the impact of a roof in critical condition on school interruption was 10 (i.e., the highest), and the score for poor condition was 7.
- As shown in Figure 5.8 c, the average score for the damage to other components caused by a roof in critical condition was 10 (i.e., the highest), and the score for poor condition was 8.
- As shown in Figure 5.8 d, the average service life for a roof in critical condition was recorded as less than a year, with 19 years for one in very good condition.

b. *Seriousness of roof defects*: Experts at TDSB provided pair-wise comparisons for the importance of the following defects: membrane-related defects, drainage-related defects, flashing-related defects, and hardware-related defects. Accordingly, the weights of the defects were calculated using the analytical hierarchy process (Saaty 1980), as follows:

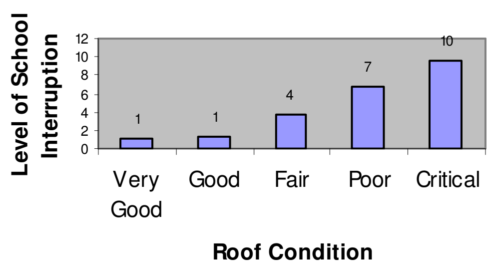
  - Membrane defects (0.5, most critical)
  - Drainage defects (0.25)
  - Flashing defects (0.20)

- Hardware defects (0.05, least critical)

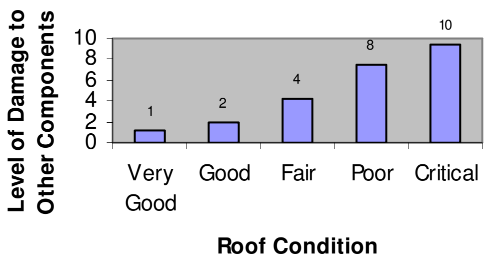
In agreement with Daud's (1992) research, three respondents identified installation defects as another type of roof defect. It was further observed that the format used for section 2 (Appendix A1) in the questionnaire for roofing was confusing for the respondents. Hence, in the questionnaires for other four components, the format for this section was modified to facilitate better understanding. As mentioned earlier, users were asked to input weights directly as percentage for the identified defects.



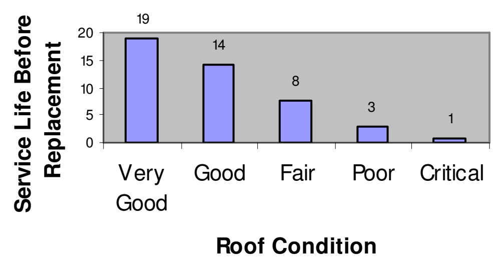
a. Level of safety concern



b. Level of school interruption



c. Level of damage to other components



d. Service life before replacement

Figure 5.8: Effect of the Roof Condition on the School

c. *Symptoms of roof defects*: The survey identified the symptoms related to roof defects and related the existence of the symptoms with one of the four condition states: good, fair, poor, or critical. Table 5.3 shows the symptoms that clearly indicate either a poor or critical condition of the roof. This list provided in the table can be useful for inspection purposes and was used to rank pictures of roofs. Most of the symptoms listed by the respondents coincide with Daud's (1992) study.

Table 5.3: Symptoms of Roof Defects

Symptoms of a Roof in Critical Condition	
1	Lifting up/large openings in flashing
2	Leakage in hardware
3	Missing/inadequate flashing
4	Cracks/broken flashing
5	Blistering in membrane
6	Splits/punctures in membrane
7	Blocked roof drains
Symptoms of a Roof in Poor Condition	
1	Outdated and obsolete hardware
2	Corroded flashing
3	Paint/exterior finish problem in flashing
4	Ridging in membrane
5	Sealant problem in flashing
6	Corroded hardware
7	Debris/vegetation growth in membrane
8	Noisy/vibrating hardware
9	Bleed-through in membrane
10	Eaves trough/downspouts damage
11	Water ponding

d. *The effect of roof leakage on other building components*: Most of the respondents (11) reported that roof leakage would result in a health hazard due to factors such as mould formation. Figure 5.9 shows the effect of roof leakage on other components according to the survey responses.

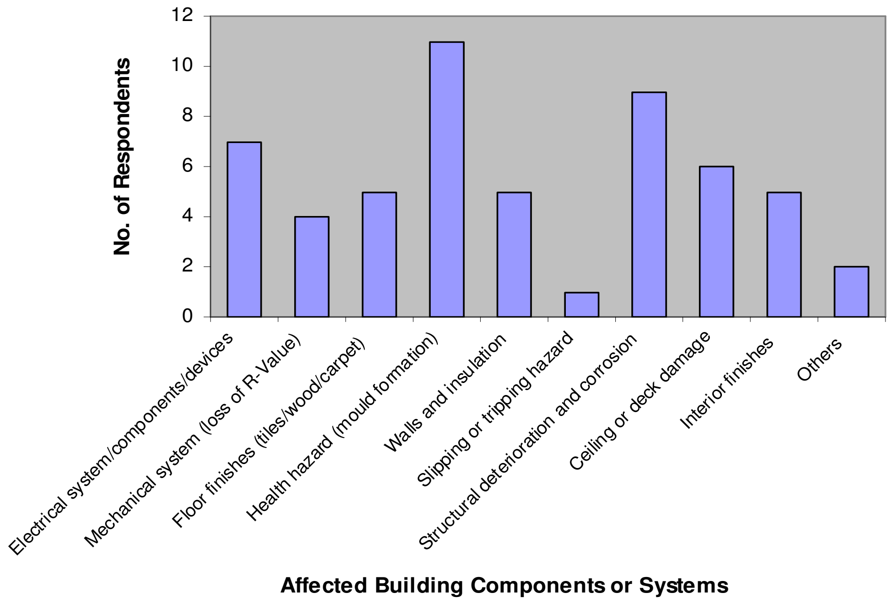


Figure 5.9: Effect of Roof Leakage on Other Building Components

Results of Stage II of the Survey

Stage II of the survey was sent electronically to the TDSB roofing experts (focus group) to confirm or modify the initial condition indicated for each picture. The experts viewed and commented on the pictures by zooming in and then re-assessing the pictures based on their knowledge and experience.

The TDSB experts made interesting observations for many of the pictures. For example, the comments about the picture in Figure 5.10 shows the blockage of roof drain was re-ranked as “fair” rather than “critical.” In the expert’s judgment, the roof needed only minor cleaning of the drain.

In another example pertaining to roof hardware, the comments about the pictures in Figure 5.11 show the expert’s opinion that it is important to assess the condition of the contact point between the hardware and the roof, rather than only the condition of the hardware. Similarly, the experts re-ranked the following flashing-related and membrane-related roof pictures in various conditions (Figure 5.12).

Initial Condition: **Critical**

Reason: Blocked roof drain resulting in water ponding on the roof.

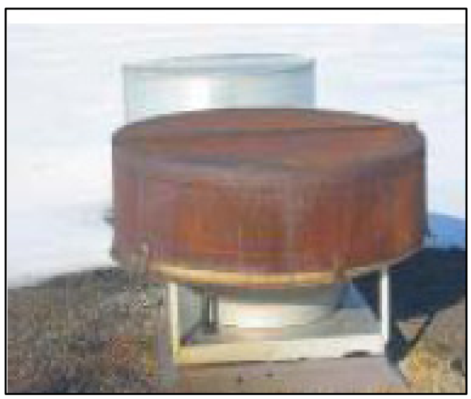
Re-Ranked Condition: **Fair**

Reason: The drain needs to be cleared and the roof condition re-assessed.

Figure 5.10: Survey Response Related to Drainage Defects in Roofing

Initial Condition: **Critical**

Reason: Extensive corrosion and damaged rooftop fans



Re-Ranked Condition: **Poor**

Reason: The rooftop fan is deteriorated but is not affecting the roof.

Initial Condition: **Poor**

Reason: A depression from added packaged boiler room and gas lines.

Re-Ranked Condition: **Critical**

Reason: The condition of the roof is affected by the depression, thereby causing leakage in the roof.

Figure 5.11: Survey Responses Related to Hardware Defects in Roofing

Initial Condition: **Poor**

Re-Ranked Condition: **Critical**

Initial Condition: **Fair**

Re-Ranked Condition: **Poor**

Initial Condition: **Poor**

Re-Ranked Condition: **Critical**

Figure 5.12: Survey Responses Related to Flashing and Membrane Defects in Roofing

The pictorial database was then modified and improved by incorporating the experts' comments and input. Based on the responses to Stage II of the survey, the pictures were rearranged to finally build an accurate database of component defects to support the inspection of roof systems.

5.5.2 Results of the Window Survey

Results of Stage I of the Survey: Of 20 Stage I survey related to window sent to the TDSB experts, 17 responses were received, the details of which are as follows:

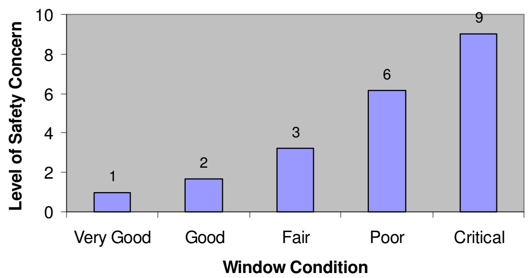
a. *The effect of the condition of the component on the school*:

- As shown in Figure 5.143 a, the average score for the impact of a window in critical condition on safety was 9 (i.e., very high), and the score for poor condition was 6.
- As shown in Figure 5.13 b, the average score for the impact of a window in critical condition on school interruption was 8, and the score for poor condition was 6.
- As shown in Figure 5.13 c, the average score for the damage to other components caused by a window in critical condition was 10 (i.e., the highest), and the score for poor condition was 7.
- As shown in Figure 5.13 d, the average service life for a window in critical condition was recorded as less than a year, with 21 years for one in very good condition.

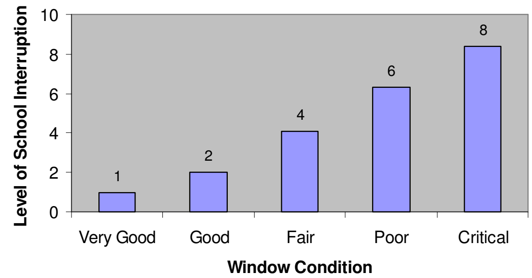
b. *Seriousness of window defects*: Experts at TDSB compared the importance of the following defects: hardware-related defects, glazing-related defects, frame-related defects, and aesthetics-related defects. For the four identified defects, the survey indicated the following results:

- Hardware defects (34%, most critical)
- Glazing defects (30%)
- Frame defects (22%)
- Aesthetics defects (11%, least critical)

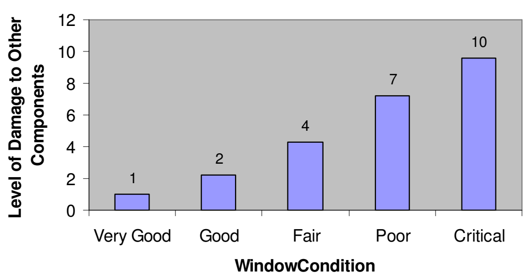
Two respondents identified installation defects and one respondent identified the design, size, and location of the opening as problems related to windows.



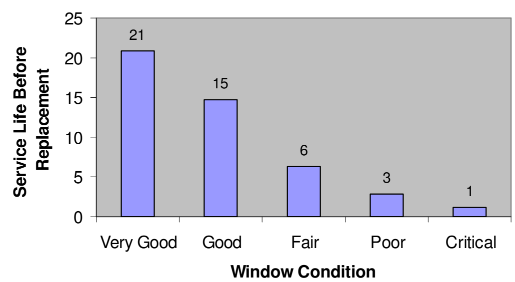
a. Level of safety concern



b. Level of school interruption



c. Level of damage to other components



d. Service life before replacement

Figure 5.13: Effect of the Window Condition on the School

c. *Symptoms of window defects*: The survey identified the symptoms related to window defects and related the existence of the symptoms with one of the four condition states: good, fair, poor, or critical. Table 5.4 shows the symptoms that clearly indicate either a poor or critical condition of the window. This list provided in the table can be useful for inspection purposes and was used to rank pictures of windows.

Table 5.4: Symptoms of Window Defects

Symptoms of a Window in Critical Condition	
1	Rust/rot in frame (pitting)
2	Deficient sealant in the glazing
3	Cracked/missing caulking along glazing
Symptoms of a Window in Poor Condition	
1	Broken hardware
2	Loose masonry components or sills
3	Water damaged window frames
4	Gaps in the frame
5	Sealed glazing unit failure
6	Seized frame components
7	Inoperable hardware
8	Windows with condensation in the glass
9	Aged or worn-out window frames
10	Heavily stained glazing

d. *The effect of window deterioration on other building components*: Most of the respondents (12) reported that window deterioration would affect the HVAC system. Figure 5.14 shows the effect of window deterioration on other components according to the survey responses.

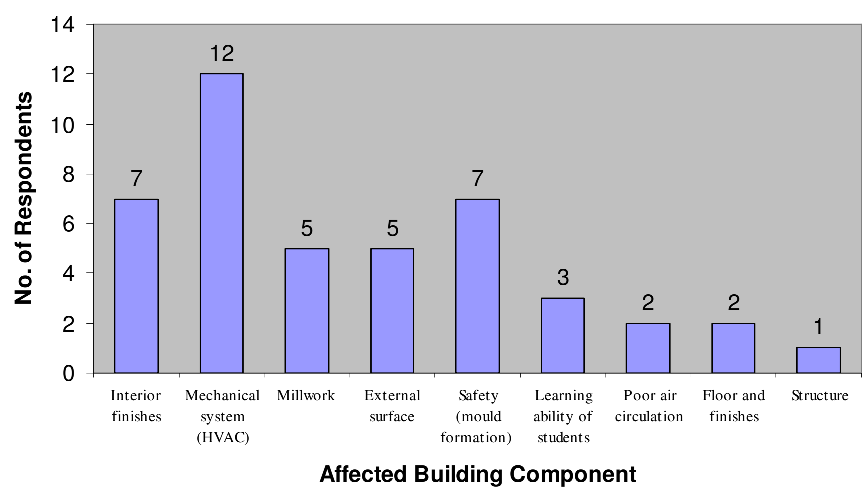


Figure 5.14: Effect of Window Deterioration on Other Building Components

Results of Stage II of the Survey

Stage II of the survey was sent electronically to the TDSB window experts (focus group) to confirm or modify the initial condition indicated for each picture. The experts viewed and commented on the pictures by zooming in and then reassessing the pictures based on their knowledge and experience. The experts added useful text for some of the pictures related to the glazing defect as shown in Figure 5.15.

<u>Initial text</u>

Reason: Laminated glass fibre on broken panel

<u>Modified text</u>

Reason: The laminated glass fibre causes possible water infiltration and problems with mould.

<u>Initial text</u>

Reason: Cracked glass

<u>Modified text</u>

Reason: The cracked glass is dangerous (safety hazard) and causes heat loss.

Figure 5.15: Survey Responses Related to Defects in Window Glazing

The pictorial database was then modified and improved by incorporating the experts' comments and input. Based on the responses to Stage II of the survey, the pictures were rearranged to finally build an accurate database of component defects to support the inspection of windows.

5.5.3 Results of the Boiler Survey

Results of Stage I of the Survey: Of 20 Stage I survey related to boiler sent to the TDSB experts, 16 responses were received, the details of which are as follows:

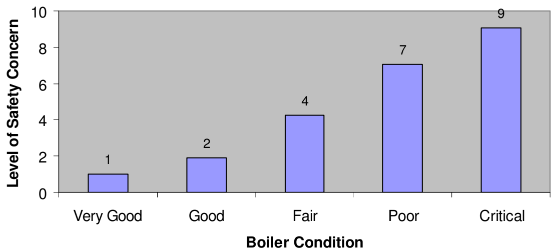
a. *The effect of the condition of the component on the school*:

- As shown in Figure 5.16 a, the average score for the impact of a boiler in critical condition on safety was 9 (i.e., very high), and the score for poor condition was 7.
- As shown in Figure 5.16 b, the average score for the impact of a boiler in critical condition on school interruption was 10 (i.e., the highest), and the score for poor condition was 8.
- As shown in Figure 5.16 c, the average score for the damage to other components caused by a boiler in critical condition was 9 (i.e., very high), and the score for poor condition was 7.
- As shown in Figure 5.16 d, the average service life for a boiler in critical condition was recorded as less than a year, with 21 years for one in very good condition.

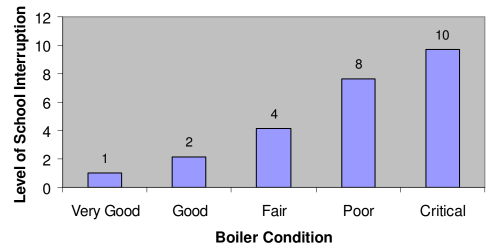
b. *Seriousness of boiler defects*: Experts at TDSB compared the importance of the following defects: operational defects, housing defects, and breaching/stacking defects. For the three identified defects, the survey indicated the following results:

- Operational defects (49%, most critical)
- Housing defects (28%)
- Breaching/Stacking defects (23%)

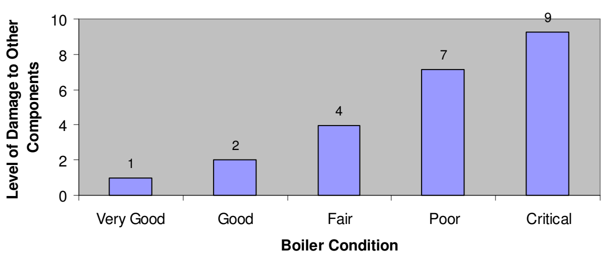
Three respondents identified installation defects as a problem related to boilers.



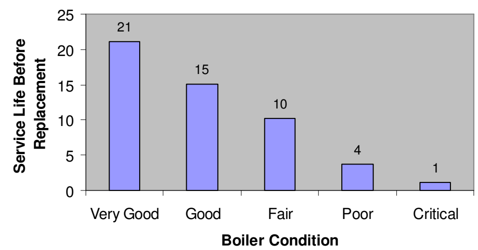
a. Level of safety concern



b. Level of school interruption



c. Level of damage to other components



d. Service life before replacement

Figure 5.16: Effect of the Boiler Condition on the School

c. *Symptoms of boiler defects*: The survey identified the symptoms related to boiler defects and related the existence of the symptoms with one of the four condition states: good, fair, poor, or critical. Table 5.5 shows the symptoms that clearly indicate either a poor or critical condition of the boiler. This list provided in the table can be useful for inspection purposes and was used to rank pictures of boilers.

d. *The effect of boiler deterioration on other building components*: Most of the respondents (6) reported that boiler problems would result in thermal discomfort for the occupants. Figure 5.17 shows the effect of boiler problems on other components according to the survey responses.

Table 5.5: Symptoms of Boiler Defects

Symptoms of a Boiler in Critical Condition	
1	Blockage in the stack
2	Inoperable boiler
3	Damaged or broken stack/breaching
4	Cracked or broken boiler casing
5	Corroded stacking/breaching
6	Leakage or flooding around the casing/housing
7	Operational tube damage or blockage
Symptoms of Boiler in Poor Condition	
1	Inoperative valve
2	Damaged boiler controls
3	Deteriorated burner condition
4	Refractory damage
5	Outdated fuel supply
6	Water stain marks on the chimney
7	White salt marks on the chimney

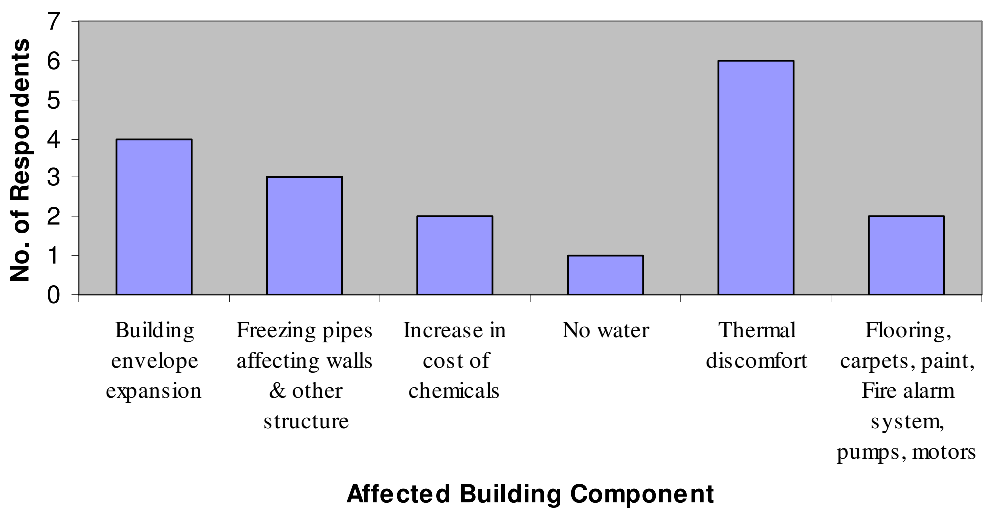


Figure 5.17: Effect of the Boiler Deterioration on Other Building Components

Results of Stage II of the Survey

Stage II of the survey was sent electronically to the TDSB boiler experts (focus group) to confirm or modify the initial condition indicated for each picture. The experts viewed and commented on the pictures by zooming in and then reassessing the pictures based on their knowledge and experience.

The TDSB experts made interesting observations for many of the pictures, such as, the comments related to the housing defect shown in the picture in Figure 5.18. In addition, the experts modified the text for some of the pictures related to the stacking/breaching-related defects as shown in Figure 5.19.

Initial Condition: **Poor**

Reason: Damaged insulation of the boiler housing.

Re-Ranked Condition: **Fair**

Reason: The insulation is damaged due to only gasket leak.

Figure 5.18: Survey Response Related to Defects in the Boiler Housing

The pictorial database was then modified and improved by incorporating the experts' comments and input. Based on the responses to Stage II of the survey, the pictures were rearranged to finally build an accurate database of component defects to support the inspection of boilers.

Initial Condition: **Poor**

Reason: Rusted boiler stack.

Re-Ranked Condition: **Critical**

Reason: Flue gases are possibly leaking from the damaged stack.

Initial Condition: **Critical**

Reason: Severely deteriorated stack/breaching.

Re-Ranked Condition: **Poor**

Reason: The rust is only on the surface of the breaching.

Figure 5.19: Survey Responses Related to Defects in the Stacking/Breaching of the Boiler

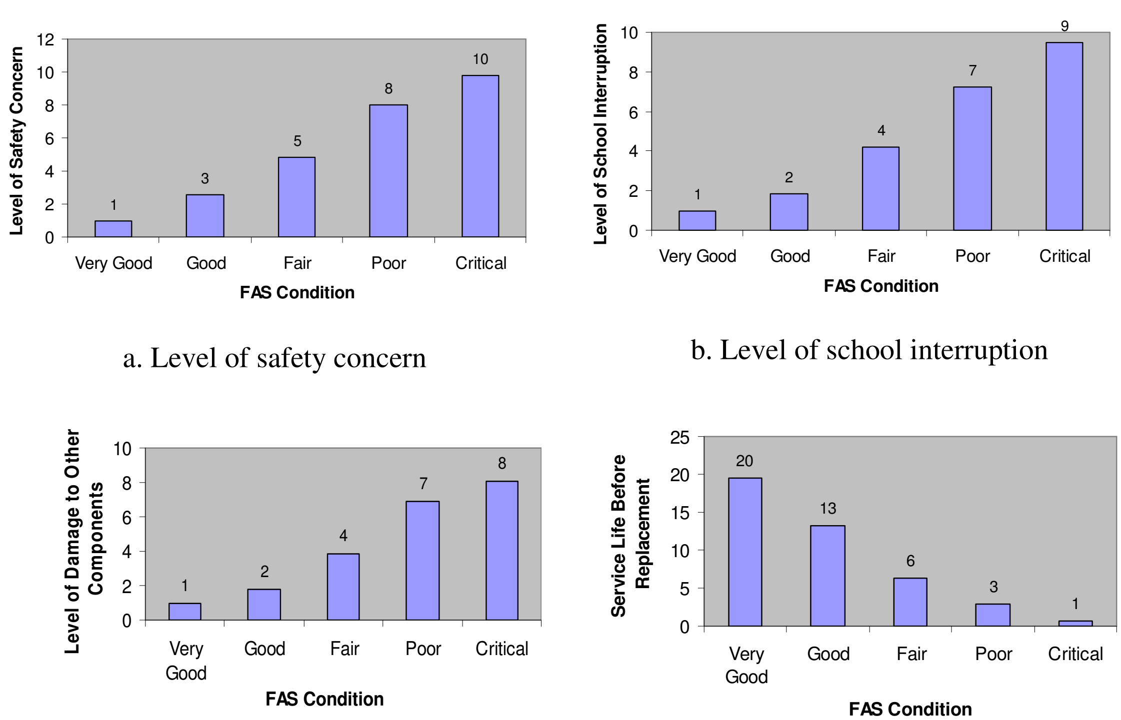
5.5.4 Results of the Fire Alarm System (FAS) Survey

Results of Stage I of the Survey: Of 20 Stage I survey related to fire alarm system sent to the TDSB experts, 15 responses were received, the details of which are as follows:

a. *The effect of the condition of the component on the school*:

- As shown in Figure 5.20 a, the average score for the impact of a fire alarm system in critical condition on safety was 10 (i.e., the highest), and the score for poor condition was 8.

- As shown in Figure 5.20 b, the average score for the impact of a fire alarm system in critical condition on school interruption was 9 (i.e., very high), and the score for poor condition was 7.
- As shown in Figure 5.20 c, the average score for the damage to other components caused by a fire alarm system in critical condition was 8, and the score for poor condition was 7.
- As shown in Figure 5.20 d, the average service life for a fire alarm system in critical condition was recorded as less than a year, with 20 years for one in very good condition.



a. Level of safety concern

b. Level of school interruption

c. Level of damage to other components

d. Service life before replacement

Figure 5.20: Effect of the FAS Condition on the School

b. *Seriousness of fire alarm system defects*: Experts at TDSB compared the importance of the following defects: panel defects, field units' defects, and alarm devices defects. For the three identified defects, the survey indicated the following results:

- Panel defects (46%, most critical)
- Field units (detectors and pull stations) defects (40%)
- Alarm devices defects (13%, least critical)

One respondent identified improper repairs and additions and another respondent identified non code compliance as problems related to the fire alarm system.

c. *Symptoms of fire alarm system defects*: The survey identified the symptoms related to fire alarm system defects and related the existence of the symptoms with one of the four condition states: good, fair, poor, or critical. Figure 5.6 shows the symptoms that clearly indicate either a poor or critical condition of the fire alarm system. This list provided in the table can be useful for inspection purposes and was used to rank pictures of fire alarm systems.

Table 5.6: Symptoms of Fire Alarm System Defects

	Symptoms of a FAS in Critical Condition
1	Obsolete heat or smoke detectors
2	Non-functional or improper working of pull-out stations
	Symptoms of a FAS in Poor Condition
1	Old and outdated fire panel
2	Low audibility levels of alarm devices e.g., horn bells
3	Poor condition of wire insulation in field devices
4	Inadequate alarm devices, e.g., fire bells

d. *The effect of roof leakage on other building components*: Most of the respondents (4) reported that fire alarm system problems would affect the HVAC system. Figure 5.21 shows the effect of fire alarm system problems on other components according to the survey responses.

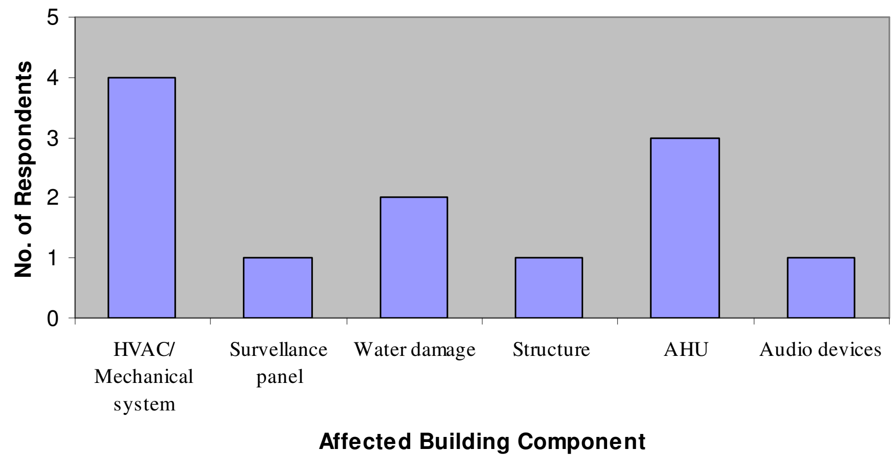


Figure 5.21: Effect of Deterioration of the FAS on Other Building Components

Results of Stage II of the Survey

Stage II of the survey was sent electronically to the TDSB electrical system experts (focus group) to confirm or modify the initial condition indicated for each picture. The experts viewed and commented on the pictures by zooming in and then reassessing the pictures based on their knowledge and experience.

The TDSB experts re-ranked the picture related to the defects in the fire alarm devices, as shown in Figure 5.22. They also made interesting observations for many of the pictures, such as, the comments about the defects related to the fire alarm panel and fire detector shown in the picture in Figure 5.23.

The pictorial database was then modified and improved by incorporating the experts' comments and input. Based on the responses to Stage II of the survey, the pictures were rearranged to finally build an accurate database of component defects to support the inspection of fire alarm system systems.

Initial Condition: **Poor**

Reason: Horn low audibility levels.

Re-Ranked Condition: **Critical**

Reason: The main function of the bell is its audibility (to make people aware) or else it is useless.

Figure 5.22: Survey Response Related to Defects in the Fire Alarm Devices in the FAS

Initial text

Reason: Clear labeling of all field devices.

Modified text

Reason: Clear labeling ensures lower maintenance costs and cut down on overtime callouts

Initial text

Reason: Functional but obsolete heat/smoke detector.

Modified text

Reason: The detector is functional; however it needs to be replaced after every 10 years of service.

Figure 5.23: Survey Responses Related to Defects in the Panel and Fire Detector in the FAS

5.5.5 Results of the Secondary Switchgear Survey

Results of Stage I of the Survey: Of 20 Stage I survey related to roofing sent to the TDSB experts, 14 responses were received, the details of which are as follows:

a. *The effect of the condition of the component on the school*:

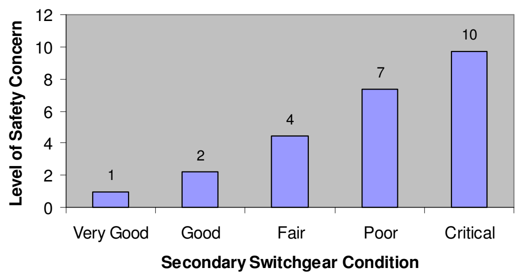
- As shown in Figure 5.24 a, the average score for the impact of a secondary switchgear in critical condition on safety was 10 (i.e., the highest), and the score for poor condition was 7.
- As shown in Figure 5.24 b, the average score for the impact of a secondary switchgear in critical condition on school interruption was 9 (i.e., very high), and the score for poor condition was 7.
- As shown in Figure 5.24 c, the average score for the damage to other components caused by a secondary switchgear in critical condition was 9 (i.e., very high), and the score for poor condition was 7.
- As shown in Figure 5.24 d, the average service life for secondary switchgear in critical condition was recorded as less than a year, with 25 years for one in very good condition (in agreement with Whensley et al. (1986) research).

b. *Seriousness of secondary switchgear defects*: Experts at TDSB compared the importance of the following defects: connection defects, capacity/operational defects, and panel defects. Of the three identified defects, the survey indicated the following results:

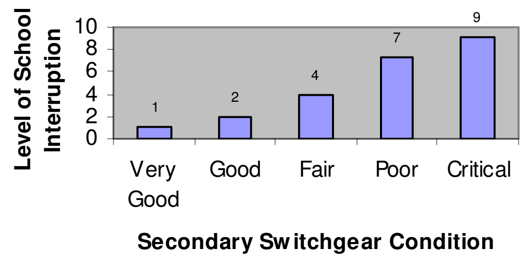
- Connection defects (49%, most critical)
- Capacity/operational defects (42%)
- Panel defects (9%)

Three respondents identified obsolete parts and unavailability of parts as problems related to the secondary switchgear.

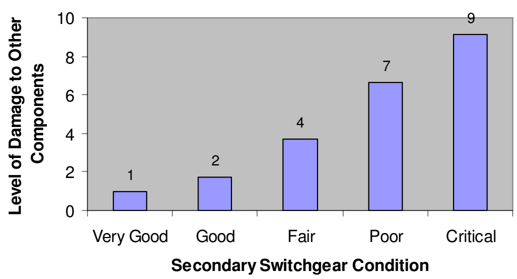
c. *Symptoms of secondary switchgear defects*: The survey identified the symptoms related to secondary switchgear defects and related the existence of the symptoms with one of the four condition states: good, fair, poor, or critical. Table 5. 7 shows the symptoms that clearly indicate either a poor or critical condition of the secondary switchgear. This list provided in the table can be useful for inspection purposes and was used to rank pictures of secondary switchgears.



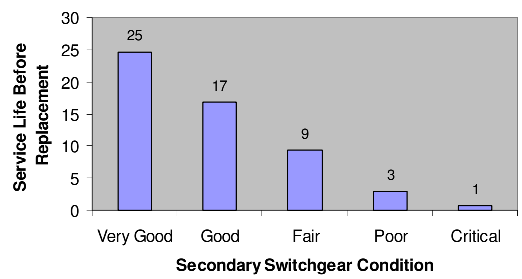
a. Level of safety concern



b. Level of school interruption



c. Level of damage to other components



d. Service life before replacement

Figure 5.24: Effect of the Secondary Switchgear Condition on the School

d. *The effect of secondary switchgear problems on other building components*: Most of the respondents (8) reported that secondary switchgear problems would result in overloads and hence accidents. Figure 5.25 shows the effect of secondary switchgear problems on other components according to the survey responses.

Table 5.7: Symptoms of Secondary Switchgear Defects

Symptoms of a Secondary Switchgear in Critical Condition	
1	Corroded connection mains
2	Inadequate capacity of the main breaker
3	Overloaded panel
4	Unsafe connection wiring
5	Defective main switch
6	Deteriorated disconnect switches
Symptoms of a Secondary Switchgear in Poor Condition	
1	Loose connections due to vibrations
2	Poor, deteriorated or inadequate wiring used for connections
3	Insufficient fuse or breaker interruption capacity
4	Outdated or worn-out breaker panel
5	Rust or corrosion on the main panel
6	Damage of the panel due to nearby activity, water or rodents
7	Discontinued replacement parts of the panel
8	Size of the panel and associated connections too small for new code compliance
9	Unprotected metre cabinet on the panel

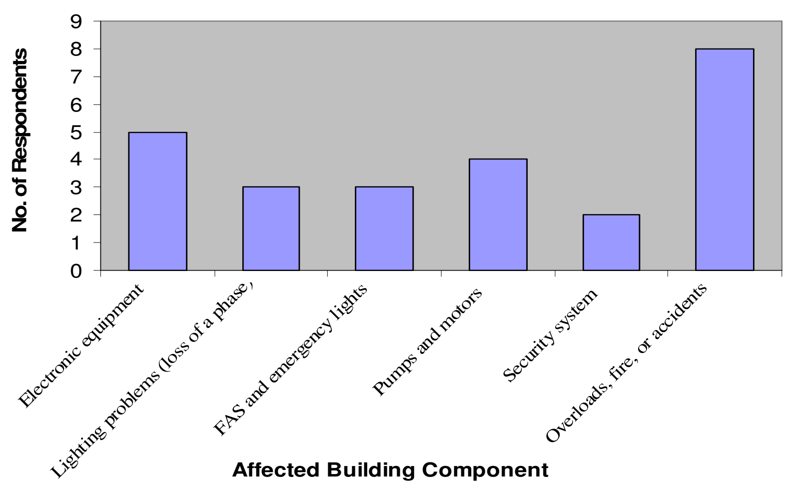


Figure 5.25: Effect of the Secondary Switchgear Deterioration on Other Building Components

Results of Stage II of the Survey

Stage II of the survey was sent electronically to the TDSB electrical experts (focus group) to confirm or modify the initial condition indicated for each picture. The experts viewed and commented on the pictures by zooming in and then reassessing the pictures based on their knowledge and experience. The TDSB experts re-ranked the picture in Figure 5.26 and made useful modifications to the text for some pictures, as shown in Figure 5.27.

Initial Condition: **Poor**

Reason: Loose connections due to vibrations.

Re-Ranked Condition: **Critical**

Reason: Loose connections pose a safety hazard due to the high voltage involved.

Figure 5.26: Survey Response Related to Defects in the Secondary Switchgear Connections

Initial text

Reason: Spare capacity available.

Modified text

Reason: extra capacity is good only if there is enough wall space to add other devices.

Figure 5.27: Survey Response Related to Defects in the Secondary Switchgear Panels

The pictorial database was then modified and improved by incorporating the experts' comments and input. Based on the responses to Stage II of the survey, the pictures were rearranged to finally build an accurate database of component defects to support the inspection of secondary switchgear systems.

5.6 Visual Guidance

The results of Stage II of the survey paved the way for the development of a pictorial database of building components. In addition to pictures, the database also contains important comments about each component in various conditions. This pictorial database is to be used as a guide by condition assessors for accurately assessing of the condition of a component. The pictorial guidance system will help support visual inspection and critical asset management decisions. It will also help make the inspection process less time-consuming, more economical, and less-subjective. Sample examples from the pictorial database for the five identified building components are provided in Appendix B (1, 2, 3, 4, and 5).

5.7 Conclusions

This chapter described the following steps in the development of the visual guidance system:

- The top building components were identified.
- Published information helped to provide an understanding of building component defects and their associated symptoms. It also aided in the design of the survey.
- The results of stages I and II of the survey paved the way for the development of a pictorial database of building components, which will make the condition assessment process less-subjective.

Chapter 6
Prototype Implementation and Testing

6.1 Introduction

The previous two chapters introduced and discussed the two components of the proposed condition assessment framework: condition prediction and inspection planning, and the visual guidance system. These components form the basis of a comprehensive framework for efficient condition assessment suitable for building infrastructure. This chapter presents the third component: the location-based inspection process with a standardized building hierarchy. It also describes the development of the proposed prototype system. Features of the prototype are presented, and an example from the Toronto District School Board is used as a case study to validate the prototype and demonstrate its usefulness.

6.2 The Proposed Prototype: A Framework for Building Condition Assessment

The purpose of developing the proposed prototype is to produce an easy-to-use automated condition inspection and assessment system that has the following features:

a. A standard asset hierarchy of building systems, components, and instances;

b. A simple user interface that uses colour coding to mark the location of Good, Fair, Poor, and Critical items directly on digital floor plans;

c. Suitable implementation on hand-held Ultra-Mobile Personal Computers (UMPC) to facilitate mobility and fast inspection;

d. Programming of a built-in digital camera that can effortlessly take and store pictures of inspected items in a location-based database; and

e. A built-in pictorial database of components in different conditions that will serve as a visual guidance during inspection and will reduce subjectivity.

The goal of the proposed developments of each feature aim is to overcome the drawbacks identified in Chapter 3. The prototype system is then described and the results of its application in five TDSB schools are presented.

A discussion of the findings of the field visits (Chapter 3) and the results of the survey (Chapter 5) with TDSB personnel led to the setting of a detailed scope for developing a condition assessment system (proposed prototype) that supports replacement-based decisions by incorporating two major components: Condition Assessment (uses location-based inspection with a standardized hierarchy and the visual guidance system) and Inspection Scheduling (based on condition prediction) as shown in Figure 6.1.

In addition to the creation of a detailed inventory of all TDSB buildings, the proposed prototype introduces improvements in two ways: (1) visual, standardized, fast, and less-subjective inspection; and (2) condition prediction based on the reactive-maintenance history and thus prioritizing inspection tasks among available resources. The details of each component of the prototype are discussed in the following paragraphs:

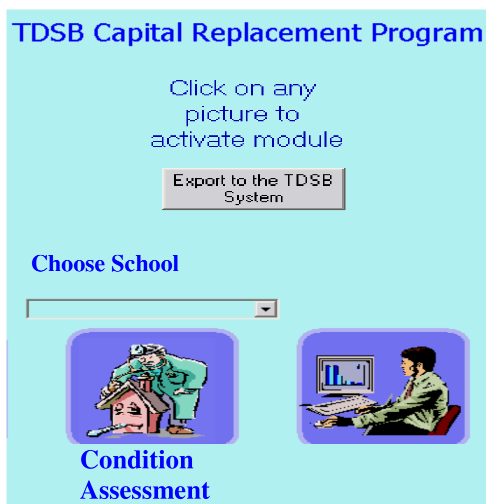


Figure 6.1: Components of Replacement-Based Condition Assessment System

The first step in the development of the prototype was to standardize the building asset hierarchy and to structure the inspection data. For the TDSB, a typical building asset hierarchy was saved into a database with a predefined list of systems (e.g., architectural), subsystems (e.g., interior structures), components (e.g., windows), and subcomponents if applicable (e.g., aluminum windows). This standard hierarchy has a total of 180 subcomponents for each building. Each item in the hierarchy is then assigned a set of four instances (for Good, Fair, Poor, and Critical conditions), as shown in Figure 6.2. Thus, the structure of the inspection data for any school includes a fixed set of records associated with a total number of instances that can be inspected (180 x 4 = 720). During inspection, the user can easily fill in the inspection data for any instance. This standardization facilitates automation; storage and retrieval; reporting; and comparisons of information among schools, years, and families of schools, etc.

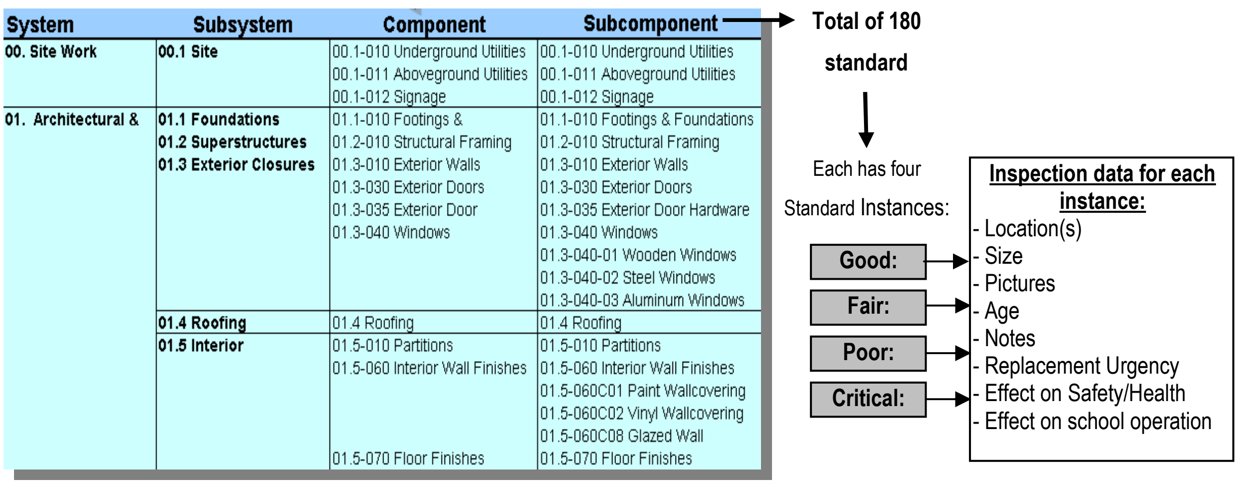


Figure 6.2: Standardized Building Hierarchy and Inspection Data Structure

Based on the standardized hierarchy, a prototype inspection system was developed using the Visual Basic programming language and was then deployed on an Ultra Mobile Personal Computer (UMPC) which has a touch-screen interface and a built-in digital camera that is programmed by the system (Figure 6.3). The main user-interface shows, in the background, the digital plan associated with the component being inspected. Once the user selects a component for inspection (e.g., roofing, as shown in Figure 6.4), a simple data entry form appears that allows access to the four instances (Good, Fair, Poor, Critical) of that component. The background floor plan also retrieves and shows, using colour coding, the locations of the

Critical, Poor, Fair, and Good instances. Selecting one of the condition instances on the form (Critical is shown in Figure 6.5), the user is prompted to enter inspection data for that instance (Table 6.1).

Figure 6.3: Prototype Inspection System Implemented on an Ultra-Mobile PC

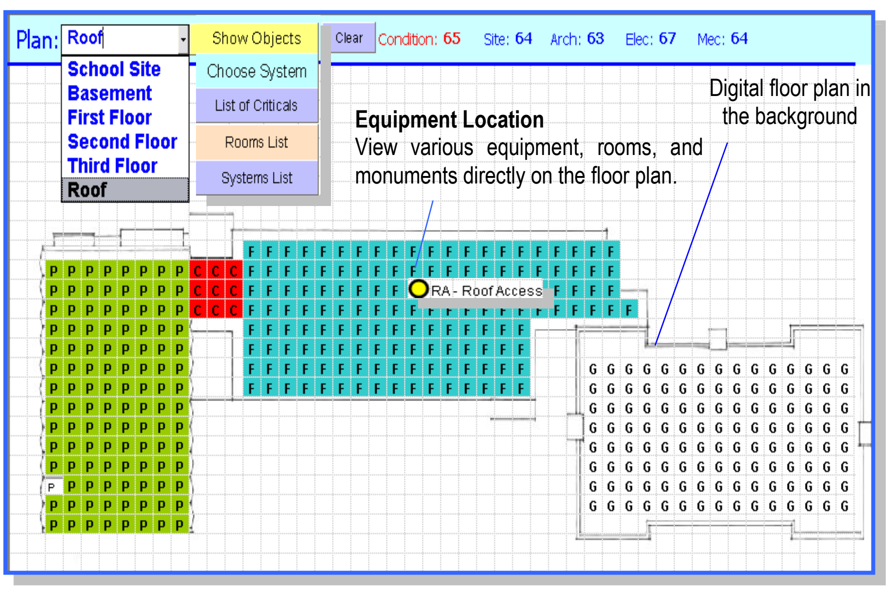


Figure 6.4: The Main User Interface in the Background Showing the Digital Plan

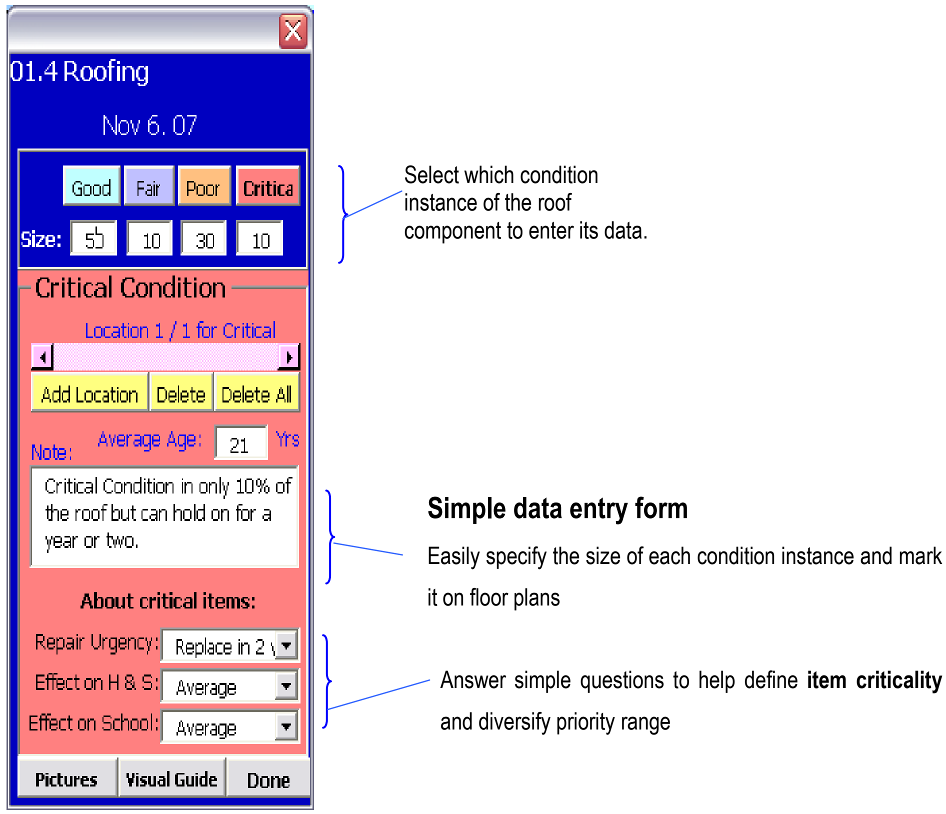


Figure 6.5: Inspection Data Entry Form

Table 6.1: Inspection Data for an Instance (e.g., Critical) of a Component (e.g., Roofing)

Data	Description
Location(s)	The user selects the cells on the floor plan, which are colour coded to indicate condition.
Size	The relative sizes (%) of the four condition instances (Good, Fair, Poor, and Critical) are shown.
Pictures	Taken pictures are coded automatically and saved in the inspection database.
Age	This field is calculated, but the user can override the value shown and enter new information.
Notes	Additional text comments can be added.
Replacement Urgency	The options are: Replace immediately (10), Replace in 1 year (8), Replace in 2 years (6), Replace in 5 years (4), or Not urgent (2).
Effect on Safety/Health	The options are: Very High (10), High (8), Average (6), Low (4), and Very low (2).
Effect on Operation	The options are: Very High (10), High (8), Average (6), Low (4), and Very low (2).

The data in Table 6.1 that is called “Sizes” represents the relative extent of the Good, Fair, Poor, and Critical instances and can be used to evaluate the overall Condition Index (CI) for the component, calculated as follows:

$$CI = \frac{\sum_{i=1}^{4}(CS_i \cdot Size_i)}{\sum_{i=1}^{4} Size_i} \qquad (6.1)$$

Where CS_i is the scale value of each instance (i) (Good = 100, Fair = 75, Poor = 50, and Critical = 25) and Size is the relative size (percentage or number of items) of the each condition instance as entered by the user during inspection.

It should be noted that the user does not enter the data for all the 720 instances in a building. The system’s default information is that all components are assigned 100% to their “Good” instances. As components deteriorate, the inspectors can then enter information for the other instances, such as “Poor” or “Critical.” It is also noted that the last three data items in the inspection form (Table 6.1) are important for providing a high level of resolution in order to diversify and differentiate among critical components, which will facilitate better decisions with respect to the allocation of funds.

The proposed inspection system also includes a visual guidance system (Figure 6.6) for five components (roof, windows, boiler, fire alarm, and secondary switchgear), which has a database of pictures of these components in various conditions. Using this tool during inspection minimizes subjectivity and, in combination with the other features of the system, makes the inspection process faster and less expensive, and eliminates the need for additional work in the office. The tool is also suitable for less-experienced personnel.

The condition prediction mechanism of the proposed system is fully automated using the Visual Basic programming language. To schedule inspection tasks, the user enters the number of available in-house inspection personnel (Figure 6.7), and the system assigns their daily inspection tasks (Figure 6.8). It is suggested that this process be used once a year, when all the maintenance data from the previous year is collected and used to schedule all the inspection tasks for the next year. Thus, one of the key benefits of this proposed condition prediction process is that it provides the ability to perform analysis on a yearly basis, without dependence on statistical deterioration models, which need to be developed for each component using a great deal of data, which can be costly and time-consuming.

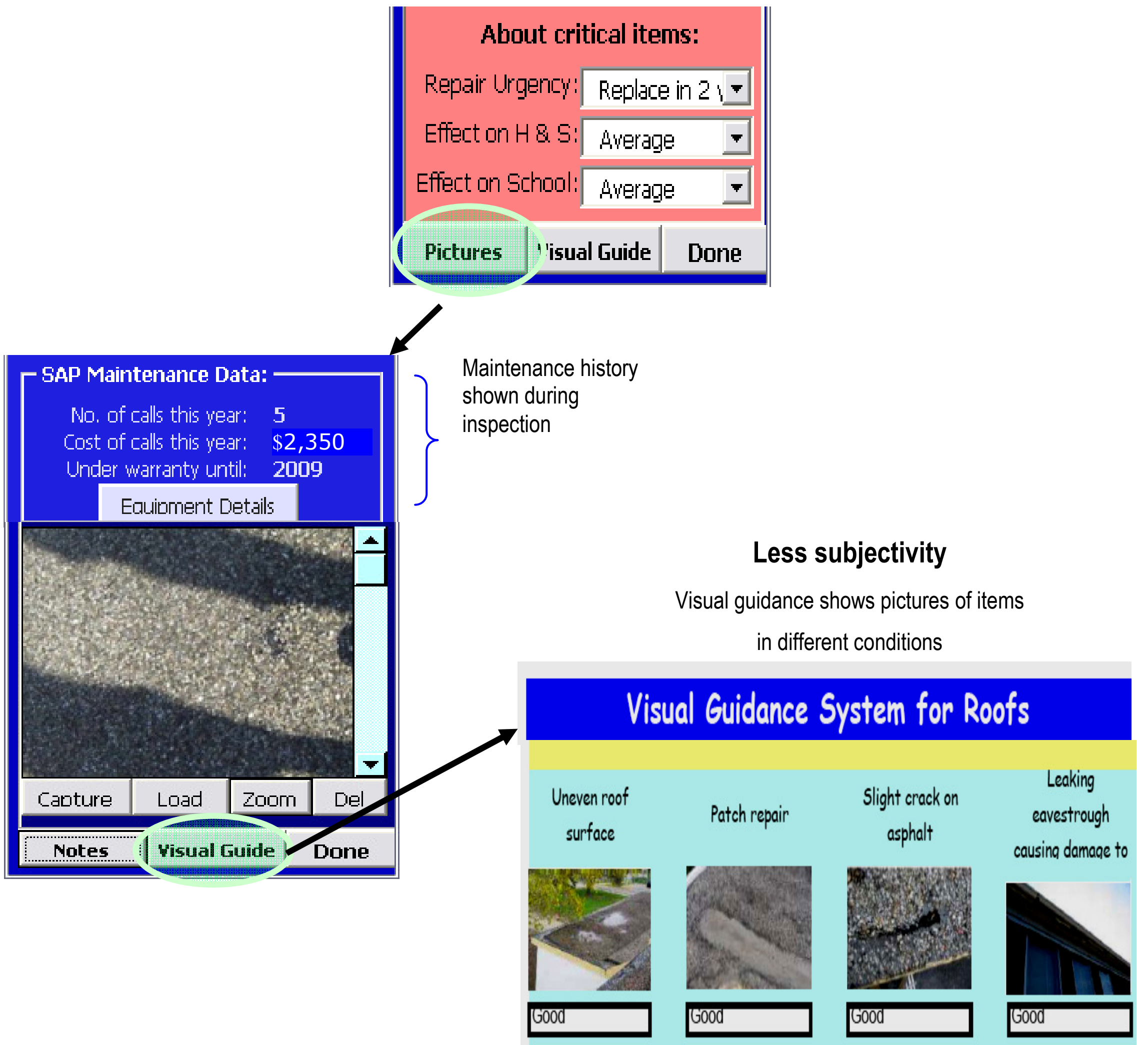


Figure 6.6: Example of the Visual Guidance System

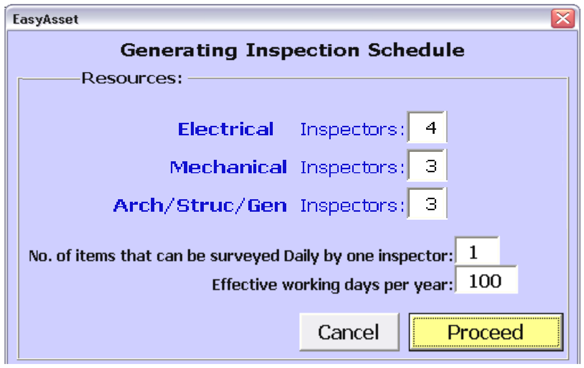


Figure 6.7: User Entry of Available Inspection Personnel

Re-Generate Inspection Schedule

Main Menu

No	Day	Family	School Name	Asset Code	Item	System	Priority	Resource Type	Resour
1	1	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-035 Exterior Door Ha	Hardware and Locks -	EXTSTRUC	75	Arch./Struct	1 / 3
2	1	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-070C07 Hardwood	Flooring - Wood	INTSTRUC	75	Arch./Struct	2 / 3
3	1	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-055 Interior Door Har	Hardware and Locks -	INTSTRUC	75	Arch./Struct	3 / 3
4	2	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-020 Millwork	Millwork / Cabinetry	INTSTRUC	75	Arch./Struct	1 / 3
5	2	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-110 Interior Stairs	Ladder - Affixed	INTSTRUC	75	Arch./Struct	2 / 3
6	2	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-035 Exterior Door Ha	Fixtures	POOLS	75	Arch./Struct	3 / 3
7	3	NE1	Lester B Pearson Cl-Dr Marion Hilliard	00.1-016 Soft Landscapin	Lawns	SITEWORK	75	Arch./Struct	1 / 3
8	3	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-110 Interior Stairs	Railings	INTSTRUC	63	Arch./Struct	2 / 3
9	3	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-100 Washroom Acce	Toilets	PLUMBING	63	Arch./Struct	3 / 3
10	4	NE1	Lester B Pearson Cl-Dr Marion Hilliard	06.7 Portable	LOCKS / HARDWARE	PORTABLE	63	Arch./Struct	1 / 3
11	4	NE1	Lester B Pearson Cl-Dr Marion Hilliard	06.2 Single Gymnasium	Gym Equipment	SCHEQMT	63	Arch./Struct	2 / 3
12	4	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-040 Windows	Exterior - Building	GLAZING	58	Arch./Struct	3 / 3
13	5	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-040 Windows	Frames - Door and W	INTSTRUC	58	Arch./Struct	1 / 3
14	5	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-040-02 Steel Window	Frames - Door and W	INTSTRUC	58	Arch./Struct	2 / 3
15	5	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-030 Exterior Doors	Doors - sStandard Me	INTSTRUC	55	Arch./Struct	3 / 3
16	6	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.6 Fittings & Equipmen	Morality Lights	EXTSTRUC	55	Arch./Struct	1 / 3
17	6	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.6 Fittings & Equipmen	Ladders - Affixed	EXTSTRUC	55	Arch./Struct	2 / 3
18	6	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.6 Fittings & Equipmen	Computer / Peripheral	SCHEQMT	55	Arch./Struct	3 / 3
19	7	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.6 Fittings & Equipmen	Classroom Equipment	SCHEQMT	55	Arch./Struct	1 / 3
20	7	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-035 Exterior Door Ha	Fixtures	EXTSTRUC	50	Arch./Struct	2 / 3
21	7	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-110 Interior Stairs	Railings	EXTSTRUC	50	Arch./Struct	3 / 3
22	8	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-050 Interior Doors	Doors - Standard Woo	EXTSTRUC	50	Arch./Struct	1 / 3
23	8	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-090 Window Coverin	Interior - Building	GLAZING	50	Arch./Struct	2 / 3
24	8	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.3-035 Exterior Door Ha	Fixtures	INTSTRUC	50	Arch./Struct	3 / 3
25	9	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-070 Floor Finishes	Flooring - Other	INTSTRUC	50	Arch./Struct	1 / 3
26	9	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-070 Floor Finishes	Flat Work Surfaces	INTSTRUC	50	Arch./Struct	2 / 3
27	9	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-050 Interior Doors	Doors - Overhead	INTSTRUC	50	Arch./Struct	3 / 3
28	10	NE1	Lester B Pearson Cl-Dr Marion Hilliard	01.5-100 Washroom Acce	Urinals	PLUMBING	50	Arch./Struct	1 / 3
29	10	NE1	Lester B Pearson Cl-Dr Marion Hilliard	06.7 Portable	CEILING	PORTABLE	50	Arch./Struct	2 / 3
30	10	NE1	Lester B Pearson Cl-Dr Marion Hilliard	06.7 Portable	ELECTRICAL - DISTR	PORTABLE	50	Arch./Struct	3 / 3
31	11	NE1	Lester B Pearson Cl-Dr Marion Hilliard	06.7 Portable	HALLS	PORTABLE	50	Arch./Struct	1 / 3
32	11	NE1	Lester B Pearson Cl-Dr Marion Hilliard	06.7 Portable	HYDRO MASKS	PORTABLE	50	Arch./Struct	2 / 3

Figure 6.8: Assignment of Daily Inspection Tasks by the Prototype

6.3 Prototype Testing

Once the inspection prototype was developed, it was used on a sample of five TDSB schools and tested extensively by TDSB personnel, who were briefly introduced to the features of the system and who had no prior training. The use of the prototype on an UMPC proved to be beneficial and greatly enhanced both mobility and ease of inspection, as compared to a Tablet PC system. The light weight and bright high-resolution screen were suitable for both outdoor and indoor uses. The touch-screen feature facilitated effortless system use, both with and without a stylus pen. The feedback from TDSB personnel demonstrated the benefits of the proposed system. Little training was required and the prototype exhibited the following abilities:

a. Provide a structured and automated approach to field data collection, including pictures;
b. Incorporate digital drawings as the basis for data storage and review;
c. Utilize reactive-maintenance data to predict the condition of components, thus reducing the frequency of inspections and enabling inspection tasks to be prioritized with respect to the resources available;
d. Predict the condition of components on a yearly basis, without dependence on statistical deterioration models that require individual planning horizons;
e. Save the cost of external inspection contracts by enabling tasks to be completed by a small in-house inspection team; and
f. Facilitate better resolution (higher diversification) of component priorities.

Among the interesting features suggested during the testing of the proposed inspection system was that it be connected wirelessly with the preventive and reactive-maintenance system of the TDSB so that the maintenance history data of the component being inspected can be presented as a guide during inspection.

6.4 Conclusions

This chapter provided a brief overview of the proposed prototype and its use in a case study. Based on the test results, the prototype shows the potential for large cost savings with no negative impact on the existing TDSB processes. If it is applied at a full scale, it would complement the capabilities of the existing system at TDSB. Its added features support better recording of asset conditions using local resources and eliminate the need for expensive outside contracts.

Chapter 7
Conclusions and Future Research

7.1 Summary and Conclusions

Educational facilities are essential for the development of young Canadians and, ultimately, for the prosperity of the Canadian economy. Because many educational buildings are aging, sustaining their healthy operation has become a great challenge, particularly in the light of constrained budgets which complicate decisions about capital renewal projects. Such decisions are highly dependent on accurate condition assessment. The main objective of this thesis is to develop an integrated framework for inspection and condition assessment that can overcome the drawbacks of traditional practices for inspecting and assessing the condition of building infrastructure.

Building networks are complex in nature due to the large number of diverse, interrelated components and systems involved. Thus, fundamental changes related to condition assessment must take place in many areas. The traditional approaches to condition assessment exhibit a high level of subjectivity and dependence on adequate resources (time, money and manpower). This research has, therefore, introduced a novel framework that makes the condition assessment process more structured, less time-consuming, less-subjective, and less costly.

The proposed 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. The framework is focused on process automation to particularly suit large organizations that have limited resources with respect to condition assessment and capital asset management.

Developing the condition prediction and inspection planning system involved the analysis of two years of reactive-maintenance data for a sample of 88 schools from the Toronto District School Board (TDSB). Based on this analysis, the challenges in the capital replacement process were identified, and a unique condition indication system based on available reactive-maintenance data was proposed to reduce inspection frequency and prioritize inspection tasks among available resources. The visual guidance system was the result of a two-stage survey conducted among TDSB professionals. The goal of Stage I of the survey was to provide an understanding of important concerns related to building components. Stage II of the survey involved collecting, sorting, rearranging, and verifying pictures of components at different condition states. The survey results were then combined to form a visual and performance-related guidance system for effective condition assessment. The proposed location-based inspection utilized digital floor plans to mark the condition of components during inspection with the use of portable hand-held devices. This facilitates speedy, one-time recording of data on-site.

Once the three components of the framework were developed, they were combined into an integrated prototype that was tested by TDSB personnel. The prototype's intuitive interface and the need for little training were well received, and demonstrated the following benefits:

a. Provide an efficient and automated approach to field data collection, including pictures;
b. Incorporate digital drawings as the basis for data storage and review;
c. Utilize maintenance data to minimize inspection effort and prioritize inspection tasks;
d. Save the cost of expensive inspection contracts by enabling tasks to be completed by a small in-house team; and
e. Facilitate better resolution (higher diversification) of priorities across the data.

The developed framework is expected to help re-engineer the traditional processes for the condition assessment of building infrastructure as well as the decision-making process for overall capital replacement programs.

7.2 Research Contributions

Based on the proposed development, this research makes a number of contributions:

- *Better understanding of the condition assessment process*: This study has reviewed the research and practice of the condition assessment process. This knowledge was obtained from previous research, survey, and interviews with experts at the Toronto District School Board.
- *Restructuring of the inspection and condition assessment process*: The goal of the study was to restructure the current inspection and condition assessment process for buildings and to overcome most of the traditional problems associated with the process. The

location-based inspection process, the standardized building hierarchy, and the organized method of storing and retrieving pictures have improved the condition inspection process. The visual guidance system decreases the subjectivity involved in condition analysis.

- *Better understanding of the interactions among building components*: The extensive surveys conducted as part of this research provide a better understanding of the way building components interact.
- *Integration of capital renewal and reactive-maintenance data*: The research helped establish the relationship between a component's condition (needed for capital renewal) and the number of reactive-maintenance work orders done for this component per year. Understanding this relationship helps in the prioritization of inspections and hence saves money and time. The standardization of the building hierarchy will improve the sharing of important maintenance data/information, not only among departments within an organization but also among organizations and asset management systems.
- *Better alignment of maintenance strategies with organizational objectives*: The proposed system promotes better alignment of maintenance strategies with the objectives of the organization because a suitable maintenance (repair based versus replacement based) strategy can be identified based on those objectives.
- *Development of a practical condition assessment framework*: The proposed framework makes the process of condition inspection and assessment of buildings more economical, less-subjective, and suitable for less-experienced individuals. The simple user interface in which colour coding digitally marks the location of Good, Fair, Poor, and Critical items directly on floor plans makes the inspection process much faster and more efficient. The portable device (UMPC) facilitates the storage, retrieval, and organization of pictures. Both features allow the whole of the inspection process to be completed on-site.
- *Efficient inspection scheduling*: The proposed automated condition indication system will be easy to use and will therefore make the field inspection process faster and less-costly because it enables family trades to participate. The automated indicators of the condition of a component and the efficient scheduling of existing resources will mean that inspection will be performed only for the components that exhibit contradictory condition data. Thus, inspection can be performed simultaneously at various buildings and the

results sent to the central office. Many fewer experts would thus be involved during the overall process of condition assessment, thereby reducing the cost.

The proposed system will also facilitate the planning of any additional field tests (destructive and non-destructive) that may be needed for some components. These tests are expensive, so efficiency will be improved and cost reduced if decisions can be made in the office about buildings to visit.

- *Less dependence on deterioration modeling*: The automated condition indication system will ensure an accurate prediction of the condition of the building component through the use of the available maintenance data, thus resulting in less dependence on deterioration modeling methods.
- *A visual guidance system that reduces the subjectivity of inspections*: The visual guidance system (pictorial database) will make the assessment process less-subjective and more uniform across multiple domains. In addition, the proposed visual guidance framework will provide permanent documentation of the condition of the asset and enable assessments to be compared at different times, thus providing a permanent record of the asset along its life cycle.
- *Benefits for large owner organizations*: The proposed system will benefit organizations, such as the Toronto District School Board (TDSB), that have a large network of buildings scattered over an extensive geographical area and that have stringent budget for maintenance. Using this system makes the process of condition assessment of the buildings fast and reduces costs.
- *Expandable prototype*: While the study focuses on educational buildings, the system can also be used for other building assets such as hospitals, hotels, offices, and commercial buildings. These assets represent a large portion of the civil infrastructure.

7.3 Future Research

Several potential improvements can be incorporated into the developed condition assessment framework presented in this study, and other areas of research related to the developed system can be explored:

- *Optimum fund allocation*: Asset prioritization and optimum fund allocation can be integral parts of the proposed system. First, standard unit costs for components can be taken from TDSB standard cost tables and used for estimating replacement costs. Then, a flexible fund-allocation model can be developed at the component level. The proposed condition assessment framework can be integrated with other asset management modules (such as deterioration modeling, repair modeling, and prioritization and fund allocation) to formulate a comprehensive asset management system that supports capital renewal decisions.

- *GIS-based reporting*: Visualization of asset management data is very beneficial for identifying relationships in the data. Because assets can be scattered over a large geographical area, Geographical Information Systems (GIS) can add demographic dimensions that will facilitate an understanding of their impact on the condition of the asset and will assist with the consequent decisions. GIS reports can show many details about the entire asset inventory, such as comparative views of condition data for any building system, funding-level comparison, comparisons among the school families, and/or comparisons of elementary and secondary schools.
- *Indoor positioning technology*: Another improvement that can be investigated is the use of indoor positioning technology to facilitate automatic identification of the components that are near the inspector as he/she moves inside the building. Such a system is expected to help building owners who are interested in a replacement-based strategy for improving the condition of their buildings, given budget constraints.
- *Expansion of the visual guidance database*: The visual guidance database could be expanded to include additional pictures of a greater variety of deteriorating components. In addition, databases could be built for more types of components. For example, boilers could have separate pictures for hot water, gas boilers, etc and windows could be further divided on the basis of their type: single sliding, double hung, etc.
- *Increased accuracy of the prediction model:* It is possible to accommodate the "level of confidence" numerically in the condition ranges identified for the HVAC systems in chapter 4 for increased accuracy of the prediction analysis.
- *Enhancement of repair-based strategies*: The results and findings of the survey described in Chapter 5 provide a better understanding of deterioration mechanism, component interrelationships, and repair needs. This understanding could be the starting point for extensive work related to the repair scenario of the asset management system.
- *Wearable inspection tools*: Being hands-free on the site, can help the inspectors to examine the condition of components, and take notes and pictures more effectively.

Hence, the use of wearable computers could be beneficial and hence be explored further for condition inspection purposes.

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Appendix A: Stage I Survey

1. Roofing

Expert's Opinion on Roofing

We ask your help in entering data, based on your experience, related to roof deterioration.

This survey has two simple sheets that will take about 10 minutes of your time.

I. How Various Roofing Conditions Affect the School?

	Level of safety concern (1=Low to 10=High)			Level of school interruption (1=Low to 10=High)			Level of damage to other components (1=Low to 10=High)			**In this condition**, the roof. will likely need to be replaced in how many years?		
If roof is Very Good												
If roof is Good												
If roof is Fair												
If roof is Poor												
If roof is Critical												

II. What are the Main Roof Defects and How Do You Compare their Seriousness?

(If you have all the following problems on one roof section, how is one more important than the other?)

* Please enter a value from **1** to **10** in the grey boxes above (**1** = same importance; **10** = Much more important). Example: a value of 5 in the box marked with a star indicates that Defect 3 (Flashing problems) is 5 times as serious as Defect 2 (Drainage Problems).

List of Roof Defects

				Seriousness Comparison: Membrane Problems 1	Drainage Problems 2	Flashing Problems 3	Hardware Problems 4	(Other, Please specify) 5
1	**Membrane Problems**	Membrane	1					
2	**Drainage Problems**	Drainage	2					
3	**Flashing Problems**	Flashing	3		*jkh i			
4	**Hardware Problems**	Hardware	4					
5	**(Other, Please specify)**	(Other, Please specify)	5					

III Please Indicate the Condition of the Following Symptoms Associated with Roofing Defects.

(You may delete, add more problems or rearrange the given examples).

* Roof Condition: ***G*** = Good; **F** = Fair; **P** = Poor; or ***C***= Critical.

Membrane Problems	Indicated System Condition*	**Drainage Problems**	Indicated System Condition*	**Flashing Problems**	Indicated System Condition*	**Hardware Problems**	Indicated System Condition*
Blistering		Roof Drains Blocked		Corrosion		Corrosion	
Bleedthrough		Inadequate Roof Drains		Paint/exterior finish		Noisy/vibrating hardware	
Ridging		Inadequate Slope		Cracks/broken		Leakage in hardware	
Cracks/torn membrane		Eavestrough/gutter damage		Missing/inadequate		Outdated and obsolete	
Vegetation growth				Lifting up/Large hole			
				Sealant problem			

IV. Please give examples of what and how OTHER SCHOOL COMPONENTS are affected by Roof Leakage?

***For example**: Roof leakage affects the Interiors Finishes of the school. This is because the water through roof leakage penetrates into the ceiling and stains and damages the ceiling tiles/interior paint.*

Example 1: ____

____

____

Example 2: ____

____

____

Example 3: ____

____

____

Example 4: ____

____

____

THANK YOU FOR YOUR TIME AND COOPERATION

2. Windows

Expert's Opinion on Windows

We ask your help in entering data, based on your experience, related to window deterioration.

This survey has two simple sheets that will take about 10 minutes of your time.

I. How Various Window Conditions Affect the School?

	Level of safety concern (1=Low to 10=High)			Level of school interruption (1=Low to 10=High)			Level of damage to other components (1=Low to 10=High)			**In this condition**, the window will likely need to be replaced in how many years?		
If window is Very Good												
If window is Good												
If window is Fair												
If window is Poor												
If window is Critical												

II. What are the Main Window Defects and How Do You Compare their Seriousness?

(If you have all the following problems on one window section, how is one more important than the other?)

Window Defects	Weight (Contribution to Failure)
1. Defects related to Frame	%
2. Defects related to Hardware	%
3. Defects related to Glazing	%
4. Defects related to Aesthetics	%
5. other Defects: ________________________	%
SUM =	***100 %***

III Please Indicate the Condition of the Following Symptoms Associated with Window Defects.

(You may delete, add more problems or rearrange the given examples).

* Window Condition: ***G*** = Good; **F** = Fair; **P** = Poor; or ***C***= Critical.

Frame Problems	Indicated System Condition*	Hardware Problems	Indicated System Condition*	Glazing Problems	Indicated System Condition*	Aesthetics Problems	Indicated System Condition*
Old/worn out frame		Broken hardware		Loss of transparency		Cracked/missing caulking	
Gap in frame		Inoperable hardware		Heavily stained glass		Windows with condensation	
Rust/rot/ corrosion in frame		Worn/aged hardware due to usage		Broken/detached caulking		Loose masonary components or sills	
Paint chipping				Deficient sealant		Paint flaking or chipping	
Seized components				Sealed unit failure		water damaged windows	
						aged/worn out windows	

IV. Please give examples of what and how OTHER SCHOOL COMPONENTS are affected by Window Deterioration?

***For example**: Window deterioration affects the mechanical system of the school. This is because deteriorated windows allow air and water penetration thus increasing the load on the mechanical systems.*

Example 1: ____

____

____

Example 2: ____

____

____

Example 3: ____

____

____

Example 4: ____

____

____

THANK YOU FOR YOUR TIME AND COOPERATION

3. Boilers

Expert's Opinion on Boilers

We ask your help in entering data, based on your experience, related to boiler deterioration.

This survey has two simple sheets that will take about 10 minutes of your time.

I. How Various Boiler Conditions Affect the School?

	Level of safety concern (1=Low to 10=High)			Level of school interruption (1=Low to 10=High)			Level of damage to other components (1=Low to 10=High)			**In this condition**, the boiler will likely need to be replaced in how many years?		
If boiler is Very Good												
If boiler is Good												
If boiler is Fair												
If boiler is Poor												
If boiler is Critical												

II. What are the Main Boiler Defects and How Do You Compare their Seriousness?

(If you have all the following problems on one boiler section, how is one more important than the other?)

Boiler Defects	**Weight (Contribution to Failure)**
1. Defects related to Casing/Housing	%
2. Defects related to Operation of the Boiler	%
3. Defects related to Stacking/Breaching	%
4. other Defects: ________________________	%
SUM =	***100 %***

III Please Indicate the Condition of the Following Symptoms Associated with Boiler Defects.

(You may delete, add more problems or rearrange the given examples).

* Boiler Condition: **G** = Good; **F** = Fair; **P** = Poor; or **C**= Critical.

Casing/ Housing Problems	**Indicated System Condition ***	**Operational Problems**	**Indicated System Condition ***	**Stacking/breaching Problems**	**Indicated System Condition ***
Rust and Corrosion		Inoperable boiler		Damaged or broken stacking / breaching	
Leakage		Outdated fuel supply		Corroded stacking / breaching	
Cracked / broken casing		Refractory damage		Blockage in stack	
Flooding around boiler		Deteriorated burner condition		White salt marks on chimney	
Insulation peel off		Tube damage / blockage		Water stains on chimney	
		Damaged boiler controls			

IV. Please give examples of what and how OTHER SCHOOL COMPONENTS are affected by Boiler Deterioration?

Example 1: ____

____

____

Example 2: ____

____

____

Example 3: ____

____

____

Example 4: ____

____

____

THANK YOU FOR YOUR TIME AND COOPERATION

4. Fire Alarm System

Expert's Opinion on Fire Alarm System

We ask your help in entering data, based on your experience, related to fire alarm system deterioration.

This survey has two simple sheets that will take about 10 minutes of your time.

I. How Various Fire Alarm System (FAS) Conditions Affect the School?

	Level of safety concern (1=Low to 10=High)			Level of school interruption (1=Low to 10=High)			Level of damage to other components (1=Low to 10=High)			**In this condition**, the FAS will likely need to be replaced in how many years?		
If FAS is Very Good												
If FAS is Good												
If FAS is Fair												
If FAS is Poor												
If FAS is Critical												

II. What are the Main Fire alarm system Defects and How Do You Compare their Seriousness?

(If you have all the following problems on one fire alarm system section, how is one more important than the other?)

Fire Alarm System (FAS) Defects	**Weight (Contribution to Failure)**
1. Defects related to Fire Alarm Control Panel	%
2. Defects related to field Units (Fire detectors (smoke and heat) and signal box)	%
3. Defects related to Glazing	%
4. Other Defects: ________________________	%
SUM =	***100 %***

III Please Indicate the Condition of the Following Symptoms Associated with Fire Alarm System Defects.

(You may delete, add more problems or rearrange the given examples).

* Fire Alarm System Condition: ***G*** = Good; **F** = Fair; **P** = Poor; or ***C***= Critical.

Control Panel Defects	Indicated System Condition *	**Field Units Defects**	Indicated System Condition *	**Alarm Devices Defects**	Indicated System Condition *
Old & outdated		Working of pull out stations		Inadequate fire bells	
Name plate of the panel		Inadequate heat and smoke detectors		Audibility levels of horn bells	
Presence/working of fan shut down		Working of heat and smoke detectors		Outdated and obsolete devices	
Presence of sprinkler zone monitoring		Obsolete heat and smoke detectors		Working of strobe light	
		Condition of wire insulation			

IV. Please give examples of what and how OTHER SCHOOL COMPONENTS are affected by Fire Alarm System Deterioration?

Example 1: ____

____

____

Example 2: ____

____

____

Example 3: ____

____

____

Example 4: ____

____

____

THANK YOU FOR YOUR TIME AND COOPERATION

5. Secondary Switchgear

Expert's Opinion on Secondary Switchgear

We ask your help in entering data, based on your experience, related to fire alarm system deterioration.

This survey has two simple sheets that will take about 10 minutes of your time.

I. How Various Secondary Switchgear Conditions (Sec. Swg.) Affect the School?

	Level of safety concern (1=Low to 10=High)			Level of school interruption (1=Low to 10=High)			Level of damage to other components (1=Low to 10=High)			**In this condition**, the Sec. Swg. will likely need to be replaced in how many years?		
If Sec Swg is Very												
If Sec. Swg. is Good												
If Sec. Swg. is Fair												
If Sec. Swg. is Poor												
If Sec. Swg. is												

II. What are the Secondary Switchgear Defects and How Do You Compare their Seriousness?

(If you have all the following problems on one secondary switchgear section, how is one more important than the other?)

Secondary switchgear Defects	**Weight (Contribution to Failure)**
1. Defects related to Enclosure/exterior	%
2. Defects related to Connection	%
3. Defects related to Capacity and Operation	%
4. Other Defects: ________________________	%
SUM =	***100 %***

III Please Indicate the Condition of the Following Symptoms Associated with Secondary Switchgear Defects.

(You may delete, add more problems or rearrange the given examples).

* Secondary Switchgear Condition: ***G*** = Good; **F** = Fair; **P** = Poor; or ***C***= Critical.

Enclosure / Exterior Defects	Indicated System Condition *	Connection Defects	Indicated System Condition *	Capacity / Operational Defects	Indicated System Condition *
Rust & corrosion		Corroded mains		Inadequate main breaker	
Inadequate labeling		Unsafe wiring		Outdated/worn out breaker panel	
Unprotected metering cabinet		Defective main switches		Discontinued replacement parts	
Damage due to nearby activity, water, or rodents		Poor deteriorated or inadequate wiring		Insufficient fuse or breaker interruption capacity	
Vegetation growth		Loose connections due to vibrations		Overloaded panels	
		Small size for new code compliance			
		Deteriorated disconnect switches			

IV. Please give examples of what and how OTHER SCHOOL COMPONENTS are affected by Secondary Switchgear Deterioration?

Example 1: ____

____

____

Example 2: ____

____

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Example 3: ____

____

____

Example 4: ____

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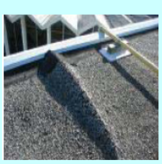
____

THANK YOU FOR YOUR TIME AND COOPERATION

Appendix B: Stage II Survey

Survey on Roofing (Built-up)

Please match the current picture with the following categories and assign the condition accordingly. You may zoom in/out for a better view.

Membrane Problems	Drainage Problems	Flashing Problems	Hardware Problems
Roof with no blisters or ridging	Sufficient number of drain	Slight paint peeling but no	New exhaust fan
			
Good	Good	Good	Good
Windswept gravel near roof perimeter	Water retention on roof surface due to improper slope	Early stage of corrosion	Weeds growing by cooling tower
			
Fair	Fair	Fair	Fair
Bare spot on roof	Damaged & lack of roof drains	Cracked sealant at roof flashing	Corosion at the base flashing
			
Poor	Poor	Poor	Poor
Severe ridging	Excessive ponding due to Inadequate slope	Excessive damaged and missing flashing	Pooling at base of utility penetrations causing extensive leakage
			
Critical	Critical	Critical	Critical

Note: These are sample pictures of a set of 40.

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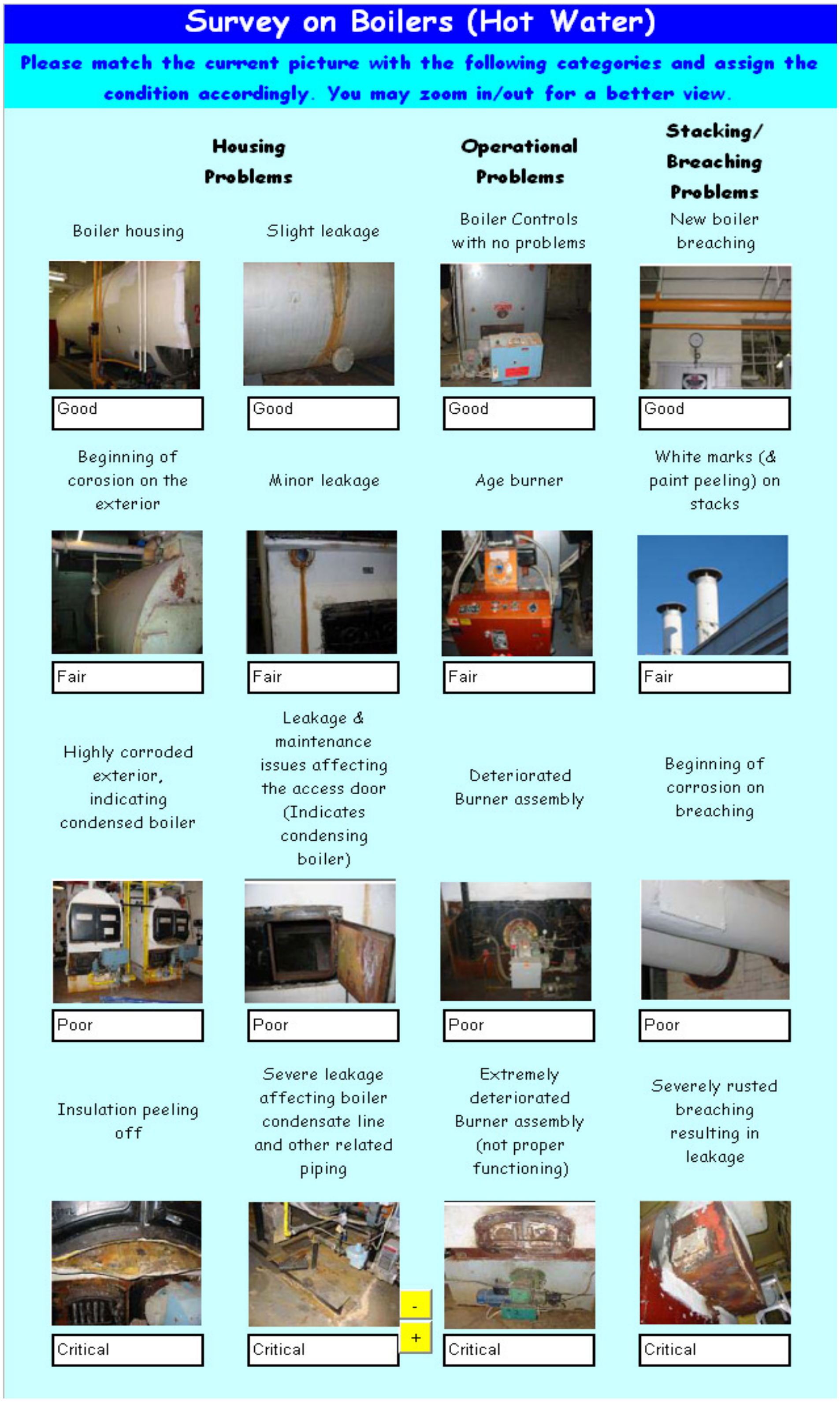
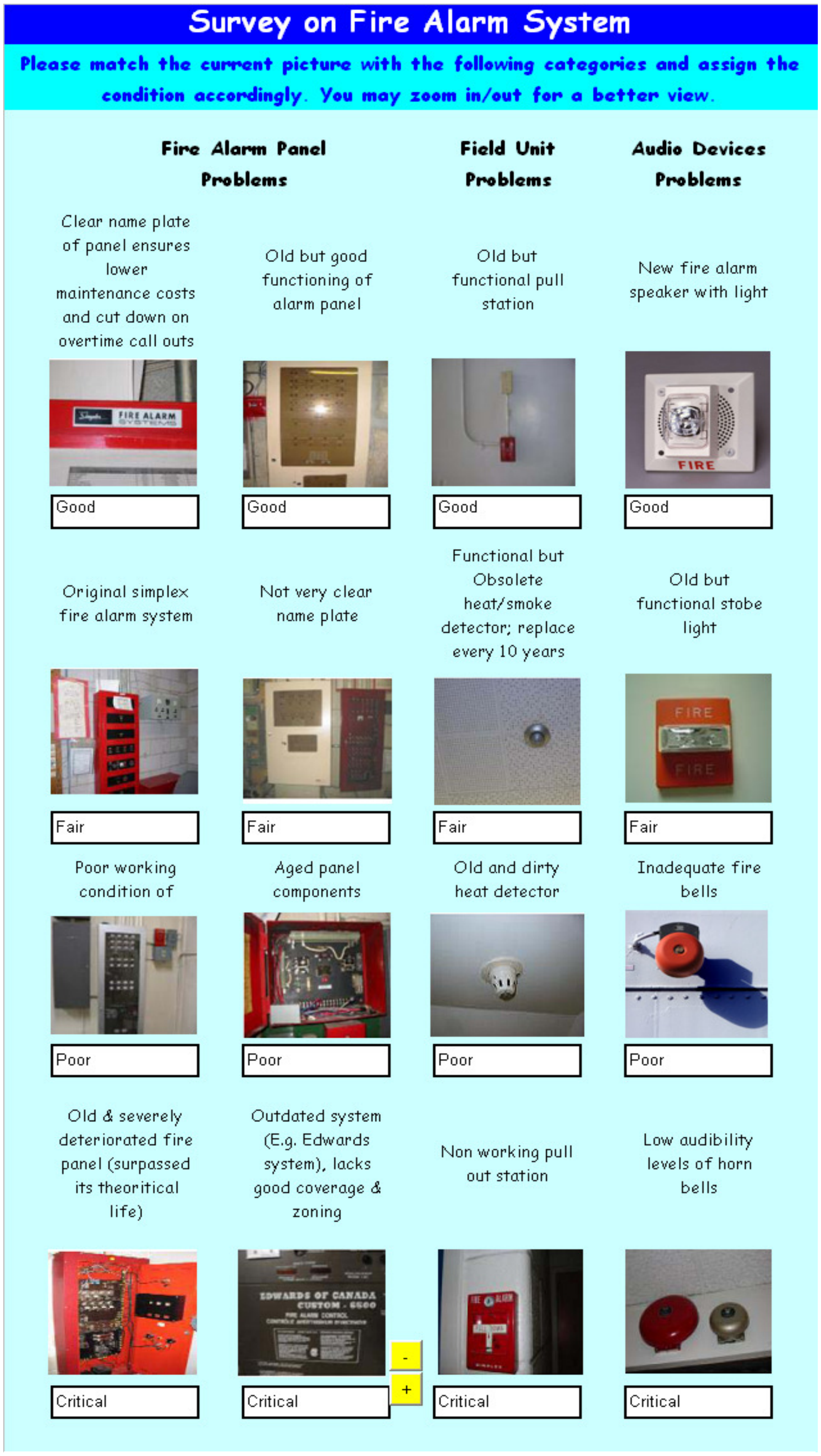


Note: These are sample pictures of a set of 40.



Survey on Fire Alarm System

Please match the current picture with the following categories and assign the condition accordingly. You may zoom in/out for a better view.

Fire Alarm Panel Problems		Field Unit Problems	Audio Devices Problems
Clear name plate of panel ensures lower maintenance costs and cut down on overtime call outs	Old but good functioning of alarm panel	Old but functional pull station	New fire alarm speaker with light
Good	Good	Good	Good
Original simplex fire alarm system	Not very clear name plate	Functional but Obsolete heat/smoke detector; replace every 10 years	Old but functional stobe light
Fair	Fair	Fair	Fair
Poor working condition of	Aged panel components	Old and dirty heat detector	Inadequate fire bells
Poor	Poor	Poor	Poor
Old & severely deteriorated fire panel (surpassed its theoritical life)	Outdated system (E.g. Edwards system), lacks good coverage & zoning	Non working pull out station	Low audibility levels of horn bells
Critical	Critical	Critical	Critical

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Note: These are sample pictures of a set of 32.

Survey on Secondary Switchgear

Please match the current picture with the following categories and assign the condition accordingly. You may zoom in/out for a better view.

Enclosure / Exterior Problems	Connection Problems		Capacity & Operational Problems
Old panel but in working condition with no major problems	Splitter & motor controls in good working condition	Code compliance, no rust, no loose connections or other deterioration	Spare capacity & enough wall space available
			
Good	Good	Good	Good
Inadequate labeling of breaker panel	Aged splitter and motor controls	Small size code for new compliance	Old but in working condition with some spare capacity
			
Fair	Fair	Fair	Fair
Damage due to nearby activty, water or rodents	Poor, deteriortaed or inadequate	Corroded mains	Insufficient fuse or breaker interruption
			
Poor	Poor	Poor	Poor
Unsafe wiring & unprotected metering cabinet	Defective disconnect/main switches	Disconnect switch & starter motors damaged by other ativities like steam leak etc.	Outdated circuit breaker panel (full & over loaded)
			
Critical	Critical	Critical	Critical

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Note: These are sample pictures of a set of 32.